Volume 40
Number 1
2012

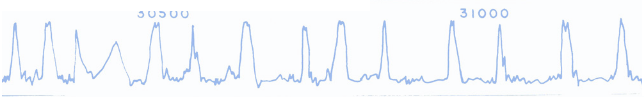
JAAVSO

The Journal of the American Association of Variable Star Observers

Parts A+B

100th Anniversary Edition

- History
- Associations
- Science
- Review Papers



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JAAVSO

The Journal of The American Association of Variable Star Observers

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Part A
of two parts:
pages 1–266

100th Anniversary Edition

History
Associations
Science
Review Papers

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The *Journal of the American Association of Variable Star Observers* is a refereed scientific journal published by the American Association of Variable Star Observers, 49 Bay State Road, Cambridge, Massachusetts 02138, USA. The *Journal* is made available to all AAVSO members and subscribers.

In order to speed the dissemination of scientific results, selected papers that have been refereed and accepted for publication in the *Journal* will be posted on the internet at the *eJAAVSO* website as soon as they have been typeset and edited. These electronic representations of the *JAAVSO* articles are automatically indexed and included in the NASA Astrophysics Data System (ADS). *eJAAVSO* papers may be referenced as *J. Amer. Assoc. Var. Star Obs., in press,* until they appear in the concatonated electronic issue of *JAAVSO*. The *Journal* cannot supply reprints of papers.

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The *Journal* welcomes papers from all persons concerned with the study of variable stars and topics specifically related to variability. All manuscripts should be written in a style designed to provide clear expositions of the topic. Contributors are strongly encouraged to submit digitized text in MS WORD, LATEX+POSTSCRIPT, or plain-text format. Manuscripts may be mailed electronically to journal@aavso.org or submitted by postal mail to *JAAVSO*, 49 Bay State Road, Cambridge, MA 02138, USA.

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Journal of the American Association of Variable Star Observers
Volume 40, Number 1, 2012

100th Anniversary Edition

100th Spring Meeting of the AAVSO, in conjunction with the 218th Meeting of the American Astronomical Society, held in Boston, Massachusetts, May 21–25, 2011

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About This 100th Anniversary Issue

John R. Percy, Editor, *JAAVSO*
Department of Astronomy and Astrophysics, University of Toronto, Toronto ON M5S 3H4, Canada

Welcome to the Centennial Issue of *The Journal of the American Association of Variable Star Observers*! The AAVSO was founded in 1911 by a small group of amateur astronomers, led by William Tyler Olcott, and encouraged by Edward Pickering, Director of the Harvard College Observatory. By 2011, it had become the most important organization through which amateurs can contribute significantly to astronomical research. In media articles about "citizen science," the AAVSO is almost always mentioned.

Initially, the work of AAVSO observers was collected by the Recorder, and made available to researchers as needed, usually in the form of light curves. By the time I became aware of the AAVSO, half a century ago, its work was being reported by Director Margaret Mayall in "Variable Star Notes," in the *Journal of the Royal Astronomical Society of Canada* (I joined the RASC in 1961). Her output was remarkable: she published dozens and dozens of these notes, highlighting both specific and general results of AAVSO observations. Some research, based on AAVSO data, was (and still is) published in other astronomical research journals.

In 1972, *JAAVSO* was launched. On its first page, Director Mayall writes "sixty-one years after the founding of the Association, we now launch an important new project—one we have hoped for and needed for many years—our own *Journal of the AAVSO*. It will be a place where professional and non-professional astronomers can publish papers of interest to the observer...." Our audience continues to be all those who are interested in variable stars, including AAVSO members and other observers, and professional astronomers and students engaged in variable star research. Together, they constitute a special "family" within the astronomical community, making the AAVSO one of my favorite organizations.

Over the years, *JAAVSO* has grown and changed, as the AAVSO has. Most obviously, it is now primarily an electronic journal, though hard copies can be ordered. Happily, therefore, *JAAVSO* is freely available, all over the world. It no longer contains the administrative reports of the Association; these (such as the Director's Report) are found in the *AAVSO Annual Report* and elsewhere on the AAVSO website. The AAVSO's 75th anniversary was marked by a special issue (volume 15, number 2, 1986). Volume 25, number 2 contained the proceedings of an AAVSO session on Mira variables, marking the 400th anniversary of the discovery of Mira's variability. Papers from our 1997 meeting in Sion, Switzerland, were (belatedly) published in volume 35, number 1, 2006. The proceedings of our first truly international meeting were published as a separate book (Percy, Mattei, and Sterken 1992).

In 2011, the AAVSO Centennial was celebrated in several ways, including by the publication of an official history of the AAVSO (Williams and Saladyga 2011), and two meetings—a joint meeting with the American Astronomical Society in the spring (May), and a Centennial meeting in October (the Annual meeting). The Spring meeting included several invited papers related to the history of the AAVSO, presented jointly with the Historical Astronomy Division of the AAS. These, and most of the invited history papers from the Annual meeting, are contained in one section of this Centennial Issue. The history sessions were organized by Dr. Thomas R. Williams, who has provided a short introduction to those papers.

The spring AAVSO-AAS meeting also included two sessions of invited papers on scientific themes relevant to the work of the AAVSO. These sessions were organized by Dr. Matthew R. Templeton, who has provided an introduction to that section.

We also commissioned a set of short science reviews of variable star types, to give a flavor of variable star astronomy at the start of the 21st century. The authors are professional astronomers with special ties to the AAVSO. We thank them for their reviews, and also for their ongoing interest in the Association. I have provided a separate introduction to those review papers.

Finally, there were a large number of papers which were contributed to the two meetings, by members, observers, and other friends of the Association. These reflect the remarkable diversity of the interests and activities of the AAVSO—observation, analysis, instrumentation, education, history, biography, and so on. Most of these papers are contributed by amateur astronomers, who carry out their work voluntarily, as a labor of love.

I close by thanking all the authors of the papers in this issue, Drs. Tom Williams and Matt Templeton for organizing the sessions on AAVSO history and science, Rebecca Turner and the rest of the AAVSO staff for their work in organizing the meetings and other Centennial events. I extend special thanks to the astronomers who review these and all other papers contributed to this *Journal*. These reviewers are normally anonymous, and therefore go unthanked in public. They play an important role in maintaining the standards of *JAAVSO*, and in improving virtually every submitted paper. Last and not least, I thank the production editor of the *JAAVSO*, Dr. Michael Saladyga, Associate Editor Elizabeth O. Waagen, and Assistant Editor Dr. Matt Templeton, for the quality and vast quantity of their editorial work, and their patience in dealing with many challenges in producing a volume like this one, not the least of which is the diversity of content and format of the "raw material." Thanks, Mike, Elizabeth, and Matt!

We hope that all readers will enjoy this collection of papers, and that many of you will order a printed version of the issue. It, along with the official history (Williams and Saladyga 2011), provides an outstanding and lasting picture of an organization that we know and love.

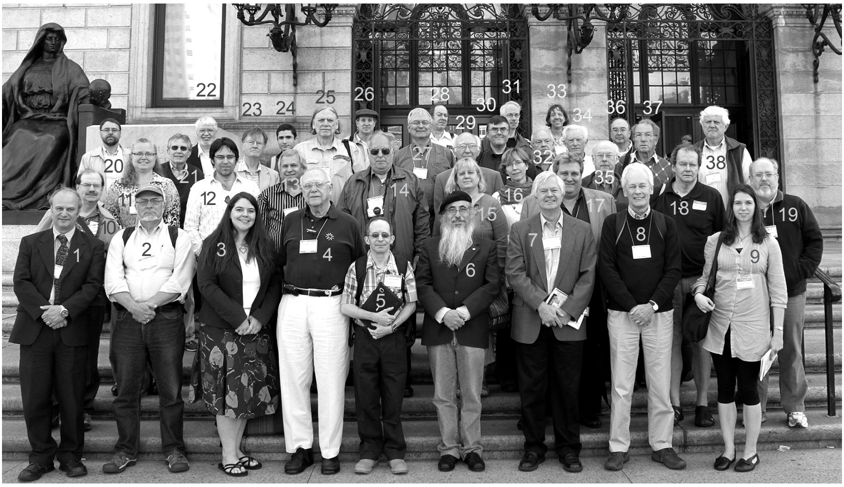
References

Percy, J. R., Mattei, J. A., and Sterken, C. 1992, *Variable Star Research: An International Perspective*, Cambridge Univ. Press, Cambridge.

Williams, T. R., and Saladyga, M. 2011, *Advancing Variable Star Astronomy: The Centennial History of the American Association of Variable Star Astronomers*, Cambridge Univ. Press, Cambridge.

Key to the cover photographs *(from upper left): 7th Annual Meeting of the AAVSO, November 10, 1917; 100th Annual Meeting of the AAVSO, October 4–8, 2011; M. Alberta Hawes, AAVSO Charter Member; AAVSO member/observers Barbara Harris, Mary Glennon, Michael Linnolt; William Tyler Olcott, William Henry, and Leon Campbell at the AAVSO Spring Meeting, 1923; at Mount Holyoke College, South Hadley, Mass., for the AAVSO's 1924 Spring Meeting; AAVSO member observer Shawn Dvorak; AAVSO members and observers at the 100th Annual Meeting—Martha Stahr Carpenter, Seiichi Sakuma, Seiichiro Kiyota, Thomas R. Williams, and Eric Broens. The background image is a portion of the historical light curve of the variable star SS Cygni.*

The 100th Spring Meeting of the AAVSO, Boston, Mass., May 21–25, 2011



The 100th Spring Meeting of the AAVSO, Boston, Mass., May 21–25, 2011

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37	Pierre de Ponthiere
38	Bill Goff

The 100th Spring Meeting of the AAVSO, Boston, Massachusetts, May 21–25, 2011

List of Participants

Martina Arndt	Bridgewater, Massachusetts
Sara Beck	AAVSO HQ, Massachusetts
Gary Billings	Calgary, Canada
David Boyd	Oxford, England
Katherine Bracher	Austin, Texas
Maria Cahill	Fort Myers, Florida
John Centala	Marion, Iowa
Phillip Coker	Colorado Springs, Colorado
Pierre de Ponthiere	Lesve, Belgium
Emily Elert	Brooklyn, New York
Jaime Garcia	Mendoza, Argentina
Pamela Gay	Edwardsville, Illinois
Owen Gingerich	Cambridge, Massachusetts
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Paul Norris	Quincy, Massachusetts
John O'Neill	Rush, Ireland

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Wayne Osborn	Delevan, Wisconsin
Joseph Patterson	New York, New York
John Pazmino	Brooklyn, New York
John Percy	Toronto, Canada
Richard Post	Lexington, Massachusetts
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David Soderblom	Baltimore, Maryland
Jeno Sokoloski	New York, New York
Matthew Stanley	New York, New York
Donn Starkey	Auburn, Indiana
Matthew Templeton	AAVSO HQ, Massachusetts
David Turner	Dartmouth, Canada
Rebecca Turner	AAVSO HQ, Massachusetts
Helena Uthas	New York, New York
Elizabeth Waagen	AAVSO HQ, Massachusetts
Gary Walker	South Yarmouth, Massachusetts
Barbara Welther	Woburn, Massachusetts
Anna Fay Williams	Houston, Texas
Thomas R. Williams	Houston, Texas
Donna Young	Bullhead City, Arizona

Schedule for the 100th Spring Meeting of the AAVSO, in conjunction with the 218th Meeting of the American Astronomical Society, held in Boston, Massachusetts, May 21–25, 2011

Friday, May 20

8:00	a.m.	Council Meeting at Headquarters

Saturday, May 21

12:00	*p.m.*	*registration*
1:00		AAVSO Membership Meeting
2:00		Special Session: AAVSO Paper Session I
7:00		AAVSO Banquet (AAVSO Headquarters)

Sunday, May 22

10:00	*a.m.*	*registration*
9:30		Special Session: AAVSO Paper Session II
1:30	*p.m.*	Special Session: HAD I—Women in the History of Variable Star Astronomy
3:20		Special Session: HAD II—Variable Star Astronomy in Theory and Practice

Monday, May 23

7:30	*a.m.*	*registration*
8:00		AAVSO Poster Session
10:00		Special Session: AAVSO—Astrophysics With Small Telescopes
2:00	*p.m.*	Special Session: AAVSO—Variable Stars in the Imaging Era
7:00		AAVSO Open House

Tuesday, May 24, and Wednesday, May 25

non-AAVSO AAS sessions

The 100th Annual Meeting of the AAVSO, Cambridge and Woburn, Mass., October 5–8, 2011

The 100th Annual Meeting of the AAVSO, Cambridge and Woburn, Mass., October 5–8, 2011

KEY TO THE PHOTOGRAPH

1 Carol J. Beaman
2 Dee Sharples
3 Robert Alan Hatch
4 Yvonne Roe
5 Jaime Garcia
6 Bill Dillon
7 Tom Williams
8 Martha Stahr Carpenter
9 Kristine Larsen
10 Richard “Doc” Kinne
11 Winston Wilkerson-Montout
12 Carmen Wilkerson-Montout
13 Seiichi Sakuma
14 Paul Norris
15 Josch Hambsch
16 James Roe
17 Anna Fay Williams
18 Richard Wagner
19 Scott Tracy
20 Anna Sudaric Hillier
21 Doug Welch
22 Arlo U. Landolt
23 John Toone
24 Alice Moat
25 Seiichiro Kiyota
26 Barry B. Beaman
27 Dan Lorraine
28 Ken Menzies
29 Chris Watson
30 Arne Henden
31 Mario Motta
32 Karen Meech
33 Gary Billings
34 Gerry Samolyk
35 Albert Holm
36 Sebastian Otero
37 Richard Sanderson
38 Jeremy Shears
39 Helmar Adler
40 Barbara L. Welther
41 Lee Anne Willson
42 John Percy
43 Marvin Baldwin
44 Mike Simonsen
45 Matthew Templeton
46 Peter Lake
47 Gerald P. Dyck
48 Will McMain
49 Frank Dempsey
50 Ann Saladyga
51 Ronald Zissell
52 Neil Simmons
53 Charles E. Scovil
54 George Sjoberg
55 Richard Post
56 Tim Crawford
57 Chris Norris
58 Robert Stine
59 Gil Lubcke
60 Louis B. Cox
61 Russell Chabot
62 Frank Schorr
63 Kevin B. Paxson
64 Gordon Myers
65 Shaun Keller
66 Tom Bretl
67 Bill Goff
68 Donn Starkey
69 Nancy Clark
70 Jeff Horne
71 Wayne Clark
72 Henri M. van Bemmel
73 Jerry Horne
74 Chris Stephan
75 Brad Walter
76 Richard Sabo
77 Adrian Ormsby
78 Gary Walker
79 George Emmons
80 Stephanie Slater
81 Horace Smith
82 Paul A. Valleli
83 John Briggs
84 Gary Ahrendts
85 Shelby Delos
86 Patrick Wils
87 Timothy Barker
88 Katrien Kolenberg
89 David Williams
90 Eric Broens
91 Edward J. Los
92 Michael Saladyga
93 Marco Ciocca
94 Sara Beck
95 John O’Neill
96 Joe Patterson
97 Elizabeth O. Waagen
98 Mike Mattei
99 Aaron Price
100 James Cottle
101 Lauren Rosenbaum
102 Ed Guinan

The 100th Annual Meeting of the AAVSO, Cambridge and Woburn, Massachusetts, October 5–8, 2011

List of Participants

Helmar Adler	Danvers, Massachusetts
Gary Ahrendts	Norton, Massachusetts
Charles Alcock	Cambridge, Massachusetts
Leonard Amburgey	Fitchburg, Massachusetts
Marvin Baldwin	Butlerville, Indiana
Mary Lou Baldwin	Butlerville, Indiana
Timothy Barker	Norton, Massachusetts
Barry B. Beaman	Rockford, Illinois
Carol J. Beaman	Rockford, Illinois
Sara Beck	AAVSO HQ, Massachusetts
Gary Billings	Rockyford, Canada
Donna Bretl	Plymouth, Minnesota
Tom Bretl	Plymouth, Minnesota
John W. Briggs	Eagle, Colorado
Eric Broens	Mol, Belgium
Leslie Brown	Waterford, Connecticut
Tom Callinan	Norwich, Connecticut
Martha Stahr Carpenter	Charlottesville, Virginia
Russell Chabot	Oak Creek, Wisconsin
Glen Chaple	Townsend, Massachusetts
Marco Ciocca	Richmond, Kentucky
Nancy Clark	St. Louis, Missouri
Wayne Clark	St. Louis, Missouri
Lou Cohen	Cambridge, Massachusetts
James Cottle	Fiddletown, California
Louis B. Cox	Deep River, Canada
Carole L. Crawford	Arch Cape, Oregon
Tim R. Crawford	Arch Cape, Oregon
Keith Danskin	Amherst, New Hampshire
Sylvia Danskin	Amherst, New Hampshire
Kate Davis	Arlington, Massachusetts
Shelby Delos	Johnston, Rhode Island
Frank Dempsey	Pickering, Canada
Dennis di Cicco	*Sky & Telescope*, Massachusetts
Bill Dillon	Missouri City, Texas
Gerald P. Dyck	Assonet, Massachusetts

continued on following pages

George Emmons	Acton, Massachusetts
Rick Fienberg	Belmont, Massachusetts
Jaime Garcia	Mendoza, Argentina
Miriam Gingerich	Cambridge, Massachusetts
Owen Gingerich	Cambridge, Massachusetts
Bill Goff	Sutter Creek, California
Ed Guinan	Villanova, Pennsylvania
Josch Hambsch	Mol, Belgium
Robert Alan Hatch	Gainesville, Florida
Arne Henden	AAVSO HQ, Massachusetts
Linda Henden	AAVSO HQ, Massachusetts
Dustin Hendrickson	Somerville, Massachusetts
Anna Sudaric Hillier	Lexington, Massachusetts
Albert Holm	Columbia, Maryland
Jeff Horne	Irvine, California
Jerry Horne	San Jose, California
Valerie Horne	Irvine, California
Margarita Karovska Neily	Allston, Massachusetts
Shaun Keller	Lexington, Massachusetts
Richard Kinne	AAVSO HQ, Massachusetts
Seiichiro Kiyota	Tsukuba, Japan
Katrien Kolenberg	Cambridge, Massachusetts
Roger Kolman	Glen Ellyn, Illinois
Peter Lake	Wonga Park, Australia
Arlo U. Landolt	Baton Rouge, Louisiana
Kristine Larsen	New Britain, Connecticut
Daniel Lorraine	Cranston, Rhode Island
Edward J. Los	Nashua, New Hampshire
Gilbert C. Lubcke	Middleton, Wisconsin
Alan MacRobert	*Sky & Telescope*, Massachusetts
Mike Mattei	Littleton, Massachusetts
Will McMain	AAVSO HQ, Massachusetts
Karen Meech	Kaneoeh, Hawaii
Ken Menzies	Framingham, Massachusetts
Alice Carpenter Moat	Orefield, Pennsylvania
Joyce Motta	Gloucester, Massachusetts
Mario Motta	Gloucester, Massachusetts
Gordon Myers	Hillsborough, California
Bob Naeye	*Sky & Telescope*, Massachusetts
Clark Neily	Allston, Massachusetts
Chris Norris	Rosenberg, Texas
Paul Norris	Quincy, Massachusetts

continued on following pages

John O'Neill	Rush, Ireland
Adrian Ormsby	Saline, Michigan
Sebastian Otero	Buenos Aires, Argentina
Joe Patterson	New York, New York
Kevin B. Paxson	Spring, Texas
Arthur E. Pearlmutter	Auburn, Massachusetts
John Percy	Toronto, Canada
Richard S. Post	Lexington, Massachusetts
Aaron Price	AAVSO HQ, Massachusetts
Jamie Riggs	Greeley, Colorado
James Roe	Wentzville, Missouri
Yvonne Roe	Wentzville, Missouri
Lauren Rosenbaum	AAVSO HQ, Massachusetts
Jessica Roy	Canton, Massachusetts
Richard Sabo	Bozeman, Montana
Atsuo Sakuma	Kawasaki, Japan
Nobuko Sakuma	Kawasaki, Japan
Seiichi Sakuma	Kawasaki, Japan
Ann M. Saladyga	Somerville, Massachusetts
Michael Saladyga	AAVSO HQ, Massachusetts
Gerry Samolyk	Greenfield, Wisconsin
Richard Sanderson	Springfield, Massachusetts
Frank Schorr	Lawrenceville, Georgia
Charles E. Scovil	Stamford, Connecticut
Dee Sharples	Honeoye Falls, New York
Jeremy Shears	Tarporley, England
Neil Simmons	Salem, Wisconsin
Irene Simonsen	Imlay City, Michigan
Mike Simonsen	AAVSO Staff, Michigan
George Sjoberg	Duxbury, Massachusetts
Linda Sjoberg	Duxbury, Massachusetts
Stephanie Slater	Laramie, Wyoming
Horace A. Smith	East Lansing, Michigan
Jeno Sokoloski	New York, New York
Connie Starkey	Auburn, Indiana
Donn Starkey	Auburn, Indiana
Christopher Stephan	Sebring, Florida
Chris Stine	Newbury Park, California
Robert Stine	Newbury Park, California
Richard J. Strazdas	Westford, Massachusetts
Vladimir Strelnitski	Nantucket, Massachusetts
Paula Szkody	Seattle, Washington

continued on next page

Matthew Templeton	AAVSO HQ, Massachusetts
John Toone	Shrewsbury, England
Scott Tracy	North Granby, Connecticut
Paul A. Valleli	Burlington, Massachusetts
Henri M. van Bemmel	Keswick, Canada
Arline Waagen	Arlington, Massachusetts
Elizabeth O. Waagen	AAVSO HQ, Massachusetts
Richard Wagner	Ottawa, Canada
Gary Walker	South Yarmouth, Massachusetts
Kathy Walker	South Yarmouth, Massachusetts
Bradley S. Walter	Lockhart, Texas
Christopher Watson	San Diego, California
Doug Welch	Dundas, Canada
Barbara L. Welther	Woburn, Massachusetts
Carmen Wilkerson-Montout	New York, New York
Winston Wilkerson-Montout	New York, New York
Anna Fay Williams	Houston, Texas
David B. Williams	Whitestown, Indiana
Thomas R. Williams	Houston, Texas
Lee Anne Willson	Ames, Iowa
Patrick Wils	Hever, Belgium
Robert F. Wing	Columbus, Ohio
Ronald Zissell	South Hadley, Massachusetts

Schedule for the 100th Annual Meeting of the AAVSO, held in Cambridge and Woburn, Massachusetts, October 5–8, 2011

Tuesday, October 4

8:00 a.m.
Council Meeting at Headquarters

Wednesday, October 5

8:00 a.m. breakfast provided
8:30 a.m. registration
9:00 History Papers Session 1: Women in AAVSO History
10:30 coffee break
11:00 History Papers Session 2: Women in AAVSO History
12:30 p.m. lunch break
2:00 History Papers Session 3: History of Variable Star Organizations
3:30 coffee break
4:00 History Papers Session 4: History of Variable Star Organizations
6:30 AAVSO Leadership Banquet at Headquarters

Thursday, October 6

10:00 a.m.
HQ building dedication and time capsule ceremonies
12:00 p.m. lunch break
5:00 Duck boat tour and lobsterbake

Friday, October 7

8:00 a.m. breakfast provided
8:30 registration
9:00 Membership meeting
11:00 coffee break
11:30 Book reading and signing; musical performance
12:00 p.m. lunch break
1:30 Paper Session 1
2:30 Paper Session 2
7:00 History Papers Session 5: Variable Star Observers

Saturday, October 8

8:00 a.m. breakfast provided
8:30 registration
9:00 Paper Session 3
10:30 coffee break
11:00 Paper Session 4
12:30 p.m. lunch break
2:00 Paper Session 5
3:30 coffee break
4:00 Poster and centennial picture session
6:30 cash bar
7:00 AAVSO Centennial Banquet

The Paper Sessions—photographs of the presenters

History Sessions

Kristine Larsen

Michael Saladyga

Elizabeth O. Waagen

Thomas R. Williams

John Toone

Josch Hambsch

Patrick Wils

Donn Starkey
for Stan Walker

David Williams

Roger S. Kolman
via cyberspace

Charles Scovil

Scientific and General Sessions

Mario Motta

Seiichi Sakuma

Karen Meech

John Percy

Paula Szkody

Robert Hatch

Barry Beaman

Gerald Dyck

Jamie Riggs

Sebastian Otero

Chris Watson

Stephanie Slater

Jerry Horne

Horace Smith

Ed Guinan

Lee Anne Willson

Kevin Paxson

Ed Los

Arlo Landolt

Meeting photo not available:

Caroline Moore
Rodney Howe

History session papers presented at the 100th Spring and Annual Meetings of the AAVSO

Introduction to the History Paper Sessions

Thomas R. Williams
9505 Northpointe Boulevard, Apt. 9304B, Spring TX 77379; trw@rice.edu

The AAVSO Centennial celebration occurred in many parts over the year 2011. But importantly, both the Spring and the Annual meetings (held in May and October, respectively) afforded opportunities to enlarge upon the general themes of the AAVSO's history presented in *Advancing Variable Star Astronomy* (AVSA; Williams and Saladyga 2011). In writing an institutional history like AVSA, it is difficult to incorporate as much detailed information about a large number of people who were active participants in variable star astronomy but not a part of the main flow of the AAVSO's history. Thus "people" became the primary focus for the history sessions in the semi-annual centennial meetings.

That keen interest in presenting more information about little known as well as major players in the history of the AAVSO actually stimulated plans for two separate series of papers: A series on women in the history of the AAVSO, and another series on important variable star astronomers. For these sessions, we solicited papers from our members and from well-known historians and other parts of the academic community where we knew interest in the individuals we wanted to highlight was high. Part of our strategy for the latter section was to couple the biographies with the history of stellar evolution and variable star astronomy to the extent possible.

It was particularly gratifying that the Women in AAVSO History section produced several nice surprises. One of those was the discovery that a biography of Helen Sawyer Hogg was being written and that the author, Maria Cahill, was willing to present a paper for the centennial meeting. Hogg had served as AAVSO president, but also provided important support to the AAVSO in other ways over her lifetime. Another surprise came when Kate Bracher volunteered a nice paper on Anne Sewell Young, another feminine figure from the earliest days in AAVSO history about whom too little was known. The grandest surprise of all, however, was that Kristine Larsen, who agreed to find out what she could about Martha Stahr Carpenter, not only did that but also discovered that Carpenter was alive and could attend the meeting. It was delightful to meet Martha Carpenter, the only president of the AAVSO to serve three consecutive terms in that position. During her term as president, she resisted attempts to relocate the AAVSO out of Massachusetts at the time the association was evicted from Harvard College Observatory (HCO). Carpenter thus preserved an important aspect of our heritage, the location of our headquarters in Cambridge, Massachusetts, near HCO.

The history of variable star astronomy received additional emphasis from historians and astronomers who considered various aspects of the discipline from its origins to modern times. Historian Robert Hatch debunked previously well-accepted understandings about the discovery of Mira as the first known variable star with an appropriate corrective discussion of "discovery" from the historian of science's perspective. That complete paper will appear in two parts in a future volume of *JAAVSO* and appears here only in the form of an abstract. Astronomer Linda French enriched the well-known story of Goodricke and Pigott's searches for, and studies of, variable stars, while historian Matthew Stanley explained in his paper on Arthur Stanley Eddington how surprisingly important the evolution of pulsation theory was to the entire development of stellar evolution theory. Steve Kawaler then carried the story of stellar evolution to modern times. Photoelectric photometry (PEP) received its share of attention when Barry Beaman summarized the earliest work of Joel Stebbins as he developed the equipment and techniques involved, and made important discoveries using them, while John Percy reviewed the history of the AAVSO PEP Committee.

Yet another theme in which we were interested involved the organization of variable star astronomy, recognizing that the AAVSO was by no means the only organized effort in this discipline. Representatives of other well-known associations of variable star observers were invited to participate in the centennial celebration with papers summarizing the history of their own organizations. We were pleased that many of these important associations accommodated our request. John Toone (BAA-VSS), Josch Hambsch (BAV and GEOS), Patrick Wils (WVS), and Stan Walker with Albert Jones (RASNZ-VSS) contributed to these presentations from other organizations, while David Williams reviewed the history of eclipsing binary observation as promoted by others, and eventually as an organized part of the AAVSO's program.

Finally, we were aware that many longer-term members of the AAVSO had stories to relate regarding their vso-ing friends who have passed from the scene. Roger Kolman chose to express those memories of many friends through his own story as a member for nearly a half-century, while Tony Hull focused on just one friend, Clint Ford, as an early supporter of a child's interest in astronomy. Charles Scovil recalled Ford as well as many other members with whom he had contact over his extended service to the AAVSO. Gerry Dyck, on the other hand, recalled an important variable star observer, Frank Seagrave, who was observing well before the founding of the AAVSO but never joined after William Tyler Olcott established our organization a century ago.

I hope you enjoy reading these and many other papers presented in these history sessions as part of the AAVSO's centennial celebration.

Reference

Williams, T. R., and Saladyga, M. 2011, *Advancing Variable Star Astronomy: The Centennial History of the American Association of Variable Star Astronomers*, Cambridge Univ. Press, Cambridge.

WOMEN IN THE HISTORY OF VARIABLE STAR ASTRONOMY

Anne S. Young: Professor and Variable Star Observer Extraordinaire

Katherine Bracher

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Presented at the 100th Spring Meeting of the AAVSO, May 22, 2011; received March 15, 2012; accepted March 19, 2012

Abstract One of the original eight members of the AAVSO, but not well known today, was Professor Anne Sewell Young of Mount Holyoke College. Miss Young taught there for thirty-seven years, and trained many women astronomers during the first third of the 20th century. This paper will attempt to present her life as an inspiring teacher, as well as a contributor of more than 6,500 variable star observations to the AAVSO.

1. Biography

Anne Sewell Young was born in Bloomington, Wisconsin, on January 2, 1871, into a family with many connections to astronomy (see Hazen 1985). Her grandfather, Professor Ira Young, held the Chair of Natural Philosophy and Astronomy at Dartmouth College. The Shattuck Observatory at Dartmouth was built for him, and designed by his older brother Ammi B. Young, a well-known architect. Ira's wife Eliza Adams' father, Ebenezer Adams, also taught astronomy and mathematics at Dartmouth. Ira and Eliza Young had two sons. Charles Augustus Young became a well-known astronomer at Dartmouth and Princeton, where he taught such luminaries as Henry Norris Russell. The younger son, Albert Adams Young, a Congregational minister and Home Missionary, served as a pastor at various churches in Wisconsin, Iowa, and Indiana; he also had an interest in science (geology). Albert married Mary Sewell, who had come from Halstead, England, as a child in 1834. Their two daughters were Anne Sewell Young and Elizabeth Adams Young, who was four years older than Anne.

Anne Young attended public schools in New Lisbon, Wisconsin, and graduated in 1886. In the fall of 1888 she entered Carleton College in Minnesota, which had been founded by the General Conference of Congregational Churches in 1866. Its founder was Charles M. Goodsell, after whom their observatory, begun in 1887, was named. The Goodsell Observatory was quite active, and as early as 1882 began to publish *The Sidereal Messenger*, which in 1893 became *Popular Astronomy*. Although Anne Young completed a B.L. degree at Carleton, she took quite a bit of mathematics and astronomy as an undergraduate.

In the fall of that year she took up a post as Instructor in Mathematics at Whitman College in Walla Walla, Washington. The College had been founded as a secondary academy in 1859, in memory of Marcus Whitman and his wife

Narcissa, early Congregational missionaries to the Oregon territory who had been massacred in 1847. In 1883 it had become a full-fledged college, with sixty students and three senior faculty. By 1892 the faculty of about five all taught a wide range of subjects: Miss Young taught geometry, algebra, analytic geometry, German, elementary rhetoric, mid-prep English, and commercial law during her three years there, and in spring 1894 offered a course in Elementary Astronomy. She also served as Secretary of the Faculty, taking minutes of monthly faculty meetings, and during her first year she founded an Astronomical Club for students. President Stephen B. L. Penrose, who came to Whitman in 1894, described her as "highly admirable for her mathematical ability, her teaching skill and her personal character" (Penrose l935).

In 1895, however, at the end of the school year, she resigned her position for reasons of ill health, and probably returned to her family. By September of 1896 she was back at Carleton, working on a Master's degree, which she received in December 1897. She then spent the spring term at the University of Chicago's newly opened Yerkes Observatory, where she worked with J. A. Parkhurst on photometric work. She continued this collaboration for many years, returning to Yerkes in summers as a volunteer research assistant. In the fall of 1898 she became principal of a high school in St. Charles, Illinois. But the turning point of her career came when she accepted an appointment as Head of the Department of Astronomy and Director of John Payson Williston Observatory at Mount Holyoke College, in South Hadley, Massachusetts. In September 1899 she arrived in South Hadley, where she was to spend the next thirty-seven years of her life (Figure 1). It seems possible that her uncle, Charles A. Young, was involved in her securing this post, as he was a Trustee of Mount Holyoke and a frequent lecturer there.

Mount Holyoke was a venerable and highly respected college for women, founded in 1837 by Mary Lyon. From its inception a brief course in astronomy had been included in the curriculum, and was required of all students until 1888. The Williston Observatory was dedicated in 1881, and provided with an 8-inch Alvan Clark refractor. A classroom was added in 1903; the observatory remains the oldest building on campus. Professor Elizabeth Bardwell taught astronomy from 1866 until her retirement in 1899. Her introductory course was by no means elementary, requiring trigonometry and physics as prerequisites; though in 1895 she added a one-credit non-mathematical course. Seniors could elect a history of astronomy course or a course in practical astronomy; an astronomy major was introduced in 1895. In 1896–1897, Mount Holyoke had 330 students, of whom 61 took astronomy. Thus when Anne Young arrived in 1899 to take Miss Bardwell's place, she found a well-equipped observatory and a firmly established program awaiting her.

At first Miss Young offered the same courses as her predecessor. But in her second year she added an observational course, and she and the students observed Nova Persei 1901. In 1900 she also began keeping daily sunspot records, an activity which was continued at Williston Observatory for at least the next sixty years (it was still being done when I was a student there in the late 1950s.) She soon added a course in celestial mechanics. And in 1902 she began observing variable stars for E. C. Pickering at Harvard College Observatory, an activity which she continued for many years.

In 1905 Miss Young decided to take a leave and pursue a Ph.D. degree; she attended Columbia University in 1905–1906, and worked under Harold Jacoby on the Double Cluster in Perseus, utilizing plates taken in the 1870s by Lewis M. Rutherfurd, a wealthy amateur astronomer and photographer. Her final result was a catalogue of 145 stars, giving right ascension, declination, precession and its secular variation, and magnitudes obtained from measures of star diameters. This dissertation earned her a Columbia Ph.D. in June of 1906.

Dr. Young then returned to Mount Holyoke, to a consistent pattern for the next several years of classes and observations during the academic year, and some time during the summer at Yerkes as a volunteer research assistant. In 1910 she held open houses at the observatory to show Halley's Comet to visitors. And in 1911, as an outgrowth of the variable star work done for Pickering, she was one of eight original members of the AAVSO, founded in that year by William Tyler Olcott. She contributed data to their monthly reports until 1935.

In 1913 a second full-time instructor position in astronomy was added to the department, and this gave Miss Young time to try a new course in General Astronomy, emphasizing recent developments. In its first year Irene Southworth (later Coulton; class of 1915) was the only student to sign up for it; but Miss Young wanted to try it out, so they did it together. Mrs. Coulton recalled in a letter that during the fall Miss Young was ill for some weeks, but gave her written assignments to do and progress reports to make in her absence. The course evidently became a success, as it was continued in subsequent years and expanded to two semesters (Coulton 1980).

The astronomy program remained unchanged during the war years, though Miss Young was in charge of Red Cross work at Mount Holyoke in 1918. She continued to attend meetings of the AAS and AAVSO (Figure 2), as she had done for years, and was elected AAVSO vice-president in 1919 and then President in 1922. In the fall of 1920 her former student Alice H. Farnsworth (class of 1916) joined the faculty as an instructor in astronomy; this marked the beginning of a long and happy association between the two.

In the late summer of 1923 the two of them, along with many other astronomers, traveled to southern California's Catalina Island to observe the total solar eclipse of September 10. Some seventy astronomers set up observing stations at Camp Wrigley, and made elaborate preparations for the much-vaunted good weather of California. But they were all doomed to disappointment, as eclipse day dawned completely cloudy and remained so all day.

However, at Mount Holyoke they soon were preoccupied with plans for the eclipse of January 24, 1925, which would be total in Connecticut, not far from the college. The eclipse would occur during the final examination period, but no tests were scheduled for that day, so that all students could go observe it. Miss Young arranged for Mount Holyoke and Smith Colleges to use the golf links at Plymouth Meadow Country Club of Windsor, Connecticut, and she also arranged for a special train to take students there.

As soon as classes resumed after the Christmas holidays, Miss Young began preparing the students for what to expect. Their chances of clear weather were about 50%; the trip would go regardless of weather, since she knew of occasions where it had been pouring rain ten minutes before totality and yet was clear at the crucial moment. By January 16 about 700 students had signed up to go to Windsor, and another seventy planned to observe at some thirty other places in the path. Pieces of dark film to look through were sold at the college post office for five cents; the train ticket cost $1.31.

On Saturday, January 24, the college was awakened at 5:15 a.m. by the fire alarm bells. An hour later, eight hundred students crowded into trolleys for Holyoke and then onto special trains to Windsor. The partial stages had begun before they arrived. Crowds toiled through the snow to the top of the hill, and stood in four below zero degrees weather to observe, under clear skies. The corona showed long streamers, out to a couple of solar diameters. Everyone saw planets, and some saw the stars of the Summer Triangle. They also remarked on the colors: the deep blue sky, with topaz yellow along the western horizon, and purple tints on the distant hills. Nearly a hundred students subsequently turned in written reports to Miss Young, and some also provided photographs. Helen Sawyer Hogg (class of 1926) remembered later the glorious spectacle and the careful training which Miss Young gave to her observers (Sawyer Hogg 1962).

After this excitement life continued more normally at Mount Holyoke. Miss Young and Miss Farnsworth went to Europe in the summer of 1927, hoping to see the solar eclipse of June 29 in England; but it was cloudy. Miss Young took a well-deserved sabbatical in 1928–1929, and spent it on the west coast as a research associate at the University of California at Berkeley. Her sister Elizabeth accompanied her, and they had a small apartment together. The two spent a few weeks at Christmas in southern California, visiting friends and Mount Holyoke graduates, and going to Mount Wilson. They met many AAVSO members during this year, especially in the San Francisco area, and noted in California considerable interest in astronomy, but not many regular observers.

After this the sisters settled back in at South Hadley, and continued their practice of entertaining students at tea. Miss Farnsworth was on leave in 1930–1931, and her place was taken by Helen Sawyer Hogg ’26. Mrs. Hogg had started at Mount Holyoke as a chemistry major, but upon taking astronomy from Miss Young in her junior year she was converted, and she went on to a distinguished career in astronomy. In the 1930s Miss Young and Miss Farnsworth added some new observational courses, and continued observing occultations, variable stars and sunspots.

On August 31, 1932, a total solar eclipse crossed the state of Maine. This was during the summer holidays, so no major venture like that of 1925 was planned. But Miss Young, Miss Farnsworth, and several others went to an alumna's home in South Portland to see the event. Their chances for good weather were about 50%. Miss Farnsworth went to Douglas Hill, at the Perkins Observatory site, and was clouded out; Miss Young and those who stayed at South Portland had a clear sky and 93 seconds of totality. They saw prominences and a fine corona.

The next few years were Miss Young's last before retirement in 1936. She continued her usual routine of courses, carrying out observations and speaking to amateur astronomy groups. Her last annual departmental report lamented the fact that since students were no longer required to take mathematics, there was an increasing reluctance among many to take anything involving figures. And she concluded by modestly saying that though she had always fallen short of what she hoped to accomplish, what she had achieved was largely due to the support of her co-workers. She was delighted to be able to leave the department in the capable hands of Alice Farnsworth.

In June 1936 she retired, at the age of sixty-five, and became Professor Emerita. She and her sister then returned to the family home in Winona Lake. But in November of 1937, the Misses Young went to Claremont, California, for the winter. By March they had decided they liked it so well that they would move there. They spent the summer of 1938 at Winona Lake, and in the fall began to build in Claremont's Pilgrim Place, a settlement for retired missionaries and their relatives. In 1939 the Indiana house was sold, and they settled in Claremont, where they happily spent the rest of their lives (Figure 3).

Anne Young never did return east to Mount Holyoke. Even in 1948, when the AAVSO met at Mount Holyoke and there was a special ceremony in her honor, she could not attend, but sent a telegram. In 1955 Carleton College gave her an Alumni Award of Merit, for "unusual accomplishments in research and college teaching." But this too was awarded in absentia. In October of 1956 she suffered a stroke, and eventually she and Elizabeth gave up their house and moved into a nursing home at Pilgrim Place, where they had rooms across the hall from each other. Miss Young still kept up her correspondence, even when she had to dictate to others, and she continued to keep in touch with her former students and keep them up to date on each other. On August 15, 1961, at the age of ninety, she died in the nursing home.

2. Conclusion

Anne Young was a thorough, careful astronomer and an enthusiastic and dedicated teacher. Helen Sawyer Hogg (1962; class of 1926) has written that "she impressed me as being devoted to her astronomy students and eager to encourage young women to major in astronomy." Margaret W. Beardsley (1980; class of 1934) noted that she was "a good teacher, an interesting lecturer and an enthusiastic astronomer," and that she and Alice Farnsworth accomplished more in the small Williston Observatory than many other departments did in much better surroundings.

Her students also remembered her as one who took a personal interest in them and their welfare. In several cases when she heard of an illness of one of her students, she paid a visit and offered the services of her own doctor. She was reserved in manner, but warm and sympathetic to those she knew.

Her influence on the astronomy program at Mount Holyoke was profound, and lasted far beyond her own time there. In 1956 we were doing lab exercises (mapping the sunset point along the Mount Tom range, drawing constellations, timing star transits with the meridian circle) which Irene Southworth Coulton (class of 1915) described doing when she was in Miss Young's class in 1913 (Coulton 1980). And students whom she trained have done much to further astronomy at Mount Holyoke and elsewhere. As Margaret Wallace (1980; class of 1916) wrote me, "for me, Miss Young was one of the real stars at Mount Holyoke."

3. Postscript

Miss Young's career and mine seem to have paralleled each other in a number of ways. I grew up in Claremont, California, where Miss Young lived in retirement; indeed, I visited her once there during my years in college. In the fall of 1956 I entered Mount Holyoke College, and took introductory astronomy from Miss Farnsworth. Unfortunately during the Christmas break she suffered a stroke, and was unable to teach thereafter; the college brought in various visiting lecturers to cover the spring semester for us. Two of these were Helen Sawyer Hogg and Dorrit Hoffleit, discussed in other papers in this issue. That spring of 1957 saw the visit of Comet Arend-Roland; I spent much extra time observing the comet, and that along with the exposure to several impressive women astronomers hooked me on majoring in astronomy. After I finished my graduate work at Indiana University, and taught for two years in southern California, I went to Whitman College in Walla Walla in the fall of 1967, and taught astronomy there for thirty-one years. My successor there is Andrea Dobson, one of my former students, as I was to Alice Farnsworth and she was to Anne Young. And so the dynasty continues, with Andrea being Anne Young's academic great-granddaughter.

4. Acknowledgements

I would like to thank Thomas Williams for suggesting this project, and for useful information. I would also like to thank the archives of Mount Holyoke, Carleton, and Whitman Colleges for access to their files, and the various Mount Holyoke alumnae who shared their memories of Miss Young with me.

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Figure 1. Anne Sewall Young, during her early years at Mt. Holyoke College. The photograph, which hangs in the Williston Observatory at Mt. Holyoke, was first unveiled there during the spring meeting of the AAVSO, May 22, 1948.

Figure 2, Anne S. Young with S. A. Mitchell of Leander McCormick Observatory, about 1919.

Figure 3. Anne S. Young with astronomer Alfred H. Joy of Mt. Wilson Observatory, in the garden at Pilgrim Place, Claremont, California, where Anne Young and her sister, Elizabeth, resided. The occasion was a visit by Helen Sawyer Hogg and the Joys in 1956. Photo courtesy of Helen Sawyer Hogg to the author.

The Stars Belong to Everyone: Astronomer and Science Writer Helen Sawyer Hogg (1905–1993)

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Abstract As a scientist and science educator, Helen Sawyer Hogg served astronomy, and especially variable star astronomy, in diverse ways while raising a family. Her long interest in and support of the AAVSO over many years took place in the context of not only that busy scientific and writing career, but also one of personal struggle to achieve parity as a female in a largely male profession. This biographical sketch demonstrates that her path to eventual status as "the Canadian face of astronomy" was both difficult and filled with uncertainty.

1. Introduction

University of Toronto astronomer Helen Sawyer Hogg (AAVSO President 1939–1941; Figure 1) served her field through research, teaching, and administrative leadership. Additionally, she reached out to students and the public through her *Toronto Star* newspaper column entitled "With the Stars" for thirty years; she wrote *The Stars Belong to Everyone* (Hogg 1976), a book that speaks to a lay audience; she hosted a successful television series entitled *Ideas*; and she delivered numerous speeches at scientific conferences, professional women's associations, school programs, libraries, and other venues. Eventually, she became known as the "Canadian face of astronomy" (Faught 2002). This article will illuminate her life and the personal and professional forces that influenced her work.

2. Early educational influences

In a speech given to the American Association of Physics Teachers and the American Physical Society, Helen spoke of childhood years with a family that was

> keenly interested in all aspects of nature. My father took me for walks along the Lowell waterways; my mother collected many things, including minerals; my aunt pressed wild flowers, and they all took me as a small child out at night to see the stars, especially the magnificent constellation of Orion, the only constellation visible

> from these latitudes with two first magnitude stars, and Halley's comet. (Hogg 1985)

Unfortunately, when Helen was only twelve years old, her father passed away; however, he was an astute banker who left his family in comfort. Helen's mother did not have to work and was able to send her daughter to college. Education was a priority (MacDonald 2004b). And when Helen began her college studies at Mount Holyoke, she took her family's love of nature and the stars with her and, briefly, became a chemistry major (Clement and Broughton 1993). However, at Mount Holyoke, the library was adjacent to Williston Observatory, and Helen found herself reading many books on astronomy (Gingerich 1987). Then Helen's professor, Dr. Anne S. Young, took her astronomy students on a special train from Massachusetts to Connecticut to view the total eclipse of the sun. On January 24, 1925, the students stood with "horribly cold feet...almost knee deep in the snow [and] view[ed] the eclipse from the path of totality." Many years later, Helen exclaimed that "the glory of the spectacle seems to have tied me to astronomy for life" (Clement and Broughton 1993). So, Helen's interest in and love of astronomy grew over time but cemented itself on that auspicious day in 1925.

Paving the way for Helen's success in her new-found field was a meeting with noted Harvard astronomer, Annie Jump Cannon, just one year after the eclipse. Shortly after their meeting, Cannon arranged for Helen to continue graduate studies under the Harvard College Observatory director, Dr. Harlow Shapley (Clement and Broughton 1993). Her graduate appointment changed her life. Of her years at the HCO, Helen said:

> My office was next to [Miss Annie J. Cannon's] and for many hours I heard the sound of her voice as she called out the spectral classifications of stars to her assistant, sometimes for many thousands of stars on one 8 by 10 inch plate. I really did not realize at the time that I was myself participating in the start of the major graduate school in astronomy at Harvard or Radcliffe, ...sparked by the dynamic personalities of Cecilia Payne and Harlow Shapley, each of whom was worthy of the term genius in various ways.... Cecilia's astronomical genius was really ahead of her time and it left her with years of frustration that, because she was a woman, she was not receiving fair treatment. Also in September 1926 Frank Scott Hogg arrived at the observatory to begin doctorate studies.... He was able to complete his doctoral work under Cecilia Payne as supervisor in three years and in 1929 he received the first Ph.D. [in] astronomy awarded by Harvard University. My own doctoral degree was in 1931, the third awarded by Radcliffe in astronomy. It was certainly one of the happy circumstances of my life that Frank and

> I were attracted to each other and were married in September, 1930, with many common interests to share. (Hogg 1985)

At Harvard, Helen established her scholarly voice and first collaborated on scholarly work with Shapley, who became her foremost professional confidante until his death in 1971. Helen's other mentor was her beloved husband and colleague, Frank Hogg. By the time she completed her Ph.D., she had already published a dozen or so papers with Dr. Harlow Shapley (Clement and Broughton 1993).

3. Early professional years as scientist, wife, and mother

In 1931, shortly after their marriage, Frank Hogg was hired at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia (Clement and Broughton 1993). According to Helen Hogg,

> In 1924 J. S. Plaskett wrote to Henry Norris Russell asking for a recommendation for an open position at the DAO. Russell noted that "quite the best of the young folks" in astrophysics was Cecilia Payne. J. S. Plaskett responded that "there would be difficulty about the observing end of it with a woman in this isolated place and I think we can hardly consider her." Not till I read this statement did I realize that my superb observing privileges with the 72-inch reflector had been made possible by the automatic presence of a built-in chaperone, my husband. (Hogg 1988)

It is not clear, other than J. S. Plaskett's simple statement, why Cecilia Payne did not receive a job offer. However, Owen Gingerich interviewed Helen in 1987, and she reflected on this critical period in her and Frank's life. According to Helen, Frank, although Cecelia Payne's student, also worked directly with J.S. Plaskett's son, H. H. Plaskett, at Harvard. Frank and H. H. Plaskett had become close. Helen did not indicate that she suspected this relationship was the reason for her husband's employment; however, it seems logical. When the DAO position opened, J. S. Plaskett had more than one qualified candidate; he picked the male astronomer who was qualified, would meet social conventions, was friends with his astronomer son, and would, indeed, bring with him another highly qualified astronomer for free: Frank's wife, Helen.

However, Helen's participation was still limited because, during the Depression, the Canadian Government considered it unconscionable to employ two individuals from one family. Therefore, Helen worked as an unpaid volunteer from 1931 to 1936. She utilized the "72-inch...telescope to search for and study variable stars in globular clusters as a 'volunteer astronomer'" (Clement and Broughton 1993). According to Helen, "I took my first globular cluster plates on September 22, 1931" (Hogg 1988). Globular cluster variable stars, the subject of her graduate research, remained the focus of her interest throughout her astronomical career (Clement and Broughton 1993).

During her years at the DAO, Helen gave birth to the Hoggs' first child, Sally, on June 20, 1932; Helen halted work for five weeks, and resumed observing on July 27th:

> As I was nursing her, it meant that she had to come to the dome with us for the night. This resulted in some world-wide publicity because the Astronomer Royal of England, Sir Frank Dyson paid a visit to the Dome. A jovial individual and traveler and a great story teller, he loved to tell how as he mounted the stairs to the observing floor of the dome he heard a whimpering and exclaimed "What's that!" and [J. S.] Plaskett calmly replied, "Oh, that's the Hoggs' baby in its basket on the platform by the pier." The story has come back to me in various forms, including one in which I was said to let the baby in her basket down on a rope from the Newtonian platform. (Hogg 1988)

In reality, Sally stayed below while her mother stood at the top of the dome in the Newtonian cage and worked. Although Helen remained a volunteer, in 1932, J. S. Plaskett helped her with a grant (Hogg 1988). In the end, Helen's work at the DAO put her in a position to eventually be hired by Dr. C. A. Chant of the David Dunlap Observatory (DDO) and the University of Toronto (UT) (Clement and Broughton 1993).

4. The University of Toronto years

For a year following Frank's employment at the DDO, while she was establishing their new home, she worked as an unpaid volunteer. However, she did not complain and continued publishing all along; and in 1936, Helen was offered a paid position as a research assistant (Clement and Broughton 1993).

Then once the depression passed and Helen was finally employed, few opportunities escaped her. In Toronto, she had a growing family of three children, and she worked hard both as a scientist and as a mother. Although employed by the University of Toronto, Helen worked as acting chair at Mount Holyoke during the 1940–1941 academic year. More than likely, she was chosen because she was a successful and collegial alumna with strong family ties to the area, yet the circumstances regarding that position are unclear. When she returned to the University of Toronto in 1941, she was promoted to a teaching position. It was the onset of WWII. Four researchers from the DDO joined the Canadian armed forces, as Helen described it, leaving only "Dr. R. K. Young, Dr. Frank Hogg, with a heart ailment, myself and Ruth Northcott, who ran the 74-inch telescope nights and taught classes at the St. George campus of the University of Toronto by day.” In 1946, Frank became director of the DDO and a full professor (Clement and Broughton 1993). During the war, many women assumed positions they had not been allowed previously. However, after the war, many women gave them up because they wanted to return to their former lives. It is possible that Helen may have advanced given those historic times, but she was already a trained and experienced scientist. Leaving was not an option for her, and she only received support from Dr. Chant and her husband, Frank.

5. Harlow Shapley and Frank Hogg

In spite of Helen’s professional advancement, through the years, she became exhausted and frustrated with her combined role of astronomer and parent. Helen was a private person, however, who did not openly share her fears or frustrations. But she shared them with the two men she trusted—Frank Hogg and Harlow Shapley. The letters that follow allow us to see Helen as few knew her. In the late 1940s, Helen experienced a strong desire to leave the university and her research at the DDO, work that she loved. In a letter to Shapley on July 25, 1949, she wrote:

> All Spring I have felt very doleful.... I left the Ottawa meetings more depressed than when I went; and the night observing which I have been tackling systematically since my return has served only to convince me once more that I cannot fit in night work with my heavy family responsibilities. In other words, I seem to have reached the end of my tether. I have asked Frank to get me an indefinite leave of absence from my university position here, but he is very much upset at the thought.... Shortly after my return from Ottawa I had a letter from the secretary of the A.A.S. informing me of the Annie J. Cannon award, which of course you know about. In my opinion, this award carries with it a certain amount of responsibility, when made to a person my age, that is. In other words, it does not look so good to take the award and quit! Therefore I have not replied to Dr. Huffer’s letter, but am turning the matter over in my mind. It has probably not crossed his mind that circumstances might make it advisable for me to refuse the award. (Hogg 1949)

This letter points to depression and a sense of overwhelming responsibilities to work and family. When she wrote this letter, she had already consulted her husband who strongly opposed her resignation. So, she turned to Shapley who, in his July 29, 1949 letter, said,

> There is little doubt but what you are undertaking too much in running a family at this critical stage...and doing everything else. A leave of absence from the University work is obviously a good idea; but a study, with astronomical literature in it, and some photographs of clusters and the computing machine—that should not be given up, even if it must be established in one corner of some room at home. And also probably there is some interesting and not too laborious writing about old books that should be done, just to keep the finger in the game until strength and time are less expensive. About that award—don't be silly, even if the weather is hot. The award is made for past accomplishments, and carries with it no responsibility for future activities. Suppose I should commence turning in medals because I have degenerated into being just a blank, blank director, personality smoother, instigator of labors by others. Let's both cheer up. One particular reason for such a resolve is that after fifteen or twenty lectures on cosmogony in the Harvard Summer School I have convinced myself that this is unquestionably the best universe I know of. (Shapley 1949)

Shapley is light-hearted and amusing, coaxing Helen out of her doldrums, while also suggesting a practical, though temporary, solution to her troubles. Shapley and Frank helped Helen persevere through this difficult time, and her work did not suffer. Over the next year and a half or so, Helen continued on, unaware of how much worse her life would become, and in such a short time.

6. A time of loss

When Frank and Helen married, they knew that he didn't have a normal life expectancy; in fact, he couldn't even get life insurance. As a boy, Frank had rheumatic fever, but it had gone undiagnosed for some time and had damaged his heart. In 1941, Frank developed a two-star sextant; quickly, radar superseded it. However, he took the sextant in a small plane to test. As a result, he caught pneumonia, and it damaged his heart even more (MacDonald 2004a).

On January 1, 1951, ten years following his bout with pneumonia, Frank Hogg went into the bedroom to take an afternoon nap. He appeared to be fine that day. But he fell asleep and did not awaken. Helen and all three children were with him at the time. Frank's death was a deep emotional loss for Helen, Sally, David, and James. Fortunately, Helen had prepared. She had an astute business sense, and she had purchased stock, one share at a time, so that when her husband died, she had a nest-egg and knew how to manage her finances. Her and her children's financial future was relatively secure (MacDonald 2004a).

Helen had always been a hard worker, but following Frank's death on January 1, 1951, she threw herself into her work. She was fearful that *The*

Toronto Star would drop Frank's column, which he had written for ten years. Even though the column was established, the agreement Frank had had with *The Star* remained week-to-week. Helen wanted to write the column because she loved writing, particularly for a lay audience, and because she also wanted the income. But it is possible, although it cannot be verified, that Helen longed to continue her beloved husband's column simply because they had been close as husband and wife as well as colleagues, and she hoped to continue the column in his tradition. Therefore, on her behalf, friends appealed to *The Star*'s management, and she was allowed to assume Frank's column at a compensation of $5.00 per week. In her grief and bereavement, Helen remained focused. Fortunately, her children were teenagers and had already achieved some degree of independence (MacDonald 2004a).

Nonetheless, Helen wrote a letter to Shapley on February 7, 1951, just five weeks after Frank's death, expressing her exhaustion between personal obligations and work:

> The past month has seemed impossibly heavy for me with the work that had to be done, but eventually I shall get some of the backlog caught up, and not feel that I am behind with everything. Dr. Heard is the acting head of the observatory. It is my understanding that the new permanent head will be appointed as of July 1 [replacing Frank Hogg]. My own promotion as Assistant Professor has come through simultaneously with a good boost in the salary scale here.... At present I am teaching two courses, which takes me virtually all of two full days in the city. I have the weekly article in The Star, which takes me several hours, but I consider quite vital. Do you know how many astronomical articles have a circulation of 400,000? I think I am making out quite well with the column. I enclose a copy of my first one, which I wrote about Frank. Then I have "[Out of] Old Books" (essays on the history of astronomy, published in *JRASC*), and all fall I had been working hard on a series about Le Gentil from the volumes I got at H.C.O. in November. This particular job ran into a hundred or more hours, and I am struggling for time to get it in final shape for three installments in the Journal. Then there are the usual meetings, long distance visitors...which cut in to time, not to mention household activities. I am well along with the settlement of Frank's estate, and have written about 200 acknowledgements so far. The time that is left from the above activities I can spend on globular cluster research. The past month there has been none left. But I think this state of affairs will alter markedly the first of April when lectures stop. I hope so. I am wondering if there is any chance that I can get over to Michigan to hear you, as I would certainly enjoy a chat with you. (Hogg 1951a)

In spite of her dedication, Helen found herself caught up in personal and professional obligations that kept her from her research. At first glance, her letter appears matter of fact, yet it is dotted with phrases like "impossibly heavy" when describing her work; "struggling for time" in reference to her writing for "Out of Old Books"; and "200 acknowledgements" when referring to correspondence resulting from her husband's death. Of course, with three teenage children, there's much not said in this letter. Noticeably, Helen speaks positively of her writing for *The Star*, "which takes me several hours, but I feel is quite vital.... I think I am making out quite well with the column."
Then, after twenty years of work in the field and fifteen years with DDO and UT, she received a promotion to assistant professor, and she mentions this to Shapley without complaint. Frank received full professorship in 1941; however, he had worked only a few years longer than she and was not known for his research. Helen wrote to Shapley on April 14, 1951, and then, again, on May 17th: But she still felt overwhelmed, expressing both gratitude with those who had proved their friendship and frustration with those who had not (Hogg 1951b, c).

This was a season of loss for Helen. Although generally healthy and vital, along the way, she had her own health problems. In 1946, she had a hysterectomy. In 1952, following Frank's death, she became very ill with serious bowel obstructions. However, while in the hospital, her daughter, Sally, stated that in a hushed, croaked voice, her mother said, "I have to write the column" [for *The Star*]. Helen was terrified if she missed a week of her column, *The Star* would drop her. So, she wrote that week's column from her hospital bed (MacDonald 2004b). Although it has been impossible to legitimize Helen's fear of being dropped, her concern was clearly confirmed by her daughter, Sally, who served as her mother's typist for several years.

From 1949 to 1953, her frustration with her work-related life and responsibilities only increased, as read in her March 3, 1953, letter to Shapley:

> This has been one of the dreariest winters I ever lived through. I think I have never in my life hated my work as I have this year. (This of course is confidential, as I am not yet willing to go on public record as an astronomy-hater.) This has been due to an unfortunate combination of a variety of circumstances. No one person is to blame for the sum total. But the past several months I have been driven more and more toward what appears to me now as an inescapable conclusion, namely that I never will be in control of my life here. I am battling too many separate things that I do not like, and I will never be able here to feel that the game is worth the struggle. It is still my hope to remain in Canada two more years, until James finishes Grade XIII at Richmond Hill high school.... I have started a separate bank account into which I am pouring a substantial sum of cash reserves. All this is preparation for the fact that I propose to

> work through one more academic year here, which I agreed to do some time back, and then for the following year, beginning July 1 1954 I intend to be as free as the proverbial birds of the air. I intend to keep on with my Star column as long as the editors will take it, because that is still pure enjoyment for me, and provides a small bit of income as well. I have felt better in my mind since I embarked on a definite course of action. I am going to the bank this noon to make my March deposit on my F. F. (Freedom Fund). All the above is super-confidential as I have discussed this matter with no one here. As you are probably aware I am not given to discussing my problems with a dozen or more friends. I do not intend to announce my plan here until next fall, which I consider fair notice. (Hogg 1953a)

Just two years following her husband's death, she was ready to leave her work at UT and DDO—leave astronomy altogether—except for her column. In the numerous interviews, no one expressed knowledge of Helen's despair. A lack of control over one's destiny can, indeed, prove the most frustrating of all. She does not, however, elaborate over the situation(s) and indicates that the problems come from a number of directions.

Shapley returned Helen's letter with a lengthy one of his own, and he did so within the week, thus dated March 9, 1953:

> Since you write me with confidence I can reply in an equally confidential manner from your old school. Things are not going well here. It has been the unhappiest of the thirty-two years I have spent in this institution.... All was sweet and rosy until I walked out of the administrative picture with the resolve and expectation of having nothing more to do with the administration here. The past should not govern the future. I have stuck with my resolution, of course.... I shall send you a copy, if I can find one, of my last report as Director. It will remind you that this was, and has been, up to now, a nice place! And now here comes the most important paragraph of this confidential communication. Almost certainly within two or three months a new director will be chosen. Mr. Conant has left the University permanently. There will be a new president.... I am hopeful not only that Harvard's eye-hold in the southern hemisphere may be in part retained, but also that the Harvard Observatory friendly spirit of past years can be rescued. Instead of those foregoing paragraphs I should have written you my regret and also my astonishment at the general tenor of your letter, I sympathize with you. (Shapley 1953)

Within this letter Shapley responds with his own departmental "woes," reflecting fondly on a time when the H.C.O. was a respected and congenial unit, and he provides his former student with words of understanding and consolation.

7. The tide turns

Just days following Shapley's response on March 24, 1953, the tide turned for Helen, and she writes that Dr. Baade offered her a summer vacation job in 1955: "especially since Frank's death, I have become a globular cluster on a desert island. I need more company with other globular clusters.... Dr. Baade does not know me personally very well, and of course he did not realize he was giving my dejected spirits a real lift!" (Hogg 1953b). Helen was twirling many plates in the air when Frank Hogg died, and it finally caught up with her. Dr. Baade's offer gave her something concrete to hold onto.

Just two years later, she was offered a year-long position at the National Science Foundation (NSF) (Hogg 1955). From September 1955 to June 1956, Helen was Program Director of the National Science Foundation in Washington, D.C. Even though UT had been unhappy with her departure, when she returned from Washington, she was offered a better appointment; her daughter, Sally MacDonald, speculated that her mother took the NSF position not only out of interest, but to hedge against struggles at UT (MacDonald 2004b). Yet, this isn't evident in her letters to Harlow Shapley. In the past, Helen had struggled with the university enough to consider leaving. From this point on, however, she remained entrenched in the University of Toronto and in her teaching and research.

8. Influence

Over the years, Helen wrote a variety of articles (for professional and lay readers) for the *Journal of the Royal Astronomical Society of Canada* (*JRASC*). In addition to her teaching at the University of Toronto, Helen's column in *The Star*, her book, and her television series exemplify her commitment to education. At the time of Helen's death in 1993, the president of the RASC, Peter Broughton, said, "But perhaps her greatest memorial is the appreciation of a larger universe which her popular writing instilled in thousands of ordinary Canadians" (Pipher 1993). Because of Helen's public writings, she became a well-known name in Canada. According to Helen's former graduate student, Christine Clement (2004), Helen said, "We women need to stick together," and she demonstrated this belief by mentoring her students and modeling the relationship that she and Shapley held.

In January 1993, Helen, Dr. Robert Garrison, and other scientists from UT (primarily female), created a film, *Discovering Science*, geared toward late elementary and middle school girls. One of the movie's final scenes is of young, middle-school-aged girls sitting around Helen and listening to her talk about the pursuit of knowledge, in general, and science, in particular. Helen looks at the girls, smiling, and says, “Not to know what’s beyond is like spending your life in the cellar, being completely oblivious of all the wonderful things around us” (Garrison 2004).

On the morning of January 25, 1993, Helen had a two hour taping session at the DDO. The evening of that last taping, Helen felt that she had made a small error, and she called the director to ask him to correct it. She became ill early the next morning, and she passed away two days later, January 28, 1993 (MacDonald 2004b; Garrison 2004).

9. Conclusion

Dr. Helen Sawyer Hogg’s dedication was evident to all. She took more than 2,000 photographs, discovered hundreds of variables, and published more than 200 papers. Her knowledge of the night sky was phenomenal. Her series of catalogues, *Variable Stars in Globular Clusters*, are valuable reference sources that are frequently cited in the literature. She published three editions: in 1939, 1955, and 1973, and was working on the fourth at the time of her death. Even in her final days, she remained involved in attracting women to the sciences, as in her participation in a video, *Discovering Science* (Clement and Broughton 1993; Univ. Toronto Women’s Assoc. 1993). A significant reason for her success, no matter her gender and the attitudes surrounding her, was persistence.

If Helen had protested and objected too strenuously to the annoying everyday inequities, they would have consumed her personal and professional life. Instead, she focused on her own goals and accomplishments because, as a child, her family taught her to appreciate the science they could see along a wooded road or in the stars of a dark night’s sky. Then, as a young college student, teachers and female scientists such as Anne S. Young and Annie Jump Cannon provided inspiration and direction. Once an astronomer, Helen’s husband, Frank, refused to let her quit, and her mentor and friend, Harlow Shapley, provided an enduring and supportive friendship. Within this framework of education, friendship, and family, Dr. Helen Sawyer Hogg succeeded in her beloved field of astronomy.

10. Acknowledgements

The archival materials researched for this article include Helen Sawyer Hogg’s personal correspondence, diaries, and notes; drafts of her articles, public addresses, and drawings; four complete drafts of her book, *The Stars Belong to Everyone*; thirty years of her weekly column in *The Toronto Star*; transcripts from her eight-week television series, *Ideas*, as well as interviews with various friends, family members, former colleagues, and students. Because of its personal nature, this article is based largely on personal letters and interviews.

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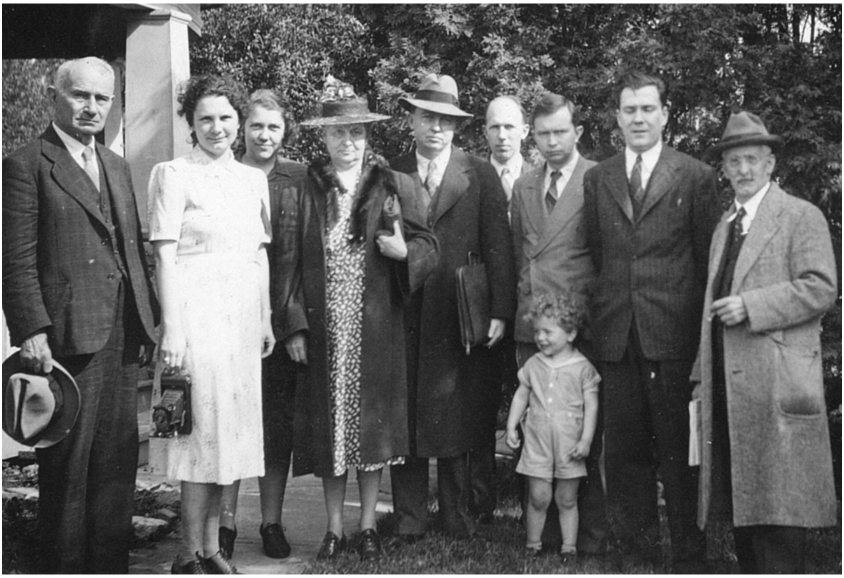

Figure 1. Helen Sawyer Hogg is second from left in this photo from the June 1940 meeting of the AAVSO held in Toronto. Pictured from left: Eugene Jones (AAVSO member/observer), HSH, Margaret Mayall (HCO/AAVSO), Martha and Harlow Shapley (HCO), R. Newton Mayall (AAVSO), Frank Hogg (DDO) and son David, Clinton B. Ford (AAVSO), and Leon Campbell (HCO, AAVSO Recorder).

Variable Stars and Constant Commitments: the Stellar Career of Dorrit Hoffleit

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Abstract The career of professional astronomer and AAVSO member Dorrit Hoffleit is summarized, highlighting her myriad contributions to variable star astronomy.

1. Early life

The daughter of German immigrants Fred and Kate Sanio Hoffleit, Ellen Dorrit Hoffleit was born on her father's farm in Alabama on March 12, 1907. According to Dorrit, her father named her Ellen, her mother named her Dorrit, and in her words, "the woman in the house always has her way" (Larsen 2009). After a suspicious fire destroyed the family farmhouse when Dorrit was still an infant, Fred moved the family to New Castle, Pennsylvania, where he had been working as a bookkeeper for the Pennsylvania Railroad. The marriage eventually fell apart and Fred moved back to the farm by himself when Dorrit was nine years old.

Dorrit recounted that watching Perseid meteors with her older brother Herbert was an important step towards becoming an astronomer (Hoffleit 1994). As a child, Dorrit fell into her brilliant older brother's shadow, facing constant comparisons from teachers who were impressed with his natural talent for languages. Dorrit was deeply proud of her brother, who received a Ph.D. from Harvard in Classics at the young age of twenty-one, and subsequently became a professor at the University of California, Los Angeles. However, she later explained that "The contrast between my brother and me is an exemplification of the childhood tale of the tortoise and the hare. Herb learned quickly and achieved early in life. I was slow but deliberate and finally made the grade. It is hard to say whose influence was the greater on our respective students" (Hoffleit 1996).

2. Education and first astronomy work

Dorrit was sent to Radcliffe College by her mother "so that her brilliant son wouldn't be ashamed of his 'dumb' sister" (Larsen 2009). At Radcliffe, Dorrit became a mathematics major as Radcliffe only offered two astronomy courses at the time. Dorrit experienced her first taste of independent research quite by accident at Radcliffe when, after completing an assigned transit experiment at Harvard's student observatory, she continued to use the instrument to observe the motion of Polaris relative to the crosshairs. For her, it was a valuable learning experience, but she later wrote "I don't think my professor appreciated the educational value of that experiment. I think I got a lot more out of the pole star than I did out of what the thing was intended for. So you see, independence wasn't appreciated even then" (Larsen 2009). Dorrit graduated from Radcliffe cum laude in 1928 and began taking graduate classes at Radcliffe while looking for work. Through a classmate she landed a job as a research assistant at the Harvard College Observatory (HCO) for forty cents per hour, half of a man's salary. She turned down a higher paying statistician job to work there, and several times subsequently turned down other, higher paying offers because of her growing love for the HCO and respect for its Director, Harlow Shapley, whom Dorrit has lauded for encouraging independent thinking (Larsen 2009). Her original position was working as an assistant to Henrietta Swope, daughter of the president of General Electric Company. Henrietta had discovered a large number of variable stars, and her father was so proud of her that he funded the assistant position that Dorrit filled. Dorrit proved herself to be an expert discoverer of variable stars as well, finding approximately 1,200 while at Harvard.

At Harvard Dorrit came into contact with the American Association of Variable Star Observers (AAVSO), an organization of amateur and professional astronomers that had been founded in 1911 by variable star observer William Tyler Olcott in order to help the Harvard College Observatory collect observations of variable stars. Dorrit became an official member of the organization in 1930, and a life member in 1943 (Henden 2006). Of her eventual 450+ publications, her first two (published in 1930) were directly related to variable stars: the first was on variable stars in Centaurus, and the second was a collaboration with AAVSO Recorder Leon Campbell on the color curve of the variable star RV Centauri. Thus began Dorrit's lifelong love for the AAVSO and its members, an organization which she once explained to this author was "my favorite" and "the friendliest organization that I'm aware of, at least in astronomy" (Larsen 2009).

Dorrit completed a M.A. in Astronomy from Radcliffe in 1932, under the tutelage of meteor expert W. J. Fisher, as she put it, "the highest degree for which I felt qualified" (Hoffleit 1992). She continued her work on variable stars during the day and worked on independent research projects at night on her own time. A question that especially intrigued her was the possibility of compiling light curves for meteors (Hoffleit 2002). This led to a pioneering study of the light curves of meteors using the accidental photographs of meteors in the Harvard plate collection. She brought her completed paper to Shapley, who submitted it for publication (Hoffleit 1933) and then called Dorrit into his office, where colleague Bart Bok was also waiting. As Dorrit described it, Shapley said, "'We were wondering why you were not continuing to work for your Ph.D. Go back to your office and think it over.' I had never been particularly bright, and this was the greatest expression of confidence in my abilities I had ever heard" (Hoffleit 1987). With more prodding from Bart Bok, Dorrit went back for her Ph.D. at Radcliffe, which she completed in 1938 with work on determining the absolute magnitudes of stars from their spectra. Part of this work was published in the *Proceedings of the National Academy of Sciences* (Hoffleit 1937). Her thesis was awarded the Caroline Wilby Prize for the best original work in any department by a student that year.

3. Astronomy career at Harvard College Observatory

Dorrit continued her work at the HCO as a research associate and then astronomer with permanent appointment, continuing her research on variable stars and other astronomical objects. She came into contact with some of the biggest names in astronomy and made a reputation for herself as a diligent worker. For example, Ejnar Hertzsprung sent her so many requests for observations of variable stars that Shapley had to finally put his foot down because it was taking too much time away from Dorrit's Harvard assignments (Hoffleit 2002). However, Shapley did continue to funnel some individual requests for variable star observations to Dorrit. In a classic example of her sense of humor, she immortalized a request from Mount Wilson astrophysicist Rudolph Minkowski, for verification of a supposed nova, in a poem included in the pamphlet A*AVSO Humor* (Hoffleit and Overbeek 1984), which concludes

> *On a plate of the given date / This lustrous star did glare at me;*
> *But when another plate I searched / The culprit from its place had lurched!*
> *To one old almanac it jolted me / And there the planet Uranus did be!*

At Harvard, Dorrit met and worked with many of the now-famous female "computers" and astronomers, including Antonia Maury, Annie Jump Cannon, and Cecilia Payne-Gaposchkin, all of whom made contributions of their own to variable star astronomy. But her favorite was undoubtedly Antonia Maury, with whom she became good friends (Larsen 2009). After Antonia's death, Dorrit became a champion for her and the rightful place of her work in astronomical history, and wrote numerous articles about her friend. In her later years, Dorrit frequently reflected upon her experience working with these women, and in works such as *Maria Mitchell's Famous Students and Comets Over Nantucket* (Hoffleit 1983), *Women in the History of Variable Star Astronomy* (Hoffleit 1993), and *The Education of American Women Astronomers Before 1960* (Hoffleit 1994) illuminated the important role played by women in astronomy. She also began writing popular level articles on astronomy, including work as an unpaid volunteer for *Sky & Telescope* magazine, authoring a column from 1941 to 1956. These short "News Notes" articles on recent discoveries and astronomical events numbered several per monthly issue, with the final total of nearly 1,200 individual items over her run.

During World War II, Dorrit, like many Harvard astronomers, became involved in "war work." She felt more compelled than most to become involved because of her German heritage, and because during World War I young classmates considered her one of the enemy (Hoffleit 2002). In 1943 she took a leave from Harvard and began work at the Aberdeen Proving Ground in Maryland, preparing aircraft firing tables. There she found herself in a private war against gender discrimination. As an academic with a Ph.D., she was clearly eligible for a professional rating but was instead relegated to a subprofessional class even though she was assigned professional class work. This led to a conflict which Dorrit rates as a defining experience in her career. Dorrit eventually won her "war" with the military, achieved her deserved rank, and after the war returned to Harvard, but continued as a consultant at the Proving Ground until 1961 (see Hoffleit 2002).

4. Dual careers: Yale and Directorship of the Maria Mitchell Observatory

Dorrit's life was drastically changed by Shapley's retirement from Harvard in 1952. As she has described it, his replacement, Donald Menzel, did not apparently value independence and, much to her horror, began discarding sections of Harvard's unique and valuable photographic plate collection in order to make more office space (Hoffleit 2002). He also played an important role in the AAVSO's eviction from Harvard, a defining event in the history in the AAVSO. (For a more balanced historical view of these events, see DeVorkin 2006, and Williams and Saladyga 2011.) Dorrit believed its eviction from HCO to be the AAVSO's "greatest blessing in disguise," for it led to the AAVSO becoming "an important independent research organization" (Hoffleit 2002).

In spite of having a permanent position at Harvard, Dorrit was forced to follow her conscience and "defected" to Yale in 1956 where she worked on large astrometric catalogue projects and where, to her unhappy surprise, she was not afforded the same independence she had enjoyed at Harvard. In her own words, "when I came to Yale, boy that was a revelation" (Larsen 2009). Fortunately, at the same time, she was offered the Directorship of Nantucket's Maria Mitchell Observatory. Due to the financial situation of the observatory, she held a split six month/six month appointment between Yale and Nantucket.

Dorrit's two decades on Nantucket allowed her to encourage a new generation of astronomers through her summer variable star research program for undergraduates. Over the years 102 young women (and 3 young men) conducted research on approximately 650 variable stars, taking and analyzing photographs, identifying variables, and determining light curves. The result was over 200 new or revised periods (Mattei and Saladyga 1999). Dorrit proudly noted in her autobiography that over 100 papers were presented by her students at AAVSO meetings, and many of these presentations were published in the *Journal of the AAVSO* (Hoffleit 2002). In many ways the summer program modeled a professional research institution, including weekly seminars and invited speakers. The success of this program goes far beyond the number of papers and presentations it yielded, for as Dorrit noted, at least thirty-five of her former students became professional astronomers and in her words “their achievements are a joy to behold” (Hoffleit 1987). To this day, being called “one of Dorrit’s girls” is considered a supreme honor.

One of Dorrit’s most beloved “girls” was Janet Akyüz Mattei, who assumed the responsibility of hosting the October 1969 meeting of the AAVSO on Nantucket at the last minute when Dorrit was unable to travel back to the island due to extreme fog. As Dorrit has often recounted, “my girl Janet had done such a marvelous thing running the meeting for me that when Margaret Mayall [Director of the AAVSO] was looking for an assistant…I got the two of them together again and Margaret of course grabbed Janet…and then when Margaret was ready to retire there were a half a dozen people who wanted her job and [Janet] was unanimously elected to that job, all because of the Nantucket fog” (Larsen 2009). It should be noted that Janet also made an equally deep impression on a young AAVSO member at that meeting, Michael Mattei, who became her husband.

Dorrit remained an untenured research associate and astronomer at Yale (supported entirely through grants—a feat she was especially proud of) even after her “official” retirement in 1975. Her main contributions at Yale include the first paper on the light variability of quasars (Smith and Hoffleit 1963), catalogues containing the proper motions of 30,000 stars (Hoffleit 1967–1970), and the third and fourth editions of the *Bright Star Catalogue* and its *Supplement* (Hoffleit 1964; Hoffleit and Jaschek 1982; Hoffleit *et al.* 1983).

5. Career achievements

Over her career Dorrit received numerous awards, including the Graduate Society Medal, Radcliffe College (1964), the Alumnae Recognition Award, Radcliffe College (1983), the Wedgwood Medallion of the Coat of Arms, Yale University (1992), the Glover Award, Dickinson College, Pennsylvania (1995), the Maria Mitchell Women in Science Award, Nantucket Maria Mitchell Association (1997), the George van Biesbroeck Award from the University of Arizona for outstanding service to astronomy (1988), the Annenberg Foundation Award from the American Astronomical Society for “service to the community in education” (1993), and the AAVSO’s William Tyler Olcott Distinguished Service Award (2002). She received honorary doctorates from Smith College (1984) and Central Connecticut State University (1998), and was inducted into the Connecticut Women’s Hall of Fame (1998). Asteroid *Dorrit* (3416) was named in her honor (1987).

Dorrit’s service to astronomy is impressive and wide-reaching; her service to variable star astronomy was perhaps nearest and dearest to her heart. Of her approximately 450 publications, 41% were related to variable stars, and over fifty were published by the AAVSO (Hoffleit 2002). She served the AAVSO in many capacities, including President (1961–1963) and Council member (1943–1945, 1954–1958, 1977–1981, 1989–1993), hosting five AAVSO meetings while Director of the Maria Mitchell Observatory, and serving on the editorial board of the *Journal of the AAVSO*. She was undoubtedly the organization's greatest cheerleader (Figure 1).

In honor of her lifetime of accomplishments, Yale University hosted special symposia for her 90th birthday in 1997, and for her Centenary year in 2006. She continued to be active in research on topics of her choice until shortly before her death on April 9, 2007, at the age of 100, and often remarked of her later years "I have become as happy and independent as I had been in my youth at Harvard" (Hoffleit 1992). Those who knew Dorrit treasured her for her intelligence, work ethic, loyalty, sense of humor, and her hearty full-body laugh. I once asked her what she liked to do outside of astronomy—she replied without hesitation "eat and sleep," and then laughed with gusto (Larsen 2009). She was a mentor to many, and a role model to many, many more. She will not be matched, and she is dearly missed.

6. Conclusion

I had the honor of introducing Dorrit when she was inducted into the Connecticut Women's Hall of Fame, and nominated her for the Honorary Doctorate she received from Central Connecticut State University. Dorrit liked my introduction of her at both events so much she included it in her autobiography, *Misfortunes as Blessings in Disguise*, and I conclude with these same words:

> *It is a basic tenet of stellar astronomy that those stars which burn hottest and brightest and draw the most attention to themselves also burn out the quickest, rapidly becoming nothing more than fading memories. Meanwhile, those unassuming stars which steadily shine in the background, content to diligently produce energy at a more modest pace, continue to influence the universe with their light and heat for many generations to come. Such is the record of your long and amazingly productive career.*

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Figure 1. Dorrit Hoffleit, on left, with AAVSO Director Janet A. Mattei in an undated photograph.

Reminiscences on the Career of Martha Stahr Carpenter: Between a Rock and (Several) Hard Places

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Abstract An overview is presented of the life and work of Martha Stahr Carpenter, three-term president of the AAVSO and member since 1946, based on her reminiscences and archival research.

1. Introduction

Martha Stahr Carpenter was the AAVSO president who served during a critical time in the organization's history: its eviction from Harvard. Very little has been previously published about her life and career, and this work is the most complete biographical study of her to date.

2. Early life

Martha Elizabeth Stahr (pronounced STAIR), or "Patty" to her friends and family, was born in Bethlehem, Pennsylvania, on March 29, 1920, the middle child and younger daughter of Reverend Doctor Henry Irvin Stahr and his wife Alice Stockwell (Moat 2011). Henry was devoted to public service, and was not only a minister for many years, but was also one of the founders and first president of the United Way of Frederick County, Maryland. He was also deeply involved with the Boy Scouts of America (Anon. 1930). As a young girl Carpenter was interested in astronomy, and joined a club in junior high school, but was disappointed when the teacher who sponsored it "didn't know anything pertinent. He mostly made imaginative speculations on such topics as little people who might be living on the moon" (Carpenter 2011b).

When she was fourteen years old her father became President of Hood College in Frederick, Maryland. There she met astronomy professor and AAVSO member Leah B. Allen, who encouraged her interest in astronomy by showing her objects through the Clark telescope. Carpenter spent her first year of college at Hood and took Allen's astronomy course, and "it suddenly dawned on me that I could actually become an astronomer" (Carpenter 2011a). She transferred to Wellesley (the college her mother had attended), where there was a full astronomy major. She joined the AAVSO, and began attending meetings. As she told the author, "I yearned to have a telescope of my own so I myself could make observations for the AAVSO" (Carpenter 2011a). With the help of another student (who had taken a mirror-making course at the Franklin Institute in Philadelphia) she began grinding her own mirror in the basement of Wellesley's observatory. She recounts that she could not find an oil drum for her grinding base, despite an exhausting campus and town-wide search; one of the food service workers in her dormitory inquired why she looked so tired, and offered her an old vegetable oil drum to use instead—a base that afterwards smelled rather distinctive (Carpenter 2011c). She attended meetings of the Amateur Telescope Makers of Boston, and with their help mounted her mirror into a telescope and portable mount, and attended the Stellafane amateur telescope-making convention. She later used the instrument to observe variable stars at her family's oceanfront summer home in Scituate, Massachusetts, and her family still owns the telescope (Carpenter 2011a, 2011b).

Carpenter remembers that the summers of 1944–1945 offered particularly great skies. There were heavy black curtains over the windows during war-time, and the skies were very, very dark. She recounted that one time the Coast Guard came to their house and "wondered about what this contraption was that I had set up" (Carpenter 2011b). They apparently wanted to make sure her telescope wasn't some kind of enemy device. Under the observer code SME Carpenter contributed 396 variable star observations to the AAVSO between 1940 and 1950, including 83 of SS Cygni, 22 of Mira, 19 of R CrB, and 16 of RS Cygni.

Carpenter graduated from Wellesley in 1941 and began graduate work at the University of California, Berkeley. She worked on a number of projects there, for example finding twenty-nine new variables in the Scutum cloud from a single photographic plate (Federer 1942). She and fellow student Leon E. Salanave also tried to calculate an orbit for Comet Vaisala 2, but according to Julie Vinter Hansen (1942) "met with difficulty." But she also did work in statistics, and obtained a Master's Degree in 1943 with the thesis "A Method of Calculating Curves of Growth." Afterwards, she spent 1944–1945 at Lick Observatory, where, using the spectrograph on the 36-inch refracting telescope, and supported by a University of California Fellowship and the Alice Freeman Palmer Fellowship of Wellesley College, she measured the radial velocities of fifty F- and G-type stars of eleventh magnitude situated within two degrees of the north galactic pole (in other words, far from the galactic plane). This study became the foundation for her Ph.D. thesis (Anon. 1944; Moore 1946). Carpenter recalls that students would ordinarily never have been allowed to use this instrument, but since it was the war years, "most of the astronomers had left. There was a discussion as to whether a woman could handle the big telescope, [but] I just went up there. The man was there doing all he could to handle it, and it wasn't before long that I was doing it with him, so they were very glad that the telescope was kept in use, because it was more than one person could handle" (Carpenter 2011b). This tension surrounding women in astronomical observatories can also be seen in the careers of Margaret Burbidge, Helen

Sawyer Hogg, and Vera Rubin, among others, and severely limited the roles for women in astronomy (Burbidge 1994; Larsen 2009; Mack 1990; Rubin 1997).

After completing her Ph.D. in 1945, she taught at Wellesley for two years. During this time she made twelve observations of Comet 1946a Timmers with the 12-inch refractor there and published the results in *The Astronomical Journal* (Stahr 1946). Her class in Practical Astronomy made variable star observations and submitted them to the AAVSO, and she herself became a life member of the organization in 1946 (Carpenter 2011b). The 1947 Spring meeting of the AAVSO was held at Hood College, with Carpenter's parents acting as hosts. According to the meeting minutes, the AAVSO members were treated to a tour of Mrs. Stahr's extensive collection of 250 vases (Seeley 1947). The following year Henry Stahr retired to Scituate, Massachusetts, and over the next few years the elder Stahrs attended a number of AAVSO social events.

3. Early career at Cornell

In 1947 Carpenter became an assistant professor in astronomy at Cornell University, and in so doing was the first woman faculty member in Cornell's College of Arts and Sciences (Rossiter 1995). That first summer she did some variable star observing with one of the female Cornell students, but devoted most of her time to a joint Astronomy Department/School of Electrical Engineering project to observe radio waves from celestial objects (such as the sun and galactic center), the first research program in radio astronomy at an American university. She noted that when the program initially wrote its grants the engineers had a collaborating astronomer already in mind, but in Carpenter's words "they ended up with me instead" (Carpenter 2011c). According to the 1948 report of Cornell's Fuertes Observatory, Carpenter

> represented the Department in the radio-wave astronomy project operated jointly with the School of Electrical Engineering. Problems include the planning of observational programs, preparation of astronomical data for the project, and the general coordination of developments in theory and observation. Qualitative observations are now being obtained with an Army 268 Radar which has been converted to receive solar and cosmic noise at 205 megacycles. (Shaw 1948)

Carpenter presented a summary of the July 1948–June 1949 Cornell solar radio observations at the June 1949 meeting of the American Astronomical Society (AAS). The Cornell data did not break any new ground, instead verifying results previously obtained by A. E. Covington of the National Research Council in Canada (Stahr 1949). In his 1948 report, Shaw had also noted that the "construction of the 'radio-wave telescope' with 17-foot parabola is nearly complete" (Shaw 1948). However, to Carpenter's frustration, it would take more than another year to get the parabolic dish scope up and running (Cornell 1949). Carpenter was troubled by what she saw as the lack of organization surrounding the building of the new dish radio telescope. As she recalls, “there were lots of delays, lots of administrative difficulties, seven changes in director in a year and a half in the School of Engineering” (Carpenter 2011b).

While waiting for the new facilities to come online, she began a project that she could do on her own, and that she felt was “appreciated,” namely the creation of lengthy bibliographies of publications on radio astronomy. As she explains it, “I tried to find all the world’s pertinent literature. Much of it was unknown to astronomers. A lot of it was in engineering journals and much of it was in foreign publications” (Carpenter 2011a).The result was a number of collections of “abstracts of the published literature pertaining to radio noise of extraterrestrial origin” and “lists of references for temporary use” until published abstracts could be provided (Carpenter 1958). The resulting volumes of *The Bibliography of Radio Astronomy* and *Supplements* appeared in 1948 through 1950 (under her maiden name), *The Bibliography of Extraterrestrial Radio Noise* and *Supplements* covered the field from 1950 to 1958, and *The Bibliography of Natural Radio Emission From Astronomical Sources* surveyed the literature of 1961 through 1963 (Appendix A). Her bibliographies (like the Cornell radio work in general) were funded by a grant from the U.S. Navy, and some of her supplemental bibliographies were issued as part of various reports to the International Scientific Radio Union and IAU Commission 40. She was a member of IAU Commission 40 and represented the Cornell Radio Astronomy Project at the General Assembly of the IAU at Rome. Carpenter wrote the abstracts for the *Bibliographies*, but relied on anonymous assistants to help her locate the pertinent articles. She found married women with children who had backgrounds in physics, engineering, astronomy, or foreign languages, and who had the time and interest to help her. Much of the work was done by correspondence. Some of the women were paid through Carpenter’s grants, while others were strictly volunteers (Carpenter 2011c). Not only were these bibliographies important to radio astronomers of that time, but in recent years historians of radio astronomy have found these bibliographies to be “indispensable” in their studies (Sullivan III 2009, 211). Interestingly, Carpenter understood that some of her work (and reports of the radio astronomy work at Cornell in general) was classified by the U.S. Government, though the exact status of that classification is unclear at this distance (see note in the Appendix at the end of this paper).

Carpenter regularly attended AAVSO meetings and gave talks on “The Sun as a Microwave Variable” at three successive spring AAVSO meetings, in 1947, 1948, and 1949. She also presented on the Cornell solar observations at the AAS meeting in 1949, and lectured on radio astronomy to the General Electric Science forum, the General Electric Research Laboratory, and the Cornell Chapter of Sigma Xi. Her paper “Radio Waves from the Sun” appeared in the book *Science Marches On*, published by General Electric in 1950 (Shaw 1954, 1956). When asked to describe her radio work at Cornell, Carpenter explained that she would point the radio telescope at the moon to see if there would be a radio reflection from solar flares. One night, she got a really nice "swish" that was clearly not static, and thought she had finally observed this effect. She contacted astronomers in Japan to corroborate but their equipment wasn't working that night, so nothing ever came of these results. She never saw the effect again (Carpenter 2011c).

For many of her years as a faculty member at Cornell she was one of only two full-time astronomy professors, the other being the Fuertes Observatory Director R. William Shaw. According to the annual observatory reports published in the *Astronomical Journal*, she developed and taught a variety of courses at the undergraduate and graduate level, including courses in the Milky Way, External Galaxies, Astrometry, Radio Astronomy and Geodetic Astronomy, Orbit Theory, Galactic Structure, and Introductory Astronomy (Shaw 1948, 1949, 1951, 1952, 1953, 1954). One of the first graduate students she worked with at Cornell was Vera Cooper Rubin, and acted as advisor for Rubin's M.A. thesis on large-scale systematic motion of galaxies apart from Hubble flow. Rubin credits one of Carpenter's courses with initially getting her interested in galactic motions, and also noted that Carpenter was very supportive of her work (Rubin 1997, 154, 198).

At Cornell, Carpenter met and then married fellow faculty member Jesse Thomas Carpenter. The son of a Durham, North Carolina farmer, Jesse was twenty-one years Carpenter's senior. A Harvard Ph.D., he came to the New York State School of Industrial and Labor Relations at Cornell in 1947 from his position as Labor Economist with the U.S. Bureau of Labor Statistics. He had previously taught Political Science at New York University for many years. An expert in collective bargaining and labor arbitration, he was the author of two books: *The South as a Conscious Minority 1789–1861: A Study in Political Thought* and *Employers' Associations and Collective Bargaining in New York City* (Cooke 2010). After a short engagement, they married on August 18, 1951, in Scituate, Massachusetts, with Carpenter's father performing the ceremony (ILR Cornell 1951, 4).

4. Carpenter and the AAVSO

During this time she took on increasing leadership roles within the AAVSO, starting with her election to the Council in 1946. She served as second Vice President, first Vice President, and finally President in 1951. During her tenure as president she had to deal with several thorny issues, such as the future of the publication of "Variable Star Notes" (given the demise of the journal *Popular Astronomy*), and serious difficulties within the AAVSO Solar Division (Figure 1). But Carpenter's second term as president also coincided with the most stressful period in AAVSO history, the ouster of the organization from Harvard. This pivotal time in the organization's history is carefully detailed in *Advancing Variable Star Astronomy* (Williams and Saladyga 2011); therefore this essay will only focus on Carpenter's role in this turbulent time.

In a November 1952 letter, Clint Ford congratulated Carpenter for her excellent stand at the October council meeting (Saladyga 2011). At that meeting Donald Menzel had spearheaded the creation of a re-evaluation committee to consider the future of the AAVSO, one of the first steps toward the eviction of the AAVSO from Harvard. Although she does not remember her actual words at this meeting, Carpenter recalls that all throughout this difficult time she was steadfast in her belief that the AAVSO should remain in Cambridge. As she explained, "it was a great part of the life of people who lived there" (Carpenter 2011b). Nevertheless, she was given the difficult task of creating this re-evaluation committee, and when she received a letter from Donald Menzel requesting that the AAVSO report be submitted by the unexpectedly early date of January 20, 1953, she had to take responsibility for handing in the report on behalf of the organization without sufficient time for the entire Council to thoroughly review, digest, and approve it (Williams and Saladyga 2011; Carpenter 2011b).

During this time, Carpenter also recalls being

> suddenly presented with a plan for the AAVSO to be moved far away, to an institution that was already planning to acquire it, and had worked out the details of hosting the organization. All that was needed to make it a "done deal" was my signature as president of the AAVSO. Apparently those who had made the decisions thought that I would immediately sign the relevant papers on behalf of the AAVSO. My response, however, was that I was not at all sure the AAVSO members would agree to such an agreement, and that first the Council members should discuss it and present their recommendations to the membership. Apparently the powers that be (or were) at Harvard were entirely surprised that I, and therefore the AAVSO, did not immediately accept their proposal. (Carpenter 2011a)

When pressed, Carpenter could not recall who actually gave her the papers, and where the AAVSO was to be moved, except that it was a small college in the Midwest she had never heard of (and cannot remember the name of to this day). In her words, "Menzel had already given the AAVSO to this organization—he must have been embarrassed when he couldn't deliver it" (Carpenter 2011b). Carpenter recounts that some claimed that she "saved the AAVSO," but she says that she "merely refused to make a decision that I felt the organization could, and should make. Harvard had every right to discontinue its AAVSO sponsorship, but I felt that it should not have tried to decide unilaterally our future course." (Carpenter 2011a)

Carpenter also had to deal with what she calls "the intense politics within the organization with regards to Harvard. Some people were so imbued with remembering how prominent Harvard and Menzel were and to do anything against their suggestions would be unheard of" (Carpenter 2011b). Others (including Margaret Mayall) were less restrained. For example, in a February 19, 1953, letter Mayall asked Carpenter if she thought Menzel should be asked to resign from his position as First Vice President of the AAVSO; in Margaret's words, "it was a very low thing to accept an office in an organization he was planning to ruin" (Mayall 1953). Carpenter replied on March 3, 1953, that "The matter of asking Dr. Menzel to resign is a delicate one but one which I suppose we shall have to face if he doesn't do so of his own accord. Personally I have been expecting that he *would* resign" (Carpenter 1953).

With Carpenter's second term as president nearing its end, the organization was thus in a serious quandary as to what to do about the next round of officers. Past president David Rosebrugh was not so quick to count out Menzel, noting in a February 22, 1953, letter to Clinton Ford that Menzel

> is merely acting upon instructions, so it might well show our confidence in him to elect him our president next fall. On the other hand others may think differently. If so we might consider electing Carpenter to a 3rd term, dropping the present First VP from the line-up, which would be somewhat smoother that failing to elect the present first VP to the presidency. However I would favor giving serious thought to continuing the succession at present. (Rosebrugh 1953a)

However, after discussing the matter with other members at a picnic in honor of Harlow Shapley, Rosebrugh declared in a May 10, 1953, letter sent to Carpenter, Ford, and others that "Third term opposed for any one" and it would be best to find a "financial man" to become president. In his words, "No honor, big headache" (Rosebrugh 1953b).

Despite some hopes of finding another candidate, in the end history was made, and Carpenter continued for another term. In the AAVSO's V*ariable Comments*, Jocelyn Gill noted that Carpenter's re-election was due to her "inspired leadership and devotion to the interests and work of the Association through this difficult period" (Williams and Saladyga 2011, 185). During her last term, Carpenter and the Council spent considerable time crafting fundraising letters by committee, an arduous task. She was also a part of the organization's Endowment committee until 1964.

5. Opportunities and new challenges

Despite the considerable problems, Carpenter's tenure as president also brought with it professional and personal joys. First, she was promoted to associate professor at Cornell in 1953 (Shaw 1953). Then in 1954 the

Carpenters finally realized their dream of visiting Australia. Jesse received a Fulbright research award for a sabbatical to study Australia's compulsory arbitration system, and Carpenter received a research grant from the Australian Commonwealth Scientific and Industrial Organization to do radio astronomy for a year. According to the AAVSO Council Minutes of May 1954, Carpenter wanted to resign the AAVSO presidency (as she would miss the October meeting) but was persuaded to remain in that role during the few months of overlap with her Australia trip, and during her time away she made a point to visit as many of the Australian AAVSO members as she could (Ford 1954).

In Australia Carpenter worked on mapping the spiral arms of the Milky Way by using the Potts Hills' radio telescopes to observe 21-cm radio waves from hydrogen, "a fascinating subject if there ever was one," she proclaimed in an October 8, 1954, letter to Margaret Mayall (Carpenter 1954). She and radio astronomers F. J. Kerr and J. V. Hindman extended the map of the Milky Way made by researchers at the University of Leyden, resulting in a number of conference presentations and publications featuring this now famous map of the galaxy, the first to combine radio data from the northern and southern hemispheres (Kerr *et al.* 1956; Kerr *et al.* 1957; Carpenter 1957). "It was so exciting to be actually able to see where the arms of the galaxy were actually made out," Carpenter later recounted (2011b). She coordinated the observations, while her collaborators focused on the analysis. Such observations not only allow for mapping of the spiral structure of the galaxy, but also provide vital information for determining the location of the plane of the galaxy. The hydrogen was found to be "remarkably flat in the inner parts of the galaxy," leading Carpenter and her colleagues to define the average plane in this region as the "principal plane of the galaxy" (Kerr *et al.* 1957, 679). Their research also found that the arms tilted up at the outer regions; in other words, they weren't just confined to the galactic plane, but they curve up at the outer edge, a phenomenon now seen in many spiral galaxies with extended HI disks (Garcia-Ruiz *et al.* 2002). At the Annual 1955 AAVSO meeting in Springfield, Massachusetts, Carpenter gave a talk on her experiences in Australia, including her meetings with AAVSO members.

With their return from Australia, change came to the Carpenters. Margaret Rossiter erroneously wrote in her seminal work *Women Scientists in America* that because Carpenter married another Cornell faculty member, she was appointed a research associate rather than promoted to associate professor. This is patently wrong, as Carpenter had already been promoted before her time in Australia. In addition, as Carpenter explained to the author (2011c), her 1955 shift to Research Associate was her own personal choice. When she and Jesse returned from Australia their goal was to start a family, which they thought would not be easy (given that she was 35 and he was 56). She therefore gave up teaching and wanted to devote her professional time to research and writing her bibliographies, which she felt would be a better fit with raising a family. Fortunately, their first daughter, Martha Alice, was conceived within their first year back at Cornell. A second daughter, Sarah Margaret, followed three years later. However, because of her relatively advanced age, Carpenter's doctors were, in her words, "trying to take extra care of me" so when she developed a cold while pregnant with Alice she had to remain in bed and missed the May 1956 AAVSO meeting at Cornell that she herself had organized (Carpenter 2011c).

When Jesse retired in 1966, the Carpenters began to make plans to move, in Carpenter's words, "below the Mason-Dixon line" so that their children could get to know Jesse's large extended family in North Carolina (Carpenter 2011b). While Jesse worked on his third and last book, *Competition and Collective Bargaining in the Needle Trades, 1910–1917*, Carpenter began investigating opportunities for astronomical research closer to North Carolina. She says that the most responsive institution was the University of Virginia (UVA) in Charlottesville, "so that's where we ended up" and where she lives to this day (Carpenter 2011b). Before Carpenter left Cornell in 1969 she had stopped her radio astronomy bibliography project, in her words "because by then it was something astronomers knew about. In the beginning they didn't really know about what was observed beyond the earth—it was something that had to sink in a little in astronomical knowledge" (Carpenter 2011b). She began as a part-time lecturer at UVA in 1969, and became an associate professor in 1973 (Fredrick 1969; Jaques Cattell Press 1992).

While UVA had a radio astronomy program (in concert with the National Radio Astronomy Observatory), between 1972 and 1981 Carpenter's research centered on using optical observations and her statistical skills to increase our understanding of the distance scale within our galaxy. This work centered on the Hyades star cluster, and was conducted with graduate and undergraduate students. Using parallax, proper motion, radial velocity, and other data, they investigated the true membership of the cluster and determined its convergent point and distance, one of the building blocks for determining the cosmic distance scale and calibrating the HR diagram. The convergent point and distance Carpenter and her student colleagues announced at an AAS meeting in 1975 was well-cited in the literature for two decades (Corbin *et al.* 1975; Perryman *et al.* 1998). Over the years she continued to refine these calculations based on increased sets of data produced by other UVA colleagues. She also studied the high proper motion, low metallicity, visual binary 85 Pegasi (Carpenter *et al.* 1975; Fredrick *et al.* 1975; Fredrick 1977; O'Connell 1981).

In 1970–1973, Carpenter served again on the AAVSO council, and encouraged one particular UVA graduate student's increasing involvement with the AAVSO: Janet Mattei (Carpenter 2011b). Most importantly, when Mattei submitted her name for the AAVSO director's position (to succeed Margaret Mayall), Carpenter requested that Mattei's credentials be "discussed at length" (Williams and Saladyga 2011, 239). Carpenter also hosted the 1973 Spring meeting of the organization at UVA. Around this time, many astronomy departments across the U.S. began the sometimes painful shift from an emphasis on astrometry to astrophysics. UVA was one of these institutions. Former colleague Bob Rood very candidly summarized this transition in an email to the author: "[Carpenter] was very much a classic old-line astronomer in my view. I was very astrophysically oriented. Early in my career I became what today would be called director of graduate studies. This led to some professional conflicts with a number of older faculty" (Rood 2011). Carpenter retired from UVA in 1985, and Jesse died the next year, after thirty-five years of marriage. She had intended to keep her hand in research, but found that UVA was slow to get her the new computer she needed to run her calculations. Eventually she let it go, and has not been active in astronomy in many years (Carpenter 2011b). However, she continues to be active in her community, and is a benefactor to community organizations and the Astronomical Society of the Pacific. At ninety-one she still drives a car and runs many of her own errands, but only in town (Moat 2011).

6. Conclusion

Despite the difficulties she encountered in her terms as president, in her words (2011a) she "so fondly enjoyed" her time of service to the AAVSO and was delighted to hear that the AAVSO still remembers her as an important member of the organization. She and her daughter Alice attended the dedication of the AAVSO Headquarters on October 6, 2011 (Figure 2), and they were greatly impressed with the growth of the organization over the past few decades. Carpenter describes her role in the field as "an observational astronomer" (2011c) and it was clear in her correspondence with this author that she did not relish the astronomical politics that she had become involved in at several stages in her career. In reflecting on her mother's career, Alice Moat, herself a computer scientist, shared that she was once asked if she became interested in science because of her father. She had replied, "no, because of my *mother*" (Moat 2011). In conclusion, the struggles and successes in the life and career of Martha Stahr Carpenter shed additional light on the history of women in American astronomy in general, and the history of the AAVSO in particular.

7. A note on the sources

This paper was largely based on three types of sources:

1) Published annual reports of observatories where she worked and studied, and her published professional papers;

2) Letters and reports housed in The Thomas R. and Anna Fay Williams AAVSO Archive; and

3) Personal communications with Martha Stahr Carpenter (Carpenter 2011a, letter dated September 7, 2011; Carpenter 2011b, telephone call

dated September 16, 2011; and Carpenter 2011c, personal conversation dated October 6, 2011) and her daughter Alice Moat (Moat 2011, personal conversation dated October 6, 2011).

8. Acknowledgements

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Figure 1. AAVSO Spring Meeting at Clarkson College, Potsdam, New York, May 1952. Martha Carpenter is in front row, second from right. To her right are AAVSO Recorder Margaret Mayall (with cane), and Helen Sawyer Hogg.

Figure 2. Martha Stahr Carpenter at the AAVSO's 100th Anniversary Meeting, October 2011, Cambridge, Massachusetts.

Appendix A: Carpenter's *Bibliographies*

Note: Examples of the bibliographies for which a security classification was considered and the ultimate classification status is unclear can be found at the Defense Technical Information Center, Fort Belvoir, Virginia (http://handle.dtic.mil/100.2/AD0008460 and http://www.dtic.mil/dtic/tr/fulltext/u2/007563.pdf). This repository also houses copies of Carpenter's Bibliographies *and the Cornell Radio Astronomy status reports. The* Bibliographies *are here listed in order of publication.*

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Guiding Forces and Janet A. Mattei

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Abstract We are all shaped by the guiding forces in our lives—some we seek out, some seek us out, many are beyond our control. These forces may be human or not, constructive or destructive, personal, cultural, social, political, historical, or environmental. If we are fortunate we have had at least one human mentor who has nurtured us and helped us to grow towards our potential. Throughout her life, Janet Akyüz Mattei was the recipient of the effects of guiding forces—good and bad—and was herself a guiding force. From childhood on, she was blessed by having mentors and she responded constructively to them. Here Janet Mattei is discussed both as she was shaped by guiding forces and mentors and how, as a mentor and guiding force herself, she shaped others.

1. Earliest influences

Janet Hanula Akyüz was born January 2, 1943, in Bodrum, Turkey, the eldest of five. Her parents, Baruh and Bulisa Akyüz, were merchants who owned several shops. University educated, Janet's father was a local leader to whom people brought problems, antiquities they had discovered for him to refer to the proper authority, and so on. Sephardic Jews who had lived in Turkey for generations, the Akyüz family was and is one of strong traditions, history, and pride. The environment in which Janet was born and grew up shaped her from the beginning. On Turkey's west coast, Bodrum was an ancient city, a crossroads of civilizations for centuries, and Izmir, a coastal resort city to which the family later moved, was the ancient Smyrna. Janet grew up being aware of history and the multicultural nature of the world; Turkey was Muslim, Jewish, and Christian. Turkey is a secular state but post-WWII there was still religious prejudice, and women were not in any way considered the equals of men.

Janet's earliest education was in a one-room elementary school, where the teacher recognized her as very intelligent. Education was highly valued in the family, and since the secondary schools in Bodrum were limited, the family moved to Izmir to provide Janet with better opportunities (Figure 1). She attended Roberts American School, a high school with college courses. Janet mentored her siblings, sisters Kadem and Beki and brothers Yusef and Hayim, checking their homework and tutoring them when needed. Miss Naomi Foster, Janet's math and science teacher at Roberts, saw her potential, and mentored

Janet in the sciences. Many of the teachers at Roberts were women—highly unusual in the Turkish culture—and so were excellent role models. Mrs. Blake, the American principal of Roberts, also strongly supported Janet, as did Janet's mother (Figure 6).

Janet encountered prejudice early: she won a national contest to represent Turkey in a student exchange but was told she could not do so because she was Jewish.

In 1961 Janet came to the U.S. to attend Brandeis University in Waltham, Massachusetts, having won a prestigious 4-year Wien International Scholarship (open by competition to international students) (Figure 3). Prior to the term starting, Janet spent three months in Vermont with AFS host family Janet and Bob MacLennan and their young children. Janet MacLennan (later Janet MacLennan Zisk after marrying planetary astronomer Stan Zisk), an archaeologist, historian, and archivist, was Janet's first mentor in the U.S. They became and remained very close friends, and Janet Mac was Janet's administrative assistant 1984–1986 at AAVSO and a mentor on organizational management (Figure 3).

Janet graduated from Brandeis in the class of 1965 with a B.S. in Physics (Figure 4). During her college years the MacLennans were her American family and her Uncle Rafael Akyüz and family in the U.S. were a source of support and family connection when her immediate family was so far away (Figures 2 and 5).

Janet had planned on attending medical school. After graduation from Brandeis she worked for one year as a hospital hematology lab supervisor, but she didn't really like it. She returned to Turkey, and in 1967 started graduate school in physics at Ege University (near Izmir). At the same time she taught math and physics at the Roberts School, where she was a very popular teacher.

Miss Foster knew the Turkish astronomer Paris Pişmiş, and in 1969 she introduced Janet to Paris as the most brilliant student she had known, telling her she thought Janet would make a good scientist—Janet was known as the "Einstein of Turkey" at this time. Paris mentored Janet, delighting in fostering her rare talent and encouraging another Turkish woman in the sciences.

Paris knew the astronomer Dorrit Hoffleit—Dorrit had been her mentor—and in a fateful move, suggested to Janet she should study under her at the Maria Mitchell Observatory (MMO) on Nantucket and introduced Janet to Dorrit. Dorrit had mentored Paris, Paris mentored Janet and introduced her to Dorrit, who also mentored Janet—they were a trio embodying the power of mentoring (Figure 7).

Janet applied to the MMO summer research program. Dorrit had already selected students for the summer, but Paris' recommendation led her to add Janet. That summer Janet photographed and analyzed RR Lyr stars while learning much about many things from Dorrit. That initial meeting led to a lifetime mentor-mentee relationship and friendship (Figure 8).

In October 1969 AAVSO held its annual meeting on Nantucket at MMO. Janet stayed to help Dorrit host the meeting and finish research. As the meeting began, Dorrit went to the mainland to a meeting at Woods Hole. Bad weather prevented her return until the concluding banquet, so she delegated hosting the AAVSO meeting to Janet, who did so very capably with the assistance of Nancy Gregg, another MMO student. At that meeting Janet joined the AAVSO, gave a paper on her research, and met AAVSOer Michael Mattei.

Her experience on Nantucket and with Dorrit and Paris decided Janet on a career in astronomy. She returned to Turkey and earned a M.S. in Physics at Ege University (near Izmir) in 1970. She then continued graduate studies in Astronomy at University of Virginia in Charlottesville. There she experienced considerable prejudice, both personal and academic—she was a woman, she was foreign, and she was Jewish—and was told not to try for a Ph.D. as she was "not Ph.D. material." She earned her M.S. in Astronomy (her thesis was on T Tauri stars) from UVa in 1972. During her sometimes very difficult days at UVa, AAVSO member and faculty astronomer Martha Stahr Carpenter (Figure 14) was a mentor to Janet (and all the astronomy female students).

Dorrit encouraged Janet to apply for the position of AAVSO Director Margaret Mayall's assistant. Her recommendation led to Margaret's hiring Janet in 1972. Mike and Janet married later that same year (Figure 9).

Margaret was planning to retire and wanted Janet to succeed her. The search committee had been active since 1971, but no real action had been taken. Janet applied for the position in January 1973 and was ultimately chosen, becoming AAVSO Director on November 1, 1973, at the age of 29. Margaret was appointed Consultant to the Director for at least one year (Figure 10).

Although Janet had been Margaret's right arm for a year, the position of Director entailed a very steep learning curve with all the science, administration, and politics to master. Things were complicated by significant issues within AAVSO Headquarters that needed resolving (for example, lack of communication with members, availability of data to researchers), the absence of budget for more staff or materials, and the delicate diplomatic issue of not offending her mentor Margaret Mayall, who was in the office all day every day.

As Janet picked up the Director's baton (Figures 11, 12), she began working to resolve these issues as she worked on learning management skills, more about types of variables in-depth, and so on. She was also her own mentor; she constantly studied organizational and financial management and grantwriting—skills she needed in her position.

Janet attended professional meetings as AAVSO Director, where she was often snubbed because she did not have a Ph.D. She re-enrolled in Ege University long-distance and earned her Ph.D. in Astronomy (her thesis was on cataclysmic variables) in 1982. Afterwards she became a full member of the IAU and participated vigorously in the appropriate variable star and education commissions and committees.

Her life-long experiences with prejudice because of her sex and religion made her determined that others would not be treated as she had been. Also, she felt very strongly that girls and young women needed to be mentored/encouraged in pursuing math and science and wanted the AAVSO to play a role, as some handwritten notes by Janet indicate: "Offer opportunity to women in science to provide unique opportunities for scientific research in the analysis of data on CVs. Policy of AAVSO: Women are minority in astronomy. to encourage women in science majors to enter the field[.] recent examples Meech, Pope, Hammel. by offering them part time research assistant" (AAVSO archives).

Thus, from a very early age Janet had experienced strong guiding forces—positive and negative—and had been both a mentor and mentee. This pattern continued for the rest of her life.

2. AAVSO mentors

Numerous AAVSOers over the decades offered guidance to Janet, including:

John Bortle—cataclysmic variables, publishing observations (*AAVSO Circular* editor) (Figure 13);

Louis Cohen—finances and investments (AAVSO Treasurer) (Figure 15);

Clinton B. Ford—finances, AAVSO history, charts (Figure 12);

Grant Foster—both mentor and mentee, AAVSO staff member, programmer and mathematician, data analyst, statistician; Grant mentored Janet in aspects of advanced data analysis and statistics; Janet mentored Grant, encouraging his great abilities in mathematics and logic (Figure 16);

Owen Gingerich—Harvard University and Smithsonian Astrophysical Observatory; history of astronomy (Figure 17);

Katherine Hazen—Mt. Holyoke College '26 chemistry major (Martha's mother), fundraising, member relations and communications (Katherine was a Headquarters volunteer and a mentor to all of us there) (Figure 18);

Martha Hazen—Harvard College Observatory plate collection curator; variable stars, member relations, astronomical community relations, organizational politics (Figure 19);

Arne Henden—U.S. Naval Observatory, Flagstaff; photometry, instrumentation (Figure 20);

Margarita Karovska—Smithsonian Astrophysical Observatory, Chandra X-Ray Center; long period variables, interferometry, astronomical community relations (Figure 21, right);

Howard Landis—photoelectric photometry (Figure 22, left);

Wayne Lowder—comparison star sequences, binocular observing (Figure 23);

Mario Motta—education, community outreach (Figure 21);

John Percy—University of Toronto; pulsating variables, particularly red variables, photoelectric photometry, science education (*Hands-On Astrophysics* co-creator, *Journal of the AAVSO* Editor) (Figure 24);

Charles Scovil—publications, charts, sequences, photometry (Figure 25);

Arthur Stokes—photoelectric photometry (Figure 22, right);

Paula Szkody—University of Washington; cataclysmic variables, astronomical community relations (Figure 26);

Theodore Wales—financial management, investments (AAVSO Treasurer); Ted believed in Janet's vision for the AAVSO and supported her sometimes substantial financial expenditures on behalf of the AAVSO (Figure 27);

Barbara Welther—Smithsonian Astrophysical Observatory; computerized data processing; she advised Margaret Mayall as well as JAM (Figure 28);

Charles Whitney—Harvard University, Smithsonian Astrophysical Observatory; stellar variations, stellar atmospheres, (*Journal of the AAVSO*, Editor) (Figure 29);

David B. Williams—organizational management, fundraising, binocular observing (Figure 30);

Thomas R. Williams—organizational management, financial management, AAVSO historian (Figure 31);

Lee Anne Willson—Iowa State University; pulsating variables, especially long period variables, stellar models, pulsation theory, astronomical community relations (Figure 32, left).

3. Government grant mentors

Janet sought out mentors in the government grants community for advice in developing grants for AAVSO programs. Among her colleagues who were particularly helpful were *Nahide Craig* (NASA Science Education Gateway (SEGway) on education; *Gerald J. Fishman* (NASA Marshall Space Flight Center, Principal Investigator on the Compton Gamma-Ray Observatory Burst And Transient Source Experiment) on high-energy astrophysics and gamma-ray bursts (GRBs); *Chryssa Koveliotou* (Universities Space Research Association and National Space Science and Technology Center, a partnership with NASA Marshall Space Flight Center) on high-energy astrophysics and GRBs; *Gerhard L. Salinger* (National Science Foundation, NSF Program Director for Advanced Technological Education Discovery Research K-12) on education; and *Edward J. Weiler* (NASA, Chief Scientist for the Hubble Space Telescope 1979-1998) on HST and other satellite mission applications.

4. Janet as mentor in teaching

Janet was passionate about education, and, a born teacher, was active in many science educational initiatives through the AAVSO and other organizations. Among the AAVSO initiatives were *Hands-On Astrophysics* (today updated and expanded as *Variable Star Astronomy*), a curriculum to teach the scientific research process through variable star astronomy and observing developed with John Percy and Donna Young (Figure 33), and *Partnership in Astronomy*, developed with Mario Motta (Figure 21) and others. A major educational program Janet (and Mike Mattei) taught in was *Towards Other Planetary Systems* (TOPS), developed by Karen Meech as an annual summer astronomy education (and much more) program for Hawaii and Pacific Rim high school teachers. Over the ten years of TOPS, variable star observing and AAVSO's *Hands-On Astrophysics* curriculum were an integral part of the program (Figure 34).

Among those outside the AAVSO was the Eighth United Nations/European Space Agency Workshop on Basic Space Science in the Developing Countries, held in 1999 in Jordan, and subsequent UN/ESA meetings, in which she successfully had *Hands-On Astrophysics* incorporated into the curricula for the participating national observatories.

Janet also was involved in alumnae mentoring and outreach in the Wien International Scholarship program at Brandeis University, the program that she had benefitted from so as an undergraduate (Figure 35). In addition, she was an active member of the Women in Science network that facilitated connections and experiences for women in the sciences in the New England area.

5. Janet as mentor at AAVSO Headquarters

Everyone who worked at AAVSO Headquarters, whether as a summer, semester, or volunteer assistant or as a permanent employee, learned from Janet far more than the details of their jobs. A particular skill or interest (astronomical or other) was always encouraged and supported by her. (Her own enthusiasm for photographing flowers was fostered by everyone at headquarters (Figure 36)). The way she interacted with everyone, responded to pressure, constant interruptions, even hostility, was a model for living life with kindness and compassion, and with fierce determination to succeed, be proactive, and find solutions. The author, who worked with Janet as her assistant and senior assistant for twenty-four years, knows this from long and cherished personal experience. Janet also taught that being a mentor or a mentee wasn't all hard work and serious discussion—it could be a lot of fun, too! (Figure 37)

Permanent assistants' work varied tremendously, depending on what needed doing. Everyone was hired with specific responsibilities and/or projects to be done, but took on other tasks as needed—no one ever said "that's not my job." Summer assistants' areas of work and research typically included identification and variability research (literature and HCO plates) of stars for preliminary charts, problematic stars, field stars, period analysis and/or mean curve creation using AAVSO data, data validation and light curve plotting for AAVSO publications, creating specialized program charts—a great variety of types of research and work. All assistants gave a presentation on their research at the AAVSO Annual meeting and published an article in *JAAVSO*—part of Janet's teaching the skills needed in the scientific research process.

Janet had over forty permanent or summer assistants (many Margaret Mayall summer assistants) during her tenure as Director. Figure 38 is a composite photo of her last staff in 2003; it stands for all of us from Headquarters since 1973. Many of Janet's assistants have gone on to professional careers as scientists and have acknowledged the importance of their time working with Janet. Some of these individuals are mentioned briefly below.

Heidi Hammel was hired as a Summer Assistant in 1980. Today, Heidi is a planetary astronomer, specializing in the outer planets. She is Executive Vice President of AURA (Association of Universities for Research in Astronomy) and is a recipient of the American Astronomical Society's (AAS) Klumpke-Roberts Award for outstanding contributions to the public understanding and appreciation of astronomy, Harold C. Urey Prize for outstanding achievement in planetary science by a young astronomer, and Carl Sagan Medal for her exemplary work in outreach and public education (Figure 39).

Karen Meech was a Mayall Assistant in summer 1979 and a Special Research Assistant during graduate school at MIT. Today Karen is Director of the Astrobiology Institute, University of Hawaii (NASA), emphasizing education and outreach, and a planetary astronomer and co-investigator on NASA cometary missions. Her awards include the AAVSO William Tyler Olcott Award for contributions in mentoring/promoting variable stars, the AAS Annie Jump Cannon Award for distinguished contributions to astronomy within five years of receipt of a Ph.D., and the Harold C. Urey Prize (Figure 40).

Shelly Pope was a Mayall Assistant in summer 1982. Today she is a professional astronomer at Lunar and Planetary Labs and Scripps Institution of Oceanography specializing in atmosphere studies, solar radiation and greenhouse gases, global warming, solar wind, and space weather (Figure 41).

Meg Lysaght Thacher was a Research Assistant 1988–1990 working on the Hipparcos mission. Today, with an M.S. in Astrophysics, she is a Laboratory Instructor in the Five College Astronomy and Physics Departments, Smith College, and a Lecturer in the English Department at Smith teaching the engineering course "Writing about Science" (Figure 42).

Mary Dombrowski, daughter of AAVSO longtime AAVSOer Phil Dombrowski, did a high school science fair project on IP Peg, observing, then analyzing—at increasingly sophisticated levels over several years—the light curve to explain evidence of an eclipsing companion, and won numerous local, state, and national awards. Today she is an M.D. in Neurology, finishing a Neurology Fellowship at Yale, and is married with a young son (Figure 43).

Ann Piening McMahon was an undergraduate Assistant 1978–1979, doing data- and science-related work. Ann became a laser communications satellite specialist for McDonnell Douglas, then a science educator for two-to-five year olds (author of *Catalyst and Friends*), and today is director of MySci, a hands-on science program for elementary students at Washington University, St. Louis (Figure 44).

Tanja Foulds was AAVSO Project and Meeting Coordinator 1991–1995. Today she is Director of Event Planning for a major hotel in Hawaii (Figure 45).

Jill Gustafson was an undergraduate Assistant 1978–1980 doing data entry and clerical tasks, and a Summer Assistant in 1980 helping with the final checking and cleaning of the *AAVSO Variable Star Atlas*. Today Jill is an M.D. in pediatrics.

Jim Allen was a high school student Summer Intern in 1979 who analyzed two stars and published a paper with Janet in *JRASC*. His AAVSO internship led to a summer job at Goddard Institute for Space Studies; in a letter he thanked Janet for encouraging his "budding interest in astronomy and astrophysics."

Peter Garnavich was a Clinton Ford Summer Research Assistant in 1982. Today he is a professor of astrophysics and cosmology physics at Notre Dame University, and specializes in supernovae, interacting binaries, and cosmology, and as a co-discoverer of dark energy, is a member of the team that won the 2011 Nobel Prize in Physics (Figure 46).

Benjamin D. Oppenheimer met Janet at a middle school star party, after which he wrote telling how much he loved astronomy and asking if he could volunteer at AAVSO Headquarters (he would gladly make coffee, anything). Janet welcomed him as a volunteer at age thirteen (the first thing he learned was how to make coffee) and took him under her wing for the next eight years and more, from middle school into graduate school. She assigned him the recurrent nova RS Oph to study and analyze, teaching him how to do research in increasing depth over the years, prepare and give presentations at the AAVSO and AAS levels, and turn those presentations into publications, and helping him develop his analytical and inquiry skills. After attending Harvard University and graduate school in astrophysics, Ben worked in cosmological modeling and simulations at the University of Arizona; he is currently at Leiden University (Figure 47).

6. Conclusion

As a child, Janet was guided by many forces. As an adult, and with her courage, determination, tenacity, persuasiveness, kindness, charity, and optimism, Janet was a guiding force herself even as forces continued to act on her. She shaped the AAVSO through her vision and continual efforts. She shaped the international amateur astronomy community through outreach to national groups and fostering collaborations with groups and individuals from other groups. She shaped the professional astronomy community—the variable star section of it, at least, and perhaps others such as education—through her unceasing efforts to teach that amateur astronomers can and do contribute valuably to research and science. Through her volunteer work for the Wien International Scholarship of Brandeis University, who knows what other areas of human endeavor she may have affected—after all, the Wien students become leaders around the world in their fields, from science of all kinds to jurisprudence to international relations to the arts. She helped to shape young lives as a mentor and encourager to many young people in many countries. Truly, guiding forces were part of Janet Hanula Akyüz Mattei.

7. Acknowledgements

My sincere thanks go to Mike Mattei, Thomas R. Williams, and Mike Saladyga for helpful discussion, to Mike Saladyga for the formatting and layout of the photos, and to Rebecca Akyüz for sharing the childhood and graduation photos of Janet Mattei with the AAVSO.

It is always risky to list individuals involved in many ways over a long time because omissions are sure to be made. My apologies go to any I may have omitted—please send omissions and/or corrections to eowaagen@aavso.org.

Figure 1. A teenaged Janet (second from right) with extended family, being embraced by her paternal grandmother.

Figure 2. Janet and her Aunt Liana, July 1962.

Figure 3. Janet and Janet MacLennan.

Figure 4. New graduate Janet with her Uncle Rafael Akyüz.

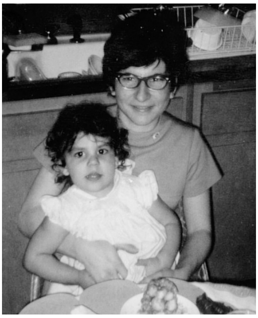

Figure 5. Janet holds her niece, Rebecca.

Figure 6. Janet and her beloved mother Bulisa (Bella) Akyüz.

Figure 7. A study in mentoring: Janet, Dorrit Hoffleit, Paris Pişmiş.

Figure 8. Presenting Dorrit with the William Tyler Olcott Award at the 2002 AAVSO Annual Meeting.

Figure 9. Janet and Michael Mattei at their engagement party in 1972.

Figure 10. Publicity photo: AAVSO Director and mentor Margaret Mayall handing over the Directorship to Janet Mattei.

Figure 11. Janet at work in 1977—the Director is in!

Figure 12. Clinton Ford, Mike, and Janet at an AAVSO Banquet in the late 1970s.

Figures 13–32, AAVSO Mentors. From top left: John Bortle; Martha Carpenter; Louis Cohen; Grant Foster; Owen Gingerich; Katherine Hazen; Martha Hazen; Arne Henden; Mario Motta and Margarita Karovska; Howard Landis and Arthur Stokes; Wayne Lowder; John Percy; Charles Scovil; Paula Szkody; Theodore Wales; Barbara Welther; Charles Whitney; David B. Williams; Thomas R. Williams; Lee Anne Willson with Janet.

Figures 33–35: JAM and pupil at a *Hands-On Astrophysics* workshop; teaching at TOPS; Rachel Zimmerman, Brandeis Univ. ‘95, JAM ‘65, Robin Shostack ‘97.

Figures 36, 37. Photographing wildflowers; mentor and mentee share a treat.

Figure 38. JAM’s last staff (2003): from left—Sara Beck, Katherine Davis, Carl Feehrer (volunteer), Kerriann Malatesta, Gamze Menali, Gloria Cruz-Ortiz, Aaron Price, Arthur Ritchie (volunteer), Michael Saladyga, Travis Searle, Sarah Sechelski, Barbara Silva, Matthew Templeton, Rebecca Turner, Elizabeth Waagen.

Figures 39–47. AAVSO Mentees: from upper left—Heidi B. Hammel; Karen J. Meech; Shelly K. Pope; Meg Lysaght Thacher; Mary Dombrowski; Ann Piening McMahon; Tanja J. Foulds; Peter M. Garnavich; Benjamin D. Oppenheimer.

The AAVSO Widow—or Should We Say Spouse?

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Abstract In past discussions of AAVSO observers over our first century of progress, the familial consequences of membership received little attention. However, non-astronomer friends commonly ask AAVSO observers, "But how does your wife feel about your spending so much time at the telescope and not in bed with her?" Although our Directors have not all been "observers," they too are forced to keep unusual office hours, answer telephones in the middle of the night, and so on. This paper attempts to portray the many surprising ways in which the AAVSO spouse (not all observers are male nor directors female!) responds to their partner's pre-occupation with variable stars.

1. Introduction

While thinking about individuals who had been inadequately recognized as part of the AAVSO's centennial celebration, it occurred to me that one whole class of individuals who had been almost completely ignored were the marital partners of AAVSO members. Some spouses of members actually not only attend meetings, but also participate actively in AAVSO work, either as observers, or in other direct support to the Association. AAVSO has been one of the corners of astronomical history in which there have been active participants of both genders. In turn, that recognition led to another realization—the AAVSO director's spouse seems always to be on call but receive little recognition for their sacrifices.

One should consider whether or not the spouse always has a choice in the matter. Some spouses accepted the problem by agreeing to marry someone already actively committed to the AAVSO. Furthermore, the problem might be complicated by consideration of other variations on the theme. Did an AAVSO member's or director's spouse really have an option that could be exercised? Well, if the marriage came before the involvement in variable star astronomy, then the answer is "probably so." Under those circumstances, the potential spouse is only confronted with the problem after consummation of the marriage. If on the other hand, a career in astronomy is already under way, the avocational or vocational involvement should be evident to the potential partner and should be a consideration. But in every case, there are later decisions to be made involving the degree of commitment; those judgments drastically influence the outlook and productivity of the astronomer whether an observer or administrator. Thus, the impact (positive or negative) of the spousal attitude on the degree of a participant's commitment to astronomy is a real concern to be recognized as part of this centennial.

So for this paper, I categorized spousal reactions to variable star astronomy as follows:

- The Director's Spouse
- The Active Participant
- The Cheerful Supporter
- The Variable Star Widow
- The Black Widow

This paper will discuss a few examples in each category. I hope to convince all AAVSO spouses that we members mean well, though we may not express it as well as we might from time to time as we walk out the back door for another session of observing, or spend hours on the on the computer in internet meetings and on discussion lists. My hope, then, is to make this paper a token of our appreciation for the sacrifices our spouses make to support us.

2. The Director's Spouse

This paper begins by honoring those whose spouse served as the leader of the AAVSO at any given point in time (Figure 2). The Association has been blessed with strong supporters in every case, and it is a good thing. The job of the Director, Recorder, or in Olcott's case, the Secretary, always proved to be time consuming and called for a great deal of sacrifice in the family. It is evident that this is the case because, whether by choice or accident of physiology, only one of the spouses involved was actually involved in parenting. Even there, four of the five Campbell children were born before Leon accepted full-time responsibility for the AAVSO. Thus, the AAVSO was spared the resulting distractions of its leadership by the extra issues related to children in the family.

2.1. Clara Olcott

On their wedding day, neither William Tyler Olcott nor Clara Hyde knew what lay ahead of them in terms of the AAVSO. Tyler displayed no interest in astronomy; that would come later. After being initiated to the beauty of the night skies by one of Clara's friends, Tyler Olcott's interest in astronomy slowly expanded until variable stars captured his attention. His subsequent founding of the AAVSO, with all the work that entailed, had to be balanced with a busy social life with Clara and her family. They lived among the social leading lights in the community of Norwich, Connecticut. World War I imposed major new work loads on both Clara and Tyler. She volunteered to work as a leader of the local American Red Cross while Tyler took on a full-time job as Secretary of the Norwich Draft Board. The burden was more than Tyler could stand physically. Under this pressure he neglected variable star astronomy somewhat during the war, leading others to take more responsibility for AAVSO. Eventually this led to the incorporation of the AAVSO in 1918. After incorporation, the new AAVSO by-laws provided for elections and a full slate of officers to ensure the continuity of the organization.

Tyler's health never quite recovered from the wartime stress, but Clara apparently sailed through the war effort smoothly while continuing to support and care for Tyler. For the next two decades, Tyler's health required that they spend winters away from Norwich, either in Florida or Arizona. Unfailingly supportive, Clara was usually seen by the AAVSO membership, hanging on Tyler's arm, helping him through his sickness and the press of AAVSO duties as well as other work. Although Tyler's health failed and he died in 1936, Clara lived until 1951. In an amazing coincidence, she passed away on exactly the same day that Leon Campbell died.

2.2. Frederica Campbell

We know a lot less about Frederica Campbell than we do about Clara Olcott. Born (and educated) in Columbia, Connecticut, in 1881, Frederica met Leon early in the twentieth century. Columbia is located between Hartford and Waterbury, and even today claims a population of only a few thousand citizens. Thus, it seems very likely that Leon met Frederica through some church activity; Columbia is otherwise a long way from Cambridge. They married in June 1905 and established their home in Cambridge. Their first child, Leon Jr., was born in August 1906, followed by their first daughter in January 1908. Some older AAVSO members will remember her as Florence Bibber (she later was Margaret Mayall's assistant for many years). A second son, Malcolm, arrived in January 1909. Another daughter, Ruth, was born in Peru while their last daughter, Ellen, was born when they returned to Cambridge from Arequipa. Thus, as a busy mother, Frederica limited her participation in AAVSO events out of necessity; it is clear that she had her hands full for most of the first thirty years of their marriage. Small wonder, then, that she shows up with Leon in so few of the pictures we have of him involved in various AAVSO activities over more than forty years.

2.3. Newton Mayall

The extensive support given to Margaret Mayall by her husband Newton over the many years of their lives together is yet another example of the importance of the spouse to the AAVSO, whether as the observer's spouse or the director's spouse. Newton joined AAVSO before he ever met Margaret; it was through Newton's work as a variable star observer that they became acquainted in 1924 at her first AAVSO meeting.

Newton was born in 1904 in Waltham, Massachusetts. As the son of a commercial designer, Newton's professional career as a civil engineer focused on design more than on construction. Sundials were a hobby for Newton and Margaret. Professionally his most prominent project was likely the sundial at front of the entrance to the National Bureau of Standards in Washington, D.C. In contrast to many of our director's spouses, Newton served actively in the AAVSO leadership as well. He served on the Council for twenty-two years, including six years as Treasurer during some of the AAVSO's toughest financial times. Newton also designed a headquarters building for the AAVSO; his design featured an observatory on top. Perhaps someday, if Arne Henden lives long enough at his current pace, we will see Newton's dream of a rooftop observatory realized on top of the present building.

2.4. Michael Mattei

Mike Mattei, like Newton Mayall, met his future bride and AAVSO director at an AAVSO meeting. Born in 1940 and educated in New Haven, Connecticut, Mike quit school before graduating, but learned carpentry during a year in a trade school at his father's suggestion. Night school helped him finally earn a high school diploma, but in the meantime he also apprenticed as an eyeglass lens grinder and became a skilled optical worker. After doing quite a bit of reading about astronomy, Mike discovered the New Haven Astronomical Society. David Dunham, then a graduate student at Yale, insisted that Mike accompany him to Nantucket for the October 1966 AAVSO meeting. Mike not only joined AAVSO at that meeting but learned of openings for night assistants at the Harvard College Observatory's Oak Ridge Station. Eventually his work at Oak Ridge played out, but in the meantime Mike attended the 1969 Fall AAVSO meeting, again at Nantucket, where he met and later began to court Janet Akyüz. Eventually, Mike went back into precision optical work and finished his career as a specialist in that field. As a long term member of the Association of Lunar and Planetary Observers, Mike specialized in observation of the clouds on Venus. So while Mike has been a long-time variable star observer, he is far better known as an amateur planetary astronomer. Mike served on the AAVSO Council from 1972 to 1976, and as as the Clerk from 1979 to 2007.

Unlike Newton Mayall, Mike's contributions to AAVSO were, for the most part, behind the scenes; he never got involved in office or council politics directly. However Janet relied upon Mike as a sounding board with whom she could discuss problems and possible solutions. Anyone close to Janet knew of the enormous insecurities that plagued her all her adult life, though she gave little evidence of her concerns to anyone except her closest friends and associates. In an oral interview, Mike revealed that she suffered a recurring concern that she would not live past age 60, and frequently expressed her desire that they should grow old together. Her concern first surfaced shortly after they were married, and again about every ten years according to Mike. So in fact

Mike's support of Janet behind the scenes facilitated the substantial progress made by AAVSO during her tenure as director.

2.5. Linda Henden

Our present Director's spouse, Linda Henden, presents an amazing contrast in styles compared to all of her predecessors. Mike Mattei remained quietly in the background, constantly available to Janet as an advisor on the home front. In vivid contrast, Newton Mayall, had his thumb in much of what happened in the AAVSO. In Linda we find yet another model of spousal behavior, a constant, quiet, and immensely supportive presence in what goes on around the office.

Born on Long Island, New York, in 1950, Linda Horn moved to Albuquerque, New Mexico, with her family. There, she attended junior and senior high school and studied biology at the University of New Mexico. While at the university, she met and began dating an astronomy graduate student by the name of Arne Henden. After they both graduated in 1968, she married Arne in 1971 and thereafter committed herself to the life of an astronomer's wife.

I said a lot less about all contemporary spouses in this presentation by design, but I can't ignore Linda's steadfast support to AAVSO as well as Arne, during their time in Cambridge. I spent a lot of time in Headquarters over a two year period; during that time Linda and Arne were present and working almost every hour, in Linda's case either at a desk doing bookkeeping and accounting for the association, or with a paintbrush in her hand. I was frankly amazed at the energy and dedication they both exhibited in fixing up 49 Bay State Road, but then Linda says it seems like she has spent most of her life fixing up homes, so I guess her current situation is part of a life-time trend.

3. The Active Participant

A few of our observers' spouses participated actively in amateur astronomy if not in variable star observing or other aspects of AAVSO (Figure 3). There may be many more, but here are just a few examples:

3.1. William Maybrick Kearons

The Rev. William Maybrick Kearons, was very well known in astronomical circles, more so than his variable star observing wife, Winifred Crossland Kearons. They lived in West Bridgewater, Massachusetts, where Rev. Kearons served for over twenty-five years as the Rector of Episcopal Parishes. Born in Liverpool, England, in 1878 William Kearons immigrated to the United States in 1907, where in 1914 he married Canadian native Winifred Crossland.

Rev. Kearons mastered the art of photographing projected images of the Sun's surface in which he captured excellent pictures of sunspots. He provided Harvard astronomer Donald Menzel with daily images of the Sun for every clear day for a number of years; his pictures of sunspots are featured in Menzel's book *The Sun*, and also in *Scientific American* and *The Telescope* magazine in the late 1930s.

3.2. Winifred Kearons

Though I don't plan to do this in most cases, I would also like to say a word or two more about the actual variable star observer in this family, Winifred Kearons. Too little attention has been paid to her separate career as an amateur astronomer. For quite a number of years Winifred Kearons' observing totals led all female and many male observers of variable stars in AAVSO. During the 1930s and early 1940s, Mrs. Kearons also observed the Sun on a daily basis. But in contrast to her solar photographer husband, and perhaps reflecting her more scientific inclinations, Winifred counted sunspots and reported the counts on a monthly basis to the international solar astronomy center in Zurich, Switzerland. When the AAVSO organized its Solar Division, the charter members included both Winifred and William Maybrick Kearons. Using her 3-inch refractor, and reporting observations as KR from 1925 to 1951, her total amounted to 9,769 variable star observations, by no means an insignificant contribution. Winifred also served as a member of the AAVSO Council for four years from 1939 to 1943. At the time of her death in 1957, Winifred Kearons ranked as the leading woman variable star observer and placed well up on the list of all variable star observers for the first forty years of AAVSO history. It was not until the early 1970s that Diane Lucas, and later Carolyn Hurless, both of Ohio, surpassed her total.

3.3. Emily Fernald

Moving forward in time to the 1950s, Cyrus Fernald, already "the ace observer" in AAVSO according to none other than Leslie Peltier, married for the first time at the age of forty-nine years. His bride, Emily Parsons Sanborn, a school teacher and accomplished organist, was ten years younger. It will come as no surprise that the Fernald's marriage produced no children. After their marriage, Emily, or Em as Cy used to refer to her, picked up on his astronomical interest, perhaps as a form of self-defense. She contributed about a hundred variable star observations but became, along with Cy, a regular solar observer and contributed sunspot observations to the AAVSO Solar Division and to Zurich. Cy claimed Em had a lot better eyes than he did and always saw more spots than he could. She made 900 observations of sunspots over her observing career.

But Em's real contribution was through her support of Cy as one of the leading variable star observers in the AAVSO as well as a council leader during the eviction from HCO. In addition to astronomy, the Fernalds shared another passion as avid birdwatchers. In fact, in decades from the 1950s through the 1970s, a number of other couples in AAVSO shared the hobby of bird watching with the Fernalds, including Leslie Peltier and his wife Dottie, and former president Ralph Buckstaff and his wife Annie Laurie. In those pre-internet days of inexpensive gasoline, these couples made driving visits to each other for purposes of bird watching as well as socializing.

3.4. Other forms of participation

Two other active couples of note include the Wilkersons and the Beamans (Figure 4). Carmen and Winston Wilkerson both served on the Council of the AAVSO, and in Carmen's case, she also served as the AAVSO Auditor for a number of years. Joint participation in AAVSO also characterized the efforts of Carol and Barry Beaman. Both observed variable stars and both participated regularly in AAVSO meetings. While Barry served on the Council, the Beamans organized an AAVSO Spring meeting in their hometown of Rockford, Illinois. After decades of service to the Astronomical League as well as the AAVSO, the Beamans rank among the strongest supporters of amateur astronomy in the United States.

4. The Cheerful Supporter

Now in many cases, equally important spousal support rendered to AAVSO observers and leaders did not involve active observing or participation in the leadership of the Association. I chose to separate these spousal supporters into a slightly different but no less important category. In these cases, it is frequently more difficult to find out something about the spouse, but that should not diminish their importance to the AAVSO (Figures 3 and 4).

4.1. Lillian Pickering

Three years older than jeweler David Bedell Pickering, his wife Lillian raised their five sons, which in itself is a life-time of work for most women. She also played an important role in the early years of the AAVSO, even before its incorporation. Lillian and David hosted the earliest large meetings of the AAVSO in their home in East Orange, New Jersey. Those successful meetings eventually led to the incorporation of the AAVSO, but outgrew the capacity of the Pickering home.

4.2. Margaret Yalden

Almost the same might be said of Margaret Yalden, the spouse of another member of "The Old Guard" (charter or very early AAVSO members), Born in 1865 in Pennsylvania, Margaret Lyon remained unmarried in New York City until she met J. Ernest G. Yalden, an Englishman who came to the United States in search of opportunities. They married in 1895, and by 1900 had settled in Leonia, New Jersey, in what was to remain their home for the rest of their lives. Five years older than Ernest, Margaret maintained a stable home for him and supported his extensive involvement in variable star observing and other forms of astronomy, especially his lunar occultation work for the AAVSO. The Yaldens frequently entertained other Old Guard members in their home. In May 1925, the Yaldens hosted the Spring meeting of the AAVSO, the last formal meeting to be held in a private home as the AAVSO outgrew such intimate surroundings.

4.3. Jane Halbach

Wisconsin native Jane E. Roth met Ed Halbach at church and they married in 1942. This happy marriage produced a family of six children. In spite of the parenting difficulties involved with such a family of six children, Jane worked full-time selling advertising for the Yellow Pages Telephone Directory. Verbally eloquent, persuasive and successful in her job, Jane had a way with words. For example, she wrote radio jingles for which she won many prizes. Most *JAAVSO* readers may not remember musical jingles as a sales technique, but in the days in which radio advertising was the most direct route to consumer awareness, jingles played a major role. Through it all Ed continued his full-time employment and his full-time service to astronomy as well, as a founder and observatory director of the Milwaukee Astronomical Society, eclipse chaser for the National Geographic Society, observing grazing lunar occultations for IOTA, and photographing aurorae for Cornell University. Ed served as founding President of the Astronomical League, in addition to observing variable stars and raising his wonderful family with Jane. Those important contributions could not have occurred without Jane's support; she loved to travel, so as often as possible, she accompanied Ed to meetings of both the Astronomical League and the AAVSO.

4.4. Barbara Kaiser and Elizabeth Dillon

Dan Kaiser and Bill Dillon served as presidents of the AAVSO during one of the most trying periods in our history, when AAVSO Director Janet Mattei fell ill and died. Their exemplary handling of this catastrophe (Dan's during the remainder of his tenure as President, through October 2003 and as Past President through October 2004, and Bill's as his successor through October 2006) stabilized the Association and ensured continuity of its leadership in a critical period. Dan relied heavily on the support of his wife Barbara as a pillar of strength and support while Bill's wife Elizabeth was an incredible source of support throughout his tenure. For that alone Barbara and Elizabeth represent exactly the type of spousal support that this paper intends to celebrate.

But Barbara had another characteristic that makes her memorable; she joined enthusiastically into the spirit of AAVSO meetings to enjoy, and to help others enjoy, the opportunities presented wherever the meeting was being held. A good example of that occurred when the AAVSO met in Houston. Earlier it was mentioned that bird watching had been a second past-time enjoyed by many AAVSO couples. Barbara and Dan had also been active as bird watchers, and always looked for opportunities to observe birds that neither had on their life-time lists. Birding is now their full time avocation as I understand it. More on that in a minute as I will come back to this story.

4.5. Bruce McHenry

Our long time member Martha Locke Hazen supported the AAVSO in many ways as the curator of the Harvard College Observatory plate stacks. Elected to the AAVSO council, she served as president, eventually resigning the presidency to serve as secretary for a decade as Clint Ford's replacement. An acrimonious divorce left her to raise two children in addition to her employment, but nevertheless Martha was steadfast in her involvement and support for AAVSO. So it was a special delight for everyone, especially those who had survived divorces and remarried, to meet Bruce McHenry as Martha's new spouse. After a career as a senior park naturalist and interpretor for the National Park Service, Bruce and Martha shared interests in many things, including travel and especially their common interest in canals and canal barges as a mode of waterway transportation. They visited modern as well as historical systems deserving of preservation. Quickly accepted as a regular spousal participant in AAVSO meetings, Bruce supported Martha as she switched from being president to secretary and extended her service on the Council. My wife Anna Fay returned enthusiastically from a whale watching trip during one of our meetings on Nantucket Island to describe how Bruce had become the de facto tour guide based on his knowledge as a naturalist and well-developed sense of the drama of nature as well as the nature of drama.

Going back now to the Houston meeting and Barbara Kaiser, Bruce and Barbara struck up a friendship because of his extensive knowledge of birds. During the Council meeting in Houston, the two of them took off on a bird hunting expedition. The Gulf coast is well known as birding territory so such a side trip could be expected. When we gathered for dinner that evening, however, Barbara and Bruce were nowhere to be seen. They eventually straggled in, claiming to have gotten lost following a pink footed whistling duck. A likely story we all laughed, and went on with the party with a sigh of relief that they were safe.

I think that short story characterizes one of the great characteristics of all of the AAVSO spouses I've met over the years—their ability to enjoy the circumstances as they find them. That personality characteristic is certainly necessary when one accepts a spouse who already has an active involvement in an organization like the AAVSO. Bruce joined an honored list of such spouses many of whom are mentioned in this paper, including Lillian Pickering, Emily Fernald, Annie Laurie Buckstaff, and Dorothy Peltier, all of whom bought into variable star observing and the AAVSO as a part of their marriage.

4.6. International associates

Over its history, AAVSO enjoyed support from other countries, most notably Canada. As AAVSO presidents, Canadians Frank DeKinder, Charles Good, George Fortier, and John Percy have all been blessed with spousal support that included regular participation in semi-annual meetings. I would mention especially Maire Percy as a frequent participant in AAVSO meetings, supporting John for thirty years or more of his active participation. Whenever our Japanese member and observer Seiichi Sakuma came to AAVSO meetings his quiet and gracious wife Nobuko accompanied him. It may be that Nobuko spoke little or no English, but she always seemed grateful for our recognition. We honor all wives who travel from other continents at considerable expense in terms of both time and wealth to help their spouses participate in the AAVSO.

5. The Variable Star Widow

Moving on to other types of AAVSO spouses, the next to be considered are those strong supporters who do not for the most part participate in AAVSO activities, identified for purposes of this paper as The Variable Star Widows (Figures 4 and 5). There are two clear sub-categories of Widows: The Strong Silent Type and The Complainers. There is no doubt some friction in the marriages of many if not most AAVSO observers, as there is in most marriages. However, the more active an observer becomes the more likely there is to be some friction.

5.1. Barbara Bortle

Of the two types, those who endure in silence and never complain (at least as far as we know), I would cite John Bortle's wife Barbara as one good example. As with the Halbachs mentioned above, the Bortles had a few children and the attention demanded by those children likely provided more than enough distraction for Barbara so that she did not object to John's heavy observing schedule. Their case is a bit more complicated, however. In addition to the limitations imposed by a large family, John and Barbara lived well away from city lights to facilitate his observing, also a disadvantage to her in all likelihood. But then there is also the fact that John's place of work for many years as a fireman in a suburb near New York City was a long way from where he lived. It was an occupation John pursued so he could work two and/or three day continuous shifts at the firehouse, and thereby have longer uninterrupted periods of time at home to observe. That pattern of frequent separations continued for many years until John's serious injuries, suffered when he fell through a roof during a fire, forced his disability retirement. I cite Barbara as an example mainly because I know about the circumstances of her case. The AAVSO is fortunate, I am sure, to be populated with many observers with spouses who were similarly supportive.

5.2. Donald Hurless

AAVSO members who visited Ohio, on the other hand, were sure to have met Donald Eugene Hurless, the spouse supporting our most prolific feminine contributor to date, Carolyn Jane Hurless. There were many different reasons why AAVSO observers might pass through north central Ohio, but one was no doubt Leslie Peltier's presence in Delphos, Ohio. Nearly as important in all likelihood was the fact that Lima, Ohio, where the Hurless family lived, was nearby. Informal gatherings in the Lima/Delphos region were a social event for AAVSOers in the central states and for many from outside the region as well.

Don, a piano player, composer, and arranger, played in his own small groups, trios and quartets, for dance clubs, and also led a larger orchestra. Born in Lima in 1928, Don was actually six years older than Carolyn Jane Klaserner, also a Lima native, when they decided to marry in 1959. Don supported Carolyn's hobbies to the extent that he could. As musicians, Don and Carolyn relied on their musical talents for their existence, Carolyn by teaching piano, and Don by teaching as well as by playing local gigs with his various musical groups. Both were also piano tuners; they maintained a comfortable life style that allowed Carolyn plenty of time for her hobbies. At first she engaged in amateur radio, then later switched to variable star astronomy. Don qualifies for the Variable Star Widower category for a variety of reasons. Obviously he and Carolyn shared many interests but astronomy was not one of them. Don came to only one AAVSO meeting that I recall (1983, where he, Clint Ford, and Dorrit Hoffleit's sister Norfleet gave a wonderful evening concert). But so far as I know, Don never complained about Carolyn's separate work as a variable star observer, publisher of *Variable Views* newsletter, or Council member and officer of AAVSO.

5.3. The Complainers

Now a different situation existed for those wives who endured their spouse's avocation, but let their unhappiness be known to others. Who knows how many are in this category, we hope not many, but it seems likely that more than a few cases exist. Dottie Nihiser must have known when she married Leslie Peltier in 1933 that she was marrying a renowned amateur astronomer, whose avocation required long hours at the telescope eyepiece at night. By then, Peltier was already well known as a variable star observer, and as a discoverer of novae and comets; Dottie knew that he would be less than fully attentive to her every whim. They did manage to have a family, two sons, Stanley H. and Gordon J. Peltier, so their relationship was one of marital bliss in the early days, as Leslie himself described it in his books.

Dorothy Nihiser was born in the same community, Marion, Ohio, into which Leslie had been born, but almost eleven years later. Privileged to attend some college at Ohio Wesleyan University, Dottie displayed a substantial interest in archeology. That likely explains the one month honeymoon that she and Leslie took in the southwestern states. There they could camp and study geology and the archeology of ruins to their heart's content.

By the 1960s though, things began to change. At the time of the August gatherings in Lima and Delphos, Dottie's attitudes were clearly on display, and in spite of her apparently cheerful serving of pancake breakfasts at the end of all-night observing sessions, she also was quite vocal in expressing her displeasure about these sessions to those present in the kitchen, always in a tone and worded in such a way that a dual interpretation was possible, that she was both ribbing Leslie but also scolding him and making her displeasure known. Though I never attended one of these gatherings, I get this message from enough different sources that I feel that the contention must have merit. The story is further supported by the fact that the Fitz and Clark lenses for Peltier's two telescopes, instruments that the AAVSO felt belonged to it, were never returned to AAVSO and have apparently disappeared into the family coffers. Dottie died in Delphos in 2008 at the age of 98.

6. The Black Widow

Some marriages break up in situations in which one of the obvious strains in the relationship involves variable star observing. VSOing inevitably infringes on a married couple's time together. It would be inappropriate to identify anyone who might fit in this category. It seems likely that variable star observing is frequently only one of many problems found in a troubled marital relationship, perhaps not even the major problem. But, one can also observe that a large number of our outstanding observers married very late in life, or suffered separations or divorces, in some noteworthy cases multiple divorces or at least very extended separations. It is quite clear in those cases that dedication to the AAVSO and/or to observing played a part in the collapse of the marriage. And of course there is no way of knowing how many would-be or actual variable star observers threw in the towel and stopped observing rather than break up a marriage. It would be unfair to stigmatize the spouses involved in all such cases, but acknowledgement of the possibility serves to reinforce the main thrust of this paper, that is, more frequent acknowledgement of the importance of spousal support to AAVSO success is important.

7. Conclusion

The AAVSO and variable star observing must be considered a family effort, an idea that had more emphasis in the past, and needs more emphasis in the future! Everyone should acknowledge from time to time how important such relationships are for all of us. Perhaps the AAVSO will make a greater effort in the future to make meetings more family-friendly, provide alternatives to the growing intensity of the science, acknowledging the fact that even those observers who are sleeping with their wives while their automated telescopes grind away through the night have devoted family resources to the project, and time to maintain the effort, reduce the data, and attend meetings.

As the founding father of the AAVSO's photoelectric photometric program, John Ruiz would readily testify that there are always times when only the family can help (Figure 6), and those of us lucky enough to be part of understanding and helpful families need to acknowledge our need and nourish those relationships right along with the science we all value so highly.

8. Acknowledgements

This paper is based on the author's historical research, and personal experiences in the AAVSO.

Editorial comment: Surely one of the most visible and appreciated AAVSO spouses of recent decades has been Anna Fay Williams! (Figure 1) Tom's contributions to the Association have been numerous, diverse, and very significant, and Anna Fay has been there to support him—and occasionally rescue him from medical emergencies. And she's not just an appendage; she has her own scholarly and cultural pursuits, so she doesn't have to come to AAVSO meetings for want of something to occupy her mind. Indeed, her varied talents make her one of the most interesting meeting attendees. Tom and Anna Fay are one of the AAVSO's "royal couples." They help make AAVSO meetings a joy to attend! —John Percy

Figure 1. Anna Fay and Tom Williams at the dedication of the AAVSO Archives named in their honor during the AAVSO Annual Meeting, October 2011.

Figure 2. From top left: Tyler and Clara Olcott; Leon and Frederica Campbell; Margaret and Newton Mayall; Mike and Janet Mattei; Linda and Arne Henden.

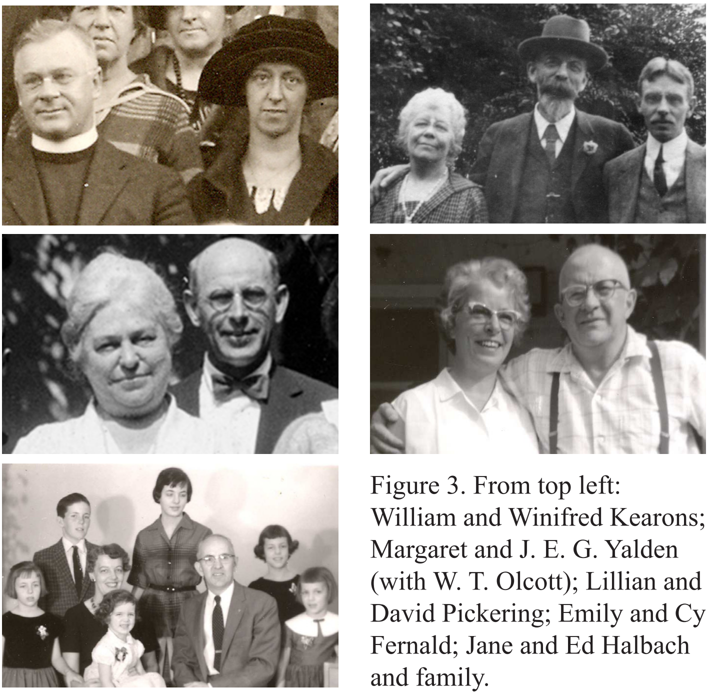

Figure 3. From top left: William and Winifred Kearons; Margaret and J. E. G. Yalden (with W. T. Olcott); Lillian and David Pickering; Emily and Cy Fernald; Jane and Ed Halbach and family.

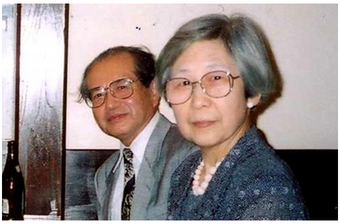

Figure 4. From top left: Carmen and Winston Wilkerson; Barry and Carol Beaman; Dan and Barbara Kaiser; Bruce McHenry and Martha Hazen; Seiichi and Nabuko Sakuma.

Figure 5.Left to right: Carolyn and Don Hurless; Dottie and Leslie Peltier.

Figure 6. AAVSO observer John Ruiz's family helping him up a steep hill, Puebla, Mexico. From their family Christmas card in 1967.

The Legacy of Annie Jump Cannon: Discoveries and Catalogues of Variable Stars *(Abstract)*

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Abstract This paper will review the many variable star projects and publications that Annie Jump Cannon brought to fruition in her forty-five-year career at Harvard College Observatory. In 1896, when Cannon joined the "Corps of Women Computers" at HCO, Williamina Fleming already enjoyed world-wide acclaim for her discoveries of novae on photographs of stellar spectra. Antonia Maury had also become renowned: she had discovered and analyzed a rare spectroscopic binary star, β Aurigae. At that time, such discoveries made headlines in newspapers, especially because they were made by women who studied astronomy by day! When Cannon was not actively involved in classifying stellar spectra, she took up HCO's project of cataloguing observations of variables. As a result, she discovered thousands of long period variable stars and half a dozen novae in the Milky Way. In 1903 she published "A Provisional Catalogue of Variable Stars" in *Harvard Annals 48*. Subsequently, Margaret Walton Mayall and Florence Campbell Bibber continued cataloguing the variables through 1941, when Cannon died. In 1918, when Cannon and others such as Edward Pickering and Solon Bailey, were made honorary members of the American Association of Variable Star Observers, Cannon wrote: "I assure you it is a pleasure to be associated in this way, with a company of ardent observers and investigators, whose results are of so much value and carried on with such enthusiasm. It well be a spur to me in my future work, especially as to the new Catalogue of Variable Stars, which I hope to finish before very long."

Margaret W. Mayall in the AAVSO Archives *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 5, 2011

Abstract AAVSO Director Margaret W. Mayall's presence in the AAVSO Archives is unique in that it was only by her effort that the AAVSO's institutional memory survived the organization's years of struggle. The history of the AAVSO could not have been written thoroughly and accurately without its archival collections. Similarly, the story of Mayall and the AAVSO within that history is not only informed, but is also formed by the materials that she chose to collect and preserve over the years.

HISTORY OF VARIABLE STAR ASTRONOMY IN THEORY AND PRACTICE

Twenty-Eight Years of CV Results With the AAVSO

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Abstract Working with AAVSO data and AAVSO staff on cataclysmic variables since the 1980s resulted in twenty-nine papers from 1984 to 2011. The early work began with characterization of optical light curves of various dwarf novae and novalikes, then moved into coordination of optical observations with satellites (IUE, EUVE, XMM, Chandra, HST, GALEX) to explore the ultraviolet and X-ray regimes of disk systems versus those containing magnetic white dwarfs. The major advances in the field that were derived from these results are summarized, ending with the recent results on the cooling of the white dwarfs and the return of pulsations in GW Lib and V455 And following their 2007 outbursts, and on the spectra of the two peculiar Z Cam systems IW And and V513 Cas.

1. Introduction

A Centennial is a time for looking back and pondering the progress that has been made and remembering the people responsible for that progress. After finishing my Ph.D. in 1975 in the field of cataclysmic variables (CVs), I was eager to pursue new objects and new ways of doing things. Having met Janet Mattei at a CV meeting, I was introduced to the AAVSO and its archives and observers who had their own telescopes. Thus began a collaboration that has continued to the present time. A brief summary of twenty-eight years of data, highlighting my personal results from twenty-nine papers that used AAVSO data is given below. This summary is divided into the eras of its two directors during that period of time, and ends with results on the ongoing projects of observing the accreting, pulsating white dwarfs in CVs and spectral observations of two peculiar Z Cam stars. The CV types that will be discussed include typical systems containing accretion disks, the systems containing highly magnetic (B > 10MG) white dwarfs termed Polars, and the subset of Low Accretion Rate Polars termed LARPs.

2. The Janet era: 1984–2004

The hot topics in the 1980s were centered on the cause of dwarf novae outbursts and the observed UV delay from the optical during the rise to outburst, the differences in outburst cycles for different objects, and the differences between theoretical predictions and observations of the boundary layer (the area where the accetion disk meets the white dwarf surface). The tools to explore these issues included the International Ultraviolet Explorer (IUE), used for ultraviolet spectra, and ROSAT and EXOSAT for the X-ray regimes. To lay the groundwork on outbursts, the large AAVSO data archive on dwarf novae was used to measure the outbursts of twenty-one well-studied dwarf novae. The rise, maximum, decline, and total outburst duration were measured and correlated with various properties (Szkody and Mattei 1984). These first studies showed a correlation of outburst duration with orbital period, as well as a bifurcated pattern of outbursts for some systems like SS Cyg. While this work provided a framework for theoreticians, only bright systems were well-observed. Since that time, it was discovered that the faint WZ Sge systems or Tremendous Outburst Amplitude Dwarf novae (TOADs; Howell, Szkody, and Cannizzo 1995) are the shortest orbital period systems but have the longest outbursts (as they only show superoutbursts which last weeks). The early work for the 1984 paper also showed some intriguing behavior apparent in Z Cam: a rising quiescent magnitude in the outbursts preceding a standstill. Some of this odd behavior is now being pursued in the Z CamPaign of Mike Simonsen (Simonsen 2011). The 1983 outburst of GK Per was well-followed and compared to past outbursts in 1975 and 1991 (Szkody *et al.* 1985) to reveal long outburst durations (50–60 days) with a high excitation emission spectrum present at ouburst. This object was then identified as an intermediate polar when the white dwarf spin was found in X-rays (Watson *et al.* 1985).

To explain dwarf novae outbursts in general as well as the peculiar outbursts of some CVs, theorists presented models for accretion disk instabilities or mass transfer instabilities. These theories had to explain the 1/2- to 1-day delay in the ultraviolet outburst compared to the optical as well as the change (or lack of change) in the accretion disk during quiescence. While several satellite campaigns used AAVSO light curves to study the delay on outburst rise, my work concentrated on the quiescent interval. Using AAVSO light curves to phase IUE data to the outburst cycle for fifteen systems, we found that the majority showed decreasing UV fluxes after optical quiescence began (Szkody *et al.* 1991). This result was contrary to the expectations for the popular theory of accretion disk instability and was a puzzle until later work showed that white dwarfs cool after outburst (Godon *et al.* 2006) and thus, the UV follows this cooling as a flux decrease.

The AAVSO light curves of systems after superoutburst also provided fodder for theorists. The photometry of AL Com after its 1995 outburst (Howell *et al.* 1996) showed a dip similar to WZ Sge that was modeled with a cooling front passing through the disk, while the orbital light curves showed the first harmonic as well as the orbital period. This was among the first indications of the common property of disks in very short orbital period systems that is indicative of a thickening of the disk at the stream impact point as well as on the opposite side of the disk. Other topics in the 1990s moved toward identifying the underlying stars in the fainter, short period systems where the disk contribution is minimal, and understanding the effects of the outburst and accretion on the white dwarf. The observed lack of the predicted boundary layer also remained a problem for CVs at this time. With the start of Hubble Space Telescope (HST), the Extreme Ultraviolet Explorer (EUVE), and Chandra X-ray observations, the probe of the white dwarf and the boundary layer could go much deeper and to different wavelength regimes than previously possible.

With the aid of the AAVSO light curves, HST was used to catch dwarf novae at outburst and quiescence, as well as to follow the effects of the outburst on the white dwarf. The HST spectra of U Gem at outburst (Sion *et al.* 1997) showed a peculiar emission profile in the wings of HeII, indicating a chromospheric structure of the disk. EUVE spectra at outburst (Long *et al.* 1996) revealed the boundary layer of U Gem for the first time, showing it to be at a temperature of 140,000K, and with a size comparable to the white dwarf. The orbit-resolved spectra revealed the presence of a wind, with emission far from the orbital plane. The HST spectra obtained at several times during a quiescent interval showed that the white dwarf cooled after heating by the outburst (Sion *et al.* 1998). Details on the interplay of the various wavelength regions was provided by an intensive campaign with RXTE, ROSAT, IUE, and optical throughout the 45-day supercycle of V1159 Ori (Szkody *et al.* 1999). The results from this compilation showed an inverse correlation between the optical and UV light curves and those from X-ray, as well as the presence of a wind during outbursts, while model fits to the UV data showed a standard disk model did not fit the observed data.

3. The Arne era: 2005 (2002)–present

Collaboration with Arne Henden began in 2002, a few years before he became Director in 2005. The hot topics of the new millenia included the general population of CVs, Polars, and a new area of pulsating white dwarfs in CVs. The Sloan Digital Sky Survey (SDSS) took center stage in the optical, while the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Galaxy Evolution Explorer (GALEX) provided data in the UV and XMM was added to the X-ray scene.

The first HST data on the low state of the Polar EF Eri showed a unique spectrum with a large dip near 1600 Å, and a large amplitude modulation throughout the orbit (Szkody *et al.* 2010b). These data could be interpreted with either a cool white dwarf (the dip being a quasi-molecular hydrogen feature apparent in cool white dwarfs) and the modulation due to the viewing of a hot spot on the white dwarf throughout the orbit, or with two cyclotron components due to different magnetic fields. XMM data on the eclipsing polar SDSSJ0155+00 delineated a viewing geometry that allowed observation of the accretion flow through the base of the accretion funnel, leading to estimates for the physical parameters of these areas (Schmidt *et al.* 2005).

Work with the SDSS spectral database led to the identification of 285 CVs, resulting in eight papers in a series in the *Astronomical Journal* (*AJ*) (see Szkody *et al.* 2011 which includes previous papers in the series). These new CVs probed to fainter magnitudes and larger distances than previous surveys. Followup observations conducted by Arne and other AAVSO members, using the U.S. Naval Observatory (USNO) telescope as well as telescopes around the world, led to the ultimate identification of orbital periods of over 100 of the new objects. These results changed the picture of the orbital period distribution of CVs, bringing the observed periods much closer to the theoretical population models and showing that the previous results were largely due to selection effects (Gaensicke *et al.* 2009). Two surprising results also emerged from these SDSS results: the identification of a likely large population of LARPs and the presence of several pulsating, accreting white dwarfs among the SDSS objects. Followup XMM observations of the LARPs SDSS1553+55 (MQ Dra) and SDSS1324+03 showed low X-ray temperatures and luminosities, implying the source of X-rays was the M dwarf secondary, not the accretion shock (Szkody *et al.* 2004).

Followup HST spectra of the pulsating white dwarfs in CVs revealed a much hotter instability strip for these systems than the hydrogen-atmosphere non-accreting white dwarf pulsators (Szkody *et al.* 2010a) and the presence of increased amplitudes of pulsation in the UV compared to the optical regions. The outbursts of two of these pulsators (GW Lib and V455 And) in 2007 allowed the unique opportunity to follow these two systems as the white dwarf, heated by the outburst and moved out of its instability strip, cooled and resumed pulsations (Bullock *et al.* 2011). AAVSO data outlined the outburst and provided the required ground coverage to determine that the observed fluxes would not harm the HST observations. While the optical magnitudes were within a few tenths of a magnitude of the quiescent brightness by years 2010 and 2011, the temperatures determined from the UV spectra were still elevated. At years three and four after outburst, GW Lib was 3700K and 1300K hotter than quiescence, while V455 And was 600K and 200K hotter. In both objects, shorter periodicities than at quiescence (interpreted as the return of pulsations) are apparent in the UV by year three after outburst. Continued observations of these two objects will provide clues as to the mass accreted during the outburst and the amount of heating of the interior of the white dwarf.

Another ongoing project stems from the Z CamPaign (Simonsen 2011) which resulted in the identification of two peculiar Z Cam stars (IW And and V513 Cas). These systems show brightenings to an outburst following a standstill, in contrast to the usual behaviour of decline to quiescence following a standstill. Spectral observations of IW And and V513 Cas combined with the AAVSO photometry of these two systems throughout the various states of outburst, standstill, and quiescence are being used to study the accretion rates during these states. The available data so far show IW And has a traditional change from Balmer emission at quiescence to absorption at outburst, while V513 Cas shows emission cores flanked by broad absorption at quiescence and an unusual strength of high excitation HeII emission during outburst.

4. Conclusions

The past twenty-eight years has shown some large changes in understanding of CVs due in large part to the coverage of outbursts and optical states provided by the AAVSO observers and archive. The long term records of outbursts and the simultaneous determination of optical states during spacecraft observations at other wavelengths have been a vital part of the research undertaken. With the continued help of AAVSO observers, these advances into the understanding of accretion disks, magnetic white dwarfs, pulsating white dwarfs, and the makeup of the CV population will continue for the next twenty-eight years.

5. Acknowledgements

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The Development of Early Pulsation Theory, or, How Cepheids Are Like Steam Engines

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Abstract The pulsation theory of Cepheid variable stars was a major breakthrough of early twentieth-century astrophysics. At the beginning of that century, the basic physics of normal stars was very poorly understood, and variable stars were even more mysterious. Breaking with accepted explanations in terms of eclipsing binaries, Harlow Shapley and A. S. Eddington pioneered novel theories that considered Cepheids as pulsating spheres of gas. Surprisingly, the pulsation theory not only depended on novel developments in stellar physics, but the theory also drove many of those developments. In particular, models of stars in radiative balance and theories of stellar energy were heavily inspired and shaped by ideas about variable stars. Further, the success of the pulsation theory helped justify the new approaches to astrophysics being developed before World War II.

1. Introduction

The idea that stars could change brightness was bizarre enough that Aristotle rejected it on general principles. Even at the end of the nineteenth century, with the existence of variable stars well documented, their exact nature remained mysterious and problematic. The key to solving this puzzle was the theoretical astrophysics developed in the early twentieth century, but in an important sense variable stars were also the keys to theoretical astrophysics. Cepheid variables inspired, framed, and functioned as laboratories for many of the critical investigations that established the discipline.

2. The Binary hypothesis

Cepheid variables were completely inexplicable until the discovery of periodic radial velocity shifts in their spectra. This led to the double-star interpretation of variability: given the evidence for regular motion toward and away from observers, it was the most natural interpretation of the data at hand. There were other suggestions offered, such as the close approach of two stars causing tidal variations and eruptions of gas at higher temperatures than the stellar surface (Renaudot 1917). But none of these had the conceptual clarity and ease of explanation of the binary theory.

Harlow Shapley in 1914 called it a “misfortune” that the lines could be so easily understood this way. This paper focused on the problems with the binary interpretation, which he called “insurmountable” (Shapley 1914). Chief among these problems was the irregularity of Cepheid light curves. He noted that the continual change of the shape of the light curve made it quite difficult to assign the hypothetical binary a normal periodic orbit. He objected that instead of these messy curves, “regularity and continuity” (Shapley 1914) would be expected of any orbital phenomena. Shapley also brought up the observed changes in spectral type, which seemed nonsensical for a binary.

Some astronomers (including Campbell, Plummer, and Ludendorff) had also argued that there were internal inconsistencies in the double star hypothesis. For example, the average Cepheid was 700 times brighter than the Sun, which yielded a volume between 15 and 20,000 times as great as the Sun. As binaries, they would thus have an orbit less than 1/10 the radii of the stars themselves, which seemed impossible.

Shapley admitted that he could “offer no complete explanation of Cepheid variability as a substitute for the existing theories that are shown to be more and more inadequate.” His paper was just suggesting new avenues of approach to these problems. He did offer one intriguing, if poorly defined, possibility. Perhaps the variability was caused by “internal or surface pulsations of isolated stellar bodies.” (Shapley 1914) Shapley listed points in favor of the pulsation hypothesis: as a result of some original disturbance there would be oscillations of several different periods, explaining the complex light curves; for pulsation maximum velocity and light would be correlated just as observed; ebb and flow of heat would explain the change of spectral type. It is important to understand that pulsation was only a hazy hypothesis at this point, without any clear technical articulation. Shapley said the difficulty of making the hypothesis more precise lay in the lack of knowledge of the processes inside stars.

3. Early pulsation theory

Martin and Plummer (1915, 1917) followed up on Shapley’s idea, integrating the Cepheid velocity curve to get a radial displacement function over time. Interpreting this displacement as actual movement of the star’s surface yielded an expansion of the order of hundreds of thousands of kilometers. Like Shapley, they did not claim any proof or decisive evidence, and their most important contribution was laying out the technical issues that needed to be solved for pulsation theory to be useful.

They argued that one of the benefits of the pulsation hypothesis was that it could explain a number of different types of variables: “There seems to be no very cogent reason against the view that, outside the eclipsing systems, the great majority of variable stars manifest the operation of one essentially uniform process in nature.” (Martin and Plummer 1917) The uniform process they were referring to was the struggle between radiative expenditure and mechanical equilibrium, a presumably fundamental process in stellar interiors. This demonstrates an important point in the early history of variable star theory. There was continual disagreement about whether Cepheids should be explained in terms of a process organic to the normal functioning of stars, or whether it should be a process outside ordinary stellar behavior.

Around the same time, A. S. Eddington had begun theoretical investigations into many of these fundamental processes, most importantly the radiative balance with gravity. In 1917 he followed Shapley to discuss the pulsation hypothesis explicitly. He noted the enormous amplitudes of expansion that would be required, commenting that since Cepheids were giant stars it was possible, "but the consequent internal changes in the star must be very far-reaching." (Eddington 1917) This framed the problem in a definite way: the validity of the pulsation hypothesis was to be solved by understanding the stellar interior. The processes of the stellar interior were essentially unknown at this point, and Eddington was largely working with a blank slate.

He began by assessing a major difficulty key to the pulsation theory. Why do the pulsations not die out? It seemed unlikely that such massive alterations in the star's structure would last for very long:

> The most difficult question is, how can these pulsations be maintained? It is suggested by Shapley that, if the pulsations were started by some cataclysm, there is one type which would decay extremely slowly; it might persist almost indefinitely with inappreciable dissipation. But I do not think this conclusion is warranted by such investigations as have been made. The problem is essentially a thermodynamical one. The main cause likely to lead to a decay of vibrations is thermal dissipation of energy due to the flow of heat between different parts of the star. (Eddington 1917)

That is, Shapley thought of this as a problem in wave mechanics. Eddington proposed treating this as a problem in energy transfer. The vibrations would presumably dissipate a great deal of energy, and there must be a system by which this energy was replaced. Stellar heat was clearly "continually liberated within the star and passes outward into space; this may be borrowed and converted into energy of pulsation." (Eddington 1917) If these were the key issues, Eddington suggested, one should use an existing body of detailed theory developed for a physically different, but conceptually similar problem: the action of a steam engine. This helped clarify what a pulsation theory would require:

> But in order to convert heat of any kind into work, the star, or some part of it, must behave as an engine in the thermodynamical sense: that is to say, it must take in heat when it is at a higher temperature than the average and give out heat at a lower temperature - just the opposite of what usually happens in natural conditions. (Eddington 1917)

He pointed out that by means of radiation pressure a portion of this energy could be captured mechanically, just as a piston captured the expansion of steam.

Eddington confessed that understanding the vibrations of a star was "a very difficult analytical problem" and it has not yet been possible to figure out how a star could "behave in the manner of an engine." (Eddington 1917) However, he said, it was important not to obsess over certainty when conceptual progress could be made:

> Though we cannot offer any adequate theory as to how the star manages to behave as an engine, we can point out some evidence that it does so behave. I am not sure whether the following mode of regarding the question is strictly allowable; but I venture to put forward the suggestion tentatively. (Eddington 1917)

The key was to find a thermodynamic situation where the stellar waves neither decayed nor increased. He speculated that varying transparency inside the star could regulate the radiation pressure and therefore the expansion forces. Also, since the outflow of radiation was greatest when the star was expanding, that would help it expand, and vice versa, which would also help maintain vibrations. He explicitly avoided the question of the origin of the pulsations, only considering their survival: "How this comes about must be left unsolved; but since it is so, it seems clear that the pulsations are likely to be maintained." (Eddington 1917) It was clear that to proceed further more detailed studies of radiation pressure would be needed, and this drove Eddington's broader studies of radiation pressure in stars.

By 1918 the pulsation theory had made serious strides. The Council of the Royal Astronomical Society (CRAS) commented that the binary theory was imperiled, but that the pulsation hypothesis had not been proven (CRAS 1918). Eddington agreed that there was no proof while still stating that there was "little doubt" that Cepheid variation must be attributed to some form of pulsation (Eddington 1918). His new investigations used dimensional analysis to shows that "globes of fluid" would oscillate in periods inversely proportional to the square root of the density, a relation that he found to be fulfilled by nearly all the known Cepheids. This allowed determination of density changes in Cepheids by measuring the change of their period (which could be done very precisely). Noting that the most recent measurements of δ Cephei showed its period decreasing by about 1 in 9 million per year, this suggested it would take 10 million years to pass from type G to F (Eddington 1918). This seemingly minor detail had enormous implications:

> This is a far slower change than that derived from the assumption that a star's heat is provided by the energy of contraction. In fact, our time-scale is enlarged a thousand-fold, and becomes much more

> easily reconciled with current theories as to the age of terrestrial rocks, the development of the Earth-Moon system, and geological change. (Eddington 1918)

Thus measuring the periodicity of Cepheids could provide a clue to the critical question of the age of the stars, and therefore, of the universe. The time scale of stellar and cosmic evolution could finally be settled (Eddington 1918, 1919a). This link of stellar evolution to variable stars provided a useful hook on which new investigations of stellar aging could begin.

Another consequence of these calculations was the suggestion that if a star's energy came solely from gravitational contraction, then its change of period should be quite large. The observed change of period of δ Cephei was 0.1 second per year, while contraction theory predicted about 40 seconds per year. Eddington confidently asserted that "I see at present no escape from the conclusion that the energy radiated by a star comes mainly from some source other than contraction." (Eddington 1919b) Investigations of variable stars had unexpectedly advanced the long stalemated mystery of the energy source of stars.

By 1919 the pulsation theory had been developed far enough that Eddington was willing to state more firmly that:

> it is concluded that the binary hypothesis of Cepheids must be ruled out, because (a) the distance of the centres of the components would have to be less than the radius of one of them, (b) because there is a uniform relation between the period and density which seems to point to a cause intrinsic in the star. (Eddington 1919a)

He made the case that the hypothesis of pulsating stars leads to results in agreement with observation, specifically the absolute value of the periods, the advance of spectral type toward the red with increasing luminosity, and the asymmetric form of the velocity curve. Eddington had made a powerful case for the likelihood of the pulsation hypothesis, and along the way provided serious impetus to the longstanding problems of stellar evolution and stellar energy.

A handful of astronomers, including Shapley, Eddington, Martin, and Plummer, moved ahead with the pulsation theory. Even with the theory in an embryonic form, they were able to make significant progress. Their success drove other investigators to ask more detailed questions about the observational consequences of the pulsation theory and to present alternative ideas.

4. Objections and alternatives to pulsation

Despite its problems, many astronomers continued to do work with the binary hypothesis—its familiarity and conceptual straightforwardness kept it popular for some time (Henroteau 1919). Others, such as Walter Adams, were reluctant to accept the pulsation theory due to a number of unresolved issues, such as the narrow, well-defined spectral lines of Cepheids being unlikely given the enormous disruption that pulsations would be expected to cause (Adams 1919).

A characteristic example of both positions can be found in C. D. Perrine, director of the Argentine National Observatory. In 1919 he vigorously defended the binary hypothesis: “The closeness with which these variations are represented by orbital motion...is in itself, in the absence of proof to the contrary, almost conclusive evidence of their binary character.” (Perrine 1919) He maintained that the characteristics of light curves of known binary systems were perfectly consistent with Cepheid curves. And like Adams, he found it difficult to believe that internal pulsations could be so uniform in length and period. Perrine pointed out that the light curves show no sign of violent disturbance, and sunspots and novae persuaded him that all forms of stellar brightness variation would be irregular. Further, it seemed impossible to reconcile the “quiescent spectra of the Cepheids with such violent activity as the hypothesis of pulsations demands” (Perrine 1921).

Perrine argued that so little was known about what was happening inside stars that one could not use the pulsation theory. Instead, he wrote, we should assume that even mysterious stars such as Cepheids did not involve any truly novel processes. Astronomers should rely on “strong presumption of a similarity in constitution and evolutionary processes among all stars” (Perrine 1919). On this reasoning, they should be treated as binary stars in the absence of extraordinary evidence. He closed by making the case that the “almost deciding factor as to the nature of Cepheid variation” was their preference for the plane of the Milky Way. This, he said, indicated that their variation did not come from “the operation of general physical or gravitational laws” but rather some external condition (Perrine 1919). That is, Cepheids were ordinary binaries driven to unusual behavior by some local property in their neighborhood of the universe.

Many of the critiques of pulsation theory were based on hopes that Cepheid variation could be explained solely through celestial mechanics and other well-understood physics. There was a wide realization that pulsation would require a great deal of messy, novel physics unpalatable to an older generation of scientists. For example, James Jeans proposed a well developed alternative that relied solely on classical astronomy and physics. In 1919 he derived a functional formula for the light curve of δ Cephei with two major terms.He proposed that the first term could be the rotation of a single elongated body and the second term was “arising from some sort of explosion which occurs whenever this body assumes a particular orientation.” The observed changes of spectral type would just be the result of the progress of the explosion (Jeans 1919). On this hypothesis, a theory would require little more than traditional calculations of spinning bodies. The period of a Cepheid would simply be the period of rotation of an elongated body tidally locked to a companion. This suggested that Cepheids were merely one peculiar type of binary star (Jeans 1925).

There were plenty of more exotic proposals as well. Johann Hagen at the Vatican Observatory rejected both the pulsation and binary theories, instead suggesting cometary tidal forces (Hagen 1921). The notoriously heterodox American astronomer T. J. J. See argued that both sunspots and Cepheid variation were caused by tidal forces from Jovian planets (See 1922). Kyoto University's Shinzo Shinjo dismissed the pulsation theory and instead proposed the rotation of an "eccentrically condensed nucleus" moving in a spherical mass of meteoric material (Shinjo 1922).

A 1924 article by François Henroteau, working at the Allegheny Observatory and later the Dominion Observatory in Ottawa, provided a massive compilation of Cepheid observations and also assessed the competing theories:

> The present state of our knowledge of Cepheid variation is scarcely adequate to explain all the phenomena involved. The ordinary binary theory may almost certainly be definitely ruled out of court, while on the pulsation theory there are certain points not accounted for. (Henroteau 1924)

His assessment was fairly accurate. The binary theory had been wounded fatally, but the pulsation theory was only appealing to those investigators willing to grapple with strange new physics. The central continuing concern for everyone was whether Cepheids were a distinct class of star, a phase of a typical star's development, or some other possibility. The nature of δ Cephei remained uncertain.

5. A comprehensive pulsation theory

The full foundation of the pulsation theory was presented in Eddington's highly influential book *The Internal Constitution of the Stars* (1926). Its chapter on variable stars was strategically designed to remove competitors and leave the pulsation theory as the only option. He chose his words carefully, stating that it appeared "improbable" that Cepheids were binaries, and that the pulsation theory was now the "most plausible" (Eddington 1926). He warned that getting rid of the binary hypothesis did not necessarily mean the pulsation theory was correct. But, he said, doing so does leave a Cepheid as a single star, and the variation must therefore be intrinsic to it. If we have only one star, then pulsation and rotation were the only real options. The rotational theory (largely put forward by Eddington's archrival Jeans) was dismissed casually: "We do not know of any theory connecting the variations with the star's rotation, sufficiently plausible to be discussed here." The problem with rotational models was the expected but unobserved line broadening. He thus left the reader with pulsations as the only reasonable alternative:

> I have never regarded the hypothesis of symmetrical pulsations as conclusively established but I am not persuaded that anything has transpired in the recent discussions to weaken the case for it as here set forth. (Eddington 1926)

Eddington built his Cepheid theory on the same structure as his general theory of stellar constitution. The core of his Cepheid analysis was his calculation of adiabatic oscillations. He rejected the idea that the pulsations were just left over from a disaster, leaving the alternative that there were causes inside the star that tended to increase and maintain a pulsation. He followed the analogy of the heat engine quite closely—looking for the stellar equivalents of cylinders, valves, and so on (Eddington 1926; subsequent developments are described in Kawaler and Hansen 2012, this volume).

Eddington linked the critical question of energy transfer to the pulsations to the larger question of stellar energy generation in general. He pointed out that the values of density and temperature needed for the energy transfer to reinforce the pulsations were quite narrow. And interestingly, those values were virtually identical to the conditions necessary for energy liberation via the transmutation of hydrogen into helium (Eddington 1926). This calculation brought three important points forward. First, it was a major clue to the stellar energy source. Second, this calculation made Cepheids fairly rare, which was a point in its favor—it explained why most normal stars do not pulsate. Finally, it succeeded in calculating a size for Cepheids that closely matched observations. Eddington reminded his readers that investigating the Cepheids was not important just for themselves, but for their ability to help understand stars in general: “If this explanation is correct we have an opportunity of extending the study of the internal state of a star from static to disturbed conditions” (Eddington 1926).

6. Conclusion

The pulsation theory was on a firm footing by the late 1920s because the hypothesis was an integral part of the wider theory of stellar structure developed in that decade. Its deep connections to the successes of the broader theory made it highly plausible, and more appealing than invoking a hypothesis that thought of Cepheids as entities completely different from normal stars. And conversely, the success of stellar structure theory in explaining the bizarre behavior of Cepheids was a major feather in its cap. The ability of stellar structure theory to explain such strange objects was an important tool for convincing skeptics of its power, and also helped legitimate the use of the innovative approaches and methods critical to that theory. In particular, the Cepheid pulsation theory provided critical stimulus to develop the theory of radiative balance, the idea of fusion as the stellar energy source, and the timescale of the lifetime of stars.

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The AAVSO Photoelectric Photometry Program in Its Scientific and Socio-Historic Context

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Abstract In this paper, I review the work of the AAVSO in the area of photoelectric photometry (PEP). This work was influenced by several trends: in science, in technology, and in the sociology of amateur astronomy. Through the 1980s, the AAVSO photoelectric photometry program competed with other such programs and, in recent years, has been overshadowed by CCD photometry programs. Nevertheless, the AAVSO PEP program has, through careful organization, motivation, and feedback, produced extensive scientific results, and can continue to do so. In the case of my own research, AAVSO PEP observations have also contributed significantly to the education of my students.

1. Introduction

The AAVSO Photoelectric Photometry (PEP) program tends to be overshadowed by the venerable visual program, and by the charge-coupled device (CCD) program which is now generating hundreds of thousands of observations each year. Nevertheless, the PEP program has played a significant scientific and technological role in the evolution of AAVSO variable star research; it has produced good science—dozens of research papers—and continues to do so. It has also demonstrated the way in which observers with diverse talents and interests can engage with and contribute to variable star astronomy in their own preferred way.

The history of PEP observing in the AAVSO has been formally and professionally examined in the centennial history of the AAVSO (Williams and Saladyga 2011), and more informally in the last issue of the *AAVSO Photoelectric Photometry Newsletter* (Percy 2008), which can be found at: http://www.aavso.org/sites/default/files/newsletter/PEP/lastpepnl.pdf

2. Photoelectric photometry

Photoelectric photometry developed over a century ago, when physicists developed the quantum theory of light. Light consists of bundles of energy called *photons*. The photon energy is inversely proportional to the wavelength of the light—light has both wave and particle properties. When light illuminates certain materials, the photons liberate electrons from that material. This is called *the photoelectric effect*. It was for this that Albert Einstein received his Nobel Prize in Physics, not for his development of the theory of relativity. The number of these *photoelectrons* could be measured; it was proportional to the brightness of the light. *Photoelectric photometry* was born.

The photoelectric effect was soon applied to measuring the brightness of stars and other celestial objects, especially by Joel Stebbins in the United States and by Paul Guthnick in Germany. Early photometers, with detectors based on selenium, were relatively insensitive, and were therefore usable only on bright stars. They were also idiosyncratic, and observers had to understand their instruments well. However, the brightness could be measured to an accuracy of 0.01 magnitude or better—an order of magnitude better than with photographic or visual photometry. It was also possible to insert standard color filters into the light path (UBV: near-ultraviolet, blue, and yellow, for instance), and measure a "standard" magnitude, or measure the color of the star.

3. The development of amateur photoelectric photometry

Not surprisingly, some amateur scientists soon took up photoelectric photometry. There were no off-the-shelf photometers in the early days; you had to make your own. Electronics was a popular pursuit among amateur scientists, right through to the 1960s and beyond. When I was in high school in the 1950s, there was no science club, just a radio club! The American Radio Relay League had been founded in 1914, and was a magnet for amateur scientists and hobbyists. Radio amateurs also provided crucial communication services in times of emergency, so there was a sense of "citizen science" (or technology) in the hobby—especially during WWII. Amateur interest in electronics re-emerged with the post-war availability of electronic (including photometer) components. Electronics was the future!

Amateur telescope making blossomed in the 1920s, with the publication of articles by Russell W. Porter and Albert G. Ingalls, and the latter's three-volume book *Amateur Telescope Making* (Ingalls 1926). The Stellafane clubhouse and observatory were founded in 1923, and the annual Stellafane convention started shortly after.

In the 1950s, the "space bug" struck, in many ways. The Smithsonian Astrophysical Observatory established *Operation Moonwatch* as a citizen science (and patriotism) project in 1956, to track the anticipated artificial satellites to be launched by the USSR and USA. "Professional" optical tracking stations were not operational until two years later. *Operation Moonwatch* grew out of *Operation Skywatch*, in which hundreds of thousands of volunteers in the Ground Observers Corps watched for Soviet bombers—another fusion of citizen science and patriotic civil defence.

As well, the Space Age produced widespread and varied interest in both space science and technology, and in astronomy in general. This interest extended to young people, especially as school science and math curricula were expanded and strengthened in response to the Space Race.

By the 1970s, the "computer bug" struck also. The first computers, developed during WWII, were large and unwieldy but, with the development of transistors and then microelectronic circuits, handheld calculators, programmable calculators, and then "personal computers" were developed. Some of these were available as kits, which appealed to electronics enthusiasts. The recent (October 2011) death of Apple computer co-founder Steve Jobs reminded us of the excitement and innovation of those times. It was not long before a few amateurs, such as David Skillman (Skillman and Sinnott 1981) were automating their telescopes and their photometers.

4. The amateur PEP revolution

Several things happened around 1980 that revolutionized the field of amateur PEP. One was the availability of moderate-sized commercial telescopes at reasonable price; observers no longer had to build their own telescopes. A second was the development of a relatively simple off-the-shelf photometer, the SSP-3, based on a solid-state photodiode detector, by Optec Inc. Another was the publication of two very useful textbooks on PEP: *Astronomical Photometry*, by Arne Henden and Ron Kaitchuck (1982) and *Photoelectric Photometry of Variable Stars: A Practical Guide for the Smaller Observatory* by Doug Hall and Russ Genet (1988; a preliminary edition had been published in 1982 by International Amateur-Professional Photoelectric Photometry (IAPPP), and Fairborn Observatory). Yet another was the formation of IAPPP itself: "bringing amateurs, students, and professionals together for research in astronomy since 1980" (to quote the cover of the *IAPPP Communications*). The IAPPP later spawned "wings" in regions of the United States and overseas. The *Communications* provided a forum for publication of instrumental developments, advice on observing programs, and preliminary results. Related to this was the organization of PEP conferences, and the publication of several books on PEP, such as *Advances in Photoelectric Photometry*, volumes 1 and 2, edited by Russell M. Genet, Robert C. Wolpert, and others. But by the early 2000s, the IAPPP was dormant; CCD photometry was on the rise; and PEP topics became a small but significant part of regular variable star conferences.

5. The AAVSO PEP program—origin

The first record of AAVSO-associated PEP is some correspondence in 1919 between AAVSO Recorder Leon Campbell and Lewis Judson Boss, who had constructed a primitive selenium photocell, and was experimenting with it on Frank Seagrave's 8-inch (or possibly 8.5-inch) Clark refractor (Williams and Saladyga 2011). Boss published two articles about his efforts in *Popular Astronomy*. He joined the AAVSO in 1921 and continued this work for a few years before his professional duties caused him to stop the project. He did, however, serve as the founding chair of the AAVSO PEP Committee from 1954 until 1967.

Organized AAVSO PEP goes back at least as far as 1952—perhaps earlier. John J. Ruiz had expressed an interest in PEP as far back as 1947 and, in 1957 (Ruiz 1957a) published a paper in *PASP* on "A Photoelectric Light Curve of u Herculis" (an Algol binary), based on photometry from 1952 to 1955, and indicating that he was a "Member of the Photoelectric Committee of the AAVSO." In the same year (Ruiz 1957b), he published "Photoelectric Observations of 12 Lacertae" (a β Cephei star) in the same journal.

AAVSO Director Margaret Mayall proposed the formation of the PEP committee in 1954, and Lewis Boss chaired it from its inception until 1966. Boss, however, acknowledged that it was Ruiz who had done most of the work of the committee (Boss 1980). In 1956, Ruiz had written the *AAVSO PEP Handbook*. In 1967, Art Stokes (1967) published PEP observations of Nova Delphini 1967; he also chaired the PEP Committee from 1966 to 1975. Throughout the 1970s, Howard Landis published many PEP papers, mostly on eclipsing and RS CVn variables in collaboration with Doug Hall (e.g. Landis *et al.* 1973). In 1975, Landis replaced Art Stokes as chair of the PEP Committee. Art and Howard were the PEP pioneers who introduced me to the potential of AAVSO PEP observations. Howard noted, in his 1978–1979 committee report, that 844 PEP observations of eclipsing binaries had been made in that year. So AAVSO PEP was well underway by then. Its organizational evolution, however, was affected by certain questions of observer recognition which are discussed in some detail by Williams and Saladyga (2011).

A more formal PEP program was organized by Janet Mattei in the early 1980s, primarily to complement the observations of some of the stars in the AAVSO visual program—ones that had both medium- and small-amplitude variability. Typical amplitudes were one magnitude or less. Most were small-amplitude pulsating red variables—giants and supergiants. I assisted in choosing the final set of program and comparison stars (no mean task for red variables!), and became the main scientific advisor to the program. The program grew from about sixty to about eighty stars, including stars that were added—or dropped because they proved to be non-variable. As of 1998, almost sixty observers had contributed to the program. For a discussion of the science and sociology of the program, see Percy (2000).

6. The AAVSO PEP program—growth

The best way to visualize the growth of the formal AAVSO PEP program is to look at Figure 1, which includes the prehistory of the program. The formal program started small, with only a few dozen observations the first year. But, especially through the patient work of Howard Landis, other observers gradually joined.

Initially, there was a "sociological" problem. The program was competing with Doug Hall's PEP program on RS CVn stars, and that yielded new results almost every season. Papers were published regularly, with the observers included as co-authors—as they should be. The AAVSO PEP program, on the other hand, was not designed to produce quick results; its power was in the information that it provided about the long-term behavior of the stars. But the program grew, as Figure 1 shows.

There are several reasons for the decline after 2000: the program was partly "in limbo" while it was being transferred to AAVSO Headquarters; some observers migrated to CCD observing; and some very active observers retired—champion observer Ray Thompson, for instance.

One way in which you can visualize the results of the program is to choose a star from the program, and go to the Light Curve Generator, entering its name (EU Del, for instance), choosing V data only, and asking for the last 10,000 days of data.

7. The *AAVSO PEP Newsletter*

The *AAVSO PEP Newsletter* was founded in 1979 with the name of *AAVSO PEP Bulletin*. By Volume 2, Number 1, dated February 21, 1980, it was *Newsletter*. It was produced by Howard Landis, Art Stokes, and Dave Skillman. The next issues are Volume 3, Numbers 1–4, which came from Russell M. Genet. The first that I edited was Volume 4, Number 1, dated June 1983. It begins by thanking "my predecessor Russell M. Genet for his enthusiastic and effective work in editing this newsletter." Apparently he wisely turned it over to willing hands (mine), because I continued to edit it, two or three times a year, often with an abject apology, in the editorial, for its lateness. Russ went on to other exciting things.

In 1992, I turned the *Newsletter* over to Michael S. Smith, in Tucson. He edited it for a few years, before handing it back to me in 1996. I edited it, with decreasing frequency, until 2008. As more and more of the work was done at AAVSO Headquarters, it has made more and more sense for communications to come from there.

During my editorships, there was a wide variety of content, usually provided by me, though I always appealed for contributions. Quite often (even before the age of widespread email), I would get brief notes and queries that I published. The most faithful contributor was Howard Landis, who always contributed a PEP Committee report, on time, with useful statistics, and acknowledgement of observers. We announced forthcoming PEP-related meetings and, where possible, summarized the contents. In particular: I published PEP highlights from the AAVSO Annual and Spring meetings. We published notices of "campaigns" (see below), and other special requests for observations. We discussed charts, the ins-and-outs of submitting and archiving observations, and data reduction and analysis. I cheerfully published mini-biographies of the observers. I often wrote about how my students had benefitted from analyzing AAVSO PEP observations for their projects, so that observers would know that their work had double benefit—to research and to education. Sometimes I would write mini-essays on the types of stars on the PEP program, or which turned up as annoying micro-variable comparison stars. Or I would summarize interesting photoelectric papers in the literature.

But most of my contributions were feedback to observers, telling them about new scientific results that their observations had produced. Often these were preliminary reports on results that were later published in *JAAVSO* or elsewhere.

8. Scientific results from the AAVSO PEP program

The scientific results from the AAVSO PEP program have been described by Percy (2008), and references given to select publications. Here, I shall review and update the results on small-amplitude pulsating red variables, which make up the majority of the program.

Until the 1980s, these very common variables were simply described as semiregular or irregular, and largely ignored. Thanks in part to the AAVSO PEP program, we now know that: all M giants are photometrically variable; these stars pulsate in one (or more) low-order radial modes; they occasionally switch modes; many have a long secondary period (LSP) of unknown cause; the amplitude is greater in cooler stars; since cooler stars are more luminous (because they lie on the giant branch in the H-R diagram), the cooler stars have longer periods. For each pulsation mode, these stars obey a period-luminosity relation almost as tight as that for Cepheids. An ensemble of these stars shows a series of period-luminosity relations, corresponding to different pulsation modes. For this reason, these stars can be especially powerful astrophysical tools.

One part of the program was *Project SARV*, in which a total of sixty-one bright red giants, suspected to be variable, were assigned to interested AAVSO PEP observers. The result was an eighteen-author paper, Percy *et al.* (1994).

In parallel with the analysis of the AAVSO PEP data on these stars (Percy *et al.* 1996), we analyzed data from a robotic telescope in Arizona (Percy *et al.* 2001). We subsequently combined the AAVSO data with the robotic telescope data for the thirteen stars in common (Percy *et al.* 2008). The combined data were especially powerful: the AAVSO data filled in the gaps in the robotic telescope data, caused by the summer monsoon season; and the AAVSO observations, which were continued long after the robotic telescope observations ceased, produced a dataset that was over two decades long. We were not only able to refine the primary periods, and LSPs, but we were also able to identify very-long-term variability.

The periods which were determined from the AAVSO PEP data have also contributed to a study of the period-luminosity relation(s) for pulsating red variables (Tabur *et al.* 2010). That was possible because our program stars are relatively bright, and therefore close enough for their parallaxes to be determined by the *Hipparcos* satellite.

9. The AAVSO near-infrared photometry program

Long-term near-infrared (NIR) photometry is valuable for all the same reasons that long-term V-band photometry is, especially for stars that emit much or most of their energy in the near-infrared. But few professional observatories were interested in or equipped for such photometry. Once again, skilled amateurs stepped into the breech. The AAVSO NIR PEP program was established in 2003. Much planning was needed, and a professional-amateur committee was formed to do this, with Doug West as a driving force. There were no off-the-shelf NIR photometers, so the AAVSO worked with Optec Inc. to develop one—called the SSP-4—that operated in the J (1.25 microns) and H (1.65 microns) bands. Five photometers were purchased by the AAVSO, and lent to interested, experienced observers. There are now about thirty stars in the program, mostly red giants, Cepheids, and eclipsing variables. See http://www.aavso.org/infrared-photoelectric-photometry-program for much more information.

10. PEP Campaigns

A *campaign* is a project in which one or a few carefully-selected stars are observed intensively for a period of time. In a sense, the AAVSO PEP program is a campaign! There are *multi-wavelength campaigns* in which the objects are observed simultaneously at a variety of wavelengths. There are *multi-longitude campaigns* in which the objects are observed from enough different longitudes to ensure continuous twenty-four-hour time coverage.

The AAVSO PEP program has participated in several campaigns. One notable one was organized by Roger Griffin, Cambridge University. ζ Aurigae binaries are long-period binaries in which one component is a supergiant. Eclipses, if they occur, would occur infrequently, but at predictable times, i.e., when one star was predicted to possibly be in front of the other. Roger provided times of possible eclipses in known or suspected ζ Aurigae binaries; we helped choose suitable comparison stars; and the observers determined which stars showed eclipses, and when, and how deep. The most significant campaign of this sort was the AAVSO's *Citizen Sky* project, in which dozens of new observers were recruited, trained, and motivated to observe the 2009–2011 eclipse of ε Aurigae; see: http://www.citizensky.org.

A more recent campaign was of a completely different kind: it was to monitor IM Peg, the guide star for the *Gravity Probe B* satellite; see http://einstein.stanford.edu. GPB was designed to test aspects of the theory of relativity by looking for two small, subtle effects on the orientation of the satellite. The RS CVn star IM Peg was chosen as the guide star because it was a point radio source whose position could be measured to milli-arc-second accuracy with radio telescopes, and it was bright enough to be seen by GPB's optical guide scope. But RS CVn stars have starspots, and the change in the starspot distribution on the star can artificially change its apparent position. Therefore a photometric campaign was organized to monitor the starspots through their effect on the brightness of the star. Much of the work was done by robotic telescopes, but these, being in Arizona, were "monsooned out" during the summer. That's where AAVSO PEP observers could fill in, and make a special contribution.

11. Educational spinoffs from the AAVSO PEP program

The observation and analysis of variable stars can be effectively connected to the goals of science and math education; that is the basis of the AAVSO's famous *Hands-On Astrophysics* project. It has since morphed into the much more powerful *Variable Star Astronomy* (http://www.aavso.org/education/vsa). The scientific research process involves elements of inquiry, investigation, problem-solving, discussion, and communication—the cornerstones of science education. Variable star observation, analysis, and interpretation is well suited for student projects and activities. Making measurements of variable star brightness visually may be simple, but the applications, analysis, and interpretation of the data involve a wide range of scientific and mathematical skills—some simple, but others quite challenging, even for experts.

Many undergraduate students carry out PEP research at universities and colleges around the world. I have even heard of high school students doing PEP, often for science fair projects. One or two did so through the AAVSO PEP Committee. At one time, my undergraduate students made PEP observations from downtown Toronto, sometimes of AAVSO PEP program stars; Doug Welch, well-known to AAVSOers, was a "graduate" of that program. But, for the last decade or two, their work has consisted of analysis and interpretation—usually of AAVSO PEP or visual data. Such projects involve doing real science with real data. They develop and integrate a wide variety of science, math, and computing skills, starting from background reading and planning; research judgement, strategy and problem-solving; continuing with pattern recognition, interpolation and measurement; recognizing and understanding random and systematic errors; construction, analysis, and interpretation of graphs; concepts of regularity and prediction, curve fitting and other statistical and numerical procedures; all the way to the preparation and presentation of oral and written papers.

My own students are of two kinds. The first are undergraduate students, either summer research assistants, work-study students, or students in our Research Opportunities Program (ROP), a competitive, prestigious program in which second-year students can work on a research project for course credit. The second are students in the University of Toronto Mentorship Program (UTMP), which enables outstanding senior high school students to work on research projects at the university.

In 2007–2008, two of my former students received special awards. One, former UTMP student Wojciech Gryc, received a Rhodes Scholarship. Another, undergraduate Kathy Hayhoe (who subsequently evolved from astronomy to climatology), won 1/2000 of half of the Nobel Peace Prize, because she is now a member of the Inter-Governmental Panel on Climate Change!

12. Final reflections

The AAVSO PEP program still attracts fifteen to twenty observers from all over the world, and produces good data and good science. It is administered by AAVSO Headquarters, with Dr. Matt Templeton as scientific advisor, and Jim Fox as chair of the PEP Committee. Collectively, the program has produced over 52,000 observations over thirty years of a total of 223 stars which are or have been on the program, mostly small-amplitude pulsating red giants. The "official" list of program stars is at:

http://www.aavso.org/content/aavso-photoelectric-photometry-pep-program

What are the strengths of a good observing program? Obviously it should produce useful scientific results, in the short or long term. Therefore its scientific value should be regularly and critically reviewed, so it will continue to be of value. Ongoing advice and support from the astronomical research community, that is, professional astronomers, can help to provide this. The program should be well-coordinated and standardized; this is especially important for programs whose strength is long datasets. It should have the opportunity for continuity, which is much easier if it is run by a well-established organization like the AAVSO than if it is run by an individual professional astronomer whose interests or status may change. It will succeed if observers receive instruction, feedback, support, motivation, and recognition—all of which the AAVSO does admirably. In this way, the program not only provides useful scientific data, but it also provides enjoyment and satisfaction to human observers. Indeed, the strength of the AAVSO is its combination of scientific relevance and human spirit.

13. Acknowledgements

The success of the AAVSO PEP program is due to the skill and dedication of the sixty-plus observers who have contributed; to the AAVSO Headquarters staff who received, processed, and archived the data; and to the chairs and members of the PEP Committee who guided the program. My personal thanks go to Howard J. Landis and the late Janet A. Mattei. I am grateful to Tom Williams for inviting me to participate in the May 2011 AAS-AAVSO history session, and to Mike Saladyga for reading a draft of this paper. I thank the Natural Sciences and Engineering Research Council of Canada, the Ontario Work-Study Program, and the organizers of the University of Toronto Mentorship Program for facilitating my work, and that of my students—whose help and inspiration I also acknowledge here.

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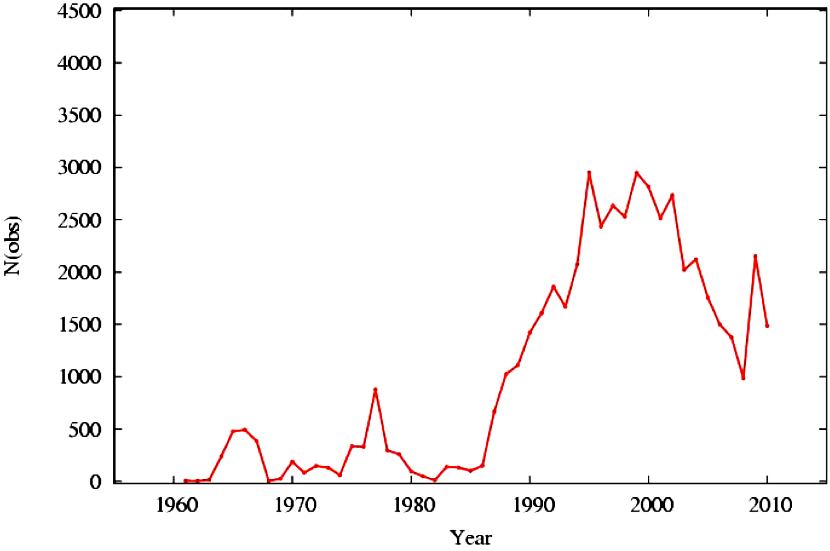

Figure 1. The number of PEP observations carried out through the AAVSO as a function of time. Data provided by the AAVSO.

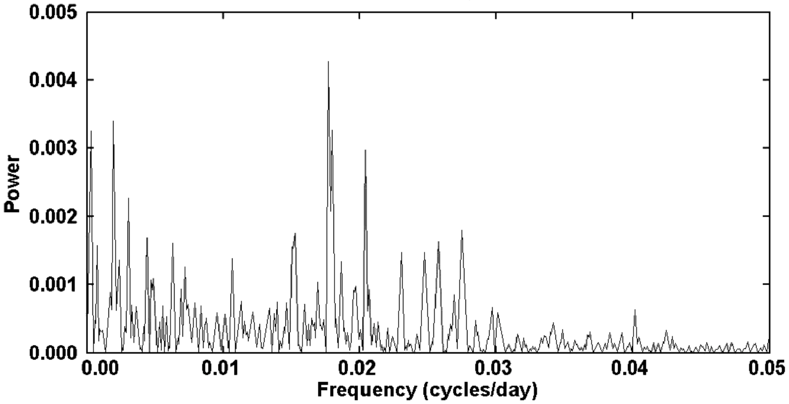

FIgure 2. The power spectrum of RZ Ari from combined AAVSO and robotic telescope photometry, showing periods of 56.5 days (0.0177 cycle/day), 37.7 days (0.0265 cycle/day), and 370 days (0.00270 cycle/day). The first two periods represent two different pulsation modes, the last period is a "long secondary period." From Percy *et al.* 2008.

John Goodricke, Edward Pigott, and Their Study of Variable Stars

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Abstract John Goodricke and Edward Pigott, working in York, England, between 1781 and 1786, determined the periods of variation of eclipsing binaries such as β Persei (Algol) and β Lyrae and speculated that the eclipses of Algol might be caused by a “dark body,” perhaps even a planet. They also determined the periods of variation of the first two known Cepheid variables, the stars whose period-luminosity relation today enables astronomers to determine distances to distant galaxies. Goodricke holds special interest because he was completely deaf and because he died at the age of 21. The lives and work of these two astronomers are described.

1. Introduction

The name of John Goodricke (1764–1786; Figure 1) is recognized by many astronomers today, but few details of his life and work are widely known. Some know that he observed variable stars, some know that he was profoundly deaf, and some know him as an amateur astronomer. Goodricke’s collaborator, Edward Pigott (1753–1825), is even less well known. Together, these two determined the periods of variation of eclipsing binaries such as β Per (Algol) and β Lyrae, speculating that the eclipses of Algol might be caused by a “dark body,” perhaps even a planet. They also discovered and determined the periods of variation of η Aquilae and δ Cephei, the first two known Cepheid variables. The period-luminosity relation of Cepheids, of course, would later enable astronomers to determine distances to distant galaxies. In 2010, the author was able to spend a sabbatical semester at the University of York, studying the journals and notebooks of Goodricke and Pigott in order to understand how these pioneers went about their work.

Richard Holmes (2008) cautions about the shroud of myths that often envelops scientists of great accomplishment. One such myth is that of the lone, heroic figure, struggling against misconceptions perpetrated by lesser minds, against his (or her) own family, and perhaps even against society itself. This myth does not apply to John Goodricke. Rather, he was able to attend forward-thinking schools that addressed his learning needs and nurtured his talents, and he had the support of a family who clearly valued and encouraged his studies.

2. John Goodricke: background and family life

The Goodricke family line is long, with several branches in England. The Goodrickes of Yorkshire took up residence at Ribston, just west of the city of York, in 1533 when Henry Goodricke became steward of Great Ribston (Figures 2 and 3). In 1641 Sir John Goodricke was created the first Goodricke baronet for his service to the King during the Civil Wars. John, the astronomer, was the eldest grandson of the fifth baronet, also named Sir John (1708–1789).

Zdeněk Kopal, the Czech-British astrophysicist, once described the Goodrickes as "fox-hunting country squires" (Kopal 1986), a characterization that the facts do not support. The Goodricke baronets were, for the most part, not content to sit at home on the Ribston estate. Sir Henry, the second baronet, was the English Ambassador to Spain from 1678 until 1682, and Sir John, the astronomer's grandfather, was Envoy Extraordinary to Sweden from 1764 until 1773. Both men, as well as the astronomer's father, Henry (1741–1784), served as Members of Parliament, and both baronets were members of the King's Privy Council (somewhat similar to the U.S. President's Cabinet).

John Goodricke, the astronomer, was born on 17 September 1764 in Groningen, the Netherlands, where his father, Henry, was employed in diplomatic service. John's mother was born Levina Benjamina Sessler; her father was Peter Sessler, a merchant of Namur, Belgium. John was the eldest surviving child, and so he would have been the heir to the baronetcy had he lived to succeed his father and grandfather.

According to the family history, John became deaf at the age of five due to a severe illness that has been conjectured to be scarlet fever. At the age of seven he went to study at Thomas Braidwood's Academy for the Deaf and Dumb in Edinburgh, the first school for deaf children in the British Isles. Braidwood was very secretive in his teaching methods. We do know that Braidwood advertised "to undertake to teach anyone of a tolerable genius in the space of about three years to speak and to read distinctly" (quoted in Pritchard 1963); that his pupils read lips and signed; and that Braidwood had originally been a mathematics teacher (Branson and Miller 2002).

John went on to study at the Warrington Academy for three years after leaving Braidwood's. Warrington was one of the "Freethinking" or Non-Conformist academies originally founded to prepare clergymen in denominations other than the Church of England. It was well known for its emphasis upon mathematics and natural philosophy; the chemist Joseph Priestley had taught there but had moved on before John Goodricke arrived in 1778 (Parker 1914). John was described as "a very tolerable classic and an excellent mathematician" in a school report (Turner 1813). During John's time at Warrington, the mathematics curriculum (which included astronomy in the second year) was taught by William Enfield (McLachlan 1943). Enfield was primarily a theologian, but he worked diligently at his teaching and eventually published his notes as a textbook, *Institutes of Natural Philosophy* (Enfield 1785), which went through many editions on both sides of the Atlantic. John's mathematics notebook is preserved in the Goodricke collection of the York City Archives, and the figure seen there can be found on the inside back cover (Goodricke 1779; Figure 4).

2.1. The Warrington sketch

The drawing shows several constellations: Orion's belt can be seen, along with the brightest star in Taurus, "The Eye of the Bull," Aldebaran; the constellation of Auriga; and "the two brightest stars in the Gemini." The Milky Way is shown, as well as the zodiac (or ecliptic), and the Moon. At the bottom of the page is a sentence describing the position of various stars on either side of the meridian, a line connecting the north and south points on the horizon and passing through the zenith. The star positions, together with the Moon's position in the sky, permit determination of the approximate date of the drawing. The only time that matches both the Moon and star positions is a one-week period in late November of 1779. On 23 November 1779, a total lunar eclipse was visible over England (Borkowski 1990). John Goodricke would have had access to textbooks with tables of predicted eclipses (such as Ferguson 1756); he would also have been taught to do such calculations in his schoolwork (Enfield 1785). Exactly how he came to produce this drawing we may never know. What is significant, however, is that he was already observing the sky in 1779, at the age of fifteen.

2.2. Correcting some popular misconceptions about John Goodricke: a "deaf-mute"?

John Goodricke is often described as "deaf and dumb," or a "deaf-mute." Evidence from the Goodricke journals suggests that, while he was certainly deaf, he almost certainly spoke. He evidently was able to read lips (teaching students to lip-read and to speak if they were capable of it was part of the curriculum at the Braidwood Academy). The evidence for this is in two passages from Goodricke's *Journal of the Going of My Clock* (Goodricke 1782a):

> 17 November 1782: Whilst I was winding up the Clock the second hand did not go on as usual–I spoke to Mr Hartley [the clockmaker] about it & he said it was caused by my not pulling down the Spring hard enough....
>
> 15 December 1782: Whilst I was winding up the Clock on the 15th the second hand did not go on as usual–As this is now the 3rd time it did so; I remonstrated with Mr Hartley about it & asked him ye reasons of it doing so–He gave me the same answer as on the 17th of Nov. last but I did not credit him–However after several trials I have since hit upon the true course & found that it was owing to a fault

> of my own in not pulling the spring down hard enough according to Hartley's directions which I did not rightly understand or he was not very particular in explaining them to me.

From the words alone, nothing could be clearer: he *spoke* with Mr. Hartley, he *remonstrated* with Mr. Hartley. The second passage makes it even more explicit that the conversation was a verbal one; Hartley explained and Goodricke did not initially understand the explanations. Had the directions been written out, it is much less likely that such a breakdown in communication would have occurred. Thus, the available evidence suggests that Goodricke read lips well enough to carry on business transactions, and that he may well have spoken.

2.3. Burial Place

Zdeněk Kopal, in his scientific autobiography *Of Stars and Men* (1986), described a visit to the churchyard of St. John the Baptist at Hunsingore (Figure 5), the burial place of John and the other Goodrickes, and came to the conclusion that John Goodricke had been buried apart from his family in an unmarked grave. Kopal wrote: "Why does he rest there forgotten by all his clan; why was he not buried with them in their family vault[?]...." He went on to speculate that John's parents and grandparents found his deafness to be "a blot on the family escutcheon." Kopal apparently did not investigate the history of the present church; if he had he would have discovered that it dates to 1868, after the Goodricke family estate at Ribston had been purchased by the Dent family. There was a Goodricke family vault under the old church, and that vault still exists. It is marked in the churchyard by a stone identical to that used for the new church, with only the words "Goodricke Vault" engraved upon the side (Figure 6). The burial records still exist (N. Yorkshire County Record Office MIC 1685), and they show that John Goodricke was indeed buried alongside his parents and grandparents in the family vault. Although the deaf were often treated inhumanely in the eighteenth century, John Goodricke's family gave him the best possible education both for his scientific research and for his stature as the Heir Apparent to a baronetcy.

The previous Goodricke baronets had attended university at either Cambridge or Aberdeen, and John surely would have been intellectually qualified for university. Why he returned to York at seventeen to live with his family is somewhat puzzling. Both John, in his journal, and Edward Pigott, in a diary, make occasional references to John's not being well, so perhaps his health had already begun to fail. At any rate, the first entry in John's formal observing journal (Goodricke 1781) comes early November 1781, when he writes: "Last evening at 9 p.m. Mr. E. Pigott discovered a comet."

During the first few entries John describes Edward's correspondence with William Herschel and with Nevil Maskelyne, the Astronomer Royal. Edward's contacts in the astronomical world, as well as his discoveries, clearly impressed John, who immediately set about keeping a record of his own observations.

3. Edward Pigott: background and family life

Edward Pigott's father, Nathaniel (1725–1804), was also an astronomer, and he was the primary source of Edward's astronomical training. The Pigotts were related to the wealthy, landed Fairfax family of Yorkshire; Nathaniel's mother Althea Fairfax Pigott was the sister of Charles Gregory Pigott (d. 1772), ninth Lord Fairfax and Viscount Emley. As Catholics, the Pigotts found life in France more congenial than life in the north of England, and they spent a great deal of time there. Edward went to school in both countries, but French was his first language, which gives an occasional "invented" feel to the wording and spelling of his journals.

Nathaniel's primary interest was in using astronomical methods such as the timing of eclipses of the Moon and the Jovian satellites to determine latitude and longitude. Although not a wealthy man, he was able to acquire instruments made by the finest craftsmen of the time, including Ramsden, Dollond, Sisson, and Bird. Between 1773 and 1775 Nathaniel and Edward collaborated with continental astronomers including Messier and Mechain to determine the latitude and longitude of several cities in the Austrian Netherlands (now Belgium; Pigott 1778).

Nathaniel Pigott owned property in Middlesex and in Wales, and in 1781 the family settled in York, where Nathaniel hoped to manage the estates of Lady Anne Fairfax, the sole surviving daughter of Lord Fairfax, and to eventually secure the estates as an inheritance for Edward's younger brother, Charles Gregory Pigott. The Pigott family took up residence in York, approximately one-quarter mile from where the Goodrickes were living. Here Nathaniel constructed an observatory said to be amongst the finest private observatories in England.

A diary kept primarily by Edward Pigott with some entries by Nathaniel (now in the Beinecke Library of Yale University) includes stories of joint Goodricke-Pigott family outings. Thus, even though the start of the official collaboration dates from John's beginning to keep the observing journal, it seems likely that the two discussed astronomy at an earlier date.

3.1. Interest in variable stars

Stellar astronomy was still in its infancy in the eighteenth century (see, for example: Hoskin 1982; Williams and Hoskin 1983). Among variable stars, a period had been determined only for the long period variable o Ceti (Mira). Ismael Boulliau, better known by his Latinized name Bullialdus, observed the star systematically between 1660 and 1666, obtaining an accurate period of nearly 333 days (Hoskin 1982; Hatch 2011). Bouilliau went on to consider sources of the star's variability, and hypothesized that the most likely cause of the variation was dark regions on the star coming into view as it rotated; in other words, spots analogous to sunspots. That long period variables do not always show an exact periodicity or reach the same peak brightness was to be expected, since the variation in the Sun's light due to sunspots is not exact. Boulliau's explanation was accepted and adopted by Newton in Book 3 of the *Principia*, and by William Herschel in his first published paper (1780), which contained observations of Mira (Hatch 2011).

As early as 1778, while observing from Wales, Edward Pigott was noticing that both the reported positions and brightnesses of stars varied from one catalogue to another, and he speculated on possible sources of the noted discrepancies. He continued this practice from York. In July of 1781, for example, Edward wrote in his journal:

> The 22nd star of Tycho's Andromeda is probably the o (omicron) of that constellation, tho' it differs very considerably both in Longitude and Latitude, which I am convinced is occasioned by an error either in the Observation or Calculation, the Prince Hesse [probably William IV, Landgrave of Hesse-Kassel] observed the o therefore it was visible in Tycho's times and has been since; See Hevelius's & Flamsteed's Observations; now it is not probable that Tycho would have overlooked a star of the 3rd or 4th mag. (Pigott 1781)

A discussion of the positional uncertainties in the catalogs of Tycho, Hevelius, Flamsteed, and the Landgrave is beyond the scope of this paper. What is significant in this passage is Edward's taking note of discrepant magnitude estimates and commenting that Tycho would not have omitted a star as bright as the third or fourth magnitude—exactly the magnitude range of the stars that he and John would soon study systematically. The implication is that the star might well have varied in brightness.

In the autumn of 1782 John and Edward decided to pursue observations of "Stars which are Variable or Thought to be so," as John wrote in the heading of one journal entry in early November (Goodricke 1782b). The first star on his list is β Persei (Algol), whose changes in brightness had been noted as early as 1672 by the Italian astronomer Geminiano Montanari. In October 1782, Edward Pigott noted, "This star is variable" for Algol, almost certainly as a result of a literature search, as he had made no extensive observations of the star up to that date. Other stars on John's list as candidates for variability included δ Ursae Majoris, not thought today to be variable, and α Herculis, now classed as a semiregular variable with amplitude of nearly one magnitude.

On 12 November 1782, John noted,

> This night I looked at Beta Persei [Algol], and was much amazed to find its brightness altered—It now appears to be of about 4th magnitude. I observed it diligently for about an hour—I hardly believed that it changed its brightness because I never heard of any

> star varying so quickly in its brightness. I thought it might perhaps be owing to an optical illusion, a defect in my eyes, or bad air, but the sequel will show that its change is true and that I was not mistaken. (Goodricke 1782c)

The two began checking Algol every clear night. They did not see another diminution of light until 28 December. By April they had seen consecutive episodes of darkening, and were able to determine that the period was very short compared to that of Mira: only 2 days and 21 hours. According to the custom of the time for reporting scientific results, John sent off a memorandum to Anthony Shepherd, Plumian Professor of Astronomy at Cambridge, to be read at the Royal Society of London. At the same time, Edward Pigott notified Nevil Maskelyne, the Astronomer Royal, and William Herschel, both of whom were eager to observe Algol. The variability was quickly confirmed by Herschel and other astronomers of the Royal Society. In his report, published in the *Philosophical Transactions of the Royal Society*, John states:

> I should imagine [the diminution of light] could hardly be accounted for otherwise than either by the interposition of a large body revolving round Algol, or some kind of motion of its own, whereby part of its body, covered with spots or such like matter, is periodically turned towards the earth. (Goodricke 1783)

The two discussed the idea of a "large body" revolving around Algol, as their journals both indicate, and in the journals both call the large body a planet. It is likely, as Michael Hoskin (1982) suggests, that the planet hypothesis originated with Edward Pigott, the more experienced observer and always the more adventurous theorizer of the two. Yet Goodricke wrote the formal report, and in August of 1783 he was awarded the Copley Medal of the Royal Society.

We now believe transits of a fainter stellar companion to be the correct explanation for the Algol system. Observations of transits are currently being used by NASA's Kepler mission to detect Earthlike planets around other stars. Yet in their own time Goodricke and, to a lesser extent Pigott, would abandon the transit hypothesis in favor of starspots. In his last completed paper, on the period of variation of δ Cephei, Goodricke would write:

> What I have before mentioned, that the greatest brightness of δ Cephei does not seem to be always quite the same, is not peculiar to this star, but is also to be observed in the other variable ones.... Even Algol does not seem to be always obscured in the same degree, being perceived to be sometimes a little brighter than ρ Persei, and sometimes less than it....This may, I suppose, be accounted for by a

> rotation of the star on its axis, having fixed spots that vary only in their size. (Goodricke 1786)

Several factors could have contributed to Goodricke's change of mind. By this time, he had visited Nevil Maskelyne at Greenwich and been exposed to the opinions of senior astronomers, who favored sunspots, as we have seen. But also, the nature of δ Cephei's light curve differs from that of Algol. There is not one single isolated diminution, but a continuous fading and brightening; a pattern that is less easily interpreted in terms of an eclipse. Finally, ρ Persei, conveniently placed for comparison with Algol, is itself a variable star, and so it may well have been "sometimes a little brighter" and sometimes less bright than Algol. Most modern observers can relate to the dilemma of choosing a comparison star that turns out to be variable! Only a century later was the eclipse hypothesis confirmed using spectral analysis (see Batten 1989 for a review).

4. Other astronomical work

John Goodricke's remaining time on Earth was short. He continued to observe Algol; in addition to determining the period of δ Cephei he also obtained the period of β Lyrae. In the autumn of 1784, as Goodricke studied δ Cephei, Edward Pigott detected the variation of another Cepheid, η Antinoi (today η Aquilae). Edward would eventually discover two more variable stars, R Scuti and R Coronae Borealis; he discovered the spiral galaxy known as M64 before Bode, and Jerome La Lande would write him that

> The observations which you sent me in 1782…have been very useful in my research into a theory for Mercury, which I have published… their ephemerides showed me for the first time that the place of the aphelion was too far advanced in my tables. (LaLande 1786)

Thus, Edward Pigott's observations may well have been among the first showing the advance of the perihelion of Mercury!

John Goodricke died on April 20, 1786, in York, 14 days after being elected to membership in the Royal Society at the age of 21. Edward Pigott completed their determination of the latitude and longitude of York and wrote of Goodricke:

> This worthy young man exists no more; he is not only regretted by many friends, but will prove a loss to astronomy, as the discoveries he so rapidly made sufficiently evince: also his quickness in the study of mathematics was well known to several persons eminent in that line. (Pigott 1786)

5. The Goodricke-Pigott legacy

John Goodricke is better known today than Edward Pigott. The University of York has a Goodricke College, and the dramatic story of Goodricke's short life figures prominently in several astronomical textbooks (for example, Fraknoi *et al.* 2006). Surely Goodricke's being awarded the Copley Medal and elected to membership in the Royal Society brought him recognition. It is clear that Edward Pigott deserves at least equal credit for their joint work. Today, Edward would be recognized as a co-discoverer of the periods of Algol, δ Cephei, and β Lyrae, while John would be credited with helping discover the period of η Aquilae and determining the coordinates of York.

The petition nominating John Goodricke to membership in the Royal Society was apparently initiated by Nathaniel Pigott; co-signers include Nevil Maskelyne, Anthony Shepard, Thomas Hornsby, Savilian Professor of Astronomy at Oxford, and William Wales, a member of the Board of Longitude, among others. Edward Pigott, on the other hand, although deserving, was never even nominated. Was this due to differences in the social standing of the two? Was there a reluctance on Nathaniel's part to push for his son's nomination? Or was Edward simply not considered a "clubbable man"? It is possible that all of these played a part.

What is certain is that the two held each other in high regard and frequently expressed that regard both in their journals and in their publications. Edward Pigott felt, justly, that his father Nathaniel did not give him enough credit for his astronomical work, and it is certain that Nathaniel cut Edward out of his will, as evidenced by Edward's pleading letters to his great-aunt Lady Anne Fairfax (N. Yorkshire County Record Office ZDV F: MIC 1132/1201). Edward did not suffer slights lightly. Yet Edward frequently mentions John Goodricke's talents both as an observer and in the interpretation of data. Neither in print nor in Edward's journals is there any hint that he resented Goodricke's authorship of the Algol paper, his reception of the Copley medal, or his election to the Royal Society.

John Goodricke clearly admired and learned from Edward Pigott. Edward's long-held interest in the nature of the stars, especially their possible variability, flowered into a productive scientific research program almost as soon as he and John Goodricke began their joint investigations. These two deserve to be better known, and to share joint credit for their discoveries.

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Unless otherwise cited, information on John Goodricke and his family comes from a family history originally written by Charles Alfred Goodricke (1897). An abbreviated version is currently maintained online by Michael Goodrick (2010). The primary source of information on Edward Pigott is the 1999 article by Anita McConnell and Alison Brech (1999) entitled "Nathaniel and Edward Pigott, Itinerant Astronomers."

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Figure 1. John Goodricke (1764–1786). Pastel portrait by James Scouler, now the property of the Royal Astronomical Society. Used with permission of the RAS.

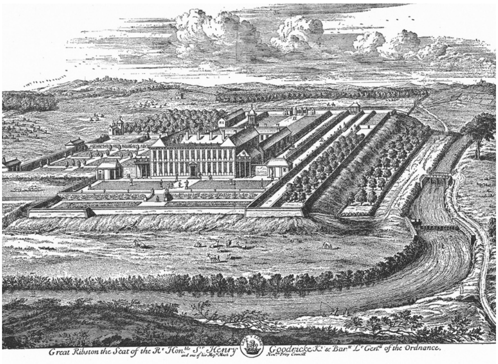
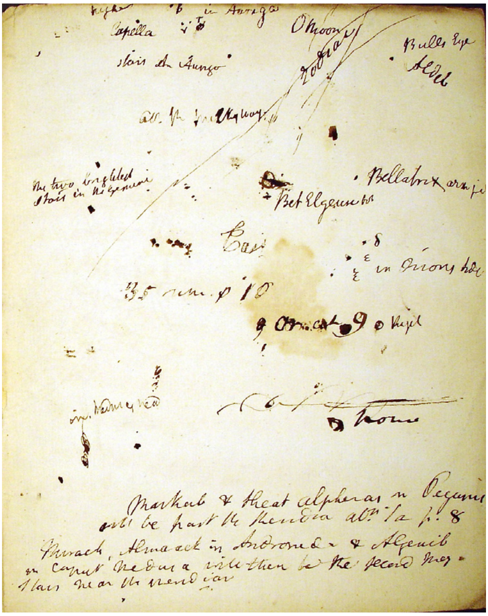


Figure 2. Ribston Hall in the seventeenth century. From the Goodricke family history website maintained by Michael Goodricke at http://www.goodrick.info/main.htm

Figure 3. Ribston Hall today. © Copyright Gordon Hatton <http://www.geograph.org.uk/profile/4820> and licensed for reuse under this Creative Commons License<http://creativecommons.org/licenses/by-sa/2.0/



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will be past the Meridian abt 1/2 p. 8
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in Caput Medusa will then be the second Mag.
Stars near the Meridian

Figure 4. Drawing found in the inside back cover of John Goodricke's mathematics notebook from Warrington Academy, 1779–1780. The constellations of Orion, Taurus, Auriga, and Gemini are shown, along with the Moon, Milky Way, and Zodiac. Positions of stars are given that are consistent with the drawing having been made in November 1779. Reproduced from an original held by City of York Council Archives and Local History (Goodricke 1779).

Figure 5. The church of St. John the Baptist in Hunsingore. The low, flat stone just to the left of center in the photograph marks the location of the Goodricke vault.

Figure 6. The east-facing side of the marker stone for the vault. The only engravings are the letter "E" at the top and the words, "The Goodricke Vault."

Frank Elmore Ross and His Variable Star Discoveries

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Abstract Frank Ross (1874–1960) was a talented astronomer who excelled in such diverse fields as computational astronomy, optical instrument design, and astrophotography. His career and astronomical contributions are briefly summarized. One contribution was finding 379 probable new variable stars. Most of these variables are poorly studied, and for a number the identifications are still uncertain and the variability not yet confirmed more than eighty years after publication. Ross's original observing cards and plates are being used to re-examine the stars and resolve the problem cases. Follow-up work on a few stars has yielded interesting results. This work is illustrated with one example.

1. Introduction

Part of the celebration of 100 years of the American Association of Variable Star Observers in 2011 was a special joint meeting with the Historical Astronomy Division of the American Astronomical Society. This paper summarizes a talk at that session, the subject being chosen because of its connection to both astronomical history and variable star astronomy. The paper starts with the history—a discussion of the career of the astronomer Frank Ross. Then it is shown how some of the historical material from Ross's career has relevance to today's variable star research.

2. Career of Frank Ross

Frank Elmore Ross (Figure 1) was a talented astronomer and optical system designer whose career can be roughly divided into three phases. His early professional years were spent as a computational astronomer. This was followed by about a decade working as an industrial physicist. His later years were spent as an observational astronomer at the Yerkes Observatory. In all three of these rather different fields he made significant scientific contributions.

Ross was born in San Francisco, California, on April 2, 1874. After attending local schools, he enrolled at the University of California (Berkeley) from which he received his B.S. in 1896 and his Ph.D. in 1901, both degrees being in mathematics. His Ph.D. was one of the first two awarded by California in mathematics (Morgan 1967), and his strong mathematical abilities can be seen throughout his career. Ross's graduate mathematics studies included work in astronomy. He both did some observing at Lick Observatory, leading to his first published paper (Ross 1899), and learned the techniques of astronomical orbit computation that he would successfully employ in his early career. His early computational strength can be inferred from the references to his work on calculating perturbations of the Watson asteroids (Newkirk 1904a, 1904b, Leuschner 1910).

In 1902 Ross moved from the west to the east coast after accepting a position as an assistant in the Nautical Almanac Office in Washington D.C. He served one year there followed by two years in a similar position at the Carnegie Institute. These appointments involved carrying out computations under the supervision of Simon Newcomb, and he continued providing service to the Nautical Almanac Office until shortly before he left the east for Yerkes Observatory in 1924 (van Biesbroeck 1961). Projects included determinations of orbits for comet 1844 II Mauvais (Ross 1905a), Saturn's distant satellite Phoebe (Ross 1905b), and the then recently-discovered Jovian satellites VI Himalia (Ross 1905c, 1905e, 1907a) and VII Elara (Ross 1905d, 1906, 1907b), as well as working on improving the theories for the observed motions of the Moon (Newcomb and Ross 1907; Ross 1910, 1911a, 1911c, 1914b, 1915, 1918a), the Sun (Ross 1916a), Venus (Ross 1913d), and Mars (Ross 1916b, 1918b; Ross and Newcomb 1917).

In 1905 Ross became the director of the International Latitude Observatory (ILO) at Gaithersburg, Maryland. There he expanded his theoretical investigations to the problem of latitude determination (Ross 1912a, 1912b, 1913a, 1913c, 1913e, 1914c). But one also finds evidence of his instrumental and experimental interest that is first seen in a 1905 paper on improving the mounting of the Lick Crossley reflector (Perrine and Ross 1905). At the ILO he investigated the zenith tube used for observations (Ross 1911b) and then developed an improved version that used photography (Ross 1914a). His PZT (photographic zenith tube) doubled the accuracy of the observations and it became the standard for latitude observations for over fifty years. Its use of photography stimulated Ross's investigations of photographic emulsions and their characteristics (Ross 1913b).

Budget considerations caused a temporary closure of the ILO in 1915 (Bowers and Sengstack 1984; Butowsky 1989) and Ross accepted a position as a physicist with Eastman Kodak in Rochester, New York. During his nine-year period in industry he carried out several of his seminal studies of the photographic process and image effects that eventually resulted in over twenty papers and culminated with his classic book *Physics of the Developed Photographic Image* (Ross 1924). Also during this period Ross began designing camera systems. This work was initially driven by the need for aerial reconnaissance cameras in World War I, but eventually resulted in a design for an efficient wide-field doublet for astronomical use (Ross 1921, Ross 1922). "Ross cameras," which can produce good star images over fields of 20° or more across, were soon installed at several observatories.

In 1924, at the age of fifty, Ross was appointed a professor of astronomy at the University of Chicago assigned to the university's Yerkes Observatory. As described by Osterbrock (1997), the appointment was recommended by Yerkes Director Edwin Frost who was seeking someone with photography experience to replace the recently deceased eminent astrophotographer E. E. Barnard. Frost expected Ross to carry on Barnard's photographic program, and he did so very productively. Ross realized that re-observation of the fields that Barnard had photographed would permit moving and variable objects to be detected, and this project was very successful. He also used a camera based on his design to produce a new atlas of the Milky Way (Ross, Calvert, and Newman 1934) that complemented the posthumously-published one of Barnard (Barnard, Frost, and Calvert 1927). But Ross also developed projects independent of those pioneered by Barnard. He continued his optics work, designing field-correcting systems and new cameras (Ross 1932, 1933, 1934, 1935), and his photographic experiments (Ross 1931b). He explored how to do accurate photometry (Ross 1936) and how to best image the planets, including photographing them in the ultraviolet and infrared as well as in visible pass bands. His UV observations led to his discovery of cloud features on Venus (Ross 1927c, 1928c).

Ross retired in 1939. He had always been a Californian at heart, and even during his Yerkes years had spent considerable time most years observing at Mt. Wilson and Lick Observatories. It was natural therefore that on retirement he relocated to southern California. He became associated with the Mt. Wilson Observatory as a consultant on optics, working on optical components for the 48-inch Schmidt and 200-inch reflector planned for Mt. Palomar. He also designed lenses for the motion picture industry (Nicholson 1961). Ross passed away on September 21, 1960, at the age of 86.

3. The Ross variable Stars

How Frank Ross is connected to modern variable star research lies in some of the work he carried out at Yerkes Observatory. Yerkes is known for its 40-inch refractor. Once the largest astronomical telescope in the world, by the time Ross joined the Yerkes staff it had been surpassed by several much larger and more versatile reflectors and was relegated to specialized observing programs. One of the areas for which the great refractors were well suited was astrometry—the determination of accurate positions—and Yerkes had a well-established program for the determination of stellar parallaxes.

The pioneer astrophotographer E. E. Barnard had taken a large number of deep plates with the Yerkes wide-field Bruce telescope in the period 1904–1922. Ross realized that by re-photographing the fields with the same camera he would be able to compare the plates through blinking and detect stars of large proper motion. Such stars would be excellent candidates for the Yerkes parallax program as large proper motion typically reflects a rather small distance. Ross eventually published eleven papers listing 1,069 high proper motion stars, three of which are even today among the fifteen closest stars known.

Ross's blinking of plate pairs also led to discoveries of 379 suspected variable stars. These were announced in ten papers published between 1925 and 1931 (Ross 1925, 1926a, 1926b, 1927a, 1927b, 1928a, 1928b, 1929, 1930, 1931a). Today, most of the Ross variable candidates have been confirmed as variables, but only a few have been studied. About 40 of his suspected variables have not been confirmed; some were shown to result from minor planets visible on one plate of a blinked pair (Bedient 2003, Marsden 2007), while for others the published positions were in error or too imprecise to unambiguously identify the star.

4. Recent work on the Ross variables

In 2010 a project was begun at Yerkes to review the Ross plates and identity the "lost" variable candidates (Figure 2). It was quickly found that Ross had marked the fields of his variables on the plates (Figure 3). More importantly, Ross's note cards for his variable work were located (Figure 4), and the combination of the cards and the plates made identification of the objects certain.

We have elected to systematically examine all of the Ross variables, not just the ones with identification problems. This has allowed us to not only determine better positions when needed but also to derive better epochs (Ross only published the local dates for the plates he used) and magnitudes more closely related to B of the UBV system (Ross's values are systematically about 2 magnitudes too bright); such data may be useful in that these observations are often the earliest known for the variable. This approach has also allowed us to look more closely at some of the more interesting objects. So far we have worked through about half of the stars (Osborn and Mills 2011).

An interesting example of how this work ties in to variable star research is provided by the star Ross Variable 4, also known as NSV 1436. Ross's note card is shown in Figure 5, and the field on the two discovery plates is shown in Figure 6. Ross 4 is the fairly bright star visible on the 1905 plate taken by Barnard but not seen on the 1925 plate by Ross. The star's position is very close to an X-ray source, so we elected to investigate its light curve using other plates of this field in the Yerkes collection. The object was found to be always at $B = 16$ or fainter except for two outbursts—the one in 1905 and another in 1948, when it brightened to at least $B=13$ (see Figure 7). These results suggested Ross 4 is a cataclysmic variable, and possibly of the rare recurrent novae type (Brown *et al.* 2010). A third outburst was observed in March 2011, and the recent observations indicate a classification as a dwarf nova is more likely. (Osborne *et al.* 2011).

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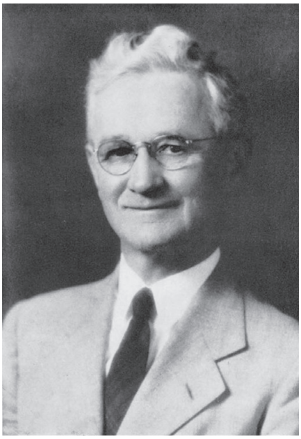
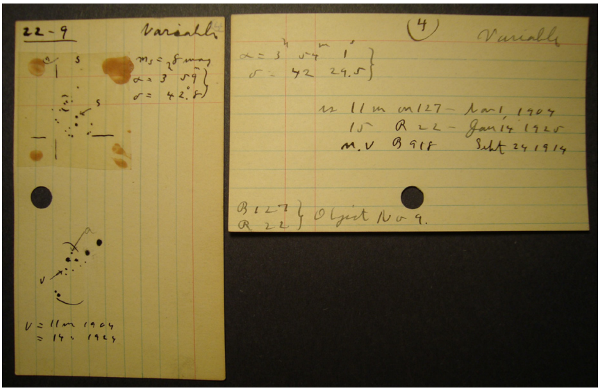


Figure 1. Frank E. Ross (1874–1960). From Nicholson (1961).

Figure 2. Yerkes volunteer O. Frank Mills prepares to examine a Ross plate. Figures 2–6 are from the author.

Figure 3. Ross's plate number 22 (R-22) with his markings of several proper motion and variable stars.

Figure 4. The box containing Ross's note cards for his variable star discoveries.



22-9 Variable

m_s = 8 mag
α = 3 59ᵐ
δ = 42.8°

V = 11m 1904
= 14 " 1924

(4) Variable

α = 3ʰ 54ᵐ 1'
δ = 42 29.5

is 11m on 127 – Nov 1, 1904
15 R 22 – Jan 14 1925
M.V B 918 Sept 24 1914

B127
R 22 } Object No 9.

Figure 5. Ross's note cards for Ross 4 (NSV 1436). The card on the left has the finding chart (compare the lower sketch on the card to the field shown in Figure 6). The card on the right gives the determined 1875 coordinates and estimated magnitudes on three plates.

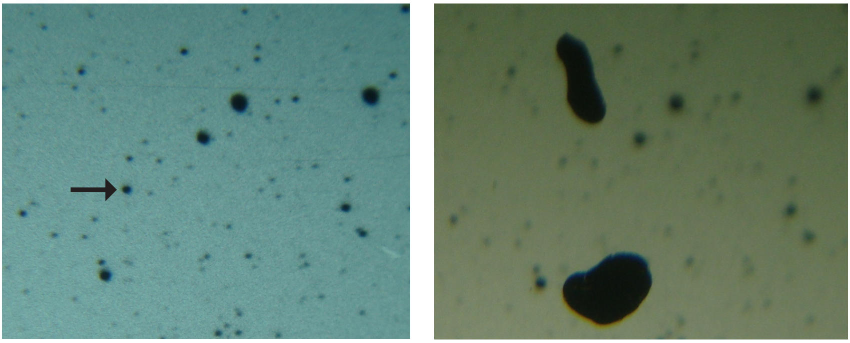


Figure 6. The field of Ross 4 (NSV 1436) on the discovery plates. The image from Barnard's 1905 plate B-127 is on the left, and that from Ross's 1925 plate R-22 is on the right. The variable is marked with an arrow on the left image, and Ross's ink marks are seen on the right image that show its approximate location.

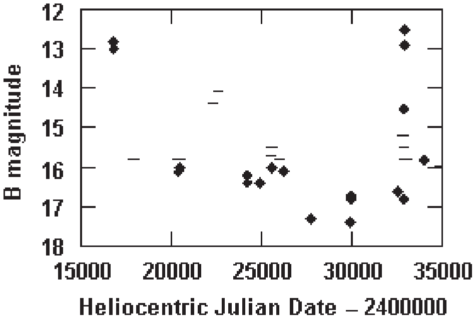


Figure 7. The light curve of Ross 4 (NSV 1436) from 1904 to 1952 From Brown *et al.* 2010.

Illinois—Where Astronomical Photometry Grew Up

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Abstract In 1903 Dr. Joel Stebbins joined the University of Illinois faculty as an astronomy instructor and Director of the University of Illinois Observatory. In 1905 he and F. C. Brown began experimenting with selenium sell photometry and developed the equipment and many of the photometric practices used then. Those practices formed the foundation on which present day photometry processes are based. This paper will trace the history of Stebbins' career and his development of photoelectric photometry from 1903 to 1922. This story explains how Stebbins' wife, May, caused a change in astronomical observing that continues today.

1. Introduction

The prairies of central Illinois may seem an unlikely place to begin a photometric revolution. Illinois is a flat land state with only about 100 clear nights per year, the average elevation is only 600 feet above sea level, and the highest point is only at 1,500 feet. Yet, Illinois has produced its share of prominent and innovative astronomers. George Ellery Hale built his Kenwood Observatory in the heart of Chicago. Edwin Hubble spent his teen years in the Chicago suburbs and was educated at University of Chicago. Grote Reber built the World's first parabolic-steerable radio telescope. It was thirty feet in diameter and located in Reber's backyard in Wheaton. Rumor has it that Wheaton still has a city ordinance limiting the size of antennas residents can construct at their homes. And then there was Joel Stebbins.

Chicago was not the only cradle of astronomical innovation, there was also Urbana, home to the University of Illinois Observatory. Built in 1896 as a teaching facility, the Observatory was typical of late 19th century facilities with its Warner and Swasey/Brashear refractor, pendulum clocks, transit telescopes, and focus on visual observations. It stands in contrast to modern observatories in which star light typically falls upon some type of electronic detector. Trace the linage of these electronic devices back through the decades and you arrive at the doorstep of the University of Illinois Observatory where you will meet

Dr. Joel Stebbins, who “[r]aised on the astronomy of the 19th century, he lived to witness much of the new astronomy of the 20th-which he helped create” (Svec 1992). Stebbins arrived in 1903 as the new observatory director. While the skies may not be as dark and clear as the western mountain top observatories, the UI Observatory did have ready access to the campus. Astronomy was a division in the Mathematics Department and Stebbins had teaching responsibilities in both math and astronomy. Stebbins was able to develop and improve new photometric instruments and pursue an astronomical research program because of willingness and ability to collaborate with the Illinois physicists.

2. The story

Joel Stebbins was born in Omaha, Nebraska, on July 30,1878, and educated in the Omaha Public Schools. His interest in Astronomy started from an elementary school class. He built his first telescope by attaching lenses to a tube made from rolled up newspapers. Stebbins’ advanced education was at the University of Nebraska where he received a Bachelor of Science degree. Graduate study started at the University of Nebraska, continued at the University of Wisconsin, and concluded at the University of California at Lick Observatory and on the Berkeley campus. Stebbins received the third Ph.D. in Astronomy granted by the University of California, in May of 1903 (Whitford 1978).

Stebbins’ first employment after receiving his Ph.D. was as the Astronomy Instructor at the University of Illinois in Urbana. Along with the instructor position he was assigned the Directorship of the UI Observatory (Figure 1). While the Observatory was a relatively new facility in good condition and well equipped with a 12-inch Brashear refractor and a polarizing photometer, it had no operating budget! The Observatory’s first year budget ended up being $7.00 and it came out of Stebbins’ pocket! But, life does get better. In 1905 he received a budget of $750.00 from the University Trustees.

Stebbins first major project at UI was a survey of 107 double stars to determine their brightness using the Observatory’s 12-inch Brashear telescope and a Pickering Polarizing Photometer made by Alvan Clark and Sons. This project was ongoing when a good thing happened. On June 27, 1905, Stebbins married his college sweetheart, May Louise Prentiss, also of Omaha. Then, in August, they travelled with Lick Observatory astronomer Heber Curtis and his wife, Mary, to study the 1905 Solar Eclipse in Labrador.

Upon returning to Urbana, Stebbins resumed his photometry program; but life at the Observatory was about to change, and the way astronomy research was conducted was about to change forever! In Stebbins’ own words:

> The photometric program went along well enough for a couple of years until we got a bride in our household, and then things began to happen. Not enjoying the long evenings alone, she found that if

> she came to the observatory and acted as a recorder, she could get me home earlier. She wrote down the numbers as the observer called them, but after some nights of recording a hundred readings to get just one magnitude, she said it was pretty slow business. I responded that someday we would do all this by electricity. That was a fatal remark. Thereafter she would often prod me with the question: "When are you going to change to electricity?" (Stebbins 1957)

In the following summer Stebbins attended a Physics Department demonstration where he met a young instructor, Fay C. Brown. Brown was demonstrating a selenium cell that, when illuminated by a lamp, would ring a bell. Stebbins had an idea: "why not turn on a star to a cell on the telescope and measure a current?" On 23 June 1907, after some improvements, Stebbins and Brown began the project to measure the variation of the Moon's light with phase:

> I soon made friends with Brown, and in due time we had a selenium cell on the 12-inch refractor; I operated the telescope and a shutter while Brown looked after the battery, galvanometer, and scale. The first trial was on Jupiter-no response; several more trials, still no response. I said to myself, "I'll fix him." The moon was shining through a window; I took the cell with attached wires off the telescope and exposed it to the moon. The galvanometer deflection was measurable with plenty to spare. Result: We spent a couple of months measuring the variation of the moon's light with phase. Our resulting light curve turned out to be the first since the time of Zollner in the 1860s. (Stebbins 1957; see Figure 2)

The involved process for the Moon project would begin with Stebbins, at a window in the observatory classroom, making a set of four ten-second exposures by pointing the cell at the Moon. One minute was allowed between each exposure for the cell to recover. Brown, at the galvanometer in the West Central Transit room, recorded the deflection and the time for each exposure. After each set the photometer was calibrated at various distances from a standard Kohl candle. A second set of lunar observations would follow the calibration. The author suspects that calibration was done at the beginning and end of the process (Figure 3).

This was not the World's first attempt at photoelectric photometry. In 1892 selenium cells made by G. M. Minchin of Dublin were used by a Professor Fitzgerald and W. H. S. Monck, an amateur astronomer who owned a 9-inch refractor that they used to detect Jupiter, Venus, and Mars. In 1895 Minchin joined with Mr. W. E. Wilson to measure some stars with Wilson's 24-inch reflector. Two short papers were published by Minchin and his associates in 1895 and 1896. In Germany E. Ruhmer used his homemade cells to observe a solar eclipse on October 31, 1902, and a lunar eclipse on April 11–12, 1903. These are the only known successful applications of selenium cells prior to Joel Stebbins' work. Stebbins (1940) wrote that he learned of Minchin and others while preparing the literature review for the paper on the phases of the moon. Hearnshaw (1996) noted: "It is doubtful that the experiments made by Minchin had much influence on the future course of stellar photometry."

Brown left Illinois for a fellowship at Princeton at the end of the summer of 1907 yet returned to Urbana to work with Stebbins during the following two summers to improve the photometer. Progress was both deliberate and occasionally serendipitous. A dropped and broken selenium cell led to the discovery that smaller cells produced a signal with the same strength but less noise. A clear, sub-zero night provided evidence that cold sensors produce less noise.

Continued improvements to the selenium cell allowed Stebbins to detect third magnitude stars. This allowed the collection of sufficient data to publish a light curve for β Persei (Algol; Figure 4). Here is Stebbins' (1940) account of the first efforts toward continuing studies of stars with photoelectric photometry:

> After many experiments we learned that the irregularities of a selenium cell were much reduced if the cell was kept at a uniformly low temperature in an ice pack, but even so there were only a few bright stars within reach of the apparatus. We began with the comparison of Betelgeuse and Aldebaran with the assumption that any changes in the relative magnitude would be due to Betelgeuse. Finally a new cell from Giltay gave about a three-fold improvement over previous cells, and we were able to take up a detailed study of Algol, which is about second magnitude.
>
> One observing season of six months was devoted almost entirely to this star, and it was possible to detect for the first time the secondary minimum of Algol, and the continuous variation between eclipses. Following this study, we tested a number of bright spectroscopic binaries for small variations in light. As luck would have it, the first two stars so tested turned out to be eclipsing binaries, Beta Aurigae, period 4 days with two equal minima of about 0.08 mag. each, and Delta Orionis, period 5.7 days, with minima of 0.08 and 0.05 mag. spaced in agreement with the eccentric orbit. Of the other stars tested Alpha Coronae Borealis also gave unmistakable evidence of an eclipse, which was confirmed later with the photoelectric cell. (Stebbins 1940)

After completion of the Algol observations in 1909, the photometry process was sufficiently developed for use as a research tool. A much higher level of observational accuracy had been achieved and allowed Stebbins the opportunity to study eclipsing variables for the direct determination of the diameter, mass, and density of stars. Stebbins concluded that there must be many spectroscopic binaries with eclipses of small range that could not be discovered using older photometric processes. He made a list the most favorable cases. The previously mentioned first two bright stars tested—β Aur and δ Ori—showed eclipses at the predicted times of about ten percent of the light at constant phase. A systematic campaign at Urbana over the following years turned up many more. As an example of this campaign, during March 1911, photometric observations were made of β Aur, α Gem, ξ UMa, δ Ori, α Ori, and α UMi, and by the following March, ι Ori, α Vir, and β Sco joined the observing program. Although productive, the selenium photometer was a challenge to operate.

3. Enter the photoelectric cell

Swiss born and educated physicist Jakob Kunz arrived in Urbana in 1909 and began a research program focusing on photoelectric cells. In 1911, Kunz and fellow Illinois physicist W. F. Schulz met Stebbins and suggested he might consider replacing the selenium cell with a photoelectric cell. One of Kunz's graduate students, J. G. Kemp, completed a dissertation in 1912. Kemp found that a potassium-hydrogen cell was about 200 times the sensitivity of the selenium cell and noted that "A design has been made for a sensitive photoelectric cell for photometric work in astronomy. It is expected to get a cell which will be sensitive enough to use instead of the erratic selenium cell now used." (Kemp 1913). It is interesting that this change replaced a solid state device (selenium cell) with a glass tube device containing special coatings and small amounts of hydrogen or other suitable gases. The potassium-hydrogen cell is a specific version of the alkali-cathode cell.

Stebbins continued with the selenium photometer up to his departure in the fall of 1912 for a sabbatical in Europe. Kunz and Schulz first observed α Aur with a photoelectric photometer in December of 1912 and then α Boo the following April. While in Europe on sabbatical in August 1913, Stebbins met Hans Rosenberg of Tübingen who was successfully using an alkali-cathode photometer. Campbell (1913) recounts:

> By way of comment on Rosenberg's paper, Stebbins went to the blackboard and wrote down the following table, contrasting the work of Meyer and Rosenberg's electric-cell photometer and his own selenium photometer...
>
> | Photometer | Telescope | Star of | Time to make observation | probable error of one determination |
> |---|---|---|---|---|
> | Electric-cell | 5-inch | 5th mag | 2 min | + 0.003 mag |
> | Selenium | 12-inch | 2nd mag | 60min | + 0.01 mag |

After returning from sabbatical, Stebbins and Kunz concentrated on developing the new photometer incorporating a photoelectric cell and Wulf string electrometer. The selenium photometer was never used again for published research. In the summer of 1915 the photometer had progressed to the point that Stebbins used it on the 12-inch refractor at Lick Observatory (Figure 5) to obtain a light curve of β Lyr.

Back in Urbana he began an aggressive research program which resulted in a series of papers in the *Astrophysical Journal* on eclipsing binaries λ Tau, σ Aql, β Per, AR Cas, ellipsoidal variables π^5 Ori and b Per, and Nova Aql No. 3 (1918). Stebbins and Kunz also travelled to Wyoming to study the solar eclipse. Public open houses were suspended in 1918 due to navigation classes supporting the war effort and time needed to reduce data from the Nova and eclipse expedition. Dr. Elmer Dershem joined the Observatory staff in 1917 and rebuilt the photometer in the summer of 1919. Dershem would leave for Berkeley and help Edith Cummings at Lick Observatory build their photometer in 1920. By 1922, Charles Clayton Wylie completed the first Illinois astronomy doctorate for his photoelectric studies of the Cepheid η Aql, and σ Aql, noting its variations due to tidal distortions.

In 1922 Stebbins moved to the University of Wisconsin to become Director of the Washburn Observatory. He completed work on an impressive number of eclipsing binaries over a period of several years. From 1925 onward, he moved to other fields of astronomical photometry and spent many summers at Mt. Wilson as a research associate. Although he was in Madison, he took with him C. M. Huffer, an Illinois mathematics graduate, who went on to become a photoelectric pioneer in his own right recording thousands of observations of eclipsing, late type, and red variables as well as galaxy magnitudes for Edwin Hubble. From the early 1930s Huffer was Stebbins' main collaborator on the photometric study of interstellar reddening. Stebbins also maintained a professional and personal relationship with Kunz who continued to provide Stebbins and the rest of the astronomical community with photoelectric cells until Kunz's death in 1938. Of the thirteen American observatories identified by Hearnshaw as conducting photoelectric research before World War II, six used Kunz photocells (Urbana, Washburn, Lick, Yerkes, Mt. Wilson, and Harvard).

4. Postscript

The Observatory continues to be a teaching facility. In recognition of the significance of the development of photoelectric photometry, the Observatory was declared a National Historic Landmark by the U.S. Department of the Interior. Deferred maintenance, harsh winters, and age have taken their toll on the University of Illinois Observatory. In conjunction with the Astronomy Department, a Friends of the University of Illinois Observatory group has formed in hopes of restoring and preserving the historic structure. For more information visit: https://www.facebook.com/U.of.lllinois.Observatory and http://www.astro.uiuc.edu/friends/fuio/

5. Conclusion

Stebbins (Figure 6) did not see central Illinois as a limitation to astronomical research. He commented "One doesn't have to go to a place where there is a large observatory to find something to do. I have found conditions here in Urbana more favorable to my work than anywhere else. At large observatories there is always something the matter" (Anon. 1916). Joel Stebbins continued to use, create, and improve photoelectric equipment and processes for the rest of his life. His last paper, written with his former student, Dr. Gerald Kron, dealt with the standardization of the six-color system in terms of black-body temperature. It was published in 1964 just two years before Stebbins died. While not the first to use photoelectric photometry, Joel Stebbins deserves the credit for developing and proving, with many papers based on countless hours of observations and many equipment and process improvements, photoelectric photometry to be the tremendous scientific tool that it has become. The key to the astronomer's success was the collaboration with physicists. Stebbins' research was motivated by astrophysics and his papers reflect that emphasis with data and analysis. It was the collaboration with F. C. Brown and then Jakob Kunz who solved the technical instrument problems that enabled the instrument to gather the data presented by Stebbins, proving the value of the photoelectric photometer. And it all started out on the Illinois prairie in a little town named "Urbana" because May had writer's cramp!

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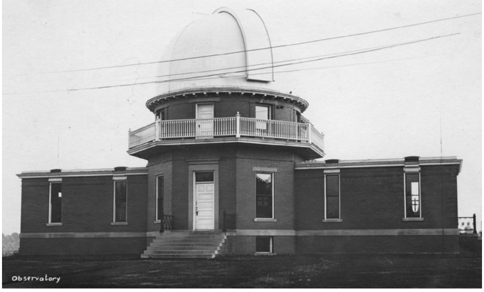


Figure 1. The University of Illinois Observatory in 1905 when Dr. Stebbins was starting to think about using electricity. From the collection of M. Svec.

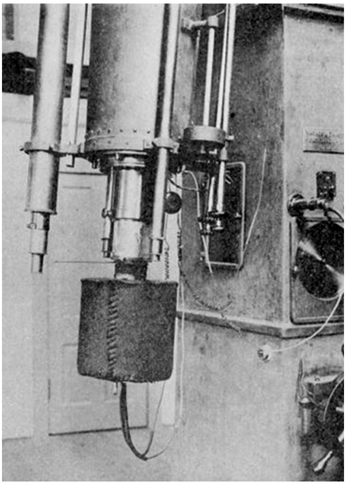
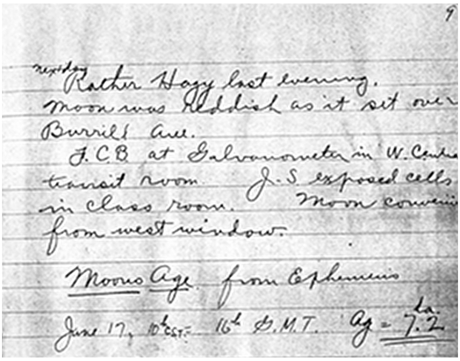


Figure 2. The University of Illinois Observatory selenium cell photometer about 1910. The cell is in an ice pack attached to the 12-inch refractor. From Stebbins (1910).



9

next day Rather Hazy last evening.
Moon was Reddish as it set ove
Burrill Ave.
F.C.B at Galvanometer in W. Centr
transit room J.S exposed cells
in class room. Moon conveni
from west window.

Moons Age from Ephemeris

June 17, 10^h CST = 16^h G.M.T. Ag = 7.2^{da}

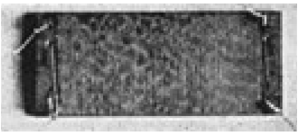


Figure 3. Page (top) from Stebbins notebook titled “Selenium 1907 Febr. 15 to 1908 January 25.” The note states that F. C. Brown was at the galvanometer in the transit room and Joel Stebbins was in the classroom exposing the selenium cell (bottom) to the Moon. Provided by M. Svec, courtesy of University of Wisconsin Archives.

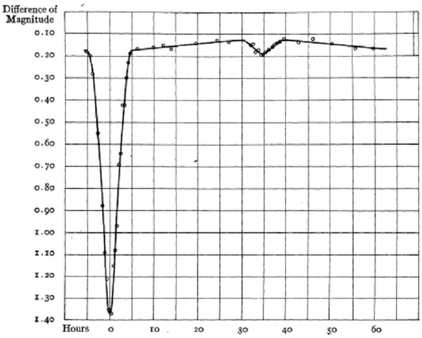


Figure 4. Classic Light curve of β Per showing two new features: the secondary eclipse and the reflection effect. From Stebbins (1910).

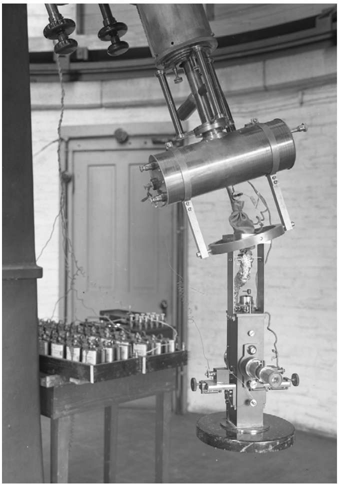


Figure 5. The photometer Stebbins used from about 1915 at the UI Observatory. The photometer contains a Kunz rubidium cell with a direct connection to a string electrometer specifically built for Stebbins by William Gaertner and Company of Chicago. The other parts were constructed by Mr. J. B. Hayes, mechanician of the Illinois physics department. The telescope is the UI 12-inch Brashear refractor. Provided by M. Svec, courtesy of University of Illinois Archives.

Figure 6. Dr. Joel Stebbins at Washburn Observatory, University of Wisconsin, about 1924. The telescope is a 15.3-inch Clark refractor. The photometer is possibly an early gimbal-mounted string electrometer.

The Man with the measuring tool! All because May had writer's cramp!

Provided by M. Svec, courtesy of University of Wisconsin Archives.

Stellar Pulsation Theory From Arthur Stanley Eddington to Today *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 22, 2011

Abstract While one could question that Eddington was the pioneer in theoretical work directly addressing the pulsating variable stars, there is no doubt that his work in the first part of the 20th Century set the stage for a transformation of theoretical astrophysics. After Eddington (the 1940s to the present day) stellar pulsation theory evolved from analytic theory into the realm of computational physics. Starting from Eddington's formulation, the flexibility provided by numerical solutions enabled exploration of systematics of pulsating variable stars in vastly greater detail. In this talk, we will trace this development that led to theoretical explanations of period-luminosity relations, new mechanisms of pulsation driving, connections with mass loss and stellar hydrodyamics, and to modern asteroseismic probes of the Sun and the stars.

King Charles' Star: A Multidisciplinary Approach to Dating the Supernova Known as Cassiopeia A *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 22, 2011

Abstract Few astronomical phenomena have been as studied as the supernova known as Cassiopeia A. Widely believed to have occurred in the latter half of the seventeenth century, it is also thought to have gone unrecorded. This paper will argue that Cas A did not go unobserved, but in fact was seen in Britain on May 29, 1630, and coincided with the birth of the future King Charles II of Great Britain. This "noon-day star" is an important feature of Stuart/Restoration propaganda, the significance of which has been widely acknowledged by historians and literary experts. The argument here, however, is that in addition the historical accounts provide credible evidence for a genuine astronomical event, the nature of which must be explained. Combining documentary analysis with an overview of the current scientific thinking on dating supernovae, the authors put forward their case for why Charles' star should be recognized as a sighting of Cas A. Finally, it will be argued that a collaborative approach between the humanities and the sciences can be a valuable tool, not just in furthering our understanding of Cas A, but in the dating of supernovae in general.

Ed. note: this paper is expected to appear in a future issue of JAAVSO

The History of Variable Stars: a Fresh Look

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Based on a paper presented at the 100th Annual Meeting of the AAVSO, October 7, 2011

Abstract For historians of astronomy, variable stars are important for a simple reason—stars change. But good evidence suggests this is a very modern idea. Over the millennia, our species has viewed stars as eternal and unchanging, forever fixed in time and space—indeed, the Celestial Dance was a celebration of order, reason, and stability. But everything changed in the period between Copernicus and Newton. According to tradition, two New Stars announced the birth of the New Science. Blazing across the celestial stage, Tycho's Star (1572) and Kepler's Star (1604) appeared dramatically—and just as unexpectedly—disappeared forever. But variable stars were different. Mira Ceti, the oldest, brightest, and most controversial variable star, was important because it appeared and disappeared again and again. Mira was important because it did not go away. The purpose of this essay is to take a fresh look at the history of variable stars. In re-thinking the traditional narrative, I begin with the first sightings of David Fabricius (1596) and his contemporaries—particularly Hevelius (1662) and Boulliau (1667)—to new traditions that unfolded from Newton and Maupertuis to Herschel (1780) and Pigott (1805). The essay concludes with important 19th-century developments, particularly by Argelander (1838), Pickering (1888), and Lockyer (1890). Across three centuries, variable stars prompted astronomers to re-think all the ways that stars were no longer "fixed." New strategies were needed. Astronomers needed to organize, to make continuous observations, to track changing magnitudes, and to explain stellar phases. Importantly—as Mira suggested from the outset—these challenges called for an army of observers with the discipline of Spartans. But recruiting that army required

a strategy, a set of theories with shared expectations. Observation and theory worked hand-in-hand. In presenting new historical evidence from neglected printed sources and unpublished manuscripts, this essay aims to offer a fresh look at the history of variable stars.

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HISTORY OF VARIABLE STAR ORGANIZATIONS

British Astronomical Association Variable Star Section, 1890–2011

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Presented at the 100th Annual Meeting of the AAVSO, October 5, 2011; received January 30, 2012; accepted January 30, 2012

Abstract A summary history is given of the British Astronomical Association Variable Star Section, the longest established organized group of variable star observers whose work extends from the latter stage of the 19th Century until today.

1. Introduction

The British Astronomical Association Variable Star Section (BAA VSS) is the World's oldest currently active amateur association of variable star observers, having been established in 1890. However, it was not the first such group to be formed as that was the Liverpool Astronomical Society Variable Star Section (LAS VSS); the BAA VSS was a direct successor to the LAS VSS that had been active for six years leading up to 1889. This paper is a summary outline of the history of the BAA VSS and was presented at the Centenary Meeting of the American Association of Variable Star Observers (AAVSO) held in Woburn, Massachusetts, on the 5th October 2011.

2. Pre-history

The formation of an association of variable star observers in Great Britain proved to be both a lengthy and difficult task in the 19th Century. As early as 1833 Sir John Herschel advocated that amateur astronomers take up variable star observing but it would not be until the 1850s that Joseph Baxendell, Norman Pogson, and George Knott commenced systematic observations. Baxendell and Knott attempted to form the World's first association of variable star observers in 1863 known as the "Association for the Systematic Observation of Variable Stars" (ASOVS) but were unsuccessful due to general disagreement over the stellar magnitude scale and lack of suitable charts and sequences. Nevertheless the proposed structure of the ASOVS was visionary and elements would be later adopted, but Britain and the World were clearly not yet ready for an association purely dedicated to observing variable stars. However, in 1881 the LAS was formed and it established a VSS in 1883, and this demonstrated that an organized group of variable star observers could be sustained provided it was supported by a large astronomical society. The LAS suddenly collapsed in

1889 due to financial difficulties and political infighting but within a year the LAS had been replaced by the BAA, which was more adequately managed on a sound financial footing.

3. 1890–1899

The BAA VSS was formed at the first meeting of the BAA in London on 24th October 1890. Besides the VSS, sections were also formed for solar, lunar, Jupiter, meteors, double stars, coloured stars, and spectroscopic and photographic work. John Gore was appointed Director of the VSS and he brought with him experience of directing the LAS VSS from 1884 to 1889. Gore was a prolific writer and binocular observer who had discovered variables such as W Cyg, X Her, and U Ori. Gore's initial plan for the VSS was to concentrate upon neglected and suspected variable stars but by 1892 he had also introduced a nova search plan (probably inspired by Anderson's discovery of T Aur in January 1892). Although initially unsuccessful the nova search plan did establish the standard method for such patrols by allocating regions of the Milky Way to specific observers to search. In 1891 the VSS had twelve members which included two clergy, two army officers, two persons based in the Colonies, and one lady. Two outstanding members of the VSS in the 1890s were Alexander W. Roberts and A. Stanley Williams. Roberts was based in South Africa and made 65,000 highly accurate visual observations and discovered twenty variable stars. Williams used photography to discover over fifty variable stars including RX And. Gore published three *BAA Memoirs* and prepared summaries of members' observations and reported LPV maxima and minima. Unfortunately Gore's eyesight began to deteriorate after 1900 and he died following being struck by a horse car in Dublin in 1910.

4. 1900–1909

Colonel E. E. Markwick (Figure 1) was appointed as VSS Director at the end of 1899 and made an immediate and lasting impact. Previously Markwick had used his binoculars to good effect on military postings and discovered T Cen and RY Sgr from Gibraltar. Markwick had a clear strategy for the VSS that was based upon encouraging systematic quality observations to a uniform photometric system. This meant preparing standard charts based on Hagen's *Atlas Stellarum Variabilium* (ASV) sequences (the first charts for eighteen LPVs were released in 1901) and introducing a fixed program of stars for the observers to concentrate upon. Initially the program covered just twelve stars in 1900 but within a year it was expanded to forty-six stars, the majority being LPVs. In 1904 the program was further expanded to include U Gem and SS Cyg, then classed as irregular variables. In 1904 the ASV sequences were replaced by Harvard photometry although the comparison stars were still identified on the charts by the ASV numbers. Markwick requested that the members adopt Knott's step method and introduced a standard report form for observations which were to be submitted on a monthly basis. Markwick also introduced *BAA Circulars* for rapid feedback to the members and established a format (including observer codes) for presenting the observations within the *Memoirs*. Markwick's energetic leadership and directives were positively received and soon useful homogenous data were being accumulated. This meant that densely packed light curves could be constructed for the program stars, some of which were published in the *Journal of the BAA* (*JBAA*) and put on display at the Franco-British Exhibition in London in 1908. Markwick publicized the work of the VSS in *Popular Astronomy* in 1904 and the first meeting of the VSS took place on December 10, 1906. Also in December 1906 the VSS recorded the second brightest maximum (to that of 1779) of Mira at magnitude 1.9. During Markwick's term twenty-seven reports appeared in the *JBAA*, fifty-two *Circulars* were issued, and three *Memoirs* were published. In all 39,940 observations of the program stars were logged (the leading observer was Arthur Brown) and when Markwick's ten-year directorship terminated at the end of 1909 the VSS was firmly established as the model format variable star association.

5. 1910–1921

Charles Brook succeeded Markwick as VSS Director on New Year's Day 1910. Brook's strategy was to consolidate and expand on the firm foundation laid by his illustrious predecessor who continued to assist in the management and administration of the VSS. Brook had previously assisted Markwick in this respect and had in 1906 implemented the reduced scatter experiment which involved using uniform instrumentation and eyepieces. In 1911 the observing program consisted of five Algol, nine short period, twenty-seven long period, and nine irregular variables. In 1914 the short period variables were dropped from the program after a summary paper on the data acquired was published. They were effectively replaced by four long period variables that were added to the program in the same year. The Great War (1914–1918) only had a slight impact on the work of the VSS because Markwick (who returned to military duties) had relinquished the directorship and the principle observers were too senior to be called up to the armed forces. During Brook's twelve year term thirty-seven interim reports appeared in the *JBAA* and three *Memoirs* were published. The *Memoir* on DN Gem (nova in 1912) was written jointly with the Spectroscopic Section. Brook was a stickler for detail and the VSS data and publications during this period are a model of high quality. The most compelling fact, however, was that 83,796 observations were logged of the program stars by twenty members (the leading observer was Charles Butterworth), which represented a doubling on the output of the previous decade.

6. 1922–1939

Felix de Roy (Figure 2) succeeded Brook as VSS Director on New Year's Day 1922. De Roy, a Belgian national, had been a member of the BAA since 1906 and had taken refuge in Croydon near London throughout the Great War. Now back in Belgium, de Roy directed the VSS with the able assistance of the VSS secretary Arthur Brown (succeeded by William Lindley upon Brown's death in 1934). Brown distributed charts and report forms, received and archived the observations, and dealt with member's correspondence, whilst de Roy analyzed the data and prepared the reports. De Roy attempted to initiate coordination with the AAVSO following IAU meetings. In 1922 he proposed to Leon Campbell that the AAVSO and BAA VSS have separate observing programs to avoid duplicated effort (this was never implemented). In 1932 de Roy was a pivotal figure in the formation of the Joint Committee of Variable Star Associations (JCVSA) which involved the AAVSO, AFOEV, and BAA VSS and was primarily concerned with standardization of sequences. Following this the VSS set up its first chart committee in 1935 tasked to update the VSS sequences in line with the directives of the JCVSA. The chart committee also replaced the comparison star ASV numbers with letters on the charts. In 1928/1929 U Gem was recorded to have spent a record time of 255 days between outbursts. Manning Prentice discovered nova DQ Her in 1934 and the γ Cas eruption in 1936 was well covered by the VSS (including an independent detection by Patrick Moore). During de Roy's seventeen-year term eleven *Circulars* were issued, thirty-five interim reports appeared in the *JBAA,* and four *Memoirs* were published. 147,495 observations were logged (Butterworth again the leading observer) and the program was expanded to cover fifty-two long period and ten irregular variables. De Roy resigned the directorship of the VSS due to ill health at the time of the outbreak of World War II.

7. 1939–1958

William Lindley is the longest serving Director of the VSS but he presided over its most difficult period. Lindley's term began positively in 1939 with three interim reports appearing in the *JBAA* and Butterworth becoming the first observer to reach the milestone of 100,000 visual observations. World War II then hit hard as Lindley received his call-up papers and most of the VSS members were soon involved directly or indirectly in the war effort. The annual observations dropped to below 2,000 in 1941 and 1942, having been at 18,000 in 1938. Extraordinary efforts were made by military personnel to continue sporadic observations. Frank Knight for instance recorded the onset of a fade of R CrB from a foxhole on the eve of the battle of El Alamein. By the time the battle was over and the sky cleared R CrB had disappeared from binocular range. BAA HQ suffered flooding from bomb damage and de Roy died in occupied Belgium just when it seemed he might be the second observer to reach the 100,000 observation milestone. Frank Holborn was the leading observer during this period despite having been inconvenienced by flying bombs in 1944. A backlog of reports soon built up and it would take another twenty years after hostilities ceased for the VSS to generate the numbers of observations being produced in 1938. Despite all this the program was expanded in 1945 to include the dwarf novae RX And, Z Cam, and SU UMa. In 1946 Knight was the first person to detect the second outburst of T CrB but his report to Greenwich Observatory was not acted upon promptly so he did not receive the proper credit for this discovery. Upon the completion of the much delayed final *Memoir* in November 1958 (LPV observations for the years 1930–1934) Lindley resigned the directorship.

8. 1959–1971

Reginald Andrews was appointed Director at the end of 1958 and he immediately set about stimulating a recovery of the VSS from the setbacks suffered during the Lindley term with a particular objective to increase the number of active observers from fifteen. One of the first tasks was to resume the work of the pre-war chart committee and 140 charts were issued in 1959 and 1960. Andrews then worked on clearing the backlog of VSS reports with thirty-three interim reports appearing in quick succession in the *JBAA*. In 1959 Holborn wrapped up his four-year campaign to monitor Z Cam when a rise to outburst from a standstill was recorded. The first VSS meeting since 1935 was held on June 23, 1963, and twelve additional stars (dwarf novae) were added to the program in 1964. By 1964 the number of observers was forty-one and they reported 13,000 observations. This enhanced level of activity by the VSS caused some concern amongst BAA council members and a dispute arose about the quantity of VSS papers being published in the *JBAA*. Andrews resigned in 1964 as a result of this dispute. John Glasby assumed the role of Director in 1965 and applied a more sedate approach to managing the VSS which was aligned with the BAA council directives. Ten interim reports appeared in the *JBAA* over five years and the observing program was adjusted (introduction of additional cataclysmic variables) following the IAU congress in 1967. In 1969 the binocular program was established in response to the formation of the independent Binocular Sky Society (BSS) in 1968 and the discovery of the nova HR Del by George Alcock in 1967. Alcock had memorized the patterns of 30,000 stars as they appeared in his binoculars and he also found novae LV Vul in 1968 and V368 Sct in 1970. Brian Carter was the leading observer during this period and Glasby resigned the directorship in 1971.

9. 1972–1980

John Isles commenced his initial term as VSS Director in 1972 and his first action was to reintroduce the *Circulars* which had been discontinued in 1935. In 1972 Melvyn Taylor prepared a large number of charts and sequences for the BSS which were adopted for the binocular program. The first results of an eclipsing binary project were published in 1973. There were special observing projects launched on flare stars and supergiant variables following requests from professional astronomers. The BSS merged with the VSS in 1974 and the observing programs were overhauled the same year with several LPVs being dropped. The VSS collaborated with the AAVSO on visual nova and supernova searching in the period 1973–1978. In terms of visual nova discoveries Alcock found NQ Vul in 1976 and John Hosty found HS Sge in 1977 as part of Guy Hurst's UK Nova Patrol managed jointly with *The Astronomer*. When nova V1500 Cyg appeared in 1975 there were multiple VSS observers who discovered it independently with the naked eye. Taylor was the leading observer throughout this period and in 1976–1977 observers reported 27,000 observations. Isles resigned in 1977 owing to business commitments and his successor was Ian Howarth. During the period 1977–1979 Howarth collaborated with Jeremy Bailey to provide improved linear sequences for the dwarf nova on the VSS program. As a by-product of this work Howarth and Bailey also calculated a visual (mv) to V conversion formula. In 1979 X-ray emission from SS Cyg detected by the satellite Ariel V was interpreted by comparison with VSS visual data. Howarth concentrated upon updating the section reports and during the period 1972–1980 forty-three interim reports appeared in the *JBAA*. Howarth was forced to resign due to increasing professional commitments in 1980.

10. 1981–1992

Douglas Saw directed the VSS from 1981 to 1987. In 1981 the North Western Association of Variable Star Observers (NWAVSO) was merged with the VSS. The NWAVSO journal *Light Curve* was amalgamated with the VSS *Circulars* and the first AGN's (NGC 4151, Markarian 421, and 3C-273) were added to the VSS program. In 1982 VSS data were used to interpret UV and IR data on SS Cyg and SU UMa at Stavropol Astrophysical Observatory. In 1982 microcomputers were used for the first time to record observations and a digitized database was established in 1991 by Dave McAdam. In 1983 Robert McNaught visually detected an outburst of VY Aqr for the first time. During this period there was success for the UK Nova Patrol team by photographic means with McNaught detecting V842 Cen in 1986 and V4135 Sgr in 1987 while McAdam detected PQ And in 1988. Alcock made his final visual nova discovery with V838 Her in 1991. Jack Ells, Andy Hollis, and Richard Miles produced extensive photoelectric photometry during the early 1980s but could not reach the output capacity of the visual observers. John Isles began his second term as Director in 1987 and Saw took up the post of deputy Director. In 1987 51,000 visual observations were reported which was a record annual total. Also in 1987 John Toone was appointed Chart Secretary and tasked to standardize all the charts to a new format (this work was still in progress in 2011). In 1988 the VSS held a meeting with professional astronomers at University College London with the object of fostering closer professional-amateur collaboration in the study of variable stars. The immediate outcome was the formation of the Professional Amateur Liaison Committee (PALC) with Roger Pickard appointed as the primary amateur interface point. The centenary meeting of the VSS was held at Crayford on October 19–20, 1991, with a main theme of professional/amateur collaboration (Figure 3). Toone was the leading observer during this period and Ed Collinson reported his last observation in 1987 some sixty-seven years after recording his first.

11. 1992–1999

Tristram Brelstaff became VSS Director on 1st November 1992. Brelstaff was previously responsible for the Eclipsing Binary Program and had become a proficient writer with his monthly publication *The Variable Star Observer* in 1991/1992. The Jack Ells automatic photoelectric telescope at Crayford produced extensive photometry of eclipsing binaries during the years 1988–1997. In 1994 the *Circulars,* which had previously been issued at irregular intervals, were fixed at quarterly intervals (March, June, September, and December). Funding was made available from the RAS to support the development of the database which reached one million observations in January 1997. In February 1995 Gary Poyner became VSS Director and immediately introduced the Recurrent Objects Program (ROP) that had previously been an initiative of *The Astronomer*. The ROP proved to be very successful in determining the true nature of many poorly observed cataclysmic variables. Mark Armstrong found the first supernova from the UK by CCD imaging in 1996 and this triggered an avalanche of discoveries by the UK Supernova Patrol team. In November 1996 the VSS web page was set up by McAdam. Poyner was the leading observer during this period accumulating up to 15,000 observations annually and in 1998 became the second VSS member (and only Director) to record 100,000 visual observations. Mike Collins used photography for nova searching and in doing so identified 157 new variables in the Milky Way in the years 1989–1998. These were given *The Astronomer* Variable (TAV) designations and many were incorporated into the VSS program in 2000.

12. 1999–2010

Roger Pickard became VSS Director on September 1, 1999, and provided stable leadership during the transition into the CCD/DSLR era (Figure 4). The PALC was discontinued in 2000 as direct e-mail communication had finally rendered it redundant. In 2000–2002 Toone worked with the AAVSO within the International Chart Working Group to establish guidelines for future visual sequences using V photometry. In 2001 there was a joint campaign with the AAVSO to monitor SU UMa for the University of Leicester who were monitoring X-Ray emission with the RXTE satellite. A mentor scheme was set up by Karen Holland in 2002 and the VSS alert group was launched in 2004 with Poyner as administrator. In 2007 Miles used a DSLR camera to record Mira at V magnitude 2.16 (brightest for 101 years) and undertake daytime photometry of β Lyr. A joint meeting with the AAVSO was held at Cambridge (England) in 2008. In 2009 Tom Boles who had the ability to image up to 1,700 galaxies per night became the world's most prolific individual supernova discoverer (he had a total of 144 confirmed discoveries by October 2011). Robin Leadbeater revived spectroscopic work on variable stars and produced outstanding data during the 2009/2010 epsilon Aur eclipse. A fade of R CrB commenced in 2007 and two years later VSS observers were reporting it to be at a record low level of magnitude 15.0. The first CCD observations were reported in 2003 and by 2008 they had exceeded the quantity of visual observations reported annually. In 2010 there were 30,000 visual and 90,000 CCD observations reported. David Boyd was the leading observer during this period and became the first VSS member to record 100,000 CCD observations by 2009. Other observers reaching milestones during this period were Toone, 100,000 visual observations in 2002; Poyner, 200,000 visual observations in 2007; Tony Markham, 100,000 visual observations in 2008 (all non-telescopic); and Ian Miller, 100,000 CCD observations in 2010. Pickard introduced the "Charles Butterworth Award" for outstanding achievements in variable star research and the first recipients were Arne Henden in 2006 and Gary Poyner in 2008 (Mike Simonsen was the third recipient in 2011).

13. 2011 and future plans

By the end of 2010 the VSS database contained 1,700,000 visual and 340,000 CCD observations undertaken by over 900 observers. A number (perhaps 300,000) of legacy visual observations and all the photoelectric photometry had still to be input and it was planned that the database itself would be accessible online from 2012. It was also planned to introduce online data submission and link the database to the AAVSO International Database in 2013 or 2014. The VSS database has a unique ability to update the data to the current sequences which means that any analyst can be confident about the homogeneity of the data. The sequences themselves are being progressively converted to the V system with a limited color range which aligns with the work of the AAVSO sequence team. In the long term the feasibility of adjusting the legacy visual data to the V system will be investigated. By October 2011 seven members of the UK Supernovae Patrol team had found 244 supernovae as well as four novae in M31. The primary internal publication remains the VSS *Circular* which is issued quarterly and covers news items and preliminary reports, but the formal refereed VSS papers and annual report are published in the *JBAA*. The Director is supported by a panel of eight officers who are all experienced amateur variable star observers and also by volunteers who assist in data inputting. The Director and officers meet regularly to ensure the smooth running of the section and members' meetings are held annually. The VSS is recognized as the most active and scientifically important of the sections within the BAA. The VSS continues to encourage undertaking all methods of photometry and considers that a national group still has a role to play in promoting the acquisition of systematic data on variable stars.

14. Summary

The BAA VSS was launched in the 19th Century and was the prototype body that set the standard for the variable star organizations that were to be formed in the 20th Century. It was never global in scale but has a long and eventful history which has been summarily recounted in this paper. Today it embraces new technology and techniques for photometric data acquisition whilst at the same time retaining its Victorian standards and values. It is as active in the 21st Century as it has ever been and fully expects to celebrate its bicentenary in 2090.

Figure 1. Ernest Elliot Markwick (1853–1925). Director of the BAA VSS 1900–1909 and president of the BAA 1912–1914.

Figure 2. Felix de Roy (1883–1942; in dark suit, right-center). Director of the BAA VSS 1922–1939. On de Roy's right is AAVSO Recorder Leon Campbell, and on Campbell's right is HCO astronomer Donald Menzel. Photographed at the 1932 IAU meeting, Cambridge, Massachusetts. Courtesy Jet Katgert, Leiden University.

Figure 3. Officers of BAA VSS at the centenary meeting of the VSS, October 19–20, 1991. From left are: John Toone, Roger Pickard, John Isles, Melvyn Taylor, Guy Hurst, and Storm Dunlop.

Figure 4. Officers of the BAA VSS, November 5, 2005, with AAVSO Director Arne Henden attending. Clockwise around table, from left: Gary Poyner, Arne Henden, Karen Holland, John Saxton, David Boyd, Andrew Wilson, Roger Pickard, John Toone, Tony Markham, Richard Miles, Guy Hurst, and Melvyn Taylor.

The "Werkgroep Veranderlijke Sterren" of Belgium

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Abstract The "Werkgroep Veranderlijke Sterren" (Working Group on Variable Stars) of the Belgian "Vereniging Voor Sterrenkunde" (Society for Astronomy) was founded in 1969. The group and its individual members have been among the pioneers in several areas of amateur variable star astronomy: CV alert bulletin boards and telegrams, CCD observing, automatic handling of observations and online availability of the data, collaboration with professional astronomers, telescope automation, remote observing, and data-mining. Realizing the importance of international collaboration for a small group, there has always been a close contact with other variable star organisations. As a result also the first European meeting of the AAVSO was hosted in Brussels in 1990.

1. **Introduction**

Although observations of variable stars were made by professional astronomers at the Royal Observatory in Uccle in the 19th and early 20th century, variable star astronomy in Belgium really started with Felix de Roy (1883–1942). Although living in Antwerp, he was Director of the Variable Star Section of the British Astronomical Association for seventeen years. A recent account of his life has been given by Shears (2010). After his death, however, no variable star observations seem to have been done until the early 1960s.

The population of Belgium is divided in two major language groups, a French speaking part in the South and a Dutch speaking part in the North. After the Second World War, most cultural (and scientific) associations split into two separate entities, and new associations were formed directed to one specific language only. Not surprisingly, the same was true for the astronomical associations in general and specifically also for the variable star groups. The French speaking observers joined the Groupe Européen d'Observation Stellaire (GEOS; http://geos.webs.upv.es/) together with observers from France, Spain, Italy, and Switzerland. This paper describes the history of the Werkgroep Veranderlijke Sterren (WVS; Working Group on Variable Stars) of the

Vereniging voor Sterrenkunde (VVS; Association for Astronomy) in Flanders, the Dutch speaking Northern part of Belgium.

2. Foundation of the Werkgroep

Interest in astronomy started to grow during the 20th century. The VVS, an astronomical association for both professional and amateur astronomers, was founded in 1944. Currently there are about 2000 members. In the 1960s more and more amateur astronomers joined. Because of the increasing availability of telescopes, many self-built, interest in observing also started to rise. Among them was an avid amateur, Frans Van Loo, who observed variable stars in cooperation with the Dutch Variable Star Section. The latter was founded in 1960, ironically after Georg Comello, one of the founders, had been observing variable stars in cooperation with a professional astronomer of the Royal Observatory in Belgium. The Belgian celestial mechanics expert Jean Meeus, a prominent member of the VVS, was also a co-founder of the Dutch Variable Star Section.

To foster the local amateur astronomers' interests in scientifically valuable observations, the VVS decided to start a number of working groups in 1969, dedicated to observing meteors, planets, artificial satellites, lunar occultations, the Sun, and variable stars, the latter with Frans as the working leader.

3. The early years

Only a few observers submitted observations in the first years, until a project on observing the naked-eye eclipsing binary Algol was started in 1975. This raised the interest of a number of young people, some of them still active at this moment. As a result in 1977 twenty observers contributed some 17,000 visual observations, a first top year. Although most of the following years the number of observers stayed between fifteen and thrty (with many new observers and other ones retiring) the total number of observations declined. In those years most of the observations were of Mira stars.

4. Years of growth

Being a small group it was soon realized also that significant results could only be obtained through international collaboration. From the early years most observations were therefore sent to the AAVSO. Intensive contacts with the AAVSO lead to the organization of the first European meeting of the AAVSO in Brussels in July 1990 (Mattei 1990).

In the early 1990s, the interest in cataclysmic variables started to increase. At the same time bulletin boards and email became more common in use. This led to many opportunities and a series of Cataclysmic Variable Circulars were published between 1994 and 1998 by Paul Van Cauteren and Tonny Vanmunster (from 1996 onwards only by Tonny) to alert an international group of observers to rare dwarf novae outbursts. The yearly number of observations increased as well, reaching 35,000 in 2003.

Almost from the very beginning when micro-computers appeared on the market, it was realized that the data gathered by the Werkgroep needed to be available electronically. At first the data were keyed in from paper forms by a few volunteers, but when the internet and email became available, soon a procedure was established to enter the data into the database observations in almost real time. An online light curve generator was created, so that observers could easily see the results of their observational work. This also resulted in a book with thirty-year light curves of variable stars (Broens *et al.* 2001). Analyzing the data (and data-mining other publicly available data) has also become an important aspect of variable star astronomy.

As soon as CCDs became available to amateurs, members of the Werkgroep started to use them to observe variable stars. Most notably Tonny Vanmunster became an early and active collaborator of the Center for Backyard Astrophysics (Vanmunster 1997). Paul Van Cauteren worked with a number of professional astronomers on short-period pulsating stars. These early contacts opened the path for other members and further projects. Some of the observers have gained a lot of experience in automating their observatories, and in using remote telescopes.

5. Recent years

The Werkgroep Veranderlijke Sterren continues its activities. As in other groups the number of visual observers and observations is diminishing (with pioneer Frans Van Loo still among the most active observers), and interest is shifted more and more to CCD observing. A project to observe High Amplitude δ Scuti stars (HADS) has been initiated (Wils *et al.* 2009). This project serves several aspects. Besides the scientific goal to detect period changes and multi-periodic pulsations in these stars, it proves to be a useful project to stimulate collaboration, exchange experiences, and help new CCD observers with their first attempts in the CCD world.

Personal contact is still an important aspect, so that in addition to other more general meetings organized by the VVS, twice a year a meeting is held by the Werkgroep, of which at least one is together with the Dutch Variable Star Section; the location alternates between Belgium and the Netherlands.

6. Summary of observations

During the forty years of the Werkgroep's history some 440,000 visual observations have been amassed and about an equal number of CCD observations (an exact tally is not kept) have been done by its members.

The most active visual observers have been Eddy Muyllaert (110,000 observations), Alfons Diepvens (82,000), Johan Van Der Looy (47,000), and Frans Van Loo, Tonny Vanmunster, and Hubert Hautecler (30,000). Mira stars and dwarf novae are the types that are mostly observed (see Figure 1). The top targets are SS Cyg (10,000 observarions), R CrB (7000), Z Cam (5000), and the symbiotic variables AG Dra and CH Cyg (4500).

The most prolific CCD observers are Josch Hambsch, Tonny Vanmunster, and Paul Van Cauteren, but many others are following in their footsteps. Almost all of the CCD observers do time-series work on cataclysmic variables, eclipsing binaries, and RR Lyrae and δ Scuti stars.

7. Conclusion

The Werkgroep Veranderlijke Sterren has been a very active group in many aspects of variable star astronomy. Being a small group, a lot of attention has been and is being given to international collaboration. Working on small projects to which many members can contribute has been shown to be fruitful to the group, as it encourages contacts and enhances activities.

Further details can be found at the website of the group: http://www.vvs.be/wg/wvs/.

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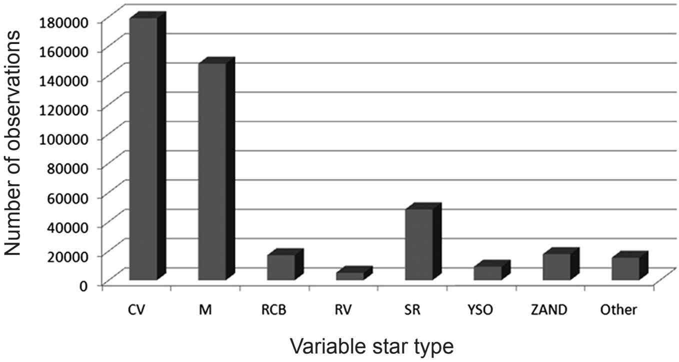

Figure 1. Distribution of WVS visual observations by variability type.

The RASNZ Variable Star Section and Variable Stars South

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Abstract The Variable Star Section of the Royal Astronomical Society of New Zealand (RASNZ-VSS) began in 1927 and has now been revived in the shape of Variable Stars South. This review introduces Variable Stars South (VSS), then continues by outlining some of the history of the RASNZ-VSS, discusses the more worthwhile achievements of the old RASNZ-VSS, and mentions some of the observers and others who contributed to those successes.

1. Introduction

Let’s look a little at Variable Stars South (VSS) as it is in 2011 before beginning a review of the Royal Astronomical Society of New Zealand Variable Star Section (RASNZ-VSS) which it has rejuvenated—but in a rather different manner. History is most useful when it allows looking at other people’s actions and providing an insight into what best to do in the future. Whilst the old Variable Star Section did very good work in producing charts, encouraging measures from members, and publishing these, it was weak in the area of communications with members at times by not making them feel an important part of the organisation. In spite of this it achieved outstanding results in variable star astronomy in the Southern Hemisphere. But we’d like to make variable star astronomy even more rewarding and enjoyable in the twenty-first century.

At New Plymouth in 2006 Pauline Loader, the acting coordinator of the old Section, convened a meeting to discuss what could be done about reviving variable star observing in this part of the world. We concluded that all observational material should be held in one area, in this case the International Database maintained by the AAVSO, and that the best role for a southern group would be to stimulate observations. The methods of achieving this were not clear at the time although a variety of ideas were discussed and thought about for the next couple of years.

Variable Stars South began early in 2009 when Thomas Richards offered his services as Director of a revived group to the parent body, the Royal Astronomical Society of New Zealand. He proposed that it should be largely a project-oriented organization with the emphasis upon astrophysics in that any projects entered into be designed to find and publish information about stars—not merely accumulate large numbers of measures of random targets. Variable Stars South furnishes reports of activities to the RASNZ each year but apart from that operates independently.

As well, information and communications with members and others is a vital part of the operation. Richards had set up the Austral Variable Star Observer Network (AVSON) website a few years previous to his appointment and at this moment the Variable Stars South website (www.variablestarssouth.org) offers information on projects and techniques and is being added to frequently. VSS also publishes a quarterly Newsletter.

Observations are the lifeblood of a variable star group. This is what it's all about. Our projects encourage these. Once analysed all observations become part of the AAVSO International Database (AID) and are available to a wide range of astronomers. In the short time we've been operating some papers have been published and several others are in progress.

The group is still feeling its way. Initially coordinators were set up in several areas—visual observing, long period variables (LPVs) (later changed to pulsating variables), cataclysmic variables, eclipsing binaries—but this proved unnecessarily complex. It now tends to operate on the basis of setting up groups when there is a demand, such as SPADES for eclipsing binaries, bright Cepheids which has partially evolved into a DSLR group, a recent eclipse of BL Telescopii and similar ideas which can be seen on the website.

2. Back to the beginning

New Zealand was a much different place in 1927. About one and a half million people were scattered over 103,000 square miles, with most living in the four main cities. Roads were poor and most travel was along the main railway which had a few branch lines. Coastal shipping was strong. There were few telephones but the mail service was good. Australia was a week away by boat, although the first crossing of the Tasman Sea by air in 1928 was not far away in time!

In this environment a young Frank Bateson persuaded the Royal Astronomical Society of New Zealand to allow him to set up a variable star observing section. Few people were much interested in astronomy—but Ron McIntosh in Auckland was looking at Jupiter and the Moon, Charles Michie of Kaitaia was observing the Sun with some special equipment, and Ivan Thomsen was later to direct the Carter Observatory.

3. Early progress

The first circular appeared on July 27, 1928, and listed nineteen variable star targets. On September 12, 1928, a further twenty stars were listed in response to observers' requests. A review of the group appeared in 1944 when the first *Memoir* was published. This mentioned a total of 35,379 observations from 1927 to 1940. From then on circulars listing the observations appeared at intervals. By the time of the Golden Jubilee in 1977 almost a million measures had been made by more than 400 observers.

Apart from Bateson another prolific early observer was Gordon Smith who contributed 15,827 of the measures quoted above. He was encouraged by an article of Alec Crust's (who wrote many articles about variable stars) in the *Dunedin Star* and made his first observation in September 1929. When observing became difficult in 1973 for health reasons he took over the recording until it became computerized in 1987.

On January 18, 1943, a new era began. Albert Jones (Figure 1) made his first measure of Nova Puppis 1942, after reading an article published in *Southern Stars* by Crust. Later Albert became interested in dwarf novae and prepared a chart for VW Hydri. Intrigued by its behavior, he checked out stars from Hoffmeister's list of suspected dwarf novae and observed Z Cha, EK TrA, and a few others. In the 1950s and early 1960s Jones' measures usually provided between 25% and 70% of the recorded observations. Later the contributions became more balanced.

One very good feature involved circulars relating to specific stars. Often these were merely summaries of observations for stars such as novae, but a few dealt with periods and changes in these and tried to understand why these happened. Simple stuff by today's standards but then today's range of detection and computing equipment, and the understanding of stellar evolution, didn't then exist. But it made people think a little about what they were observing.

4. The chart project

Charts and comparison stars have always been a problem to observers. In the south, star photographs of any type were scarce. Thus many of the Section's first published charts came from work by Jones—both in sketches of the area and sequences.

The upsurge in the 1960s saw a demand for more than the original published set of twelve stars. Bateson secured a grant from the International Astronomical Union (IAU) to produce charts of all variables brighter than a certain magnitude and south of 30 degrees south. This was to be self-funding so charts were sold to members in sets of fifty. Well over a thousand charts were produced in this manner. Comparisons were a problem as published values could differ up to half a magnitude dependent upon the source.

Jones, Ian Stranson, and Bateson began the chart task but later Mati Morel took over most of the work (Figure 2). Robert Winnet and Bruce Sumner also helped with many charts. Barry Menzies and Peter Gordon led the sequence-determining team at Auckland Observatory and produced many sequences in V, with B–V colors available. Pamela Kilmartin and Alan Gilmore also measured some sequences from Mt. John and occasionally professionals like Nicholas

Vogt or Brian Warner produced a sequence for a star of particular interest like EX Hydrae, an intermediate polar.

5. A decade of growth

The years 1966 to 1976 saw a dramatic change in the local variable star scene. One main catalyst to this was the opening of the Mt. John Observatory in 1965, which led to considerable interest in the Christchurch area. The Auckland Observatory also opened in 1967 and a strong variable star group was associated with this.

The Christchurch amateur group, led by Clive Rowe, decided to emulate Mt. John with photoelectric equipment—but of a more current design—which had interesting results which are described in another paper at this Centennial (see http://www.variablestarssouth.org/index-php/member-publications/posters/149-aavso-centennial-conference-poster-paper-rasnz-photometry-section).

On the visual scene the Auckland group was strong. Charts were obtained from Bateson, some meetings were held to discuss results, and about fifteen to twenty people, later more, began observing. Coincidentally, around this time Nova Delphini 1967 (HR Del) appeared and at third magnitude for some months it created considerable interest.

Discussions with Bateson continued at intervals and many Auckland observers, as well as observing LPVs, developed an interest in Cataclysmic Variables, a relatively new field where they were to make some useful contributions for many years.

Most of these new observers were members of the RASNZ and attended the Annual Conferences where informal discussions about variable star observing, both photoelectric and visual, attracted many amateurs in other areas of New Zealand. Many observers developed an interest in CVs using charts based upon Jones' work. Developments along similar lines took place in Australia.

6. IAU Colloquium 46

This colloquium celebrated fifty years of the RASNZ Variable Star Section. It was held in Hamilton from November 27 to December 1, 1978, and attracted eighty-one participants.

There were many well-known names: David Allen, M. K. V. Bappu (then IAU President), Barnes, Fabian, Feast, Gascoigne, Kron, and Keenan, Robinson and Schoembs; Shobbrook, Slee, Whelan, and Warner, who were all to help the Auckland Observatory; Smak, Sterken, Vogt, and Wood were others.

A small contingent of AAVSO people was also there: Clint Ford, Dorrit Hoffleit, Tom Cragg, and Danie Overbeek.

The Variable Star Section was well represented with Brian Marino, Stan Walker, Frank Bateson, Albert Jones, Arthur Page, John Beuning, Graham

Blow, Harold Kennedy, Bill Allen, and Mervyn Thomas all presenting papers or collaborating in them. But there were many other members there. A most enjoyable and informative gathering.

The first sessions related to Cataclysmic Variables were highlighted by a review by Brian Warner. Many of the astronomers mentioned above were working in this field and it was particularly interesting. At that time new discoveries were being made frequently, new observing techniques used, and the whole area was exciting and stimulating. Flare stars at that time came under this heading but they're a different type of object physically.

From there the timescale changed dramatically to red variables—Miras, LPVs, R CrBs and similar. These sessions were perhaps noteworthy for a north/south clash over pulsation modes in Miras and some interesting discussions. Cepheids also featured prominently.

Relatively high-speed variables of assorted types were discussed; modern photoelectric techniques had already produced a considerable amount of new observational material. Even eclipsing binaries were not overlooked. And, to follow up an earlier section of this paper, Clinton Ford outlined the then present work on AAVSO charts.

In all, sixty separate papers were presented and included in the proceedings: *Changing Trends in Variable Star Research* (1979), edited by F. M. Bateson, J. Smak, and I. Urch.

7. After the colloquium

The next few years were some of the most productive for New Zealand astronomy. The original photoeletric conference, PEP1, was held at Carter Observatory in 1976 and was followed by PEP2 in 1982 in Auckland, the Small Telescope Symposium in 1985 in Christchurch, as well as some easily accessible meetings in Eastern Australia, and PEP3 in Blenheim. The University of Canterbury set about building a 1-meter telescope for Mt. John Observatory and improving their spectrographic equipment.

The Carter Observatory set up the Black Birch outstation and transferred the Ruth Chrisp telescope to that site. The Auckland University became strongly involved with developing high-speed photoelectric equipment for use at Auckland Observatory and the other two major sites, Black Birch and Mt. John. The U.S. Naval Observatory also set up an outstation for a five-year project at Black Birch.

The Colloquium had been attended by many local variable star observers and the enthusiasm was contagious. Numbers of observations increased and Bateson's encouragement of observers to write articles for the *Communications* strengthened the astrophysical aspect of observer's ways of thinking. Now we not only observed the changes in brightness but thought more about why these were happening and modified the techniques to provide more and better information about the target stars.

8. The photoelectric separation

It was gradually becoming clear to the photoelectric observers that their presence in the Variable Star Section was a little awkward, perhaps unwanted. The Director did not understand what the capabilities of filtered photoelectric photometry were and tended to strongly favor the visual observers to the extent of failing to pass on PEP measures to researchers.

This led to the setting up of the Photometry Section of the RASNZ based upon the Auckland Photoelectric Observers' Group (APOG). The Photometry Section had considerable support from many astronomers. But it should have been an integral part of the RASNZ-VSS which would then have kept up more closely with technological developments. In retrospect the decline and almost disappearance of the VSS would not have occurred if Bateson had not forced this separation. The AAVSO has avoided this mistake, treating all observers and methods of observing as equally important.

9. Clouds on the horizon

The continued pressure of directing the Section began to affect Bateson's health in the 1980s. As well, his eyesight was failing. Whilst Ranald McIntosh, Albert Jones, and Mati Morel were assuming many of the responsibilities none of the other variable star observers wanted to lead the group unless Bateson would partially stand aside and allow a more member-interactive structure.

On the positive side McIntosh set up a computerised database in 1984 and began by loading data from monthly paper summaries by observers. By 1989 many observers were sending the data by mail on a disc each month. As well, Don Brunt of Murupara digitized over half a million observations from the archived records. These were included in the database and ultimately included in the AAVSO International Database.

Operation of the Section demanded time and space. Various ideas to resolve these problems were explored. To provide room at Headquarters much of the old literature on variable stars was sent to the Auckland Observatory. But publication of the *Communications* became very sporadic and offers by Gordon Herdman and Grant Christie to edit these were declined. Effectively the Section in the 1990s was operated by Jones, Morel, and McIntosh.

But even in these latter years useful research was done in collaboration with others. Karen Pollard from the University of Canterbury spent some time at "Headquarters" studying the records of R CrB and RV Tauri stars, and an analysis of eighty-eight Mira stars to explore what appeared to be period changes but which were actually alternations of periods was presented by Peter Cottrell (1998)—coauthors, Jones, Bateson, and Walker—at the IAU General Assembly in 1997. Peter Williams, McIntosh, and Morel contributed articles for the *Communications*.

In 1989 Bateson attended one of the very popular PEP Conferences, PEP3 at Blenheim. At this event several speakers paid tribute to his work and the very profitable relationship between the visual observers and photoelectric photometry. This meeting effectively was his retirement although in the absence of a formal notification the Section continued under his direction, although not effectively and many observers were lost. Fortunately many continued to observe and submitted their measures directly to the AAVSO.

10. A final meeting of the old variable star section

In 2004 the RASNZ sponsored a meeting to celebrate Bateson's eighty years in astronomy. Many observers, friends, and family attended as did Brian Warner (Figure 3). Papers from this meeting were published in *Southern Stars* (Vol. 44, No. 1) in 2005. At this meeting Bateson announced his retirement, thus clearing the way for a much anticipated revival of the Section.

11. The revival in the new century

The continued operation of the Section in the 1990s can be attributed to the dedication of three people: Albert Jones, Mati Morel, and Ranald McIntosh, with support from the Director's secretary, Maureen Phizacklea.

Whilst Jones had achieved the 100,000 visual observations target many years before (and has since passed the 500,000 visual mark) about this time two Australian observers, Rod Stubbings (Figure 4) and Peter Williams (Figure 5), also achieved this milestone, making three members of a rather select group from the Section.

After the 2004 meeting Pauline Loader, Secretary of the RASNZ, assumed the role of coordinator. Some circulars were published and requests from researchers placed on the RASNZ website but it was not until Conference 2006 (where AAVSO Director Arne Henden was a welcome visitor) that any formal attempt was made to seek a way forward.

In mid-2008 Walker offered to oversee the publication of a quarterly newsletter for the next two years and the first of these appeared in November of that year.

Shortly thereafter Tom Richards discussed with Pauline Loader and interested others the possibility of him assuming the role of Director in a new organization, Variable Stars South, operated in a more friendly and project-oriented manner than the old RASNZ VSS. Richards was appointed in early 2009 and we were under way again!

12. What did the RASNZ VSS achieve?

We should conclude by looking at what the Section achieved. In simple terms it added about 1.5 million visual observations of variable stars to the AAVSO International Database, produced charts for about 2,000 southern variables, and put together good comparison star sequences for many of these. Numbers are hard to be certain about as many observations were made of stars not on the Section's official listing and other observers, mainly Tom Cragg and Danie Overbeek of the AAVSO, supplied both the RASNZ-VSS and the AAVSO with measures. Some members of the BAA did the same.

Most importantly, it persuaded many people that good science could be carried out with a small telescope and simple equipment. It provided a sense of belonging to a group with a worthwhile purpose—not just celestial sightseeing.

It also created a situation where observers were encouraged to do more than just observe: it challenged them to find out what the observations meant and to understand what the stars were doing and why. As well, in offering research projects which needed more than visual measures, it saw the adoption of techniques such as photography and, more importantly, UBV photometry. But it was not really involved in CCD photometry. Many of the PEP people inspired by the old Variable Star Section now support the Center for Backyard Astrophysics (CBA) and other specialized groups such as those for Gamma-Ray Bursters (GRBs) and microlens searches for planets.

Many of the visual observers collaborated in projects, both in New Zealand and overseas, often supplying information about what various southern stars were doing at the moment. This was very helpful in the early days of CV observing when almost everything about them was new and little observed. However, the longer period stars received their share of attention as well.

The 1978 Colloquium introduced many amateurs in New Zealand and Australia to professionals either using their observations or looking at the same stars with similar equipment and, in its way, led to the successful PEP conferences. These are discussed in a separate poster paper which is essential to understanding the amateur variable star scene in our part of the world.

The authors and Tom Richards are pleased, as are many others, to have been part of the local variable star scene and look forward to even better things in the future.

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Figure 1. Albert Jones, the Section's most prolific observer, with more than 500,000 visual observations to his credit, relaxing in his office. Courtesy John-Paul Pochin.

Figure 2. Frank Bateson with Mati Morel, who produced most of the charts, and Peter Williams, with more than 100,000 visual observations to his credit.

Figure 3. Frank Bateson's farewell conference celebrating his eighty years of astronomy. Frank is seated center front with his daughter Audrey. To Audrey's right are Carolyn and Albert Jones, John Toone representing the BAA, and Interim Director Elizabeth Waagen representing the AAVSO; at the other end of the row is Brian Loader, RASNZ President, and Brian Warner, University of Cape Town. Tauranga, New Zealand, December 4, 2004.

Figure 4. Another prolific observer, Rod Stubbings, who now has made over 200,000 visual observations.

Figure 5. Peter Williams, who has passed the 100,000 visual observations mark.

The RASNZ Photometry Section, Incorporating the Auckland Photoelectric Observers' Group *(Poster abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract This review traces the development of amateur photoelectric and CCD photometry in New Zealand from its beginnings in the late 1960s at Christchurch and Auckland, through the Auckland Photoelectric Observers' Group and the RASNZ Photometry Section to its present place in Variable Stars South. For this period of over forty years the participants have been heavily involved with southern hemisphere variable star astronomy and observatories such as Carter, Mt. John, and Auckland, together with which were sponsored the highly successful photoelectric conferences, PEP 1-5. Samples of various projects are shown and described. The full text can be seen at http://www.variablestarssouth.org/index.php/community/member-publications/posters

Introduction to BAV *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 5, 2011

Abstract The Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne was founded 1950 in Berlin. The intention was—and still is—to support amateurs in the systematic observation of variable stars. The history of the German workgroup, the classical working focus (maxima and minima and single estimates), and the main publications (*BAV Mitteilungen* and Lichtenknecker-Database of the BAV) will be described.

The GEOS Association of Variable Star Observers *(Abstract)*

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Abstract Groupe Européen d'Observation Stellaire (GEOS) is an astronomical association created in the 1970s to promote research among amateurs in Europe. We started in Belgium, France, and Italy, later extended to Spain, Switzerland, and Germany, and more recently, added U.S. amateurs. The basic idea was that amateurs should themselves extract scientific information from their observations (visually at first and later electronically) and publish their results. Some GEOS members have become professional astronomers and the amateur-professional collaboration has strengthened over the years. From the beginning, it has been clear that the study of variable stars is a privileged topic where such projects can develop. Since the 1980s GEOS members have published a number of scientific papers, even in refereed professional journals. Presently, observations are mainly done using CCD cameras though visual measurements still exist. In the past decade our main development has been the creation of a public RR Lyr star maxima database. This is a unique tool for the study of RR Lyr stars, as it enables the user to follow period variations since a star's discovery, some over 100 years ago. In parallel to the database, a project called "GEOS RR Lyr survey" was designed. Its aims include: first, add significantly more maxima timings of the brightest RR Lyr stars essentially using robotic telescopes; second, study fainter understudied stars to refine their period and find new stars which exhibit the so-called Blazhko effect; third, characterize the Blazhko effect, one of our main research topics. Other variable stars are also studied: eclipsing binaries, δ Scuti stars, and so on. GEOS has a good cooperation with other variable star associations, mainly BAV and AAVSO.

History of Amateur Variable Star Observations in Japan *(Poster abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract Japan has about 100 years of history of variable star observing since Naozo Ichinohe, professional astronomer in Tokyo Observatory, observed δ Cep in 1906. The first amateur variable star observer is Yoshihiko Kasai, who began observing variable stars in 1918. I introduce a brief history of Japanese amateur variable star observation, including topics of variable star organizations, nova and supernova hunters, collaborations with the AAVSO and the world, PEP and CCD observations. I also introduce the most active variable star observer, Hiroaki Narumi, who made over 260,000 visual estimates since 1975. VSOLJ was established in 1987 in collaborations with the variable star sections of Nihon Tenmon Kenkyu-kai (NTK) and the Oriental Astronomical Association (OAA). VSOLJ maintains a database of Japanese variable star observations (http://vsolj.cetus-net.org) and publishes the *Variable Star Bulletin* in English.

HISTORY OF AAVSO OBSERVERS, PROGRAMS, AND SUPPORTERS

The Visual Era of the AAVSO Eclipsing Binary Program

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Abstract The beginning of eclipsing binary minima timings by visual observers in North America is described, and the history of the AAVSO's Eclipsing Binary Committee during the era of visual observation is outlined, with particular attention to the observational programs, the production of charts and ephemerides, and the reduction and publication of the minima timings. During the period 1965–2005, AAVSO observers timed more than 17,000 minima, determined periods and light-curve types for neglected and newly discovered eclipsing binaries, and improved the light elements and corrected erroneous periods for many more.

1. Introduction

If Harvard College Observatory Director E. C. Pickering was the godfather of the AAVSO, Dr. Joseph Ashbrook, editor of *Sky & Telescope*, fulfilled that role for the AAVSO's eclipsing binary program. Before 1960, pioneer amateur photoelectric observers such as John Ruiz and Donald Engelkemeier timed a few minima of bright eclipsing binaries, but no visual observers in North America were timing minima. Indeed, visual observers were unaware that they could make a useful contribution in this field.

Pickering himself suggested adding Algol-type eclipsing variables to the AAVSO program as early as 1913, but William Tyler Olcott didn't think the more intensive observing required for such stars would appeal to observers, and AAVSO remained focused on the more leisurely long period variables. In 1951, AAVSO Recorder (Director) Margaret Mayall consulted with Ashbrook (Figure 1), then at Yale University, about the possibility of visual observers timing the minima of eclipsing binaries. Ashbrook had a longstanding interest in the subject, having observed β Lyr as far back as the 1930s. Ashbrook drafted a memorandum on how to observe these stars and noted that minima timings were "of sufficient importance to warrant such a program" (Williams and Saladyga 2011).

Nothing further was accomplished at that time, but in 1957 AAVSO member Jeremy Knowles authored an Observer's Page article in *Sky & Telescope*, "Another Look at Algol" (Knowles 1957). He noted that the period of Algol is variable and described the tracing paper method for determining an eclipsing binary's time of mid-eclipse. He also declared, "There is a broad field open to amateurs in the timing of minima of eclipsing variables." Visual estimates of an Algol minimum made by Ashbrook were used for illustration. Ashbrook now served on the magazine's editorial staff and was surely responsible for selecting this article for publication.

Ashbrook made a first attempt at stimulating visual minima timings with an Observer's Page article on U CrB in the April 1959 *Sky & Telescope*, including a chart, comparison sequence, and predictions of future minima (Ashbrook 1959). But U CrB is a difficult star with a long, slow minimum requiring a night-long vigil, and apparently no readers responded to this appeal.

In June 1960, astronomer Alan H. Batten authored a feature article in *Sky & Telescope*, "Why Observe Stellar Eclipses?" in which he noted the professional astronomer's need for EB observations (Batten 1960). In the same issue, Ashbrook tried again and published a Celestial Calendar article about the eclipsing binary SZ Her with a chart and minima predictions (Ashbrook 1960). A few months later he published a similar article on RZ Cas. Both of these stars have rapid, deep minima and can be observed effectively in only two or three hours. This time several readers responded. Ashbrook reduced the observations and published the resulting times of minima in later issues. The era of visual timings of EB minima had begun.

Over the next few years, Ashbrook introduced additional eclipsing binaries, such as X Tri, XZ And, and Y Leo, good targets for visual observation and known to exhibit period variations. By 1964, several observers were regularly reporting minima timings to *Sky & Telescope* and represented a growing community of interest.

The birth of the AAVSO Eclipsing Binary Committee had some parallels with the birth of the AAVSO. In 1912, William Tyler Olcott became section leader for variable stars in the new Society for Practical Astronomy (SPA) at the same time he was organizing the AAVSO. When Olcott resigned from his SPA position to devote himself to the AAVSO, most of the other section members followed him. In 1965, Illinois college student David B. Williams took the first steps to organize amateur eclipsing binary observers as part of a proposed National Association of Stellar Observers. This activity seems to have attracted the AAVSO's notice, because he soon received a letter from AAVSO Director Margaret Mayall, inviting him to chair an AAVSO Eclipsing Binary Committee. He and most of the other EB observers were already AAVSO members, so he immediately accepted.

Ashbrook, who was also named to the committee, prepared instructions for observers and, calling upon his vast knowledge of the literature, compiled a list of ninety-eight EBs that were suitable for visual observation and were known to have variable periods or other features of interest. Ashbrook's list became the "official program" and, with Williams providing predicted times of minima and charts, the AAVSO Eclipsing Binary Committee was off and running.

Williams (Figure 2) continued as chairman until 1969, when he was succeeded by the program's most active observer at the time, Marvin E. Baldwin, who continued to lead the EB Committee for almost forty years. Baldwin was succeeded in 2007 by Gerard Samolyk, who had served effectively as Baldwin's deputy on the committee for many years (Figure 3).

2. Observations

Unlike most of the variables in the traditional AAVSO program, for which a single estimate of brightness could be made at any time, an eclipsing binary required estimates made every 10 or 15 minutes, covering both the descending and ascending branches of the light curve, to determine the time of mid-eclipse. This meant a commitment of two to four hours (and sometimes more), depending on the rapidity of the light changes, so that at least 0.5 magnitude of variation was observed.

At first, the AAVSO EB program operated conventionally, with most observers timing minima of the recommended stars. But for some, this short list didn't satisfy their observing appetites. Baldwin was the first to start investigating non-program stars, identifying likely candidates in the catalogs, calculating predictions from the published light elements, and then trying to catch a minimum. His discovery that the eclipses of V342 Aql were arriving 2.5 hours early led to publication of a report in the *Information Bulletin on Variable Stars* (*IBVS*; Baldwin and Robinson 1965), the first of many papers to appear in *IBVS*, *JAAVSO*, and the weightier professional journals, all emanating from the AAVSO EB program and its growing corps of enthusiastic observers.

Within a few years, there were enough accumulated minima timings to begin tracking period variations. The first papers based on AAVSO visual timings reported improved light elements for sixteen stars that had drifted from their predicted times of minima (Baldwin 1973, 1974).

By the mid-1970s, the program usually involved fifteen to twenty active observers, who were reporting from 300–500 minima timings each year. The earlier solo efforts to investigate neglected EBs also evolved into several team efforts. The Puppis Project targeted more than a dozen EBs with unknown periods or types in that constellation. Observers were invited to monitor these stars on a continuous basis until enough minima were found to reveal the period and plot a complete phased light curve. One target of this project, MP Pup, was found to have the remarkably inconvenient period of 0.999 day (Baldwin *et al.*, 1994).

One very important but brief campaign involved θ^1 Orionis A in the Trapezium, a newly discovered EB with an announced period of 195 days.

Baldwin monitored this star and found it faint at a time that suggested the period might be only one-third of the published value. The next minimum based on this shorter period was predicted for August 23, 1976, and AAVSO observers were asked to examine θ^1 Orionis A low in the east at dawn. Two observers were favored with clear skies and horizons and found the star faint, confirming the shorter period (Baldwin 1977).

The Southern Project, to begin observing some of the sorely neglected EBs at far southern declinations, was launched in 1978. Jan Hers in South Africa prepared some charts, but this project never gained real momentum due to lack of dedicated southern observers. Finally, in 1994 Samolyk took direct action and, taking a portable telescope to Bolivia during a solar eclipse expedition, he timed half a dozen minima of far southern stars.

Newly discovered EBs provided many additional opportunities for cooperative observing campaigns. When nova hunter Dan Kaiser noticed the deep eclipse of the suspected variable NSV 3005 (now OW Gem) on his search photos, he alerted chairman Baldwin and the remainder of the 16-day minimum was documented (Kaiser *et al.* 1988). An examination of the Harvard patrol plates revealed the 1,259-day period (Kaiser 1988). Williams (1989) used photoelectric photometry to find the shallow, highly displaced secondary minimum. A successful campaign was organized to record the next observable primary eclipse (Hager 1996, Kaiser *et al.* 2002), and eventually AAVSO CCD observers provided a light curve that, combined with radial velocities, allowed professional investigators to determine the radii and masses of the component stars and the unusual evolutionary status of this remarkable binary system (Terrell *et al.* 2003).

Over the next several years, Kaiser continued to discover new EB stars brighter than tenth magnitude, and he was soon joined (and put out of business) by the ROTSE and Hipparcos satellites, which found dozens more, several with minima deep enough to be timed by careful visual observers. All these new discoveries led to the development of a conveyor-belt process of investigation: the visual observers monitored each star until the period could be determined, then the CCD observers compiled a complete light curve, and finally the professionals added radial velocities and performed the combined analysis, resulting in publication.

3. Charts

The first charts for eclipsing binaries with comparison star magnitudes were presented in *Sky & Telescope* in the articles introducing each star—small fields encompassing only the variable and its comparison sequence. AAVSO observers were accustomed to charts of various scales to assist in finding as well as observing variables. So in 1965, chairman Williams began drafting and distributing charts that showed each field on a broader scale, similar to the "a" scale charts with which AAVSO observers were familiar, with an inset box identifying the variable and its comparison sequence.

A few new stars were added to the chart list using the resources then available. Some EBs were already identified on existing AAVSO charts—RT And, for example, with a good comparison sequence for nearby RZ And. V346 Aql and SS Lib were also plotted on existing AAVSO charts for other variables. Z Dra was located and charted using the Franklin-Adams photographic atlas accessed at a professional observatory. To provide visual comparison star sequences for these stars, Williams used the classical "step" method to estimate the brightness differences of selected comparison stars; then the variable's published visual magnitudes at maximum and minimum provided two calibration points on the step scale that could be used to convert the step values to magnitudes.

Baldwin began to identify many additional EBs and create his own sketch charts by using published light elements to calculate times of minima, then monitoring the stars nearest the variable's position until one of them dimmed into eclipse. Having identified the variable, he then chose suitable comparison stars differing by approximately 0.5 magnitude and assigned them arbitrary values of 10, 20, 30, and so forth. This "modified" step method was rough but adequate for timing minima, since the only requirement was that the light curve be symmetrical.

When observer David Florkowski enrolled in the astronomy program at the University of Florida, a center for EB research, he was able to exploit the library and find identification charts for many EBs. Finally, with the advent of the Vehrenberg photographic *Atlas Stellarum*, the persistent chart problem could be solved in a comprehensive manner. Ed Halbach and his team at the Milwaukee Astronomical Society made enlargements of EB fields from the Vehrenberg atlas and produced 380 charts in AAVSO format (mostly "d" scale). Gary Wedemayer performed extensive library research at the University of Wisconsin-Madison to identify many EBs for this project. These charts served the program well for a quarter of a century, until in 2002 the AAVSO's computerized chart-plotting program began to generate standard charts.

Chart distribution was a less creative but no less vital task. Williams distributed charts from 1965–1967; Leonard Kalish 1967–1973 (he copied and distributed 21,000 charts during his term of service); Gary Wedemayer during the 1974–1980 interval; and finally Gerard Samolyk from 1981 until standard charts became available from AAVSO headquarters at the end of the visual era.

4. Ephemerides

Along with charts, the essential ingredient in the growth of the AAVSO EB program was the provision of predictions of future minima of target stars. Without predicted times of minima, observers could not know when to give their attention to an EB and obtain the needed run of estimates covering both branches of the eclipse light curve. Each observer could, of course, make these calculations for himself, but to do so for a large number of stars was neither appealing nor practical.

The first ephemerides were published in *Sky & Telescope* for the stars introduced in its pages. But these occasional listings included only one, two, or three stars, so on many nights there were no observable minima. As the number of charted stars increased, Williams was able to address this need by preparing and distributing a monthly table of predictions. In those pre-computer days, he used a desktop adding machine, beginning with the JD day and decimal of a known time of minimum for each star and simply adding its period value over and over again, then selecting the minima observable from North America and converting the JD days and decimals into calendar dates and UT times.

Fortunately, this formidable monthly chore was soon eliminated when the Computer Age dawned early for the AAVSO EB program. Observer Don Livingston had access to a computer at his place of employment. (Readers born after 1965 need to realize that in those days, computers were the size of automobiles and were possessed only by a few universities and large commercial enterprises.) He was able to program this machine to generate monthly tables of predicted minima almost instantly for any number of stars, and a major obstruction to the continued growth of the EB program was eliminated.

Livingston provided this vital service from 1967 to 1979. He was succeeded by Peter Taylor, 1980–1983, Paul Sventek 1984–1985, and Gerard Samolyk from 1986 through the remainder of the visual era (and continuing in the CCD era). Eventually, printed ephemerides were supplemented by more flexible, Web-based services, such as Shawn Dvorak's Eclipsing Binary Ephemeris Generator (www.rollinghillsobs.org), which can include an unlimited number of stars, select those that are visible during dark hours from each observer's location, indicate the orbital phase of each system at any particular time, and provide links to additional information.

5. Reduction and publication

One spur to the success of the AAVSO EB program was the publication of minima timings with the identity of the observer attached to each timing. This provided much more recognition than the traditional AAVSO observing program (a need now met by the Quick Look page and Light Curve Generator on the AAVSO Web site for all reported observations).

The reduction and publication of times of minima were initially handled by Ashbrook at *Sky & Telescope* until 1965, when he passed this responsibility to assistant editor Leif J. Robinson. The lists of minima timings were now too long for publication in *Sky & Telescope*, so Robinson began submitting lists to the *IBVS*. When *Sky & Telescope* withdrew from the EB program in 1969, chairman Baldwin assumed responsibility for both reduction and publication of data. He continued to publish the results in *IBVS* until that publication ceased to accept papers based on visual observations in 1973. Baldwin then shifted publication to the new *JAAVSO*, 1974–1978. Then from 1993–2007, Baldwin and Samolyk prepared a series of twelve monographs, *Observed Minima Timings of Eclipsing Binaries*. Each of the first eleven monographs included new times of minima for fifty stars. Each star's new timings were presented on a separate page, which included an O–C diagram showing all the accumulated timings plotted against a constant period, so readers could see each star's period variations at a glance. The final monograph included all remaining unpublished times of minima.

At first, and for many years, the classic tracing paper method was used to determine the times of mid-eclipse. This involved plotting the observations, tracing the plot on transparent paper, then flipping the tracing and moving it left and right over the original plot to find the position of best fit between the original and the reversed light curves. This simple graphical procedure is surprisingly effective but required an enormous investment of time to plot the thousands of estimates for hundreds of minima each year. Calculating the heliocentric correction for each timing was an additional burden, which was partly ameliorated by preparing graphs of the heliocentric corrections for each of the most commonly observed stars. The correction could be read off the graph for any day of the year without having to enter the long formula into a scientific calculator (with the potential for input errors).

After 1975, the flood of observations created a growing backlog of minima timings. Finally, in 1986, with the assistance of Ron Baldwin, the chairman's son, and Samolyk, the tracing paper procedure was computerized with a program running on an Apple II. After the times and estimates were entered and verified, the program read a sequential file of observations with each light curve separated by a delimiter. The program displayed the first light curve on the screen with a mirror image. The operator moved the mirror image back and forth using the arrow keys until the best fit was found. Hitting "enter" produced the time of minimum with heliocentric correction, saved that result to a file, and displayed the next light curve. Thanks to this program, a large number of light curves could be reduced in a single session.

6. The visual era ends

During most years of the visual era, one or two photoelectric observers submitted a very few high-precision minima timings. But the arduous nature of the observing procedures meant that PEP could never compete with visual timings in quantity, and most PEP observers were limited to stars brighter than about eighth magnitude. Then in 1994, Gilbert Lubcke submitted the first minimum timing derived from CCD observations. Five years later, ten CCD observers were contributing timings.

Image-based CCD photometry was much more efficient than PEP because the variable and comparison stars were recorded simultaneously and a new image could be taken and downloaded every few minutes. CCD images also recorded much fainter stars than could be reached by PEP with the same aperture. CCD timings could equal the precision of PEP timings if all the correct procedures were followed. The final step to victory for CCD cameras in the timing of EB minima was the advent of computer-controlled telescopes, which could acquire a field, take a prescribed number of timed images, then move to another field with little or no intervention by a human operator.

In 2002, twenty percent of the entries in *Observed Minima Timings of Eclipsing Binaries #7* were derived from CCD photometry. A year later, thirty-three percent of the timings in *Observed Minima Timings #8* were CCD. In 2004, the CCD timings in *Observed Minima Timings #9* still represented only a fraction of the total, but the minima lists for forty-eight of the fifty stars included CCD timings. This was the tipping point. When visual timings were the only data available, they were invaluable. But when CCD timings were also available, researchers would ignore the visual timings because the CCD timings were ten to one-hundred times more accurate. By 2005, automated telescopes with CCD cameras were providing at least one CCD timing (and often more) for almost every EB within reach of visual observers, and the visual era of the AAVSO program had reached its terminus.

The visual era of the AAVSO eclipsing binary program was highly productive. More than 17,000 times of minima were observed and published, and a continuous record of the period variations of hundreds of EBs was compiled. Periods and light-curve types were found for many new or unstudied EBs, and erroneous periods were corrected. Many amateur astronomers enjoyed the opportunity to contribute observations of real astrophysical interest and to see their timings used in research papers. Everyone who participated in the visual program can feel a justified sense of accomplishment, and many of those observers continue to advance eclipsing binary astronomy as CCD photometrists for the re-named Eclipsing Binary Section.

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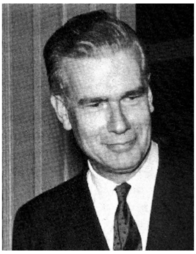

Figure 1. Joseph Ashbrook of Yale University and, later, *Sky & Telescope* editor, advised AAVSO Director Margaret Mayall on establishing a program to monitor eclipsing binary stars. From *Sky & Telescope*, October 1980; courtesy of *Sky & Telescope*.

Figure 2. David B. Williams, AAVSO Eclipsing Binary Program chair 1965–1969.

Figure 3. Marvin E. Baldwin (left), EB chair 1969–2007, with Gerard Samolyk, EB chair 2007–2009 and since 2009 co-chair with Gary Billings.

Walking With AAVSO Giants—a Personal Journey (1960s)

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Abstract Through pictures, anecdotes, and remembrances, the authors recount the inspiration, friendship, and camaraderie Roger S. Kolman shared with such legendary AAVSO figures as Leslie Peltier, Clinton B. Ford, Carolyn Hurless, Thomas A. Cragg, Margaret Mayall, and others during the decade of the 1960s that led to his fifty years as an AAVSO member and observer, and a career as a physicist, astronomer, and educator.

1. Background

The idea for a presentation at the AAVSO's 100th Anniversary Meeting arose when AAVSO historian Thomas R. Williams and AAVSO staff member Mike Simonsen requested information regarding the origin of the so-called "August Orgies" in Delphos and Lima, Ohio, in the 1960s. After some conversations, we decided to set up a narrative on how the "Giants of the AAVSO" had inspired a new, young observer. Since I was unable to attend the centennial meeting personally, Mike and I decided that we would prepare the material through a series of interviews, Mike would give the presentation at the Historical Session, and I would participate by remote connection (Skype). We then prepared this narrative with Mike providing the prompts (in italics) followed by my responses.

2. 1961 got it all started

Mike: How did you get started in observational astronomy in general and the AAVSO in particular?

I had a friend across the street from me who had a Tasco 60-mm refractor. We did quite a bit of observing with it, mostly the moon, planets, and a few deep sky objects. One evening we were looking for M81. My friend was searching for it without success. After about forty-five minutes I asked him if I could try to find it. He dismissed my comments, but finally agreed to let me try. I quickly found it. This led to my purchase of the scope from him.

We went to the Adler Planetarium each month since we had no other place to purchase *Sky & Telescope*. In December 1961 I read an article by AAVSO Secretary Clint Ford entitled "Sidelights on Observing Variable Stars" (Figure 1). To think that an individual with a small telescope could make observations of scientific value excited me. I wrote to AAVSO Director Margaret Mayall for information and was sent a packet of material. I made my first observation of R Leo on April 12, 1962. I was hooked! My enthusiasm led to my correspondence with Margaret and Clint on a regular basis. To their credit, they answered every letter I sent. Finally, even though I was four months shy of the lower age limit for membership, Clint told Margaret, "Let the kid in" (perhaps remembering that he, too, was allowed to join at age 15). My membership commenced on May 11, 1962.

3. Meeting Dick Wend

What local mentoring help made you take off as an observer?

In those days the AAVSO published a list of members along with contact information. Richard E. Wend was one of the names on this list (Figure 2). He lived only a couple of miles from my home and only two blocks from the high school I attended. After several attempts at meeting Dick (he was a travelling salesman), we finally got together. By this time I had a 4-inch Dynascope. We immediately clicked. This led to a friendship that lasted almost fifty years, until his death in 2009.

A few months after we met, Dick felt that I should have a larger telescope with which to observe variables. He assisted me in obtaining a 6-inch Dynascope. This telescope proved to be a short-term solution to aperture fever!

One evening I was visiting Dick and he showed me a 16-inch mirror blank on which he was working. I spotted a large tube in his basement that I thought was an old water heater. He told me that this was a tube for a 10-inch Cave reflector that he had. It had no mount. We talked about it and he said we could sell the Dynascope and he would help me assemble the 10-inch. I was working as a junior draftsman at a local railroad engineering company. I designed a mount for the scope, the company fabricated it for me, we sold the Dynascope, and the 10-inch Cave became my main scope until the 1980s.

4. First trip to Delphos

When did you first get the chance to meet Leslie Peltier and Carolyn and Don Hurless?

Dick Wend and I enjoyed discussing the AAVSO and the many great observers of the 1950s. He was a long time member of the Milwaukee Astronomical Society (MAS) and a friend of such luminaries as Ed Halbach, Walter Scott Houston, Bill Albrecht, and A. R. Ball. I was in awe when I met and observed with all of them, except Ball, whom I never had the chance to meet. Dick brought up the possibility of meeting the celebrated observer Leslie Peltier, which greatly excited me. He contacted Carolyn Hurless (Figure 3) and a visit was scheduled for November 23, 1963. This was, of course, the day after the assassination of John F. Kennedy, so our trip began on a somber note.

We had a great time visiting with the Peltiers and the Hurlesses. Talk and viewing went far into the night. Carolyn suggested contact with Curtis Anderson and a correspondence began with him and many other AAVSOers. Carolyn could not keep up with all of the correspondence and ultimately launched an informal newsletter which she called *Variable Views*. She did this with a "ditto" spirit duplicator machine sending a compilation of notes and observations to those on her subscriber list. Incidentally, Leslie commented to Carolyn after our visit "I thought they would never leave." I guess my enthusiasm was overwhelming to him. Carolyn felt otherwise and she told us that she was looking forward to another visit, soon.

5. 1964—first AAVSO meeting

When did you first attend an AAVSO meeting?

My first was the AAVSO Spring Meeting in 1964, held in St. Louis. Dick Wend and I made the trip where I gave my first paper. This eighteen-year-old was quite nervous, about to speak in front of an audience that included Clint Ford, Tom Cragg, and many others about whom I had read. Margaret Mayall took me to the side and told me to just speak to her—not to pay attention to the rest of the audience. This settled my nerves and the talk went well. Following a question and answer session, J. Allen Hynek (at the time the Department Head of Astronomy at Northwestern University) came up from the bar with a martini in hand and said, "That was a fine talk, young man. Margaret has been saying some fine things about you." I almost lost it then. This was my first face-to-face meeting with many of the Giants of the AAVSO.

6. August 1964—Schoonover Observatory dedication and the first "August Orgy"

Tell me about the legendary "August Orgies."

The Lima (Ohio) Astronomical Society (LAS), in concert with the City of Lima, built the Schoonover Observatory. The main instrument is a 12-1/2-inch Cassegrain reflector. The city financed the building and LAS managed it. Carolyn invited AAVSOers from around the country for this event. We had the opportunity to meet Carolyn's protégés, Ernst Mayer (who served as AAVSO President), Paul Sventek (who served several terms on Council), and Vicki Schmitz (who went on to become a highly regarded lawyer and judge). Carolyn knew how to pick them!

Headquarters for the gathering was the Hurless home in Lima that was buzzing with activity. Sessions went far into the night. Among those attending from out of town were Tom Cragg, Clint Ford, Chuck Scovil, George and DeLorne Diedrich, Diane Lucas, Art Stokes, John Ruiz, Ed Oravec, Newton Mayall, Leslie Peltier, and Curtis Anderson.

Speaking of Curtis Anderson (Figure 4), I must say that he was a most remarkable man. Carolyn met him at the 1959 AAVSO Spring Meeting at the Adler Planetarium in Chicago. He was an imposing figure standing at six feet, eight inches. Observing with a 10-inch reflector from his home in a Minneapolis suburb, he submitted prolific numbers of variable star observations—many of them Inner Sanctums (13.8 magnitude or fainter). Shortly after the meeting, he was diagnosed with Multiple Sclerosis. His case was particularly aggressive and, by 1961, he was confined to a wheelchair. In spite of this, he continued to observe at virtually the same rate as before his confinement. Meeting him was an additional inspiration to me, seeing how the passion he had for variable stars could help him overcome his great handicap. He was awarded the AAVSO Merit Award in 1965 and was a member of AAVSO Council from 1965 to 1969. During his time as an observer, he contributed 600 consecutive monthly reports! Sadly, he succumbed to his disease in 1976. In more ways than one he was a Giant of the AAVSO!

Tell me about the SS Cygni contest you had with Carolyn Hurless.

We had an observing session at Leslie's observatory in Delphos, Ohio. Carolyn had brought her 8-inch reflector from Lima and I brought my 10-inch reflector from home. During the evening a discussion arose about who could find SS Cygni (which was our favorite variable) using the star-hopping technique. Each of us felt that we could do so faster. Finally, Curtis Anderson said, "Why don't you have a race and settle this once and for all?" We agreed.

Each of us put our telescopes in a neutral position, Curtis made the call, and we were off. In a few seconds, we each found the field and SS Cygni. I made the call first, just ahead of Carolyn. She maintained she found it first, but had not made the call. In reality, it was too close to call. Each of us maintained we won. Those in attendance got a good laugh out of the race.

7. Ford Observatory dedication, 1965

I understand that the next August Orgy took place on the road. Tell me about it.

We had learned that there was going to be a mountain near Wrightwood, California, named after Leslie Peltier, and an observatory placed on the mountain. The observatory was to be named after Clint Ford and would house an 18-inch telescope donated by Claude Carpenter. Once we were invited to the dedication, Dick Wend and I planned a western vacation.

Dick had been a long time member of the Association of Lunar and Planetary

Observers (ALPO), so he asked ALPO leader Walter Haas to set up a meeting in Las Cruces with Clyde Tombaugh on the way out to Mt. Peltier (Figure 5). I brought my 6-inch *f*/4 richest-field telescope (RFT) along so I would not miss any observing time. Upon arrival at the Tombaugh home, Clyde saw the 6-inch RFT in the back seat of Dick's car and got excited. "I haven't seen one of those since I made one in 1920-something." We then exchanged views through the 6-inch and Tombaugh's 16-inch telescope.

Tombaugh's telescope was a behemoth! It was of long focus, since he was a planetary observer. It looked like an oil derrick. Tombaugh wanted to show us Jupiter, which was not easily accessible to the eyepiece. Being very practical, he had a long plank near the observing platform. He pulled out the plank, and told Dick and me to stand on one end to weigh it down. He then walked out to the end of the plank to reach the eyepiece and observe. When he was done, he walked back and said, "Okay, now it's your turn." Dick and Clyde stood on the end of the plank to weigh it down for me. Now, I was much skinnier then, but it was still pretty scary. However, this was a chance to observe with Clyde Tombaugh, so I wasn't about to chicken-out. After I finished, Clyde and I stood on the plank for Dick. Another interesting tidbit is the fact that Tombaugh, being the practical man he was, used a peanut butter jar for the secondary cover, and a garbage can lid for the mirror cover.

We did a great deal of sightseeing on the way to Wrightwood. Finally, we arrived, settled into a motel, and were off to see the Ford Observatory.

We arrived a few days before the dedication and found that there was much to do before the site would be suitable for visitors. We pitched in to help with the preparations. While cleaning up things, Dick called out to me, "What kind of snake is this?" There was a rattler coiled up in front of him. Fortunately, I had been a pitcher on my high school baseball team. I told him to stand very still, picked up a rock, and sent the snake to its maker. We threw the snake off the side of the mountain. Later, when we told the story to Larry Bornhurst (one of the Ford Observatory group), he said, "So where are the rattles? You didn't save the rattles? My kids are saving them!"

There were no "facilities" available, but bizarre as it may seem, there was a toilet just sitting there in the middle of the observing field on top of the mountain! So we fashioned a porta-potty out of some leftover plywood and made a sign: one side said "Be careful, in use"; the other side said, "It's Okay now."

Thomas A. Cragg was a solar observer at the 150-foot tower at Mount Wilson Observatory in Pasadena, California. He arranged a tour for us and, while we were in the 60-inch telescope dome, we heard that word had spread among the astronomers on the mountain that Leslie Peltier was visiting. They stopped what they were doing to come meet the legend in person—a Giant of the AAVSO.

8. The 1966 meeting in Chicago

The AAVSO held its 1966 Spring Meeting in Chicago. I was now 21 and of age to be included in the legendary “Clint Ford Hospitality Suite.” I had heard about it, but had never been allowed in because of my age. Now, I was allowed in! It was awesome. He had a room filled with all kinds of liquor and beer. Early on, the partying was rather mild-mannered. Then Carolyn Hurless said she was pretty tired and told everyone “goodnight.” A minute after she left, Clint said, “all right, let the fun begin!” He then proceeded to quote limerick after limerick, many of which would make a sailor blush. Clint loved his limericks and he knew a LOT of them. I was now indoctrinated!

9. The 1968 meeting in Lima, Ohio

In 1968, you gave two papers at the Lima, Ohio, meeting. Tell me your memories of that meeting.

I do recall that among the speakers at that meeting were: Newton Mayall, Leif Robinson, Clinton Ford, Charles Scovil, Marv Baldwin, Carl Anderson, Robert Cox, Walter Scott Houston, Lawrence Hazel, Tom Cragg, Cyrus Fernald, and Art Stokes. I was shocked when Margaret Mayall asked me to chair one of the sessions. Giving two papers was a treat, but chairing some of the Giants of the AAVSO was unbelievable!

10. Conclusion

My first exposure to the AAVSO came in the form of an article in *Sky & Telescope* magazine (December 1961) about amateurs observing variables, written by Clint Ford. I was so impressed by the fact that ordinary people using backyard telescopes could contribute to science that it impacted the rest of my life. I became a physicist and now teach astronomy courses at Harper College in Palatine, Illinois.

I joined the AAVSO as a teenager in 1962, which makes me one of the longest-standing members of the AAVSO. My first variable star observation was R Leo in April of that year. In 2012, I will reach the fifty-year mark (Figure 6). I have witnessed decades of development and have known many of the famous personalities in AAVSO history personally. Sadly, almost all the AAVSO Giants of the 1960s are gone now, but their influence and legacy lives on through me and the generations of dedicated observers that have followed in their footsteps.

Figure 1. Clint Ford, about 1963.

Figure 2. Dick Wend, 1964.

Figure 3. Carolyn Hurless, in Peltier's "Merry-Go-Round" observatory, 1964.

Figure 4. Oravec, Kolman, Peltier, Hurless, Cragg, Anderson, Ford: Delphos, Ohio, 1964.

Figure 5. Kolman, Tombaugh, Wend, 1965.

Figure 6. Roger Kolman, observing with his 18-inch reflector.

Variable Star Observers I Have Known

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Abstract I would like to share with *JAAVSO* readers some personal recollections of a few of the outstanding individuals I have become acquainted with through forty-five years as an AAVSO member. In one manner, or another, all have played an important role in the AAVSO's 100 years of service to the astronomical community.

1. Introduction

By virtue of my forty-five years as an active visual observer with the AAVSO, as a small part of our celebration of 100 years as amateur scientists contributing to the field of variable star monitoring and solar observation through the auspices of the AAVSO, I would like to share with you some personal recollections of a few of these individuals (Figure 1). Some of you who have devoted decades to the association, as I have, will undoubtedly recognize these names immediately. For others of you who have joined the organization more recently, but perhaps have perused the volume *Advancing Variable Star Astronomy*, it may add a degree of more personal familiarity to those individuals otherwise known to you only as written names on a page. In one manner, or another, all have played an important role in the AAVSO's 100 years of service to the astronomical community.

2. Clinton B. Ford, observer par excellence

I first met Clint Ford in 1962 when I discovered Stamford Observatory and joined the Fairfield County Astronomical Society which runs it. He became president of the Society a couple of years later. We became quite good friends. I think he saw a potential observer in me. At the time I was building myself a 4-inch refractor, and I had never heard of variable stars. The observatory's 22-inch telescope was still under construction. Clint bribed me by loaning me a 10-inch reflector he had just replaced with a new 12.5-inch in his backyard observatory. His one requirement was that I build an observatory in my backyard to house the telescope, since the 10-inch would be too big to haul in and out. The paint on the observatory had hardly dried when he came over with some strange blueprint star charts and a gleam in his eye. He taught me how to make variable star estimates, and as the saying goes, the rest is history. Eight years later I was president of the AAVSO.

Clint first started observing variables at age fourteen in Michigan where his father was a math professor at The University of Michigan. Clint was too young to be accepted formally as an AAVSO member until he turned fifteen in 1928, so he became a member the year I was born. Also in 1928 he had the privilege (for one of his tender years) of attending his first AAVSO meeting, where he met such dignitaries as Leon Campbell, William Tyler Olcott, and David Pickering. This cemented his interest in variable stars. In Michigan near the family home Clint had an observatory at the top of an old tower, where he used a borrowed 3.5-inch Clark refractor. He made many observations from that location, and from the family summer place on Cayuga Lake in central New York State. He spent part of one summer as an assistant at Yerkes Observatory where he used an 8-inch refractor for his observations. Through three years at Carleton College in upper New York State, and later at the University of Michigan for his senior year and his studies for his Master's degree he continued observing as time permitted.

The war years proved difficult for observing, but again, whenever he could he stuck with it. He spent part of the war as a Naval Reserve Lieutenant teaching navigation at Rensselaer Polytechnic Institute in Troy, New York, where he used their observatory's 12-inch.

Clint and his first wife, Alice, built a home in Suffield, Connecticut, in 1948. In Suffield he built his first roll-off roof observatory, which housed the 10-inch telescope. That telescope was built by a friend of Clint's and was pretty good. It would regularly reach the mid-14th magnitude range even in not so good Connecticut skies. That meant that Clint was often able to reach the "Inner Sanctum" (positive estimate fainter than 13.8 or fainter-than estimate fainter than 14.0) and he liked to observe the fainter end of the variables' cycles.

After Clint's divorce and remarriage he moved to Wilton, Connecticut, to work for the Perkin-Elmer Corporation. There he built his second roll-off roof observatory, a slightly larger version of the one in Suffield. The new observatory housed a 12.5-inch scope made by Cave Optical Co. in California. By that time Clint knew Tom Cave quite well, so he got a fine telescope. With it he was able to reach into the mid-15th magnitude range. Clint willed his 12.5-inch scope to Ithaca College where it is in use again.

While still in Michigan, Clint had become friends with Claude Carpenter, who owned an 18-inch telescope. When Claude retired from his job with the Post Office he moved to Southern California and set up the telescope in a rickety observatory out in the desert. Several other amateur friends got together and found a site in the mountains near Wrightwood, California, where they built a new observatory to house the 18-inch. Since Clint supplied most of the funds for the building they named it after him. The project made the cover of *Sky & Telescope* for March, 1966, with a feature article inside.

The 18-inch was a big brute of a scope, and being a Newtonian it required climbing on a ladder or platform to get to the eyepiece. At first the eyepiece location in the usual spot opposite the attachment point of the Declination axis sometimes made it impossible to reach. Clint eventually solved that problem by having a rotating top end built. At any rate, once the 18-inch was operational the limit was about 17th magnitude. Now we were getting somewhere! Clint used to go to California with his wife three or four times a year, usually for two or three weeks spanning the dark of the Moon. At first they stayed in a local motel, but that got old pretty soon so Clint bought a three-bedroom house for his visits and for use by the local observers. I stayed there on many occasions when we went to California together after his second divorce. Altogether Clint made 61,874 observations in his lifetime.

Clint was Secretary of the AAVSO for forty-four years so he always had a report to give at meetings. His writing style was rather dry and old fashioned. I suppose it was a product of his times and his educational background. I always found it rather stuffy but I never complained. Later when we got into the chart making we differed strongly on many issues and I let him know my opinion. John Griesé used to say we sounded like an old married couple—always bickering.

We knew that there were far more visually observable variables than the AAVSO had charts for. Clint had gotten a bunch of material for new charts from Dr. Charles Olivier of the University of Pennsylvania. He started drawing charts from that material but the photos supplied were of poor quality and very hard to work with. He constructed what he called his "e-maker" (e-scale charts) with a couple of mirrors and an opaque projector to enlarge the photos. Soon after our 22-inch Gregory-Maksutov telescope came on line in Stamford I began taking photos for the new charts, and then assisting with the drawing of them. Clint was not a good draftsman and it drove me nuts to see what he turned out. First I made up a chart form to get away from his sloppy outlines. Soon computers came along and we were able to start at least drawing the chart forms and the lettering that way. The next step was a program to take the irregular star dots from my photos and make them into perfectly round dots that we could scale any way we wanted to. The program was written by our local Society member Gil Wiengarten. We called it very scientifically "Roundify." At last we could make charts entirely using the computer. There was still a bit of art in it since we had to choose the disk scale that would make it look like the sky. Local Society member Bob Leitner and I designed the computerized chart forms and consulted with Janet Mattei on final details.

Clint and I often went to various scientific meetings together. In 1988 we went to a reunion of astronomy graduates and staff at Cornell where many notables including Carl Sagan gave talks. Clint was involved with Cornell in supplying a part of the funds for them to use the 200-inch at Palomar.

Clint was prevailed upon by Dorritt Hoffleit to write his memoirs. They are called *Some Stars, Some Music* and make fascinating reading. Copies are still available from AAVSO Headquarters. I highly recommend this booklet. Also, Dorrit Hoffleit wrote an obituary of Clint after he died in 1992 that was published in *JAAVSO*, Vol. 21, No. 2, pp. 144-146.

3. Danie Overbeek

At the 1972 AAVSO Meeting we met South African observer Danie Overbeek and his wife Jeanne. After the meeting we all met at Clint's house in Wilton. We all got along famously and they said "You simply must come visit us in S.A." Of course we never thought it would happen, but in 1975 Clint and I did just that. We spent twenty days touring South Africa with Danie and Jeanne, and had a great time. We talked to every astronomy Centre in the country (sixteen of them) about amateur astronomy in the U.S.

Danie had his observatory on top of his garage, ten feet from his kitchen door. It was accessed by climbing a vertical ladder up the side of the building. He had a home-made 12-inch reflector of rather short focal length, ideal for variable work. The finder had a mechanical shutter type arrangement so that he could cut down the aperture when using it on very bright variables. When he needed to go back into the house he wore a set of WW II red aviator goggles to preserve his night vision.

Danie worked for South African Airways as head of their pilot training department. Since they bought their planes from Boeing, he was frequently in the United States to check out the latest simulators and we got together now and then.

While in Cape Town we met Reginald de Kock, who held the AAVSO's lifetime record at that time with 160,777 variable star observations. Danie later exceeded that mark by a considerable margin with 292,711 visual observations. *[Ed. note: there is a memoria page to Danie, who died in 2001, at http://www.aavso.org/memorium-danie-overbeek]*

4. Wayne Lowder

Wayne lived not too far from Stamford and became a member of our Society. He often came to visit and observe because we had better skies than he did at home. He used binoculars and his own 8-inch and a 10-inch telescope we had. He was so interested in variables that he taught himself to read Russian so he could do research in the library at Harvard and find out what they were writing about stars that might prove to be of interest. Wayne was one of those who checked each new chart we turned out. We called him "The electronic eyeball" because his estimates were so good. He would even make new sequences by eye-estimates. Wayne made 208,571 visual variable star observations, many of them highly-precise estimates of small-amplitude variables. *[Ed. note: there is a memorial page to Wayne, who died in 2003, at http://www.aavso.org/memorium-wayne-m-lowder]*

5. Ed Oravec

Ed lived in nearby Westchester County, New York, only a few miles from us, and like Wayne he often visited us since our skies were better than he had at home. He brought his own large binoculars and did mostly bright stars. His observations were extremely accurate. Ed doesn't observe any more, but he made 170,453 visual observations between 1943 and 2003.

6. John Bortle

John Bortle was another member who came from Mt. Vernon, New York. He did both binocular and telescopic observing, and was also interested in comets. That was a subject for which he became world famous. He later married and moved to a far better location in Stormville, New York, where he built his own observatory. In those early years at Stamford Observatory we also had as members Bill and Florence Glenn from the Bronx, New York. They were also binocular observers and came very often to observe. It was this total group who dreamed up and proposed the two new AAVSO publications: *The Journal of the AAAVSO*, and *AAVSO Circular*. We proposed them to Margaret Mayall, and with her approval and input both were started. John Bortle became editor of *AAVSO Circular* which dealt with rapidly varying stars such as CVs and novae, and Bill Glenn became editor of *JAAVSO*. I was production manager and typist/layout editor of *JAAVSO*.

That group was also the genesis of *The AAVSO Variable Star Atlas*, since we realized that there was no atlas of the heavens that showed where all our "pet" variables were. I proposed that as a trained draftsman I could make such an atlas if we could find as suitable base atlas giving us the stars. We finally got the right to use *The Smithsonian Astrophysical Observatory Atlas*, and I was off and running. *[Ed. note: John is still going strong and has just passed the 200,000 visual variable star observations mark.]*

7. Tom Cragg and Claude Carpenter

I first met Tom at a Spring Meeting in Tucson, Arizona, in May 1972. Of course we went to Kitt Peak and I got my first look at really large telescopes. Tom was in his element, having worked with the 60-inch and the 100-inch at Mt. Wilson, where he was the Solar Observer and jack of all trades. He and Clint Ford were old pals and Tom was a very amiable guy, so we all got along well. We went on from there to California to observe with the 18-inch at Ford Observatory on Mt. Peltier near Wrightwood. I think it was on that trip that I first visited Mt. Wilson. Naturally Tom showed us around, and I also briefly met Larry Bornhurst, who was one of the founders of and did most of the actual building of Ford Observatory. Larry had his own little dome on Mt. Wilson.

Tom Cragg had the use of a wonderful 6-inch Clark telescope at Mt Wilson. His eyesight was so good that he regularly broke into the 15th magnitude range.

On that same trip I also met Claude Carpenter, who owned the 18-inch scope in Ford Observatory. He was a bit of a character. You didn't want to cross him or you could expect a tongue-lashing. All bark and no bite, of course. In general he was a likeable person. He was older than the rest of us and rather set in his ways, having lived as a bachelor most of his life. *[Ed. note: Claude died in 1992. There is a memorial page to Tom, who died in 2011, at http://www.aavso.org/thomas-cragg]*

8. John W. Griesé, III

John Griesé showed up at the Observatory as a high school student in the early 1970s. He lived across the road from Richard Perkin (of the Perkin-Elmer Corp.) and had observed with Perkin's 24-inch reflector on a few occasions. He joined our group and began observing variables, eventually becoming my assistant at Stamford. He helped in taking photos for the chart work and also ran the public open house nights for years. He taught Adult Education courses throughout Connecticut. He studied for and got his Master's Degree and is now going on studying for his Ph.D. John was elected to the AAVSO Council where he served from 1985 to 1990. John has made nearly 22,000 visual variable star observations so far.

9. Fr. Ronald Royer

On one of our trips to Ford Observatory I met Fr. Ronald Royer (now Msgr. Royer). At the time he was one of several priests at his church, but later he became the Rector. He was a regular guy who had started observing variables in his teens and continued even through his studies for the priesthood. He had his own 12-inch scope in the backyard of the church. He was also one of the founders of Ford Observatory, and frequently went there to observe on his days off. On one of our later trips to California, one night John Griesé and I stayed at the Rectory, which was also the residence of the local Bishop. As I recall, that was on our trip to the Riverside Telescope Makers Convention at Big Bear. He has made nearly 10,000 variable star observations so far, mostly visual but some PEP and CCD, too.

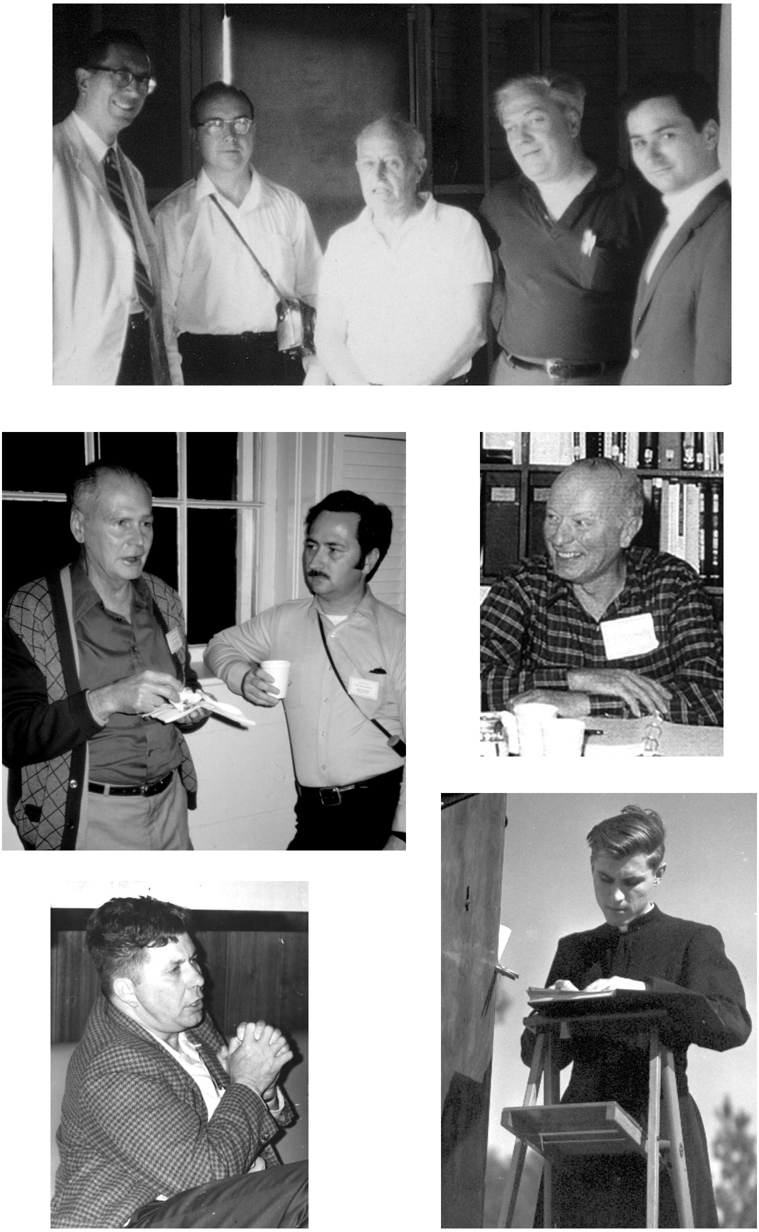

Figure 1. AAVSO Observers: *top*, Ed Oravec, Charles Scovil, Leslie Peltier, Clint Ford, John Bortle; *middle left,* Danie Overbeek and John Bortle; *middle right,* Wayne Lowder; *bottom left,* Tom Cragg; *bottom right,* Fr. Ron Royer.

An Appreciation of Clinton B. Ford and the AAVSO of Fifty Years Ago

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Abstract This is a rather personal story about Clinton B. Ford, my boyhood mentor in astronomy, and about the influence of the AAVSO and Clint on my life and career. While much has been written on Clint, this addresses the man, and his kindness.

1. The start

Clint and Alice Ford (Figure 1) lived on Loomis Road in Suffield, Connecticut, a 300-year-old tobacco farming town on the Massachusetts border, and on the West Bank of the Connecticut River. They were neighbors of my family, living just 0.4 mile to the East. Clint worked for a company that made photographic developing equipment in nearby Springfield, Massachusetts, owned by another Suffield resident, Hinny Smith. I recall that Clint was vice president and also did engineering at this company, yet due to Clint's father's foresight in buying early IBM stock, part of his life was managing this investment. However, his love was clearly astronomy and in particular the AAVSO.

The Fords became great friends of my mother and grandmother, and by 1953 it was standard Sunday afternoon fare for either Clint and Alice to visit us, or for us to visit the Fords. This always pleased me, especially visiting the Fords. My interest in the night sky started at age eight. Part of this was a childlike fascination with the radio show *Buzz Corey and the Space Patrol*. My little brother and I had learned to climb out on the roof of our old farmhouse after mother thought we had gone to bed and lie there, with blankets, looking up. It was two or three years later when the close friendship between the Fords and the Hulls matured. I remember sitting in the Ford's living room, full of adult talk by the others, and being quite happy thumbing through Clint's *Sky & Telescope* magazines. Clint would notice, and was always happy to answer questions. And I asked many. Then off to the observatory we would go to look at hardware, always a special pleasure.

The AAVSO was integral to Clint's and Alice's social life. I had the opportunity to meet and see frequent Suffield guests Margaret and Newton Mayall, Claude Carpenter, Cy Fernald, and others. Later Clint generously donated a 4-inch Unitron Refractor to my high school, Suffield Academy. I became the first president of the School's Astronomy Club, and enjoyed assembling the scope and using it for the first time.

It was rather cool to be interested in astronomy then. After all, this was the start of the space race, with Sputnik being all the talk in the fall of 1957 (Figure 2). Starting in 1955, some of my interest had diverted into rockets, an interest which Clint did not share. With my little brother and best friend, we learned the basics of rocket design, nozzles, and how to pour a fuel core and had some successes, a little like the film *October Skies*. We also had a fantastic failure which pretty much ended my rocket career. Fortunately no one was hurt.

When I was fifteen, Clint nominated me to membership in the AAVSO, and there was little surprise that I was elected to membership at the 48th Annual Meeting at Nahant, Massachusetts, October 1–4, 1959. The meeting was coincident with the October 2nd Sunrise Total Eclipse which was "rained out." I watched what I could of it through Suffield clouds.

After making some variable star observations, in a period competing with time for playing sports, and crushes on girls, the momentous 50th Annual Meeting at Harvard College Observatory came up in October 1961. This was the first trip on my own, taking a bus from Springfield to Boston, the MTA to Harvard Square, and a very long cab ride to my very nearby hotel. It also involved a choice. I was on the football team, and missing a game would mean being dismissed from the team. I did the right thing and never had a single regret.

I loved being at the 50th Annual Meeting (Figure 3), and regret that I could not be at the 100th Annual Meeting. I recall seeing Harlow Shapley and Donald Menzel and other great names in 20th Century astronomy there. I was somewhat familiar with these from reading *Sky & Telescope*, and the books I had begun to collect. I also recall meeting Constantine Papacosmos of Montreal, just a few years older than I and a person with much enthusiasm. Clint kindly kept an eye on me from a distance but let me have my own experience. I still recall the dinner speaker making the classic joke over dessert of this "seeming to be a meeting of a gastronomy society" rather than an astronomical society. Overall this was a great experience and the AAVSO enriched my love of astronomy.

2. Clint's Suffield observatory

Clint's home observatory was a marvel of intention and practicality. While Clint had the means to have much more, his observatory was ideally matched to his interest. He described the utility of the roll-off roof design, allowing him to nimbly move about the sky. Suffield of the late 1950s still had fairly dark skies, and wind was not much of a factor. His telescope of choice was a 10-inch Newtonian reflector (Figure 4), built by someone else and acquired by him. Clint explained to me that there are two kinds of astronomers: those who develop telescopes and do little astronomy and those who do astronomy with telescopes developed by others. I had not realized then that this lesson had special relevance for me. After graduate school, I elected to work in aerospace developing telescopes and instruments, largely for spaceborne projects.

Rather than an optical finder, Clint preferred a piece of tubing in the "pea-shooter" configuration. Clint understood in detail everything about the observatory. He knew optics, to the level that he could sit down with a pad of paper and explain the optical difference between the war surplus Erfle eyepiece he loved and his Kelner eyepieces. Clint would spend hours teaching me about telescopes, both in showing me equipment in the observatory, and in chats in his living room. The latter was inevitable as I devoured his *Sky & Telescopes*, and wanted to know about everything. Clint taught me all, from the basics of astronomy to the utility of rare earth glasses in optical design. This interest in design became more intense when I encountered the *Amateur Telescope Maker* three-book series by Albert G. Ingalls. While Clint's interest was clearly in observing, he had a consummate knowledge of telescopes and was very generous with his time as I asked a thousand questions.

Clint valued his clear night observing time, and had a schedule of what observations he would want to make in each month of the year. Nevertheless, he would make time to not only have Cub Scouts visit, but to teach me how to observe, how to hold a chart correctly, find objects in the sky, and use averted vision to see faint objects. On that note, Clint had a "lazy eye," and my family had concern that this was an artifact of observing at the telescope. Nevertheless, they, too, continued to encourage me with astronomy. I started saving up the sum of $33.75 to buy a 3.5-inch Skyscope. While a very simple *f*/11 Newtonian telescope, Clint felt the optics were good and that it would let me do variable star observations on brighter objects. I still have this telescope.

3. Clint the observer

Astronomers come in various flavors. I have met many over my career, both professional and amateur. Of these only a handful had a love for being at the telescope the way Clint did. In fact, of the astronomers I have known, I think only University of Pennsylvania Professor Leendert Binnendijk matched Clint's love of being beside the telescope. Clint was happiest as he observed variable stars, and moved his telescope about with a sense of complete familiarity with the sky. His proficiency at variable star observing is written into the records of the AAVSO. Clint was an amateur in the best sense: one who is motivated by his love for the field. He also loved the sense of contributing in a meaningful way to the understanding of time-domain astronomy, variable stars. He often led campaigns on interesting faint stars within reach of his telescope. I think of Clint also as a professional, including having received a M.S. degree in Astronomy from the University of Michigan, but more so because of his consummate knowledge of what he was doing. He clearly had the stuff the best professional astronomers are made of.

I would like to report that among the equipment Clint showed me was a photoelectric polarimeter he had developed in the late 1940s, roughly contemporary with the work on the interstellar medium by Hiltner and Hall and the predictions of Chandrasekhar of intrinsic polarization in late type stars. This certainly anticipated the fluorescence of photoelectric polarimetry. While I never saw Clint operating this instrument, I was impressed that he had recognized the importance of measuring the polarization attribute of light, and that it might be relevant to the stellar objects he studied. Years later in graduate school at the University of Pennsylvania, I had the opportunity to conduct a polarization survey of contact and over-contact eclipsing binary stars. As I did this, I recalled that Clint could have been a pioneer in this field.

4. Clint the mentor

I can trace the progression of opportunities I have had in astronomy to Clint's mentorship. I would be remiss in not stating this. Because of the background training Clint had given me, and my experience with the AAVSO, I was already at the intermediate astronomy course knowledge level when I went to college. As a freshman at Penn, I was put into an advanced Practical Astronomy class, competing with two junior majors, two senior majors, and two graduate students. Practical Astronomy was an in-depth class aimed at acquiring a working knowledge of Spherical Astronomy, the application of precession and nutation, the precise calculation of time, and the method of least squares for reducing observations. The rigor of this class in turn enabled me to obtain summer work with Peter van de Kamp at Sproul Observatory, Swarthmore College, and then two summers and a semester at MIT's new Haystack Observatory, where I published my first paper, still cited, on the radio star method of correcting the pointing of large altitude-azimuth telescopes, which expanded on the principles of reducing meridian transit observations. In turn this assured that I would pursue graduate studies in astronomy.

While I have chosen mostly the telescope and instrument development side of astronomy, the course of my life would have been very different if it had not been for the mentorship and kindness that Clint Ford showed a neighborhood child. I have had the privilege to build imaging systems used throughout the solar system, to be NASA technologist for the Terrestrial Planet Finder Coronagraph, and Program Manager for the optical manufacture of the James Webb Space Telescope mirror suite, NASA's next flagship mission and sequel to Hubble. There is something about being behind a telescope I still love. I frequently think back to those early days in Suffield with Clint's example. Clint's love of astronomy, and the sense of its importance, has been a central and consistent inspiration for who I have become—and I am just one of the people whom Clint trained and the AAVSO continues to train to aspire to the stars.

Per Aspera ad Astra.

Figure 1. Clint and Alice Ford (top row) at the AAVSO spring meeting in 1952, about a year before my family started regular Sunday visits with them.

Figure 2. At the 1957 Annual Meeting. Dorrit Hoffleit is holding a newspaper announcing the USSR Sputnik satellite launching. Clint is at the right in this photo.

Figure 3. 50th Annual Meeting of the AAVSO in 1961 at Harvard College Observatory. This was my first trip away from home alone, and resulted in being kicked off the football team for missing a game, but it was worth it. The left arrow indicates the author; the right arrow points to Clint Ford.

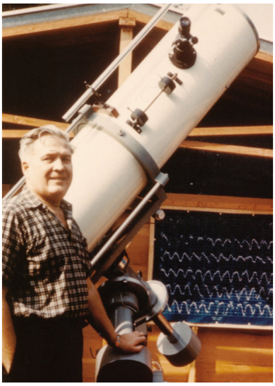

Figure 4. Clint at his 10-inch Newtonian reflector at his home in Suffield, Connecticut, about 1964.

An Overview of the AAVSO's Information Technology Infrastructure From 1967 to 1997

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Abstract Computer technology and data processing swept both society and the sciences like a wave in the latter half of the 20th century. We trace the AAVSO's usage of computational and data processing technology from its beginnings in 1967, through 1997. We focus on equipment, people, and the purpose such computational power was put to, and compare and contrast the organization's use of hardware and software with that of the wider industry.

1. Introduction

There are some organizations and purposes for which data processing and computers seem to have been tailor-made. One of these is the AAVSO. To their credit, the organization's leaders, specifically Directors Margaret Mayall and, later, Janet Mattei, realized this synergy fairly early on. During the AAVSO's Annual meeting in 1966, Mayall consulted with AAVSO member Professor Owen Gingerich at the Smithsonian Astrophysical Observatory (SAO) about the feasibility of digitizing the AAVSO's variable star observational data (Welther 1970). In 1967, with the cooperation of SAO, Mayall and the AAVSO began digitizing observations for what would become the AAVSO International Database. This was followed, in fairly short order, by the start of custom programming, again with the cooperation of SAO, to analyze the observational data being compiled (Welther 1970).

Along with other organizations of the AAVSO's size and non-profit mission, the 1980s were a transitional decade that saw computer technology used not just for data, programming, and analysis (although that certainly continued), but also for routine office work. The 1990s, for both the AAVSO and the wider world, was the "decade of networking," with Janet Mattei overseeing both the installation and use of a local area network, and the marriage of the organization to the then new World Wide Web.

2. Early developments

As early as 1958, Margaret Mayall considered "the possibility of processing all variable star data at headquarters by means of IBM punched cards" (Williams and Saladyga 2011); but it was not until 1966 that Mayall and the AAVSO Council began to bring that idea into fruition. During the AAVSO's Annual Meeting in 1966 Gingerich, Mayall, and the AAVSO Council discussed how this might occur. Gingerich, in what would become the first of a long line of important contributions to the AAVSO, believed he could donate some free access time on the SAO computers to the AAVSO. All that the AAVSO would need to invest in, he said, would be a card punch (keypunch) machine. At the May 1967 meeting, the AAVSO Council decided to rent a keypunch machine to begin a critical process of remaining relevant and moving to increased professional acceptance of the organization (Saladyga and Williams 2011).

Prior to this decision, observations were recorded in ledger books, and light curves were hand-plotted from these data for particular, special, or requested stars. Incoming data started to grow in leaps and bounds at this point and new ways had to be found to graphically represent the data. Data digitization enabled plotting and analysis programs to be used, which greatly enhanced the usefulness of the data for both amateur observers and professional astronomers alike. Once the AAVSO crossed this Rubicon, going back was unthinkable.

Digitized cards had other uses that observations in ledgers could never approach. Cards could be handled in discrete batches, sorted automatically based on criteria, and could serve as input to computer programs.

Once photometric data were digitized, it was easy to find reasons to use them in that form. Over the next few years, for example, the AAVSO made an effort to use computer programs and software plotters to help automate and produce compilations of observations and light curves of selected stars—the *AAVSO Report* series—using the keypunched data that had been collected.

By 1971 the AAVSO had digitized one million observations. There were millions more, but it was decided at that time that digitizing current observations as they came in would take precedence, assuming that astronomers would need current data more than archival data.

By 1973 keypunch machines were common in large office and scholastic environments. Charles Scovil, for example, made arrangements with Darien High School in Connecticut to use their keypunch machines during off hours (Scovil 1972). The AAVSO developed its own keypunch training program which enabled volunteers and staff to enter the observations that came in each month (Figure 1). Some observers were already starting to send observations to AAVSO Headquarters on keypunched cards (Mayall 1973).

In just six years the number of cards being processed and physically stored by the AAVSO—then at about 100,000—was becoming a problem (Mattei 1974). At this point only data from 1960 on, with the exception of a two-month period in 1973, had been digitized; the project of digitizing AAVSO observations from 1911 to 1960 had not yet begun. *Report 30* was being compiled, and the 130,000 published observations used for *Report 28* and *Report 30* were stored on four separate magnetic tapes kept in four separate locations for safety. With those tapes the AAVSO had a small taste of the future, and was gearing up for its second data processing revolution.

The AAVSO had digitized its membership list by 1973 as well, allowing the office to create computerized mailing labels and to generate selective mailings (Ford 1974; Mattei 1974). Data analysis programs had been part of the AAVSO from the start of its digitization process created at that point by AAVSO member Barbara Welther, who was a staff researcher at SAO. One program written by Welther during this period was one that found and noted maximum and minimum dates for Mira variables for *Report 30*. Up to this point the AAVSO staff were processing these data by hand, augmented by a program that produced 10-day mean light curves. It now became faster to do it all by computer, and Barbara Welther came up with the program with which to do it.

3. The second revolution—better control of data

1974 saw its first of many AAVSO in-house programmers when MIT student Richard Strazdas joined the staff (Figure 2). Under Strazdas the AAVSO continued to move away from the hand-plotting of light curves, a road which eventually led to the web-based Light Curve Generator that we know today. Strazdas' method involved deriving light curves from density curves where the number of observations at specific magnitudes were printed at each date. This method, for the first time, allowed the AAVSO staff to easily find observational outliers, notifying and guiding observers toward gathering better data. At this point light curves were produced using alphanumeric characters on line printers. Their resolution was quite poor. It was not possible to plot individual observations, only 5-day means, using this technology (Mattei 1975).

Over the next four years Strazdas wrote several programs in FORTRAN (a language the AAVSO still uses productively today) that specifically used data that were stored and read from magnetic tapes. The data processing procedure began with observations being keypunched onto cards, which were then stored on magnetic tape. A program called VALID initially checked the data and corrected or flagged it for errors in designation, star name, and so on. BSORT then read the output of this program, which was also stored on tape, taking the place of a mechanical card sorter. A third program, BMERGE, combined the two different sorted data sets. Thus the first half of the second data revolution for the AAVSO had been accomplished. Instead of using cards for computer program input, the cards were now a backup to the much more flexible magnetic tapes (Hill 1977).

The second half of the second revolution involved two computer plotting units then owned by SAO; a Versatec electrostatic plotter, and a Calcomp ink-based plotter. These plotters, under the direction of Strazdas-written programs, aided by Robert S. Hill, allowed for the first time individual data points to be plotted as the computerized light curves that we would recognize today. With such improved resolution in computer produced light curves, the observational density and scatter in a plot of observations (always evident on the data hand-plots) finally became apparent (Ford 1977). This method was used for all future reports and publications, thus completing the AAVSO's second data processing revolution (Hill 1977). It had started with punch card processing and gone to tape processing, and from line-printer produced 10-day mean light curves to plotted individual observations. The plotting aspect of the revolution, while seemingly starting out well, had a hard birthing.

Technology continued to move forward in late 1978, but the AAVSO had to halt for a technological pit stop. The Harvard-Smithsonian Center for Astrophysics (CfA) upgraded its main computer from a CDC 6400 to a DEC VAX 11/780 and all the programs that ran on the CDC 6400 had to be rewritten for the DEC VAX architecture. Having no full-time programmer at the AAVSO, this conversion took weeks—it was supervised by Richard Strazdas with the help of two students, Christopher Walton and Sandra Galejs. The switchover put the publication of *Reports 38* and *39* on hiatus while Strazdas and his team converted the needed programs and developed new ones (Mattei 1979).

Data entry, something the AAVSO had gotten rather good at, forged ahead through mid-1980. Under Elizabeth Waagen's direction, all data from 1960 up to the then current time—325 boxes of IBM punch cards comprising 650K of data—were now on magnetic tape and sorted by star name and date. Light curve plotting stumbled, however, and the *Reports* could not be published. The Calcomp plotter that Strazdas had written his plotting programs for had never been moved to the new DEC VAX 11/780 from the CDC 6400. The AAVSO purchased a new plotter—an FRS80 Graphics computer from AVCO Computer Services—and Strazdas adapted his plotting programs to it (Mattei 1980).

By mid-1981, with the data from 1960 onward now machine-readable, progress towards the goal of converting into machine-readable format all data from the founding of the AAVSO to 1960—2.5 million observations—began (Mattei 1981). With this project, and the need to continue keeping up with incoming observations, the AAVSO was pushed into its next revolution, its largest yet: independence.

4. The first in-house computer system

The technology and cost of microcomputers had just gotten to a point where they might be a feasible alternative for the AAVSO. At the other end of the scale, the increasing volume of IBM punch cards was literally filling Headquarters and squeezing everything else out. An in-house system was needed that could deal directly with floppy disks and maintain the publishing schedule the AAVSO had created. Mattei initiated a massive research and funding project to find and purchase an appropriate and affordable microcomputer system. It culminated in the AAVSO obtaining, through a grant from the Research Corporation, two

Ithaca Intersystems computers in December of 1981 (Mattei 1982). The first was a Z80-based computer running CP/M, with a graphics terminal and a plotter. The other was the DPS-8000, a Z8002-based multi-user system running COHERENT, a UNIX look-a-like operating system, with three terminals for data entry, word processing, and other office work (Figure 3). Both systems boasted 64,000 bytes of random-access memory.

The acquisition of its own computer did not immediately cut the AAVSO's ties to Harvard—not by a long shot. While the Ithaca Intersystems computers were advanced microcomputers for the time, they were too small to handle the AAVSO's data processing needs. The Ithaca's greatest contribution was that it enabled the AAVSO to move past punch card storage to eight-inch floppy disks for temporary data storage. Now, instead of data being punched onto cards which were stored and then retreived to be read onto magnetic tape, data were keyed onto the disks, then verified (re-keyed to check for errors), then converted to a DEC-readable format, read into the PDP 11/60, transferred to the DEC VAX 11/780 for processing, and stored on permanent tape, while storing the diskettes as a backup.

The monthly data inflow to the AAVSO—15,000 to 20,000 observations at this point (Waagen 1984)—was too much for the microcomputer to handle; observations were still stored on magnetic tape which the AAVSO could not read on its own. When observations of a specific time period were needed for publication, the storage tape would be read into the VAX, transferred to the PDP, and copied onto diskettes for processing at the AAVSO. In 1984 the PDP 11/60 was decommissioned and its disk readers transferred to the VAX 11/780, taking one step out of this process (Waagen 1984).

While diving into computer use itself, the AAVSO also recognized that its observers were able to take advantage of this technology as well. To assist them, the AAVSO sponsored a computer workshop as part of its AAVSO 73rd Spring Meeting in 1984, in Ames, Iowa.

Despite the advances in information processing, the huge *Reports* were abandoned as Mattei learned that researchers preferred a long span of data on one star to a short span on hundreds. Capitalizing on the information technology that it did have, the AAVSO began publishing a *Monograph* series, each of which concentrated on the twenty-year light curve of a specific star. The International Astronomical Union (IAU) welcomed and praised this initiative (Mattei 1984).

5. Growth in data processing capability and application

In 1986 the AAVSO moved to Birch Street and prepared to celebrate its 75th Anniversary. As one can imagine, the move put most work on hold for awhile as things were packed, moved, and unpacked (Mattei 1986). Still, the staff, under Mattei's leadership, continued to gain technological ground. A

Perkin Fund grant enabled the hiring of two full-time staff for the archival data entry project. With their help, by 1986, twenty-five percent of the AAVSO archival data for 1911–1961 had been converted to machine-readable form.

The IBM PC clone, and the first stages of networking, came to the AAVSO in 1987. The clone, sporting a 40-megabyte hard drive, connected the AAVSO to CfA through a modem device. The Kenilworth Fund bought Headquarters a laser printer and scanner. Observers began submitting data to Headquarters using diskettes and email. By 1989 the first articles featuring computer analysis of variable star data by AAVSO members were being published in *JAAVSO* (Mattei 1988). FORTRAN programs originally written for the VAX 11/750 were now rewritten for the IBM PC. Also, Grant Foster (Figure 4) began to write a series of graphical programs which allowed real-time manipulation of light curve data on the computer screen; these programs were not for data entry and editing, but for actual statistical analysis of the data (Mattei 1989).

The addition of 600 megabytes of hard drive space on the main computer in 1990 allowed all the variable star photometry from 1960 onward to come home from CfA. AAVSO staff migrated the data from storage tape to magnetic cartridges. The AAVSO installed its first local area network (LAN) in 1991 using 10base-2 LANtastic technology. These were used to tie together ten PC clones bought for the staff through a NASA grant (Mattei 1991). Headquarters began experimenting with commercial data services by putting astronomical data on Compuserve in 1992 (Mattei 1992).

A Theodore H. Dunham Fund for Astrophysical Research grant expanded the hard drive storage capability at AAVSO Headquarters to 2.4 gigabytes in 1993, just in time to aid in the completion of the archival project. Now the AAVSO had the entire AAVSO International Database in computer readable form right on site! Spearheaded by Grant Foster, AAVSO staff wrote programs to facilitate analysis of the data that Headquarters had spent more than twenty years digitally archiving.

In 1995 William Mackiewicz (Figure 5) became the AAVSO's first webmaster; he created the organization's first website and file transfer protocol (FTP) server. An IBM PC clone running GNU/Linux provided the AAVSO's first Internet services. By 1997, the AAVSO used its website to provide charts, and its *AAVSO News Flash*, *Circulars*, and *Alert Notices* to the public. With over 400 visits a day, the AAVSO website was named one of the top education-related sites on the Net (Mattei 1998). Users responded in kind with fully fifty percent of the monthly reports being sent to Headquarters electronically by 1997.

The AAVSO went from one computing strength to the next, but there were a few potholes along the way. Increasing reliance on technology meant that problems would crop up from time to time, and the AAVSO was not immune to this. In 1991 a bad sector on a hard drive caused the first AAVSO data loss. Through redundant diskette backups the staff was ultimately able to recover the data. In 1997 a vandal broke into the Linux server but did not compromise data. The vandal only created and ran his own chat room.

6. Successfully riding the technological wave?—an assessment

It seems clear that the AAVSO had a good track record of using technology to accomplish its mission. How close was the AAVSO to "riding the technological wave" that confronted it? Some non-profits don't do well with this, usually due to limited funds.

It is difficult to assess the exact state of a technological wave in a practical sense. Keypunch machines and keypunch cards were in use before WWII. The AAVSO started using them in the mid-1960s, borrowing time and resources from larger organizations to build its computational legacy. The AAVSO's computational technology from the mid-1960s until 1980 was dependent on the resources used at SAO and CfA, so during this time how the AAVSO fared technologically was somewhat tied to how those organizations fared.

The AAVSO moved to punch cards at the very end of their practical life. For programming purposes punch cards had fallen out of use in production environments by the 1970s, but they would continue to be used for data storage at the AAVSO right through the early 1980s, largely due to the availability of older machines in large data centers. In the end, the AAVSO was driven from cards for the exact same reason everyone else was—lack of space.

The AAVSO, through its partnership with CfA, kept up with hardware advances pretty well with the VAX 11/780 mini-computer. CfA upgraded to this computer in 1978, less than a year after DEC announced it at the Annual Shareholder's Meeting in 1977 (Digital Equipment Corp. 1997).

Sometimes being close to the edge can have its downside if looked at in hindsight. The AAVSO spent a good bit of time and research toward purchasing their two Ithaca Intersystems computers. To modern eyes the purchase of a CP/M system in 1981 looks shortsighted, but at that point there really wasn't any other microcomputer option available. The very first IBM PC went on sale in August of that year and had no track record as yet. Furthermore, DOS was not designed as a multi-user operating system, or as a file server. CP/M had over a ten-year history and, indeed, IBM itself had originally selected CP/M as the operating system of the IBM PC, but talks in 1980 with Digital Research, Inc. failed, and IBM decided to go with with Microsoft for its operating system (Anthony 2011).

While perhaps the best choice, the Ithaca Intersystems computers also featured a swan song in terms of storage. The system initially used eight-inch floppy disks introduced for CP/M in 1977. This was the last introduction of an eight-inch floppy drive. While old technology, the drive featured one megabyte of storage formatted for CP/M, while the best a 5.25-inch floppy could do at the time was 87.5 kilobytes (Sollman 1978).

The first IBM-compatible was released in late 1982. Several companies struggled for a year or so before finally achieving an acceptable level of compatibility with it (Reimer 2005). It took until 1987 for PC-compatible computers to show up at AAVSO Headquarters, by which time they had become commodities. In this case the AAVSO waited five years to enter the PC market. In parallel, that first AAVSO PC-compatible allowed communication with the CfA through a Hayes Smartmodem compatible, which was released in July of 1981 (Markoff 1983).

In contrast, in terms of local area networking, once the PCs arrived at Headquarters, the AAVSO stepped right into setting up a LAN. While Artisoft's LANtastic is not widely remembered today, at that time it rivaled Novell in the PC networking market. Neither Novell nor Artisoft foresaw the rise of TCP/IP networking, but both products still exist today. LANtastic is currently on version 8.

Arguably, one of the most significant information technology events for the AAVSO was its adoption of the World Wide Web. Sir Tim Berners-Lee released the Web in August of 1991 (Berners-Lee 1991). The AAVSO's first web server went online in 1995. While a four-year lag may seem somewhat significant, Berners-Lee's Web did not take off until the introduction of the Mosaic web browser in 1993 (Andreessen 1993).

In the same year that Berners-Lee introduced the Web, Linus Torvalds introduced the Linux kernel (Torvalds 1991) which the AAVSO's first, and all subsequent, web servers ran on. Torvalds' release of the kernel under the GNU General Public License in 1992 accelerated the creation of the free UNIX-like operating system which we know today as GNU/Linux (Stallman 1997). In March 1994 Linux reached version 1.0 and Linux distributions such as Slackware and Debian were in wide release. The AAVSO adopted GNU/Linux just over a year after it became practical.

7. Conclusion

While the AAVSO is a non-profit corporation, it may not be valid to compare them to other non-profits such as librairies in their technological adoption curve. At its heart the AAVSO is a technological organization and so it needs to come up to a higher bar. Couple this with the financial issues that most non-profits seem to go through—and the AAVSO is no stranger to financial challenges—the organization seemed to do a pretty impressive job of taking advantage of technology whenever it could.

Taking advantage of technology when it became available requires adaption to change at a very fundamental level. Both people and organizations find that difficult. It takes strength in an individual and strong leadership in an organization. Margaret Mayall, with the help of technologically astute people on the AAVSO Council at the time such as Clint Ford, as well as friends at SAO such as Owen Gingerich and Barbara Welther, allowed the AAVSO to make its initial leaps into using technology to improve the efficiency of the organization.

When Janet Mattei initially came on board she continued with the progress that Mayall had begun. Soon, though, spurred on by the success of the initial digitization project that allowed her to reach for larger government contracts and backing, Mattei made significant steps of her own that not only continued to improve the efficiency of the organization, but allowed it be stay competitive and relevant in the face of progress.

8. Acknowledgements

The author would like to acknowledge Elizabeth O. Waagen, AAVSO Senior Technical Assistant, and Michael Saladyga, AAVSO Technical Assistant, for serving as co-authors on the poster that preceded this paper. Dr. Saladyga's assistance with the AAVSO Archives was invaluable. We would like to acknowledge the rest of the AAVSO staff as well, especially Dr. Aaron Price, for their inspiration and support.

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Table 1. Timeline of events in the development of AAVSO information technology.

Date	*Event*
1967	Computer processing starts for the AAVSO using facilities at the Smithsonian Astrophysical Observatory to put data on IBM punch cards.
1972	Charles Scovil makes arrangement with Darien (Connecticut) High School to use its key punch machine in off hours. With that help, the AAVSO staff is working on keypunching incoming observations and working on starting work on reports from 1911 and later.
1973	The AAVSO membership list information is now put on IBM punch cards. The main data processing thrust at this point is using keypunched entered data in preparing the *Reports*. At this point *Report 30* is being compiled. The published data for *Reports 28* and *29*—130,000 observations—are being put onto four copies of magnetic tape.
1975	MIT student Richard Strazdas develops (based on an existing program) a method wherein light curves are obtained as density curves in which the number of observations at specific magnitudes are printed at each date. The program then plots the light curve. This allows the study of computerized plots and the detection of anomolous observations. Observational data from 1960 to May 1968 are processed. June 1968–November 1974 is not processed or must be reprocessed due to error. This became known as “The Gap.” AAVSO staff computerizes the membership database and mailing labels for mailings which are made using SAO computers and printers.
1978	Harvard-Smithsonian Center for Astrophysics (CfA) upgrades its CDC 6400 computer to VAX 11/780. The AAVSO converts all data and programs to be compatible with the DEC VAX 11/780. The PDP 11/60 is still in use there as a data reader.
1979	All data from 1960, sorted by star and date, are now on magnetic tape and are machine-readable.
1980	The “Gap Data” are finally processed. The AAVSO begins computerization of data from 1911 to 1961. This is a multi-year project. AAVSO Headquarters is taken over by punch cards; Director Mattei is determined that something needs to be done about their storage. The AAVSO researches the feasibility of purchasing its own computer system using 8-inch floppy diskettes as storage media. An in-house system is needed to offset increasing publishing costs. The

table continued on following pages

Table 1. Timeline of events in the development of AAVSO information technology, cont.

Date	*Event*
	system needs to have a graphics terminal, plotter, and printers and be compatible with the DEC VAX at CfA.
1981	Through the Charles M. Townes Fund, the AAVSO buys two Ithaca Intersystems microcomputers with the CP/M operating system. One is a single-user system comprised of a computer, terminal, graphics terminal, and plotter which is used to plot data on screen, check, edit, and plot the data to paper. The other is a multiuser system with three terminals, two for data entry, and one for word processing for *JAAVSO*, correspondence, mailing list, and other office work. Incoming observations are now stored on 8-inch disks and processed using the VAX at CfA, and stored on magnetic tape at CfA.
1982	AAVSO Treasurer Theodore Wales buys a terminal and a pair of disk drives for the new AAVSO computer system. The monthly inflow of observations attains the 15,000–20,000 level—too big for the Intersystem computer to handle. These data still processed at CfA.
1984	CfA decommissions its PDP 11/60. The disk readers are put on the VAX allowing the VAX to read AAVSO data directly. Charles Jones, an MIT student, writes a data editing program for the Intersystems computer allowing editing to be done in-house. The AAVSO holds a Computer Workshop as part of its 73rd Spring Meeting.
1985	25% of archival data from 1911 to 1960 is put to tape. HQ uses its computers to produce the *AAVSO Monograph* series.
1986	The AAVSO moves to Birch Street. HQ begins exploring the possibility of observers submitting data on diskettes or via modem. There is a near-complete turnover in AAVSO programming staff.
1987	A new IBM PC connects AAVSO HQ with the DEC VAX at CfA via modem. The PC has a 40 megabyte hard drive. The Kenilworth Fund buys HQ a laser printer and scanner for the PC clone.
1989	The first *JAAVSO* articles detailing computer use in amateur variable star observation and research begin appearing. VAX FORTRAN programs are rewritten to run on PC clone. Data processing is now done at HQ, not CfA, but CfA equipment is still used for tape storage. The AAVSO begins supporting the HIPPARCOS data mission. The AAVSO researches data storage solutions with the goal of migrating

table continued on next page

Table 1. Timeline of events in the development of AAVSO information technology, cont.

Date	*Event*
	all CfA-stored data to in-house storage. The archival data project is 77% complete. Grant Foster writes a new light curve plotting program that uses a scale compatible with existing hand-plotted light curves.
1991	NASA grants provide a terminal or stand-alone computer system (IBM clone 186, 386, 486) for each staff member (ten in all). All workstations are networked via LANtastic LAN to the main computer for file access. First reported data problem: bad sectors on a disk cause data loss that needs to be recovered. The archival data project is 97% complete.
1992	Grant Foster writes programs to plot light curves on-screen for any star, expand any portion of the light curve, identify observations of observers on the light curve, and evaluate an observation and change its status. The AAVSO is now listing data on Compuserve.
1993	AAVSO staff complete the data entry phase of the archival data project. Now the data have to be processed! The plan is to have this done in three years. A Dunham Grant adds 1.8 gigabytes of storage to the main computer system bringing its total to 2.4 gigabytes. The AAVSO now switches its focus somewhat to writing programs to analyze its data.
1994	The AAVSO purchases its first Pentium computer and CD-ROM reader through a NASA HIPPARCOS grant.
1995	The AAVSO appears on the World Wide Web. William Mackiewicz, the AAVSO's first webmaster, also establishes an FTP site. Internet services are being run on a PC clone using GNU/Linux.
1996	The AAVSO acquires two Pentium computers, and places 114 charts on its FTP site. The AAVSO website sees about 228 visits per day.
1997	The AAVSO uses its website to distribute the *AAVSO News Flash, Circular*, and *Alert Notices*. The website now sees 483 visits per day. The FTP site has 2,179 files downloaded each month. The entire AAVSO database is archived on ZIP disks. 50% of monthly observing reports arrive electronically, up from 32% the previous year. Archival processing completed. Grant Foster writes WWZ, a time-series analysis program. All workstations are running Windows95 and are upgraded to 486s or Pentium. A vandal breaks into the GNU/Linux server. The AAVSO website named one of the best education-related sites on the web.

Figure 1. Keypunching operations performed by work-study students at AAVSO's Concord Street Headquarters in the early 1980s.

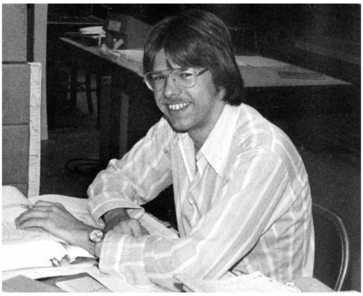

Figure 2. Richard Strazdas, MIT student who wrote data processing and file-transfer programs for the AAVSO beginning in 1974.

Figure 3. The Ithaca-Intersystems computer at AAVSO's Concord Street Headquarters, early 1980s. The system brought AAVSO's data processing operations in-house. Some of the hundreds of boxes of punch cards can be seen on the left, forming a work-area partition.

Figure 4. Grant Foster, AAVSO programmer from the late 1980s to the early 2000s.

Figure 5. William Mackiewicz became the AAVSO's first webmaster in 1995.

20 Million Observations: the AAVSO International Database and Its First Century *(Poster abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract The American Association of Variable Star Observers (AAVSO) turns 100 in 2011—a century of service to the astronomical community! Another milestone was reached in 2011: the AAVSO International Database (AID) received its 20 millionth variable star observation! The AID contains observations of over 14,750 objects contributed by over 7,500 amateur and professional astronomers worldwide. Data on hundreds of objects extend from the AAVSO's founding in 1911 or earlier (mid-1800s) to present. Some objects' data are of shorter duration but of intense, high-precision coverage. Historical datasets come from published/unpublished professional/amateur observations, astronomical plate collections, and contributed archives of other variable star observing organizations. Hundreds of observations are added to the AID daily as observers upload their data in near real-time. Approximately 69% (~13.9M) of AID observations are visual, 30.4% (~6.2M) CCD (BVRI, unfiltered, Sloan colors, others), 0.5% (~75K) PEP (BVJH), and 0.1% (~17K) photographic/photovisual. Many objects have exclusively visual data, some PEP or CCD data only, and many a combination of types and bands. Objects range from young stellar objects through highly evolved stars. Included are intrinsic variables—pulsating (SX Phe stars through Miras and semiregulars) and eruptive (cataclysmic variables of all types)—and extrinsic variables—eclipsing binaries, rotating (RS CVns)—and exoplanets and suspected variables. Blazars, polars, quasars, HMXBs - today's AID is a thriving, exciting resource! The AID is maintained in a dynamic MySQL database, easily accessible to contributors and users alike through the AAVSO website (http://www.aavso.org). The Light Curve Generator, Quick Look page (recent observations), and Data Download form offer different ways to view/investigate your targets. Quality control performed from submission through validation ensures reliable data for your research. Visit the AAVSO website if you need data; contact us if we may help you observe your targets. We are here for you!

Professional Astronomers in Service to the AAVSO *(Poster abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract Throughout its 100-year history, the American Association of Variable Star Observers (AAVSO) has welcomed professional astronomers to its membership ranks, and has encouraged their participation as organization leaders. The AAVSO has been fortunate to have over 60 distinguished professionals serve as officers (Directors, Presidents, Council), and as participants in its various scientific and organizational committees.

The Variable Star Observations of Frank E. Seagrave *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 7, 2011

Abstract I will discuss the relationship between Frank Evans Seagrave (1860–1934) of Providence, Rhode Island, and the Harvard College Observatory, and analyze the modest contribution Seagrave made to our database between 1895 and 1913, relating a few anecdotes from his life as a self-taught astronomer whose relationship with Dr. Pickering ended in controversy, but whose legacy is carried on by Skyscrapers Inc., the astronomical society which now owns and operates Seagrave Observatory in North Scituate, Rhode Island.

Apollo 14 Road Trip *(Poster abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract In January-February 1971, five astronomy enthusiasts, Dennis Milon, Alan Rowher, Sal LaRiccia, Mike Mattei, and Paul Valleli, drove from New Haven, Connecticut, to the Kennedy Space Center at Cape Canaveral, Florida. They joined with ALPO Jupiter Recorder Julius Benton in Atlanta.

After several stops along the way, the six arrived at the Apollo 14 launch site to observe pre-launch activity, met NASA personnel, and toured various facilities. On launch day, thanks to press passes provided by Dennis Milon who was there as the official photojournalist for *Sky & Telescope*, they met the Apollo crew and witnessed the launch. On the return trip, they made time to meet Mike Mattei's new girlfriend, Janet Akyüz, who was working on her Master's at Leander-McCormick Observatory in Charlottesville, Virginia. Janet gave the six men a tour of the observatory, including the the 26-inch Clark Telescope.

Scientific session papers presented at the 100th Spring Meeting of the AAVSO, in conjunction with the 218th Meeting of the American Astronomical Society

Introduction to the Joint AAS-AAVSO Scientific Paper Sessions

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Preparations for the joint AAS-AAVSO meeting (May 2011) were well underway in 2010 when I began planning the joint sessions that would bring the AAS and AAVSO together. As someone with roots in both organizations, I wanted to plan science sessions that would bring the Amateur and Professional researchers and observers into the same room and provide an opportunity for each to learn about new science and new initiatives by the other. I worked closely with AAS Vice Presidents Lee Anne Willson and Christine Jones-Forman to schedule a day's worth of sessions that would interest both of our communities. We settled on two special sessions that would highlight both the field of amateur observing and the astrophysics that we hope to gain from studying variable stars.

On the observing side, we chose "Astrophysics with Small Telescopes" to give a forum to researchers using small telescopes to do big things. There are two parallel trends operating in research astronomy today. On one hand, astronomical researchers face smaller budgets and more competitive access to astronomical facilities, and those professional facilities that exist increasingly consist of very large telescopes not necessarily appropriate for doing astrophysics on bright variables. On the other hand, we are seeing increasingly sophisticated detectors and telescopes of high quality but low cost available through the consumer market. Given the technology that's currently available, the number of projects available to researchers with modest equipment is growing rapidly, and we wanted to highlight some recent novel uses of small telescopes that have brought us new and valuable astronomical and astrophysical knowledge. Ultimately, the goal of the session was to highlight the fact that there remains a great deal of astrophysics left to be learned at brighter magnitude limits, exactly where the amateur observer community can make its greatest contributions to science.

AAVSO Director Arne Henden led the session with an overview of how observers with very modest telescopic resources can and do make observations of remarkable quality, opening new opportunities for astrophysical research. This was followed by a talk by Michael Simonsen, who led the AAVSO's "Z-CamPaign," a wholly-amateur effort to characterize a large number of candidate Z Camelopardalis variables, yielding light curves of superb quality along with some surprising astrophysical results, chief among them that many "Z Cam" stars are not Z Cam stars at all! Long-time Pro-Am leader Joseph Patterson then gave a review of the Center for Backyard Astrophysics research program on cataclysmic variables, which has not only produced great new astrophysics but also serves as a model for how Pro-Am collaborations among geographically distributed, dedicated researchers can work. Gaspar Bakos presented a talk on HATNet, a novel robotic observatory using small telescopes to search for transiting exoplanets. The fact that HATNet can produce such great science on exoplanets highlights the fact that small-telescope observers can and do make great contributions to this new field of stellar astrophysics, but HATNet also highlights a growing trend of using very small telescopes to survey bright nearby variables that are being left behind by ever-larger professional facilities. Robert Stencel provided a review of the recent multi-year campaign on ε Aurigae, with extensive participation in observations by the amateur community. Stencel highlighted the enormous contributions that the amateur community has made via the most recent and historic eclipses, as well as new tools—like digital photography and amateur spectroscopy—that provided novel astrophysical information about ε Aurigae's once-in-a-generation eclipse. To end the session, John Percy highlighted one of the AAVSO's greatest treasures—our long-term data archives. Data archives such as those held by the AAVSO and other amateur Variable Star Organizations provide astrophysicists with one of their only views of variable star behavior on long timescales. Such data archives are a rich mine of data for variable star researchers—amateur, professional, and student alike.

For the afternoon session on astrophysics, we chose "Variable Stars in the Imaging Era" as the unifying theme. We are moving forward into a new era where we see stars not as astrophysical point sources but as resolved objects with detectable structure using technology like optical interferometers and space-based observatories operating at all wavelengths of the electromagnetic spectrum. Variable stars are of particular interest in this field because we can then gain deeper understanding by coupling knowledge of their spatial structure with knowledge gained from studying their variability. By combining the new information from imaging with additional photometry by the amateur community, we can improve our understanding the underlying astrophysics.

Margarita Karovska led the session with a discussion of direct imaging of stars and systems with space-based telescopes like the Hubble Space Telescope and Chandra X-ray observatory, and how these observations expand our understanding of stars and stellar systems across the Hertzsprung-Russell diagram. This was followed by a talk by Thomas Barnes on the use of interferometric measurement of Cepheid diameters as an important direct check on the Cepheid distance measure calibration so critical in modern cosmology. Brian Kloppenborg presented a talk on the use of interferometric imaging in the optical and infrared, and how such measurements complement photometric measurements obtained by more traditional variable star observation. We note especially that Brian was a member of the team that made interferometric observations of the ε Aurigae system that proved so strikingly the eclipse of the primary star by a large disk around the secondary. Angela Speck gave a talk on the critically important role that stars play in the evolution of the interstellar medium. She highlighted recent results on mass loss from AGB stars and the properties of interstellar medium surrounding them, gained from observations with new and greatly-improved infrared instrumentation on the ground and in space. Finally, Sam Ragland ended the session with a talk on how optical and near-infrared interferometry are allowing us to probe structure in AGB star atmospheres. Ragland and collaborators have made a number of fascinating discoveries in recent years, including the remarkable one that most if not all Miras show asymmetries suggestive of large-scale photometric variations in their photospheres. New techniques in imaging these stars will provide new insight in this important phase of stellar evolution.

I hope that attendees took at least two things away from these sessions beyond the specific projects outlined here. First, there is an enormous amount of astrophysics left to be learned “at the bright end.” While the technological capabilities of astrophysics continue to expand, there remains a great deal of extraordinary science to be done with “ordinary” instrumentation that is within the means of a far larger pool of researchers than major research facilities can serve. Second, the professional and amateur research communities can and do complement one another in the modern era, just as they always have. Fundamentally the amateur community continues to provide support to the professional research community by providing things like long-term observations of variable stars. However, what has changed more recently is the capability of the amateur community to innovate and become more directly involved in specific research projects, either in collaboration with individual professionals or through novel research programs of their own. There remains a great deal of room for observers at all levels—from casual amateurs enjoying an evening outside under the stars to dedicated amateur researchers pursuing their own astrophysical questions—to contribute to variable star astrophysics in the modern era. The community of variable star astronomers remains a diverse and thriving one.

I would like to extend my thanks to all of the speakers who were willing to contribute to these sessions and present their work and ideas to a diverse audience. I would also like to thank the two people who assisted with the planning and scheduling of these sessions, Dr. Lee Anne Willson of Iowa State University, and Dr. Christine Jones-Forman of the Harvard-Smithsonian Center for Astrophysics. I am greatly indebted to all of you.

ASTROPHYSICS WITH SMALL TELESCOPES

Long-Term Visual Light Curves and the Role of Visual Observations in Modern Astrophysics

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Abstract Thanks to organizations such as the AAVSO, visual observations of variable stars have scientific strengths: they are numerous, sustained, and standardized. Though many people have predicted the demise of visual observation, the demand for such observations increased dramatically in the last quarter of the 20th century. In addition to their value in detecting, timing, and studying outbursts in CVs, fadings in R CrB stars, and eclipses in binaries, they are uniquely useful in studying the behavior of pulsating stars, especially slow, irregular, and long-term behavior, and changes in period and amplitude. In this review, I give a general review of this topic, with some emphasis on my own work on pulsating red and yellow variables, and on T Tauri stars. Much of this work has been done by undergraduate students and outstanding high school students; I highlight the importance and potential of AAVSO visual data for educational use.

1. Introduction

AAVSO observers have accumulated over 13.7 million visual measurements of variable stars in the last 100 years. Indeed, earlier visual and photographic measurements are now being digitized, so that the AAVSO International Database (AID) is being extended *backward* as well as forward. The AID is a unique resource for studying the long-term behavior of variable stars. For many stars, observations are made on an almost daily basis, often by multiple observers, so the datasets are often also dense and continuous.

Furthermore: the AAVSO has endeavored to maintain uniform sequences and magnitudes of comparison stars over time, so the measurements are stable over time. From time to time, however, the AAVSO and other variable star observing groups have noted that their comparison star sequences and magnitudes differed. Also: photoelectric V magnitudes are now available for most comparison stars. In the first decade of the 21st century, the AAVSO embarked on a massive project to create the best possible set of charts and comparison star sequences, and make them available on-line.

2. Long-term visual light curves

For stars in the AID for which the datasets are long and dense, the light curve shows the behavior of the star on time scales from days to decades. This is important for classifying the star, and for noting novel or unusual behavior, as well as for discovering and studying long-term variability which would not be evident in shorter datasets. I remember when the AID first became digitized, and it was possible to plot long term light curves of variable stars. I was especially interested in yellow supergiants at the time, and was excited to see the long term light curve of the RV Tauri star U Mon. It was known to have a long secondary period of about 2,500 days; hence it is classified as an RVB star. The AID light curve clearly showed multiple minima, separated by 2,500 days, which were reminiscent of an eclipsing binary. It is now generally accepted that most/all RVB stars are binaries containing a dust ring or torus which periodically eclipses the star (e.g. Van Winckel *et al.* 1999).

Individual visual observations, from an ensemble of observers, have an average typical accuracy of 0.25 magnitude, as determined by self-correlation analysis (e.g. Percy and Terziev 2011 and many other similar studies). An individual experienced observer, with a good chart and sequence, can probably achieve better than 0.1 magnitude accuracy if the sequence is given to hundredths of a magnitude, and if they are not rounding to the nearest tenth of a magnitude; a group of observers using the same chart and equipment, and under the same sky conditions, is also probably good to 0.1 magnitude (Templeton 2011a).

If the observations are sufficiently dense, and if the time scale of the variability is sufficiently long, then the observations can be binned in, for example, 30-day means whose accuracy is much higher—sometimes approaching photoelectric accuracy. This approach has been used to delineate the variability of stars such as ρ Cas, with a period of about a year and a small amplitude (Percy *et al.* 1985).

3. Timing semi-predictable minima and maxima

The AAVSO has a long history of timing the minima of eclipsing variables, and the maxima of RR Lyrae stars. In these cases, the stars are sufficiently periodic to predict the *approximate* time of minimum or maximum. The observer monitors the star for a short interval around the predicted time, and is more-or-less assured of being rewarded. The precise time can be determined from the observations, using Hertzsprung’s method or the tracing-paper method.

Of course: if the time was *perfectly* predictable, there would be no need to observe the star, but both types of stars show period changes. Also, the observations can be used to refine the value of the period, even if the period is constant.

In eclipsing variables, period changes are generally due to mass transfer or loss in the system. Uniform mass loss causes O–C (observed minus predicted or calculated time of minimum) to vary parabolically with time. Stars with non-parabolic (O–C) behavior are of special interest, since the cause of the period change is less obvious.

In RR Lyrae stars, the period changes are generally due to evolution. The slow evolutionary expansion or contraction of the star, if uniform, produces parabolic (O–C) behavior. However, the observed rates of period change seem to be greater than those predicted by evolutionary models and, in some stars, the behavior is distinctly non-parabolic (Smith 1995). Long term period changes in RRab stars (which are pulsating in the fundamental mode, and have maxima which are sharp and easy to measure) have recently been determined by Le Borgne *et al.* (2007). RRc stars, which are pulsating in the first overtone mode, and have maxima which are flatter and harder to measure, have been less well-studied. My students are currently working on some of these.

Visual timing of these minima and maxima is gradually being replaced by CCD observations, but the visual observations, stretching back for many decades, are essential for measuring rates of period change. The accuracy of these increases as the *square* of the length of the dataset.

Cepheid variables are arguably the most important pulsating variables, because of their use in distance determination, and because their period changes can be directly and effectively compared with evolutionary models. This work is almost exclusively done with photoelectric photometry; visual observations have played and probably will play a minor role (Turner 2012, this volume).

In Mira stars, the (O–C) behavior is dominated by the effects of random cycle-to-cycle period *fluctuations*, first studied by Eddington and Plakidis (1929). Such fluctuations are also found in RV Tauri stars, a few long period Cepheids, and at least one W Virginis star; see Turner *et al.* (2009) for a brief review.

In the 1980s, Petrusia Kowalsky, Janet Mattei, and I, with support from the J.P. Bickell Foundation, carried out a study of seventy-five years of visual data on almost 400 Mira stars. We measured the cycle-to-cycle period fluctuations; they typically averaged a few percent of a cycle (Percy and Colivas 1999). A very few stars showed large period changes which were due to rapid evolution; these have been studied in more detail by Templeton *et al.* (2005). Beneath these random changes, however, we were able to detect the slow evolution of the ensemble of stars, at least at the 2σ level (Percy and Au 1999).

Professional astronomers often need to know the visual brightness or phase of a variable star at the time when they make observations using other techniques or at other wavelengths. If the star is strictly periodic, this is straightforward. If the star is irregular, it is not, but AAVSO monitoring can help. As one example: the European Space Agency *Hipparcos* mission observed Mira stars in order to measure their parallax, but the magnitudes of the stars, when observed, had to be optimal. AAVSO observers monitored a large sample of target Mira stars continuously, providing the *Hipparcos* team with the necessary magnitude data (Menessier *et al.* 1992).

4. Observing unpredictable maxima and minima

One of the most important contributions of AAVSO visual observers to modern astrophysics has been in monitoring and reporting outbursts in dwarf novae, recurrent novae, and novae. These result from mass transfer in a close binary system consisting of a normal star and a white dwarf or neutron star. When an outburst occurs, astronomers can quickly mobilize ground-based and space telescopes to study the outburst and its mechanism. AAVSO observers also monitor the visual variability of the star during outburst, for comparison with other data. This work is so important and interesting that there is a separate paper on it in this volume, by Paula Szkody.

Unpredictable *minima* occur in R Coronae Borealis stars—hydrogen-deficient, carbon-rich stars which occasionally eject a cloud of sooty dust which obscures and dims the star. These are rare objects; only a few dozen are known in the Milky Way and nearby galaxies. AAVSO observers monitor these and, when a fading begins, notify professional astronomers who can use a variety of techniques and facilities to study the progress and nature of the fading.

The times of onset of the fadings serve another purpose: it has gradually been realized (Crause *et al.* 2007) that, in many or most of these stars, the onset of fading is "locked" to a pulsation period in the star. This implies that the ejection of the cloud may be caused by the pulsation. The times therefore contribute to our understanding of the *cause* of the R CrB phenomenon. In a few stars (notably RY Sgr: Figure 1), the pulsation is large enough to be studied using visual observations; one of my students is currently studying the long term systematics of the pulsation in this star.

5. Period analysis of variable stars

For decades, the AAVSO's "bread and butter" was observing Mira stars. These are large-amplitude pulsating red giants. From this came periods and amplitudes in hundreds of Mira stars. Both the periods and amplitudes are notoriously variable, and the importance of studying these variations has only recently been appreciated.

For periodic variables, *time-series analysis* (Templeton 2004) provides information about the periods and amplitudes, and their changes. Fourier analysis of visual observations of semiregular (SR) pulsating red giants (Kiss *et al.* 1999) reveals multiple periods, representing multiple pulsation modes, and also "long secondary periods" (LSPs) whose nature and cause is still not understood. Wavelet analysis of AAVSO Mira star data reveals a small fraction of stars whose periods are changing due to the rapid evolution of the star (Templeton *et al.* 2005; Templeton 2011b).

Smaller-amplitude pulsating red giants are normally observed photoelectrically; indeed, most of the stars on the AAVSO Photoelectric

Photometry (PEP) program are stars of this type. Visual observations of these stars can, however, yield pulsation periods and LSPs (Percy *et al.* 1993), as long as the periods are reasonably coherent and the dataset is sufficiently dense and long.

One of the best examples of the power of visual observations is the study by Kiss *et al.* (2006) of pulsating red supergiants. They studied forty-eight SRc and Lc stars, using visual observations from the AID. The mean time-span of the data was sixty-one years. They found pulsation periods, typically hundreds of days in length, in most of the stars. Eighteen stars showed multiple pulsation periods. In some of these cases, there was a long secondary period, similar to the LSPs found in about a third of pulsating red giants. From the Lorentzian shape of the individual power spectra, they deduced the presence of period "noise," which they ascribe to interplay between pulsation and convection. Thus in this study, visual observations revealed fundamental properties of the stars (pulsation periods), an astrophysical mystery (LSPs), and clues to the physical processes (convection) going on in the stars. There may be useful astrophysical information in the detailed power spectra of other kinds of stars in long term datasets in the AID.

An interesting case, from my own research, involved T Tauri stars—sunlike stars in the process of formation. They vary, usually irregularly, on many time scales, mostly due to variations in the rate of accretion of gas onto the star. But the stars are also rapidly rotating, and have non-uniform surfaces, so may also be rotating variables with coherent periods of a few days, which are their rotation periods.

Back in the 1970s, some AAVSO visual observers began observing these stars. They tend to occur in specific star-forming regions, so they can be observed very efficiently. The observers were able to make many thousand observations of them each year, and thus rank high on the annual lists of top observers. Finally, Director Janet Mattei declared that visual observations of T Tauri stars would be devalued by a factor of ten in the annual observer totals. The observations languished, unvalidated.

I was able to convince AAVSO staff to validate the observations of a few well-observed stars, as a pilot project, and my student Rohan Palaniappan (a high school student at the time) analyzed them (Percy and Palaniappan 2006). Using Fourier analysis, he was able to detect and measure the rotational periods with amplitudes of only about 0.03 mag in the visual data!

6. Irregularity

A large fraction of all stars in the AID are classified as irregular, often because there are insufficient observations to characterize the behavior of the star more fully. As one example: RV Tauri stars are defined as pulsating yellow supergiants showing alternating deep and shallow minima; SRd stars are irregular pulsating yellow supergiants. Detailed analysis of AAVSO visual observations of these stars shows that there is a smooth continuum of behavior from RV Tauri to SRd. There is even a link to W Virginis stars, in that some of these show a slight alternation between deep and shallow minima.

As mentioned above: many of the semiregular pulsating red giants (SR stars) are multiperiodic. My students and I have just completed a study of visual observations of several dozen red giants in the AID which have 250 or more observations, and which are classified as *irregular* (L type stars) (Percy and Terziev 2011). Their amplitudes are a few tenths of a mag in only a few stars; many/most are microvariable; quite a few are or probably are non-variable. A very few have a detectable period. Most of these stars are candidates for photoelectric observations, but the scientific value of such observations is not clear.

In pulsating yellow supergiants such as RV Tauri and SRd stars, there is strong evidence that the irregularity is a consequence of dynamical chaos. The same physical principles which produce coherent pulsation in dense, compact stars produce irregular pulsation in more distended stars. Theoretical studies have been made by Toshiki Aikawa, Robert Buchler, Zoltan Kollath, Geza Kovacs, Pawel Moskalik, Mine Takeuti, and their colleagues, and compared with long term AID light curves of Miras, RV Tauri, and SRd stars.

7. Other applications of visual observations

There are many other applications of visual observations, some of which are described elsewhere in this volume:

- Visual discovery and study of supernovae: observers such as Robert Evans in Australia have discovered dozens of supernovae in relatively nearby galaxies; these are very useful for calibrating supernovae as “standard candles” for cosmological purposes.

- Monitoring hypergiants such as P Cygni and ρ Cas for outbursts or other unusual behavior.

- Visual monitoring of T Tauri stars for slow, long term variations which are usually due to variations in their rate of mass accretion.

- Visual monitoring of symbiotic stars—close binaries with a cool giant component and a hot normal or compact star: these undergo eruptions, eclipses, and, in some cases, pulsation.

- Although visual observation of small-amplitude variables is not usually recommended, there are a few observers who, given the right star and the right circumstances, can achieve a visual accuracy of a few hundredths of a magnitude. A notable example is the study by Otero (2011) of the Be star δ Sco.

8. Educational considerations

The AID is a wonderful treasure chest of publicly-available scientific data which can be used by high school and university students to develop and integrate their science, math, and computing skills. Some of the data have never been fully analyzed; by analyzing these data, students can be motivated by the thrill of doing real science research. I have co-authored dozens of papers and presentations with undergraduate research students, and with outstanding senior high school students in the University of Toronto Mentorship Program (Percy *et al.* 2008). This educational potential was recognized early on by me and the late Janet Mattei; it led to the AAVSO's *Hands-On Astrophysics* (Mattei *et al.* 1996) which has evolved into *Variable Star Astronomy* (www.aavso.org/education/vsa).

Students can also observe bright stars (such as Mira and δ Cep) visually, just as the first variable star astronomers did centuries ago. In the case of δ Cep, they can tie their observations of the time of maximum brightness with those of John Goodricke and Edward Pigott in the 18th century, and actually detect the evolution of this star. There is great interest, among historians of science, in re-creating the key observations and experiments in the history of science.

9. Final reflections

Are visual observations obsolete? This is a question which has been asked for over three decades. In the first twenty-five years of "the space age" (the last twenty-five years of the 20th century), however, the demand for visual observations *increased* by a factor of 25, due to the rise of high-energy astrophysics (Szkody 2012, this volume). In 2011, the question is driven by the fact that visual observations now represent a small fraction of all the observations submitted to the AID, and by the impending advent of massive nightly robotic surveys of the sky. A slightly different driver is the fact that so many long-time visual observers are retiring, but this factor is more related to the "greying" of amateur astronomy; we must recruit more younger people to amateur astronomy, and variable star observing. And we must recruit both men and women, of all races and backgrounds. The popularity of projects such as *Galaxy Zoo* suggests that there are many thousands of untapped "citizen astronomers" out there.

My personal view is that visual observations can still play an important role, but it would help if the AAVSO provided stronger guidance, and if observers were willing to take it. Observers need a certain amount of flexibility and freedom, but they probably don't want to think that their observations are of little scientific value. Through a combination of training, motivation, and feedback, we can provide observers with the assurance that their observations are continuing to contribute to science.

Users of AAVSO data, such as myself, have a responsibility here; that's why my students and I like to use AAVSO data and to present our results at AAVSO meetings, and publish them in *The Journal of the AAVSO*. The newly-formed observing sections can also play a role in guiding the observing programs so that they are maximally effective. Formal reviews of the AAVSO observing programs, by either internal or external reviewers, could be carried out every few years. Those of us with research grants have our observing plans reviewed every time we apply to renew our grants!

Even if robotic sky surveys were to provide complete coverage of the sky currently performed by visual observers alone, existing and future visual observations (and the backward extension mentioned in the first paragraph) would continue to be useful because, for many purposes, the usefulness of a light curve increases with its length. It would therefore be important to be able to "match" the visual data to data from these surveys.

I would like to think that visual observations of variable stars will continue to be useful for decades to come—if only because there is a special joy in having the human eye and brain come in direct contact with the cosmos.

10. Acknowledgements

I thank the AAVSO observers and staff for providing, validating, and archiving millions of visual observations for the benefit of science and education. I also thank Dr. Matthew Templeton for his comments on this paper. Special thanks to the late Janet Mattei, my long-time colleague, friend, and guide to AAVSO data. I thank my students for their inspiration, talent, and hard work. Finally, I thank the Natural Sciences and Engineering Research Council of Canada for research support, and the Ontario Work-Study Program and the University of Toronto Mentorship Program for facilitating the involvement of my students.

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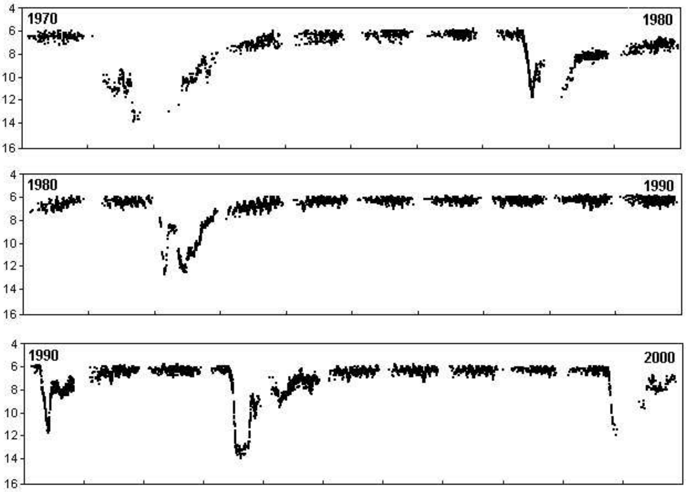

Figure 1. AAVSO thirty-year visual light curve of the R CrB star RY Sgr. The fadings, and their onsets, are clearly visible. The small-amplitude 40-day pulsational variability is also visible as a "sawtooth" when the star is at maximum.

Contributions by Citizen Scientists to Astronomy *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract The AAVSO's experience in utilizing the skills, equipment, and enthusiasm of amateur astronomers towards its research is not unique in astronomy. Citizen Scientists have contributed to our understanding of asteroids, exo-planets, solar system weather, light echoes, and galactic streaming, as well as inventing new equipment and software. This talk will highlight some of the recent advances by Citizen Scientists, and suggest some areas where they can contribute in the future.

Lessons Learned During the Recent ε Aurigae Eclipse Observing Campaign *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract The eighteen-month-long eclipse of the third-magnitude star, ε Aurigae, is forecast to end during May 2011, based on six eclipse events, in 2010, 1982, 1955, 1930, 1902, and 1874. In partnership with AAVSO, Hopkins Phoenix Observatory, and others, we have organized observing campaigns during the past several years in order to maximize data acquired during this rare event and to promote reporting and analysis of observations of all kinds. Hundreds of registered participants have signed up for alert notices and newsletters, and many dozens of observers have contributed photometry, spectra, and ideas to the ongoing effort—see websites: www.CitizenSky.org and www.hposoft.com/Campaign09.html. In this presentation, I will provide an update on the participation leading to extensive photometric results. Similarly, bright star spectroscopy has greatly benefited from small telescope plus spectrometer capabilities, now widely available, that complement traditional but less-frequent large telescope high dispersion work. Polarimetry provided key insights during the last eclipse, and we promoted the need for new data using this method. Finally, interferometry has come of age since the last eclipse, leading to the direct detection of the transiting dark disk causing the eclipse. Along with these traditional measurements, I will outline campaign-related efforts to promote Citizen Science opportunities among the public. Support for

these efforts derives in part from AAVSO/NSF-Informal Science Education, NSF AAG grant 10-16678, and a bequest to the University of Denver Astronomy Program by alumnus William Herschel Womble, for which I am grateful.

Ed. note: a more complete version of this paper will appear in the forthcoming epsilon Aurigae special issue, part of JAAVSO *Vol. 40, No. 2.*

Cataclysmic Variables in the Backyard *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract The last decade has seen plummeting prices and significant advances in CCD-camera and smart-telescope technology, reaching all the way to the humblest of telescopes. There are now thousands of well-equipped amateur astronomers interested in using their telescopes for research, and many hundreds already doing so in coordinated campaigns. Variable star science has benefited tremendously. Since it's always dark and always clear somewhere, coordinated photometry can accumulate nearly 24-hour coverage—and since the observers own their telescopes, very long campaigns are feasible, with little worry about weather. I'll describe one network of observers, the Center for Backyard Astrophysics (CBA). The telescope apertures are 20–50 cm, enabling good signal-to-noise and time resolution down to V=18. We organize campaigns of time-series photometry of cataclysmic variables (novae, dwarf novae, magnetic variables, some X-ray binaries)—and routinely achieve thousand-hour campaigns with no significant aliasing, since the telescopes are distributed around the world. This enables sensitive searches for periodic signals, extending even to long time scales (months). We now produce most of the world's supply of accretion-disk precession periods, and keep close watch on all the other clocks in cataclysmic variables (orbit, white-dwarf rotation and pulsation, and quasiperiodic oscillations).

Planet Hunting With HATNet and HATSouth *(Abstract)*

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Abstract Transiting exoplanets (TEPs), especially those found around bright stars, are particularly important as they provide unique opportunities to study the physical properties of planetary mass objects. The Hungarian-made Automated Telescope Network (HATNet) project—one of the small telescope surveys—has been extremely successful in the field of TEPs, contributing twenty-seven published discoveries, and one independent discovery of a previously published planet. Publications on several additional planetary systems are in preparation. I will discuss how HATNet operates around the globe, and how these fully automated small (11cm diameter) telescopes produce big science. I will also mention the related HATSouth project, now in full operation, and monitoring selected southern fields round-the-clock. Finally, I will conclude on how small and big telescopes collaborate in exoplanet science.

The Z CamPaign Early Results *(Abstract)*

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Abstract The Z CamPaign is an observing project designed to acquire enough detailed, long-term data to unambiguously classify dwarf novae as bona fide members of the Z Cam sub-type or not. Because the defining characteristic of all Z Cam dwarf novae are "standstills," a temporary period of relative quiet between maximum and minimum light, we are monitoring these systems for this specific activity. Amateur astronomers are gathering all the data with backyard telescopes as part of an AAVSO Cataclysmic Variable Section observing initiative. We will discuss the organization, science goals, and present early results of the Z CamPaign.

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VARIABLE STARS IN THE IMAGING ERA

Variable Stars and the Asymptotic Giant Branch: Stellar Pulsations, Dust Production, and Mass Loss

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Abstract Low- and intermediate-mass stars (1–8 $M_\odot$; LIMS) are very important contributors of material to the interstellar medium (ISM), and yet the mechanisms by which this matter is expelled remain a mystery. In this paper we discuss how interferometry plays a role in studying the interplay between pulsation, mass loss, dust formation and evolution of these LIMS.

1. Introduction

1.1. The importance of cosmic dust

At the beginning of the Universe, all matter was in the form of hydrogen and helium: all elements heavier than helium form via nuclear fusion in stars. Newly-formed elements are ejected from stars either explosively (in the case of supernovae) or more gently over a few hundred thousand years for lower-mass stars like the Sun. These new elements then become part of the interstellar medium (ISM), from which new stars and their planets form.

With the emergence of infrared (IR) astronomy in the late 1960s, the importance of dust particles in the Universe began to be revealed. Dust is a vital ingredient in many astrophysical environments (Videen and Kocifaj 2002; Draine 2003; Krishna Swamy 2005). It plays an essential role in star formation processes, and contributes to several aspects of interstellar processes such as gas heating and molecule formation (Krügel 2008). In addition, since mass loss from evolved stars is driven by radiation pressure on dust grains, it is intimately linked to the precise nature of the circumstellar dust (Woitke 2006). Furthermore, dust has been observed at higher redshifts than expected, and understanding this phenomenon is vital to our understanding of the cosmos at large and its evolution (Sloan *et al.* 2009; Bussmann *et al.* 2009). Moreover, the detection of dust at high redshift raises concerns about the use of standard candles (for example, Type Ia Supernovae) as accurate distance indicators (Jain and Ralston 2006). Understanding the dust at high redshift is vital to cosmological models and dark energy studies (Corasaniti 2006; Jain and Ralston 2006). Dust needs to be well understood in its own right, if we are to understand how it contributes to many aspects of astrophysics.

1.2. Low- and intermediate-mass stars (LIMS)

The type of stars that produce the majority of the dust complement for the Galaxy start their lives as low- and intermediate-mass stars (0.8–8$M_\odot$; LIMS). Up to 95% of stars are LIMS (Kwok 2004). Studying the nature of dust around LIMS is important for three reasons: (1) this is where the dust originates, and thus knowing its initial state will allow us to predict more accurately its fate in and effect on the ISM and beyond; (2) the environment around most of these LIMS is relatively benign (little UV) and thus has simplified chemistry, which aids in our attempts to understand the processes in play and test current hypotheses of dust formation (which are also applied to many, more complex astrophysical environments); and (3) the evolution of LIMS is intimately linked to their dust production, and thus a feedback loop exists between dust production and stellar evolution. The precise nature of the dust grains must be assessed in order to understand this evolution. Since LIMS are major contributors of new elements to the ISM from which the next generation of stars and planets form, understanding their contribution to the ISM is crucial to our understanding of Galactic and Universal chemical evolution. In fact, mass loss is the main reason that LIMS do not explode as supernovae. We cannot understand mass loss fully until we understand the physical nature of the dust. As will be discussed below, interferometric techniques can provide data on evolved LIMS that are essential to understanding dust formation.

2. Stellar evolution

LIMS eventually evolve off the main-sequence to the red giant branch and subsequently become asymptotic giant branch (AGB) stars, ending their lives as cooling white dwarfs. Between the AGB phase and the white dwarf phase some of these stars may become planetary nebulae (PNe) as the previous AGB mass loss is illuminated by the shrinking, heating central core. However, precisely which AGB stars go through the PNe phase is not clear (see, for example, Sahai *et al.* 2010, and references therein).

2.1. Asymptotic giant branch stars

As LIMS evolve they become asymptotic giant branch (Iben and Renzini 1983) stars: luminous ($L_\star \approx 10^4 L_\odot$), cool ($T_{\rm eff} \approx 3000$ K) giants ($R_\star \approx 1$ AU), which lose mass at high rates (10^{-7} to a few times $10^{-4} M_\odot$/yr). AGB stars pulsate due to dynamical instabilities, leading to intensive mass loss and the formation of a circumstellar shell of gas. Pulsations levitate atmospheric material, allowing it to achieve an altitude where temperatures permit molecules to form, followed by the formation of small particles (dust grains). The dust grains tap into the tremendous luminosity power of the star and drive a radiation-pressured wind (see, for example, Höfner and Dorfi 1997), leading to a circumstellar outflow of dust and gas. This outflow (wind) causes AGB stars to lose mass at such tremendous rates that they wither into white dwarfs rather than explode as supernovae. Generally, the mass-loss rate, $\dot{M}$, increases over time as an AGB star evolves, and ends in an episode of extremely high mass loss, the superwind (SW) phase (Iben and Renzini 1983; Bowen 1988; Bowen and Willson 1991; Blöcker and Schönberner 1991; Vassiliadis and Wood 1993; Willson 2000). During the SW phase $\dot{M}$ exceeds $10^{-5}\,M_{\odot}/yr^{-1}$. Continued AGB star mass loss causes the dust shell to increase in depth both optically and geometrically as mass-loss rate increases, shown schematically in Figure 1. As these stars approach the SW phase they become invisible at optical wavelengths and very IR-bright. During this SW stage, intense mass loss depletes the remaining hydrogen in the star's outer envelope, and terminates the AGB phase. The rapid depletion of material from the outer envelope of the star means that while AGB mass loss may last for > 10^5 yrs, this extremely high mass-loss SW phase must have a relatively short duration (a few × 10^4 years; Volk *et al.* 2000).

During their ascent of the AGB, these stars also evolve chemically, starting with oxygen-rich atmospheres. Helium burning forms ^{12}C, which is dredged up to the stellar surface by strong convection currents in the mantle. Thus, carbon is injected into the stellar atmosphere. The stability of the CO molecule in the stellar atmosphere means that the carbon-to-oxygen ratio (C/O) controls the chemistry around the star: whichever element is less abundant will be entirely locked into CO molecules, leaving the more abundant element to control dust formation. Therefore, AGB stars can be either oxygen-rich or carbon-rich. For the O-rich AGB stars C/O can vary from approximately cosmic $C/O \approx 0.4$) to just less than unity. Once C/O is greater than unity these stars become C-rich. Other nuclear processes (for example, the *s-process*) also occur in the He- and H-burning shells of AGB stars and thus other new elements are also dredged up and enrich the dust formation region. For a more detailed description of AGB stars we refer to Habing (1996) and Habing and Olofsson (2004).

2.2. Post-AGB stars

Once the AGB star has exhausted its outer envelope, the AGB phase ends. At this stage the mass loss virtually stops, and the circumstellar gas and dust shell begin to drift away from the star. At the same time, the central star begins to shrink and heat up from ~3000 K until it is hot enough to ionize the surrounding gas, at which point the object becomes a planetary nebula (PN). The short-lived post-AGB phase, as the star evolves toward to the PN phase, is also known as the proto- or pre-planetary nebula (PPN) phase. However, not all post-AGB stars will become PNe; for some post-AGB objects the expansion speed of the circumstellar shell, combined with its density, will preclude a visible nebula of ionized gas. (Indeed, the term pre-PN was adopted to replace proto-PN to reflect the idea that not all PPNe will end up as PNe.)

As the detached dust shell drifts away from the central star, the dust cools, causing a PPN to have cool IR colors. Meanwhile, the dust shell spreads out, becoming less dense and optically thinner, leading to changes in its spectral characteristics that may also be related to an evolution in the intrinsic nature of the dust grains (that is, composition, crystal structure, grain size, and grain shape, not just optical depth and temperature). This structural evolution of the dust shell is illustrated schematically in the upper panel of Figure 1. This post-AGB evolution of the circumstellar envelope changes its appearance, revealing features that were hidden during the AGB phase.

The geometry of the dust shell also changes. Whereas observations suggest that the AGB phase has mostly spherically-symmetric mass loss, there is clearly a deviation from spherical symmetry somewhere in the evolution of these stars and their mass loss, since PNe are rarely spherical. It has been suggested that mass loss can explain the structural changes alone (Dijkstra and Speck 2006). By studying the distribution of matter in these AGB and post-AGB circumstellar shells we can gain a better understanding of the mass-loss processes involved in the evolution of these stars and test hypotheses for the effect of dust. However, the observations needed require high angular resolution, and thus interferometric techniques are vital to these studies.

3. Astromineralogy

Astromineralogy is the study of the precise nature (that is, the composition, crystal structure, size, and shape) of dust grains in space. This field has developed rapidly over the last decade or so (see reviews in Speck *et al.* 1997; Speck 1998; Speck *et al.* 2000; Molster 2000; Waters and Molster 1999; Henning 2003; Kwok 2004; Pitman *et al.* 2010; Guha Niyogi *et al.* 2011a, and references therein).

The major factors that determine the astromineralogy of dust grains are the chemistry, density, and temperature of the gas from which the dust forms. The chemistry determines the type of atoms available to form dust particles, whereas the density determines how likely these atoms are to come into contact and make dust particles. The temperature determines which solid state materials will be stable. For AGB stars the chemistry and density of the dust-forming region are in turn determined by the nature of the central star, including its metallicity and its initial mass, and by the evolution of the star. Stellar changes may lead to a transformation in the nature of the dust that is produced, which may in turn influence stellar evolution, indicating a feedback relationship between the changes in the star and dust formation in its circumstellar envelope. For instance, if mass loss is radiation-driven, the opacity of the dust grains affects the force of the radiation and thus mass-loss rate. Opacity is determined by the astromineralogy of the dust grains. Therefore, the nature of the dust grains affects mass-loss rates (and changes therein) which, in turn, affects stellar evolution. Stellar evolution cannot be fully understood until we determine the nature of the dust in the circumstellar region.

Typically, astromineralogy is studied by means of IR spectroscopy; dust in a circumstellar envelope absorbs visible light from the central star and re-radiates it at IR wavelengths. Dust particles of a given size, shape, temperature, structure, and composition have their own signature IR spectra. We can thus use the IR spectra of candidate dust species studied in the laboratory to identify IR spectral features observed in astronomical environments. However, many astromineralogical studies have yielded contradictory results. For instance, a spectral feature at ~ 13µm has been attributed to a variety of minerals including corundum, spinel, and silica (see Sloan *et al.* 2003, and references therein) and its true identity remains a mystery. The shapes and positions of the spectral features have sometimes been used to make attributions without thorough consideration of the nature of the dust-forming environments in which they occur (see, for example, Zhang *et al.* 2008). There are other constraints or lines of evidence that can be used to aid our studies of dust in space, including spatial distributions of materials, theoretical models for dust formation and evidence from meteoritic studies of presolar grains (see section 4).

4. Dust Formation

4.1. Competing dust formation mechanisms

There are effectively three competing dust formation mechanisms for circumstellar environments: (i) thermodynamic equilibrium condensation (see, for example, Lodders and Fegley 1999); (ii) formation of chaotic solids in a supersaturated gas followed by annealing (see, for example, Stencel *et al.* 1990); (iii) formation of seed nuclei in a supersaturated gas, followed by mantle growth (see, for example, Gail and Sedlmayr 1999). The latter should follow thermodynamic equilibrium as long as density is high enough for gas-grain reactions to occur.

Several observational studies support the thermodynamic condensation sequence (see, for example, Dijkstra *et al.* 2005; Blommaert *et al.* 2007), which is consistent with both (i) and (iii). In mechanism (ii), chaotic grains form with the bulk composition of the gas, and then anneal if the temperature is high enough (Stencel *et al.* 1990). This mechanism predicts that at low C/O ratios, the dust grains would comprise a mixture of olivine, pyroxene, and silica, rather than be dominated by olivine alone. At high C/O ratios, Al-O bonds are predicted to form preferentially, leading to dust dominated by oxides rather than silicates. These predictions are inconsistent with observations (Dijkstra *et al.* 2005; Blommaert *et al.* 2007).

If we assume that dust formation follows either (i) or (iii) we expect to see a condensation sequence shown schematically in the left panel of Figure 2.

4.2. P-T space in the condensation zone around AGB stars

The composition of AGB star dust depends upon pressure and temperature

(P-T) in the dust-formation zone around the star. The precise astrominerals that can form depend on various parameters, most notably C/O ratio and gas pressure (Lodders and Fegley 1999; Gail and Sedlmayr 1999). Gas pressure is a measure of the mass-loss rate ($\dot{M}$) convolved with the photospheric temperature ($T_\star$) and outflow velocity (v_{exp}). Detailed calculations of the outflow structure (and its temporal variations) require the stellar temperature, radius, and luminosity. These can be provided using interferometric methods.

Applying the method from Speck *et al.* (2008, 2009) we can estimate the P–T space around a mass-losing star and compare with theoretical models for dust compositions forming under various P–T conditions. For a star with a mass-loss rate $\dot{M}$ and an expansion velocity of v_{exp}, the density ρ of the circumstellar shell at a radius r is given by:

$$\rho = \frac{\dot{M}}{4\pi r^2 \, v_{exp}} \tag{1}$$

If we know the temperature and luminosity of the star and the composition of the outflowing material we can combine this information with the Ideal Gas Law and a $T(r) \propto 1/\sqrt{r}$ temperature distribution to determine the gas pressure at the condensation radius, which is the distance from the star where the gas has the condensation temperature.

For simplicity, the solid and gas phases are assumed to be at the same temperature. While this is clearly a simplification (Chigai and Yamamoto 2003), the temperature difference is small compared to the difference needed to significantly affect dust formation. We assume that most of the outflowing material is atomic hydrogen. In fact it will probably be a mixture of atomic and molecular hydrogen (H_2) since H_2 forms around 2000 K and the temperature in the outflow is decreasing from the stellar surface temperature of ~3000 K to the dust condensation temperature in the 1000–1800 K range. An entirely molecular hydrogen gas would halve the gas pressure compared to the the atomic gas. However, we also assume an outflow velocity of 10 km/s, which reflects the speed of the outflowing material after radiation pressure acceleration. Adopting the pre-dust-formation outflow speed ($\lesssim$5km/s) would increase the pressure. Thus we can estimate where dust condensation zones fall in P–T space as a function of mass-loss rate, as shown in Figure 3. For C-rich environments we expect to form carbon before SiC in most cases, but the order is sensitve to mass-loss rate, C/O ratio, and metallicity (Speck *et al.* 2006). For O-rich environments, the condensation sequence is essentially the classic condensation sequence and is similar to that shown schematically in the left panel of Figure 2.

4.3. Presolar grains

The isotopic compositions of certain grains found in primitive meteorites indicate that they originated outside the solar system and are thus dubbed "presolar". The majority (~99%) of the "presolar" dust grains emanated from AGB stars based on their isotopic compositions and the nuclear processes expected to occur in those stars. Presolar grains demonstrate that the AGB dust grains become part of the next generation of stars and planets (Clayton and Nittler 2004, and references therein). This also means that we have real samples of the circumstellar dust that we can observe spectroscopically around evolved stars. The precise physical characteristics of these meteoritic dust grains (for example, sizes, crystal structures, and compositions) can be used to help constrain the nature of the dust we see in our astronomical observations.

Silicon carbide was the first presolar grain to be found in meteorites (Bernatowicz *et al.* 1987) and remains the best studied (see Bernatowicz *et al.* 2006, and reference therein). Other carbon-rich grains, such as graphitic onions and seed-core grains of various refractory carbides, have also been well studied (see Bernatowicz *et al.* 2006, and reference therein). Presolar examples of refractory oxides, spinel and alumina, have been found in meteorites. Detailed studies of the nature of these grains (especially crystal structure) are in their infancy, but can be used to constrain candidates for the 13µm feature. For example, Stroud *et al.* (2004) have analyzed the crystal structure of two presolar alumina grains and found that one is indeed a crystalline form (corundum), while the other is amorphous. Many astronomical studies have falsely assumed that the use of the word "corundum" in the meteoritics literature refers to this particular crystal structure, when it actually refers only to the composition of the presolar grains.

Isolating the C-rich grains can be achieved chemically, whereas presolar silicates can not be separated chemically from their terrestrial/solar system brethren. However, *in situ* techniques have been developed which led to the discovery and analysis of presolar silicate grains. Recent work on these presolar silicate grains suggests that there is more iron in silicate grains around AGB stars than our current models allow (see, for example, Stroud *et al.* 2008; Bose *et al.* 2010).

5. Astronomical observations of AGB circumstellar dust

For carbon stars the dominant dust formed is amorphous or graphitic carbon which does not have diagnostic spectral features, merely contributing to the IR continuum. SiC exhibits a spectral feature at ~ 11.3µm which has been used extensively to diagnose the physical parameters of carbon star dust shells (see reviews in Speck *et al.* 2005, 2009; Thompson *et al.* 2006).

The spectra of O-rich AGB stars exhibit a diverse range of IR dust spectral features. The spectra of AGB stars are generally classified according to the gross shape of the silicate emission feature at ~10µm. Various attempts have been made to classify these mid-IR features according to their shapes and positions, which reflects a progression from a broad feature to the classic narrow 10µm silicate feature (see, for example, Little-Marenin *et al.* 1990; Sloan and Price 1995; Speck *et al.* 2000; Sloan *et al.* 2003; see Figure 4). This progression of the spectral features can be interpreted in terms of a dust condensation sequence (see, for example, Grossman 1972; Tielens 1990; shown schematically in Figure 2) and expected to represent evolution of the dust from the early forming refractory amorphous oxides to the dominance of amorphous silicates (the classic 10μm feature; see SE 8 in Figure 4).

The most recent version of this IR spectral classification scheme divides the observed AGB spectra into eight groups based on the silicate emission (SE) feature from SE1 to SE8 (Sloan and Price 1995; Sloan *et al.* 2003). Classes SE1–SE3 are expected to correspond to low-contrast alumina-rich amorphous dust seen in evolved stars losing mass at low rates and have optically thinner shells. Moving up the sequence, classes SE3–SE6 show structured silicate emission, with features at 10 and 11μm. The upper end of the silicate dust sequences (SE6–SE8) consist of sources with the classic silicate emission feature believed to be produced by amorphous silicate grains. These sources have optically thicker shells and higher mass-loss rates than sources at the other end of the sequence. However, recent findings (for example, Pitman *et al.* 2010; Guha Niyogi *et al.* 2011a) show the evidence for Fe-rich crystalline silicates on some of the stars from SE1 class (for example, T Cep, RX Lac, T Cet), which calls the classic dust condensation sequence into question. The new condensation sequence is shown schematically in the right panel of Figure 2. These empirical observational results cannot easily be reconciled with the classic conception of dust formation as shown in the left panel of Figure 2. In order to understand these new findings we need interferometry measurements of closeby AGB stars to provide stellar radii for input into models of dust formation. In particular the variations in dust formation as a result of stellar pulsation require precise information on how the stars change in radius, temperature, and luminosity with time.

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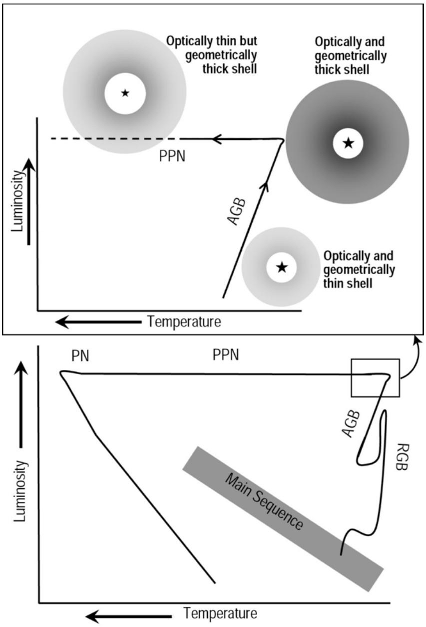

Figure 1. Schematic H-R diagram showing post-main-sequence evolution of LIMS. RGB = Red Giant Branch; AGB = Asymptotic Giant Branch; PPN = pre- or proto-planetary nebula; PN = planetary nebula; *upper panel* shows close up on AGB and PPNe phases and cartoons the changes in dust shell densities.

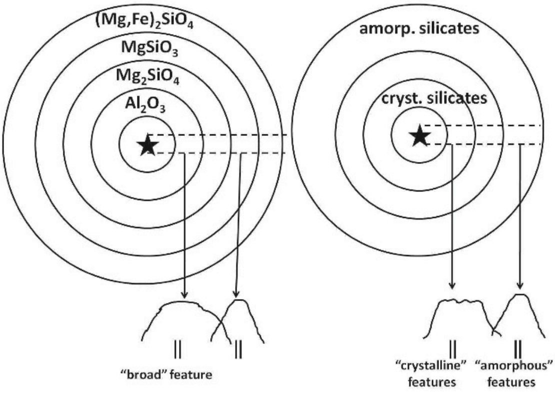

Figure 2. Schematic structure of dust shells. *Left*: Classic condensation sequence from, for example, Grossman (1972), Tielens (1990); see also thermodynamic equilibrium sequence in Figure 3; *Right*: New sequence suggested by the study of low mass-loss rate stars (for example, T Cep) as shown in Guha Niyogi *et al.* (2011a, 2011b) and Guha Niyogi (2011).

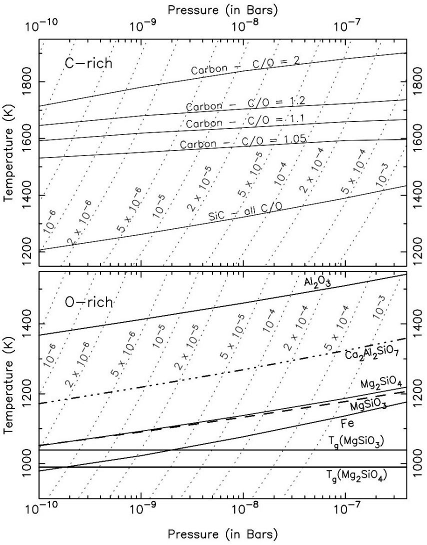

Figure 3. Pressure-temperature space in dust-condensation zone around AGB stars. *Top panel* is for C-rich stars; *bottom panel* is for O-rich stars. *x*-axis is outflow gas pressure in bars, *y*-axis is outflow gas temperature in Kelvin. Solid and dashed lines indicate T_{dust} for a given pressure from thermodynamic equilibrium calculations (relevant compositions are labeled; from Lodders and Fegley 1995, 1999). For all $\dot{M}$ values, Al_2O_3 forms at a significantly higher temperature than the silicates, and thus can form a seed nucleus. Light grey dotted lines indicate the P–T paths for the outflowing gas for a range of $\dot{M}$ (indicated in $M_\odot$/yr) as calculated from equation 1 and described in the text. Thick dark grey horizontal lines indicate glass transition temperatures (T_g) for Mg_2SiO_4 and $MgSiO_3$.

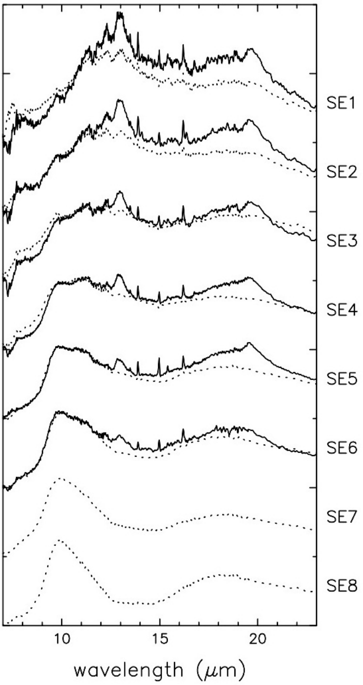

Figure 4. Continuum-subtracted ISO SWS spectra of O-rich AGB stars. Spectra are divided into classes according to the shape/strength of their silicate feature (designated by SE#, where # = 1 to 8; SE8 has the strongest classic silicate feature, SE1, the weakest). Solid lines: spectra which exhibit the 13μm feature. Dotted lines: spectra which do not exhibit a 13μm feature. From data presented in Sloan *et al.* (2003).

Interferometry and the Cepheid Distance Scale

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Abstract Systematic uncertainties in the Cepheid distance scale have been greatly reduced in recent years through stellar interferometric observations. Interferometry has made possible direct measurement of Cepheid distances through interferometric pulsation distances. These results compare very well with recent Hubble Space Telescope trigonometric distances. Interferometry has also demonstrated that infrared surface brightness distances are quite reliable, making possible direct comparison of Cepheid luminosities in the Galaxy and the Magellanic Clouds.

1. Introduction

This year is the centennial of Henrietta Leavitt's discovery of the period-luminosity relation for classical Cepheid variables (Leavitt and Pickering 1912). In honor of Leavitt's discovery, the Cepheid period-luminosity relation is now usually called the Leavitt Law. This year is a good time to see just how far we have come in calibration of the Leavitt Law in the preceding century.

Leavitt's discovery made use of Cepheids in the Small Magellanic Cloud, all of which are sensibly at the same distance from us. A plot of their apparent magnitudes versus log (P) thus demonstrates the Leavitt Law (Figure1). Within the Galaxy, Cepheids are not so conveniently located. We must combine many individual distances to Cepheids to establish the relation. It has proved to be a very difficult task to achieve the accuracy that we desire in the relation. New techniques have significantly improved the situation.

Much of the progress is based on trigonometric parallax measures made with the Hubble Space Telescope (HST; Benedict *et al.* 2007) and on pulsation distances made with stellar interferometers. In the following I discuss the interferometric distances and then compare them with HST parallaxes. A more extensive review has been given by Barnes (2009).

2. Cepheid distance measurements

There are four principal means for determining Cepheid distances: open cluster distances, infrared surface brightness distances, interferometric pulsation distances, and trigonometric parallax distances.

2.1. Open cluster distances

There are twenty-four Cepheids known to be members of Galactic open clusters and associations (Turner 2010). Using the cluster main sequence fitting method, we may determine a distance to each cluster and thus to the Cepheids within them. This is accomplished in a color-magnitude diagram by comparing the apparent magnitudes of stars on the main sequence of the cluster to the absolute magnitudes of main sequence stars in a cluster at a known distance. The displacement in magnitude is attributed to distance. A good example of this method in application is given by Turner (1986) for S Nor in the cluster NGC 6087. Ever since Cepheids were discovered in open clusters (Irwin 1955), this has been the preferred method for establishing the Cepheid distance scale.

Cluster distances are limited in precision by several effects. Open clusters lie in the Galactic plane and are usually affected by considerable interstellar reddening. Correcting for the reddening is difficult, and the difficulty is often compounded by changes in the reddening across the face of the cluster. A second effect comes from the varying metal abundances of open clusters. The main sequence location in the color-magnitude diagram can change with metal abundance, impacting the distance measurement. Finally, the number of Cepheids in open clusters is modest, which affects our ability to define the Leavitt Law well. The table in Turner (2010) shows that Cepheid distances based on open cluster distances have precisions in the range ±4–22%. Fouqué *et al.* (2007) have demonstrated that open cluster distances are fully consistent with distances from the infrared surface brightness technique and trigonometric parallaxes.

2.2. The Infrared Surface Brightness Technique

As a Cepheid variable pulsates, the photosphere expands and contracts relative to deeper layers of the star. The linear motion of the photosphere along the line of site to the Cepheid can be measured through the Doppler effect, that is, a radial velocity curve. An integration of the radial velocity curve, with appropriate correction for geometric and atmospheric effects, gives the linear distance that the surface moves over a pulsation cycle. The angular motion of the surface perpendicular to the line of site can be inferred from photometric measurements through a method called the surface brightness technique, introduced by Barnes and Evans (1976). The method was later improved by using infrared (VK) photometry (Welch 1994; Fouqué and Gieren 1997). The Infrared Surface Brightness Technique is an improvement upon the well-known Baade-Wesselink method for Cepheid radius determination.

By matching the angular distance traveled to the linear distance traveled, we can determine the distance through simple trigonometry. The beauty of the method is that it is applicable to any Cepheid for which radial velocities and infrared photometry may be measured. This puts Cepheids throughout the Local Group of galaxies within range of individual distance measurements.

The method was suspect early in its use for two reasons. First, the conversion of the photometric measurements into angular distances was thought to be subject to potential systematic errors. Second, the conversion of radial velocity into true pulsational motion could be subject to additional systematic errors. These concerns were finally put to rest. Kervella *et al.* (2004c) showed that angular diameters inferred from the infrared surface brightness technique were fully compatible with diameters found using interferometry. This resolved the photometric issue. Regarding the radial velocity correction, Barnes (2009) and Storm *et al.* (2011a) compared determinations of Cepheid distances using the infrared surface brightness technique, which depends on this correction, to trigonometric determinations, which do not, and found excellent agreement at the few percent level.

Storm *et al.* (2011a) applied the infrared surface brightness technique to 111 Cepheids in the Galaxy and the Magellanic Clouds. The mean precision in distance was better than ±5%, with a range of 2–16%.

2.3. Interferometric pulsation distances

For relatively bright Cepheids, stellar interferometers can now measure the angular diameter of the Cepheid directly as it pulsates. Once again, the angular distance traveled by the photosphere (from interferometry) is matched to the linear distance traveled (from integrated radial velocities). This method eliminates the photometric inference involved in the infrared surface brightness technique.

A new, potential uncertainty is introduced. The conversion of interferometric observations into angular diameters for Cepheids requires prior knowledge of the Cepheid limb darkening, which is obtained from theoretical models; there may be errors in those models although the uncertainty is expected to be small in the infrared. Any errors in conversion of the radial velocities to linear distances remain in this method.

There are eight Cepheids for which distances have been determined this way (Table 1). The most distant is *l* Car at 525 parsecs. This distance method produces distances precise to ±2–45%.

2.4. Trigonometric distances

Trigonometric parallaxes are the gold standard, geometric method for measuring distances. There are very few assumptions that enter into the method. However, Cepheids are distant and their parallaxes are small which has made determination of their distances by trigonometry very difficult. Recently the HST Fine Guidance Sensor was used to determine trigonometric distances to ten Cepheids (Benedict *et al.* 2007) as listed in Table 2. The most distant one is T Vul at 526 parsecs (coincidentally similar to the above distance to *l* Car). The precisions are ±4–14%.

3. Stellar interferometry

Stars are frustratingly small in angular size on the sky. The largest stellar disk (other than the Sun) is less than 0.06 arcsecond across. The largest Cepheid angular diameter is that for *l* Car which is twenty times smaller. The change in angular size due to its pulsation is five times smaller yet. (For a list of angular diameters of bright Cepheids, see Moskalik and Gorynya 2006.) Cepheid diameters are far below the capabilities of even the largest single telescopes to measure. It takes a special technique to measure such small angles.

It is impossible in this short paper to do justice to the principles of interferometry. For a summary see Hajian and Armstrong (2001). The basic concept of stellar interferometry is most easily understood using the wave nature of light. Consider two separate telescopes viewing the same star as shown in Figure 2. After correcting for the different distances of the two telescopes from the star, the wavetrains arriving at the two telescopes are interfered to form a "fringe pattern." As the telescopes are moved further apart, the fringe pattern changes in a manner that depends on the stellar angular diameter and the separation of the telescopes. This change is quantified in a parameter called the "visibility" as shown in Figure 3. If the star is a point source the visibility does not change with baseline. On the other hand, the larger the stellar angular diameter, the sharper the visibility pattern and thus the easier it is to measure the diameter. Adding additional telescopes to the system can improve the capabilities of the interferometer.

There are four stellar interferometers that have measured the change in angular diameter as the Cepheid goes through its pulsation cycle. The following list gives the name, citation for a description of the interferometer, the baseline used for the Cepheid observations, and the Cepheids for which measured angular diameter variations were obtained. Not all of these interferometers are still in operation.

1) Palomar Testbed Interferometer; three 0.4 m telescopes with a 110-m baseline (Colavita *et al.* 1999): η Aql (in 2002), ζ Gem (2002);

2) Very Large Telescope Interferometer; two 8-m telescopes with two 0.35-m siderostats with a 140-m baseline (Glindemann *et al.* 2000; Kervella *et al.* 2003): η Aql (2004), W Sgr (2004), β Dor (2004), *l* Car (2004);

3) Center for High Angular Resolution Astronomy; six 1-m telescopes up to a 313-m baseline (ten Brummelaar *et al.* 2003): δ Cep (2005), Y Oph (2007), Y Sgr (2007); and

4) Sydney University Stellar Interferometer; 0.14-m telescopes with a 40-m baseline (Davis *et al.* 1999): β Dor (2006), *l* Car (2009).

4. Interferometric pulsation distances

A good example of a Cepheid distance by interferometry is that for *l* Car (Davis *et al.* 2009) obtained with the Sydney University Stellar Interferometer. In Figure 4 Davis *et al.* (2009) show the radial velocity curve assembled from several sources. This velocity variation is integrated and corrected for projection and atmospheric effects to obtain a curve showing the movement of the atmosphere over the pulsation cycle (not shown here).

Figure 5 shows the angular diameters measured using SUSI (symbols in the figure). The mean angular diameter is 2.99 ± 0.01 mas. The amplitude of the variation is 0.56 mas with a typical uncertainty on each datum of ± 0.035 mas.

This measurement is equivalent to watching a 5.5-m ball on the surface of the moon vary in size by ± 50 cm and measuring the variation with a precision of ± 6 mm. It is a remarkable, technical achievement.

In Figure 6 Davis *et al.* show the measured angular diameters against the linear displacement at the same phase in the pulsation. The slope of the fit is inversely related to the distance and the zero point of the fit, to the mean angular diameter. They determined a distance of 525 ± 26 parsecs, the mean angular diameter quoted above, and a linear radius for the Cepheid of 169 ± 9 solar radii. The linear displacements are scaled to the distance and to the measured linear diameter to obtain the smooth curve in Figure 5. The curve fits the observed angular diameters well without any systematic deviations.

5. Discussion

Figure 7 demonstrates that interferometric pulsation distances determined for Cepheids are fully compatible with trigonometric distances. Unfortunately there are few additional Cepheids for which interferometry and trigonometry can provide new distances with current instruments. Thus the importance of the agreement between the two methods lies in the demonstration that a distance determined from the pulsation of a Cepheid is as accurate, and sometimes as precise, as a trigonometric distance.

Recall from the discussion of the infrared surface brightness method that it has been shown to give angular diameters in agreement with those from stellar interferometers. That result, combined with the excellent agreement between interferometric pulsation distances and trigonometric distances, gives us confidence that distances from the infrared surface brightness method are reliable. This has recently been demonstrated by Storm *et al.* (2011a, 2011b). They have determined distances to 111 Cepheids in the Galaxy, LMC and SMC using this method. The infrared K magnitude Leavitt Law they obtained is shown in Figure 8. The scatter about the relation is ± 0.22 magnitude.

I believe Henrietta Leavitt would be pleased.

6. Acknowledgements

The author thanks Dr. Hal McAlister for permission to use two of his figures, and Dr. Antoine Mérand for permission to quote an unpublished result. The author also thanks Dr. G. Fritz Benedict for his review of the draft of this paper.

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Table 1. Cepheids with interferometric pulsation parallaxes. Adapted from Fouqué *et al.* 2007.

Star	*Log P (days)*	*π (mas)*	*σ(π) (mas)*	*Distance (pc)*	*σ(d) (%)*	*Source*
δ Cep	0.72	3.52	0.10	284	2.8	Mérand *et al.* (2005)
Y Sgr	0.76	1.96	0.62	587	30.6	Mérand *et al.* (2012)
η Aql	0.85	3.31	0.05	302	1.5	Lane *et al.* (2002)
W Sgr	0.88	2.76	1.23	362	44.6	Kervella *et al.* (2004b)
β Dor	0.99	3.05	0.98	328	3.1	Kervella *et al.* (2004b), Davis *et al.* (2006)
ζ Gem	1.01	2.91	0.31	344	10.6	Lane *et al.* (2002)
Y Oph	1.23	2.16	0.08	463	3.7	Mérand *et al.* (2007)
l Car	1.55	1.90	0.07	525	4.9	Kervella *et al.* (2004a), Davis *et al.* (2009)

Table 2. Cepheids with trigonometric parallaxes from Benedict *et al.* 2007.

Star	*Log P (days)*	*π (mas)*	*σ(π) (mas)*	*Distance (pc)*	*σ(d) (%)*
RT Aur	0.57	2.40	0.19	417	7.9
T Vul	0.65	1.90	0.23	526	12.1
FF Aql	0.65	2.81	0.18	356	6.4
δ Cep	0.73	3.66	0.15	273	4.0
Y Sgr	0.76	2.13	0.29	469	13.6
X Sgr	0.85	3.00	0.18	333	6.0
W Sgr	0.88	2.28	0.20	438	8.8
β Dor	0.99	3.14	0.16	318	5.1
ζ Gem	1.01	2.78	0.18	360	6.5
l Car	1.55	2.01	0.20	497	9.9

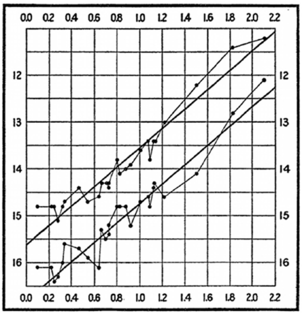

Figure 1. The first Cepheid period-luminosity relation as found in the Small Magellanic Cloud. Apparent magnitude at maximum light and at minimum light vs. log (period) for 25 variables. From Leavitt and Pickering (1912).

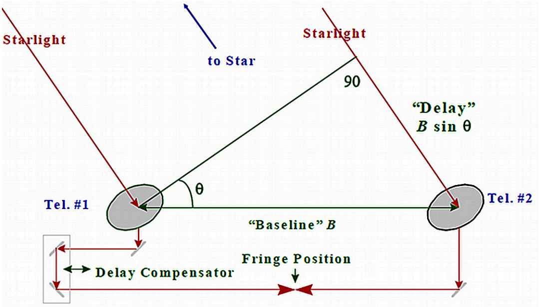

Figure 2. A simple interferometer. Figure courtesy of McAlister (2012).

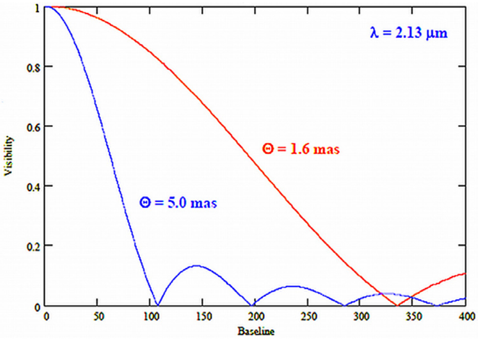

Figure 3. Examples of visibility curves for two different angular diameters. The separation of the telescopes (baseline) is given in meters. The units of angular diameter in the figure are milliarcseconds (mas). Courtesy of McAlister (2012).

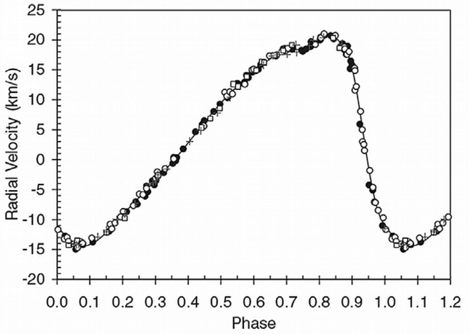

Figure 4. The radial velocity variation as a function of pulsation phase for the atmosphere of the Cepheid *l* Car. Courtesy of Davis *et al.* (2009).

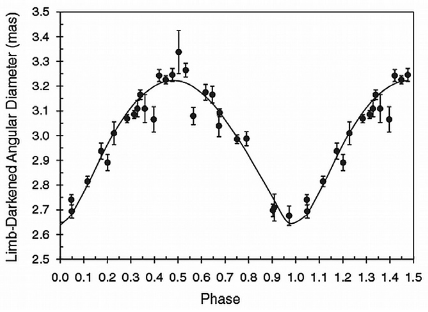

Figure 5. The observed angular diameter variation of *l* Car (symbols) and the linear displacement variation scaled to the measured distance (curve). Courtesy of Davis *et al.* (2009).

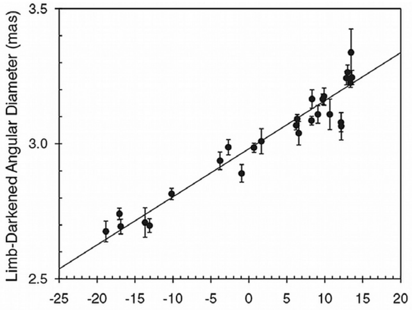

Figure 6. The fit of the angular diameter variation onto the linear variation for *l* Car. Courtesy of Davis *et al.* (2009).

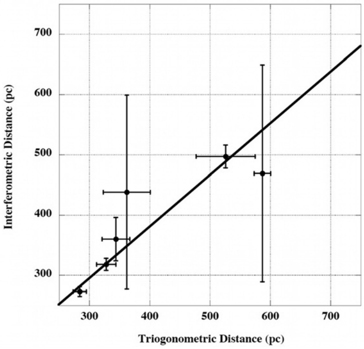

Figure 7. A comparison of interferometric pulsation distances to trigonometric distances for Cepheids. η Aql and Y Oph do not have trigonometric distances and are not plotted.

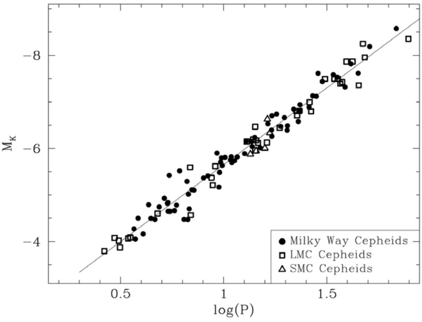

Figure 8. The Leavitt Law in the K magnitude based on Galactic, LMC, and SMC Cepheids. Courtesy of Storm *et al.* (2011a).

Imaging Variable Stars With HST *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract The Hubble Space Telescope (HST) observations of astronomical sources, ranging from objects in our solar system to objects in the early Universe, have revolutionized our knowledge of the Universe its origins and contents. I highlight results from HST observations of variable stars obtained during the past twenty or so years. Multiwavelength observations of numerous variable stars and stellar systems were obtained using the superb HST imaging capabilities and its unprecedented angular resolution, especially in the UV and optical. The HST provided the first detailed images probing the structure of variable stars including their atmospheres and circumstellar environments. AAVSO observations and light curves have been critical for scheduling of many of these observations and provided important information and context for understanding of the imaging results of many variable sources. I describe the scientific results from the imaging observations of variable stars including AGBs, Miras, Cepheids, semiregular variables (including supergiants and giants), YSOs and interacting stellar systems with a variable stellar components. These results have led to an unprecedented understanding of the spatial and temporal characteristics of these objects and their place in the stellar evolutionary chains, and in the larger context of the dynamic evolving Universe.

Probing Mira Atmospheres Using Optical Interferometric Techniques *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract Modern optical interferometric observations of Mira atmospheres are discussed. The earlier near-infrared closure-phase measurements of a sample of Asymptotic Giant Branch (AGB) stars and subsequent imaging observations of a handful of brighter ones show that asymmetry is common in the cool atmospheres of late-type stars. The potential of optical interferometric observations in conjunction with radio interferometric observations in studying the structure and kinematics of the envelope around Mira stars are highlighted.

We explore the use of other interferometric observables, such as, (1) null-leakage in the mid-infrared combined with near-infrared squared-visibilities in constraining the temperature structure of the extended atmosphere of Mira stars, and (2) differential phase in detecting asymmetry in the molecular and dusty shells of Mira stars.

Spots, Eclipses, and Pulsation: the Interplay of Photometry and Optical Interferometric Imaging *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract Present optical/IR interferometers like CHARA are not only capable of probing the environment surrounding stars, but also resolving surface details on the stars themselves. Because of this, interferometers can produce results on the classical topics of photometry: namely pulsation, eclipses, and star spots. In this talk I discuss these three common areas, and how interferometry and photometry can be used in conjunction to yield superior results.

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1) provided separate from the main body of the text;
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References:

1) References should relate directly to the text.
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3) In the case of three or more joint authors, the text reference should be written as follows: (Smith *et al.* 1976).
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   Brown, J., and Green, E. B. 1974, *Astrophys. J.*, **200**, 765.
   Thomas, K. 1982, *Phys. Report*, **33**, 96.
5) Abbreviations used in references should be based on recent issues of the Journal or the listing provided at the beginning of *Astronomy and Astrophysics Abstracts* (Springer-Verlag).

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2) Magnitude will be assumed to be visual unless otherwise specified.
3) Manuscripts may be submitted to referees for review without obligation of publication.

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100th Anniversary Edition

100th Spring Meeting of the AAVSO, in conjunction with the 218th Meeting of the American Astronomical Society, held in Boston, Massachusetts, May 21–25, 2011

100th Annual Meeting of the AAVSO, held in Cambridge and Woburn, Massachusetts, October 5–8, 2011

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Papers and posters presented at the general and scientific paper sessions of the Spring and Annual Meetings

Secular Variation of the Mode Amplitude-Ratio of the Double-Mode RR Lyrae Star NSVS 5222076, Part 2

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Presented at the 100th Spring Meeting of the AAVSO, May 21, 2011; received June 28, 2011; revised July 15, 2011; accepted July 15, 2011

Abstract We present results from our ongoing investigation of the double-mode RR Lyrae (RRd) star, NSVS 5222076, and specifically of the long-term temporal variation of the amplitude-ratio, A0/A1, of the star's fundamental and first-overtone pulsation modes. Our earlier paper on this subject (Hurdis and Krajci 2010) described a seemingly monotonic decrease of the amplitude-ratio in the *V* band, from 1.93 in 2005 to 1.76 in 2008 to 1.48 in 2009. After further observation of the star during the 2010 and 2011 observing seasons, we report that the *V*-band amplitude-ratio continued to decrease to 1.40 in 2010, but then increased to 1.82 in 2011. This suggests that, rather than decreasing monotonically toward a switch of dominant pulsation mode, A_0/A_1 may be varying in an oscillatory manner.

1. Introduction

The current paper is a continuation of our investigation of NSVS 5222076 (Hurdis and Krajci 2010), and in particular of the long-term temporal variation of the star's mode amplitude-ratio, A_0/A_1. Our equipment and methods remained the same as in the earlier study and the reader is referred to that paper for those details.

The earlier paper described a rapid, and seemingly monotonic, decrease of the amplitude-ratio in the *V* band, from 1.93 in 2005 to 1.76 in 2008 to 1.48 in 2009, and raised the possibility that NSVS 5222076 could be on the verge of switching its dominant pulsation mode from the fundamental to the first-overtone. It was noted that precedents for mode switching had been observed in the globular cluster M3, where four stars (V79, V166, V200, and V251) had been observed to switch their dominant pulsation modes (Corwin *et al.* 1999, Clementini *et al.* 2004, Clement and Thompson 2007). Among these, V79 has been the most changeable. Goranskij *et al.* (2010) have recently chronicled the history of its observed switches from fundamental mode pulsator to mixed-mode pulsator with dominant first-overtone, then returning to fundamental mode pulsation but with a Blazhko period of 65.4 days. V79 having revealed this menu of possible options for RR Lyrae behavior, it would seem important for observers to continue to monitor the variation of the mode amplitude-ratio of NSVS 5222076, a field star located well out of the Galactic plane in Bootes, and unimpeded by the crowded star field of a globular cluster.

In 2010 and 2011, all observations were made with the Wright28 telescope, under the aegis of the AAVSO robotic telescope network (AAVSOnet). In 2010, 919 *V*-band images and 913 *I*-band images were taken on ten nights, between JD 2455272 and JD 2455367. In 2011, 892 *V*-band images and 886 *I*-band images were taken on twelve nights, between JD 2455600 and JD 2455666.

As in the earlier study, two software packages were used to perform period analysis of the photometric data extracted from the images. These were PERANSO version 2.20 (Vanmunster 2005), and PERIOD04 (Lenz and Breger 2005). The mode amplitudes were derived from PERIOD04 by least-squares fit of the computed Fourier frequencies to the measured light curves.

2. Results

Among the five individual data sets from the five years that the star has been observed, the computed pulsation periods for NSVS 5222076 vary slightly, but in a random manner, i.e., not in a manner clearly attributable to coherent period change. These random variations may be related to the Blazhko-like modulations reported in our earlier paper (Hurdis and Krajci 2010), which may overwhelm the detection of any long-term period changes. Moreover, we find no correlation between these small year-to-year variations in computed period and the corresponding variations in amplitude-ratio reported below. Our observations are all available in the AAVSO International Database for researchers to apply other statistical methods. The means of the five yearly values computed for the fundamental and first-overtone periods were P0 = 0.49405 ± 0.00005 day and P1 = 0.36684 ± 0.00011 day.

The 2010 and 2011 amplitude-ratio results were as follows. In the *V* band, A_0/A_1 decreased from 1.48 ± 0.01 in 2009 to 1.40 ± 0.02 in 2010, but then increased to 1.82 ± 0.02 in 2011. These results are graphically illustrated in Figure 1, where the upper half of the figure shows (for all five years that the star has been observed) the number and distribution of the time-series observations, while the lower half shows the time variation of A_0/A_1. We note that the 2005 observation time-series and amplitude-ratio results are those of Oaster *et al.* (2006). In the *I* band, A_0/A_1 decreased from 1.52 ± 0.03 in 2009 to 1.38 ± 0.03 in 2010, but then increased to 1.81 ± 0.03 in 2011. These results are illustrated in Figure 2.

In conclusion, two additional years of observation of NSVS 5222076 have revealed that the seemingly monotonic decrease of A_0/A_1 has ended in both wavelength bands, and that in 2011 it increased. This suggests the variation of A_0/A_1 with time may actually be oscillatory. We note that no observations of the star exist between those of 2005 (Oaster *et al.* 2006) and those in 2008

(Hurdis 2009), so it is unknown how A_0/A_1 may have varied during that interval. Continued observation of NSVS 5222076 will be needed to clarify the interesting behavior of its mode amplitude-ratio.

3. Acknowledgements

The authors acknowledge AAVSO Director, Arne Henden, for providing his Sonoita Research Observatory photometric calibration of the star field. They also gratefully acknowledge Director Henden and the AAVSO for authorizing our use of the AAVSO robotic telescope network (AAVSOnet). In addition, they acknowledge Prof. Christine Clement for her helpful comments and for calling to their attention the recent paper on the behavior of V79 in M3.

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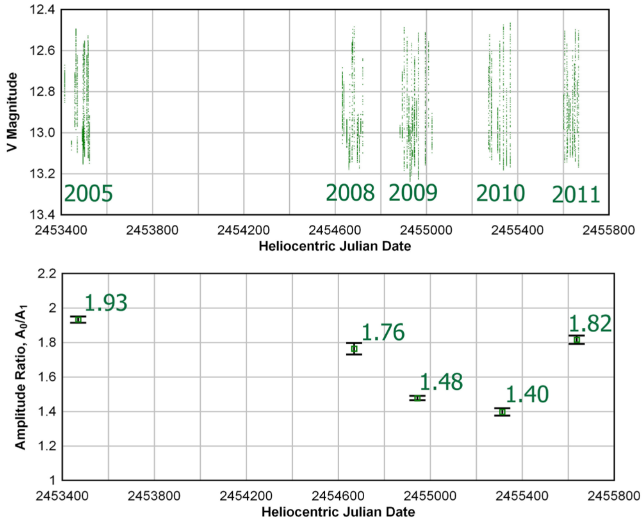

Figure 1. Secular variation of mode amplitude-ratio, A_0/A_1, for *V* band. Upper plot: combined data sets: Oaster *et al.* 2005, Hurdis 2008, Hurdis and Krajci 2009, 2010, and 2011, *V* filter. Lower plot: Time variation of amplitude ratio, A_0/A_1, *V* filter.

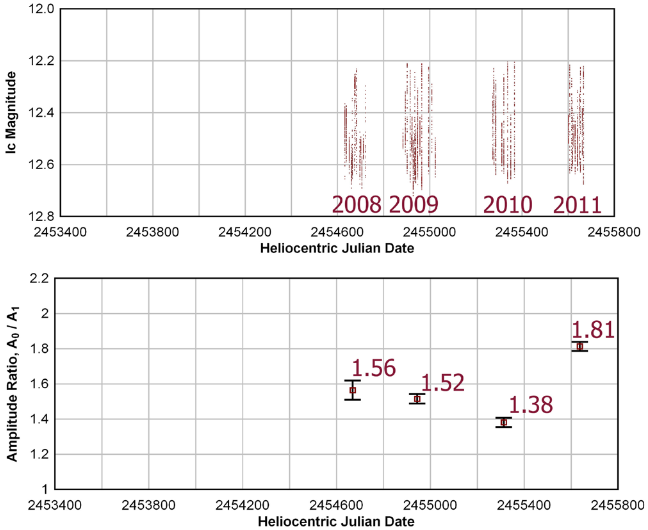

Figure 2. Secular variation of mode amplitude-ratio, A_0/A_1, for *I* band. Upper plot: combined data sets: Hurdis 2008, Hurdis and Krajci 2009, 2010, and 2011, *I* filter. Lower plot: Time variation of amplitude ratio, A_0/A_1, *I* filter.

The Pulsational Behavior of the High Amplitude δ Scuti Star RS Gruis

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Abstract RS Gruis is a high–amplitude δ Scuti–type variable star with a mean amplitude of almost half a magnitude in V and a period of almost 3.5 hours. The most recent study of this star by Derekas *et al.* (2009) suggests the presence of a low–mass dwarf star companion close to the variable star with a period of 11.5 days. Rodriguez *et al.* (1995) have also shown a decreasing rate of the period of $dP/Pdt = -10.6 \times 10^{-8}$ / y. Using an extended dataset comprising BVIc CCD observations acquired at the Astronomical Observatory of the Instituto Copérnico, data from ASAS and HIPPARCOS, and the existing CCD observations in the AAVSO International Database, we have performed an extensive periodgram and times of maximum analysis looking for long term variations. As a preliminary result, we confirmed that the period varies, but, since 1995, instead of decreasing, it has increased. We also found a small peak in the power spectrum in good agreement with the period suggested for the binary companion.

1. Introduction

RS Gru (HD 206379, HIP 107231) is a monoperiodic high–amplitude δ Scuti variable star, or HADS, for short, with a pulsation period of 0.147 d (3.5 h), corresponding to a frequency of 6.8027 d^{-1}, and a mean magnitude of 7.9 mag, and an amplitude of 0.6 magnitude in Johnson V filter.

Its light variation was first detected by Hoffmeister (1956) and studied later by Eggen (1956) and Oosterhoff and Walraven (1966).

Kinman (1961) made photometric and spectroscopic observations and measured a mean velocity of 81 $km\,s^{-1}$ with a velocity amplitude of 45 $km\,s^{-1}$.

Further photometric studies from McNamara and Feltz (1976) and later by Rodriguez *et al.* (1995) led to determined period variations.

Extended radial velocity studies by McNamara and Feltz (1976), Balona and Martin (1978), and more recently by Derekas *et al.* (2009) show that RS Gru is a spectroscopic binary with a companion completing an orbit once approximately each 11.5 days.

2. Observations

We use the following datasets in V:

- AAVSO International Database (3,837 Johnson V measurements covering HJD 2454373–2455525) (Henden 2011)
- ASAS3 (479 V measurements covering HJD 2451873–2455129) (Pojmański 2002)
- HIPPARCOS (198 V measurements covering HJD 2447880–2449062) (Perryman *et al.* 1977)
- Our own observations (For this paper we used only the Johnson V dataset, 313 Johnson V, 343 Johnson B, 344 Cousins I_c measurements covering HJD 2455390–2455482)

Our observations were made using the remotely controlled equipment from the Instituto Copérnico Astronomical Observatory, located at Lat. 34° 42' 33" S, Long. 68° 21' 44" W, in Rama Caída, Mendoza, Argentina. The telescope is a Schmidt–Cassegrain Celestron 11–inch with a focal reducer operating at *f*/3.3. The telescope control software is THE SKY X+ASCOM without auto guiding system. The CCD camera is a ST402MXE with a KAF chip 765 × 510 pixels at 9 µm, with a field of view of 26' × 17'. The filters used were the standard set BVIc provided by the camera producer. The camera control and image calibration were performed using MAXIM DL software (Diffraction Limited 2004). For the photometry we used IRAF software.

All data were reduced with standard tools and procedures. The transformation coefficients for the Observatory were obtained using the M67 field photometry (Henden 2011). We performed the corrections for the model of the atmosphere for each night using Landolt (1992) standards and Cousins (1976) pairs.

The CCD observations were reduced in MAXIM DL, including bias and dark removal and flat–field correction using sky–flat images taken during the evening or morning twilight. Magnitudes were calculated with aperture photometry using two comparison stars of similar brightnesses; Table 1 gives information on these comparison stars. In Figure 1 we can see the field including the comparison stars.

To avoid a shift in magnitude, the V magnitudes of the HIPPARCOS dataset were corrected using the table published by Otero (2003).

3. Analysis

The aim of this work was an extensive study of period variations, since the most recent study covering this issue was seventeen years old (Rodriguez *et al.* 1995). Their study was carried out nineteen years after the previous one by McNamara and Feltz (1976). The very short period of the star means that in the seventeen years since the last study the star had completed more than 50,000 cycles.

This paper covers two analyses, first a Fourier analysis of the observed datapoints, and second a classical O–C analysis of maximum light epochs.

Using our data plus the three other datasests described above we performed a DCFT analysis by means of PERIOD04 software from Lenz and Breger (2005).

The result of the analysis gives the higher peak in frequency at 6.8021777 d^{-1} equivalent to a period of 0.14705874 d, clearly shown in Figure 2. The folded light curve for all four datasets over that frequency is shown in Figure 3.

After an extensive periodogram analysis (16 frequecies were pre–whitened), we found that the strongest peak in the region trough 0 to 2 d^{-1} was centered on ~0.087 d^{-1}, corresponding to a period of ~11.5 days (with a S/N ratio of 2.5). This result was in good agreement with the results for the binarity from radial velocity data obtained by Derekas *et al.* (2009). The portion of the power spectrum can be seen in Figure 4.

Regarding the O–C analysis, we picked times of maximum light available in the literature in order to improve the elements for the ephemeris and to try to verify the increase in period that we had already determined in the periodogram analysis. We also established times of maximum light in Heliocentric Julian Date for the sets of observations from the AAVSO International Database and for our own observations, for a total of 37 times of maximum light covering the long span from 1952 to 2010 (Table 2).

We computed the O–C diagram, adopting the ephemeris from Rodriguez *et al.* (1995):

$$\mathrm{HJDmax} = 2447464 + 0.147010864\,E, \tag{1}$$

and we perceived that the tendency reflected in the periodogram analysis was also present in the O–C diagram.

We searched for a better linear fit, performing a least squares fit, and we found the new elements $T_0 = 2447464.7228$ (0.0008444) and $P_0 = 0.147011323$ (0.00000001773) d, reflecting the behavior in Figure 5 and with the computed O–C values in the fourth column of Table 2.

As the standard error of the fit was 0.005, we performed a further cubic regression. As a result we find the following ephemeris for the maximum light of RS Gru:

$$\begin{array}{lllll} T_{\max} = \mathrm{JD}\ 2447464.71497 & +\,0.147011239\,E & +\,4.230\times10^{-12}\,E^2 & +\,4.188\times10^{-17}\,E^3 & (2) \\ \qquad\qquad\ \pm 0.00101 & \pm 0.000000026 & \pm 0.511\times10^{-12} & \pm 0.816\times10^{-17} & \end{array}$$

The standard error of the fit was 0.0028, and the computed O–C values can be seen in the fifth column of Table 2.

4. Conclusions and future work

The increase in period seen in RS Gru is not usual behavior for a HADS, which normally present a decrease in period, such as seen in DY Per, VZ Cnc, or BS Aqr. We will continue the long term monitoring of RS Gru, and we will study other HADS in search for another specimen showing this unusual behavior.

5. Acknowledgements

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Table 1. Comparison star information used to observe RS Gru.

Comparison Stars	*R. A. (J2000)* *h m s*	*Dec. (J2000)* ° ′ ″	*V*	*B*
C1 = HD 206480	02 43 41.37	–48 07 54.77	10.389	10.769
C2 = UCAC3 84–413359	21 43 53.04	–48 09 19.45	11.143	11.799

Table 2. Times of maximum light of RS Gru.

Max	*(HJD)*	*Epoch*	*(O–C)l*	*(O–C)c*	*Origin*
1	2434325.2940	–89377	0.00226859	–0.00133290	1
2	2434573.4510	–87689	0.00415386	0.00029731	1
3	2436756.5710	–72839	0.00599404	0.00142493	2
4	2436760.5380	–72812	0.00368829	–0.00087989	2
5	2436801.5540	–72533	0.00352893	–0.00102922	3
6	2436853.3030	–72181	0.00454292	–0.00000149	3
7	2441538.4027	–40312	0.00036174	0.00067392	4
8	2441538.5490	–40311	–0.00034958	–0.00003718	4
9	2441610.4379	–39822	0.00001304	0.00043395	4
10	2441611.3200	–39816	0.00004509	0.00046734	4
11	2441611.4677	–39815	0.00073377	0.00115624	4
12	2441612.3493	–39809	0.00026582	0.00068963	4
13	2441915.4856	–37747	–0.00078404	0.00010108	4
14	2442687.5892	–32495	–0.00065713	0.00141754	5
15	2443355.4610	–27952	–0.00130158	0.00179679	6
16	2443355.6092	–27951	–0.00011291	0.00298569	6
17	2443360.4584	–27918	–0.00228660	0.00081935	6
18	2443360.6050	–27917	–0.00269792	0.00040825	6
19	2447464.7095	0	–0.01332706	–0.00547332	7
20	2447468.5324	26	–0.01272149	–0.00486554	7
21	2447468.6793	27	–0.01283281	–0.00497678	7
22	2447472.6489	54	–0.01253856	–0.00468025	7
23	2452920.0196	37108	0.00056588	0.00359375	8
24	2452921.9311	37121	0.00091867	0.00394131	8
25	2452922.0772	37122	0.00000735	0.00302958	8
26	2452923.9905	37135	0.00216014	0.00517714	8
27	2452925.0188	37142	0.00138087	0.00439505	8
28	2454373.9612	46998	0.00017257	–0.00168922	9
29	2454374.9930	47005	0.00289331	0.00102738	9
30	2454387.9288	47093	0.00169680	–0.00022118	9
31	2454417.0373	47291	0.00195467	–0.00008102	10
32	2454417.9216	47297	0.00418673	0.00214745	10
33	2454423.9464	47338	0.00152245	–0.00054130	10
34	2455391.7254	53921	0.00497726	–0.00147251	11
35	2455394.6654	53941	0.00475078	–0.00171373	11
36	2455481.6920	54533	0.00064703	–0.00625784	11
37	2455482.5796	54539	0.00617909	–0.00073029	11

1 Hoffmeister (1956); 2 Oosterhoff and Walraven (1956); 3 Kinman (1961); 4 Dean et al. (1977); 5 McNamara and Fetz (1976); 6 Balona and Martin (1978); 7 Rodriguez et al. (1995); 8 Derekas et al. (2009); 9 AAVSO ID (ARX); 10 AAVSO ID (DSI); 11 present paper

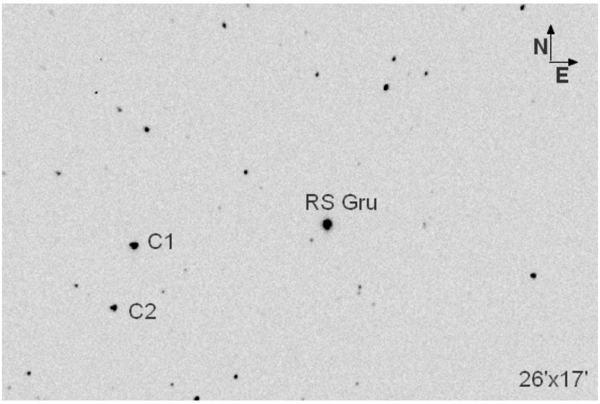

Figure 1. Finder chart for RS Gru. Information on comparison stars is in Table 1.

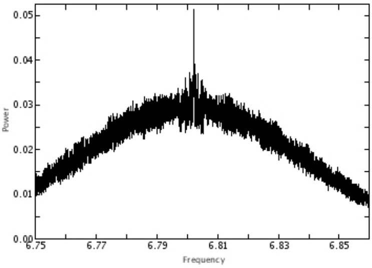

Figure 2. Fourier analysis results for RS Gru showing peak in frequency at 6.8021777 d^{-1} equivalent to a period of 0.14705874 d.

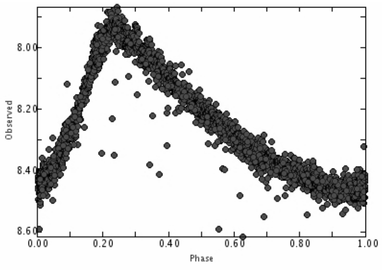

Figure 3. V–band light curve for RS Gru (AAVSO, ASAS, HIPPARCOS, and author's data) folded to frequency 6.8021777 d^{-1} = period 0.14705874 d.

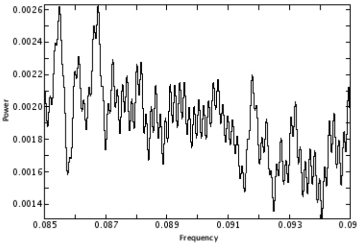

Figure 4. Power spectrum of RS Gru.

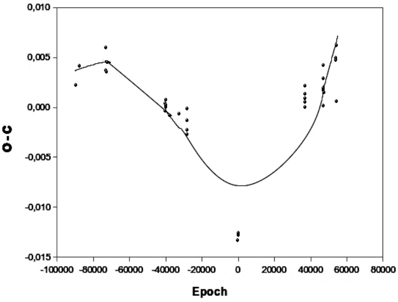

Figure 5. O–C diagram for RS Gru based on the new elements T_0 = 2447464.7228 (0.0008444) and P_0 = 0.147011323 (0.0000001773) d.

RS Sagittae: the Search for Eclipses

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Abstract New V-, B-, I_c-, and R-band photometry of RS Sge has been obtained for 2010 and 2011. These new observations, when combined with previous observations, provide clear verification of RS Sge as an RVb-type variable. The observations also allowed development of B–V, V–I, and V–R color indexes for RS Sge and an examination of calculated vs. observed minima. The light curve shows evidence of both a primary and secondary eclipse with a period of 55.427 days, although the eclipse is difficult to detect because of the intrinsic short and long period variation of the star. The eclipse data have been analyzed following the principles of the Wilson-Devinney method resulting in development of a binary model for the RS Sge system.

1. Introduction

The designation for RS Sge in the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2011) is RVB+EA. That is, this star is a RV Tauri, type b star (RVb). It is the only RV Tauri star in the GCVS which is also labeled as an eclipsing binary (EA) (GCVS 2011), since two "Algol-like" fades have been previously reported (Kardopolov and Filip'ev 1985). Since then, there have been no published reports of eclipses for this star.

As part of its *Eyepiece Views* notices, periodic observations of RS Sge were recommended by the AAVSO (Broens 2007). In part because of this recommendation, and other discussions at the AAVSO annual meeting in 2009, a detailed multi-year study of RS Sge was begun in 2010, utilizing both AAVSOnet and the author's telescopes in order to detect eclipses for RS Sge.

RV Tauri stars are giant or supergiant stars, having masses close to that the Sun, of spectral types of F or G at maximum light and G or early K at minimum light (Fokin 1994), and typically have periods between 30 and 150 days (Sterken and Jaschek 1996). Most have low metal abundances (Fokin 1994). RV Tauri stars are known to be strong infrared sources (Jura 1986) from substantial amounts of dust surrounding them (Fokin 1994). It has also been postulated that it is common for RV Tauri stars to be part of binary systems (Van Winckel *et al.* 1998). The majority of RV Tauri stars are in the RVa subclass, while a smaller percentage of these stars, the RVb subclass, also show a long term variation of hundreds to thousands of days (Pollard *et al.* 1996).

Because of the alternating shallow and deep minima of RV Tauri stars, the usual method of determining the period from adjacent minima is not used. The established convention for these types stars places the primary or deepest minima at phase 0.0, and the secondary, or shallow minimum at phase 0.5. Additionally, the primary or fundamental period is defined to be the time between the deepest minima. The period between adjacent minima is then designated as the half-period (Fokin 1994).

2. Previous observations

RS Sge first appears as a variable in the German publication A*stronomiche Nachrichten* in 1905 (Wolf and Wolf 1905). It was also noted as a variable by Walter Baade, who provided more precise coordinates (Baade 1928).

The first detailed study of the star was published by Tsessevich in 1977. He reported both "fast" and "slow" fluctuations in the light curve over an approximately twenty-year period. Between JD 243600 and 2443000, Tssesevich noted the "fast" period, corresponding to the time between adjacent minima, as 41.1975 days. Tsessevich noted that "slow" fluctuations had a period of 1123 days. This first full light curve, generated for the long term variation in RS Sge, is shown in Figure 1.

Kardopolov and Filip'ev (1985) focused on the short term variability of RS Sge and observed two types of minima, one deep (11.1 to 12.0 V mag.), one more shallow (11.25 to 11.70 V mag.), and noted the fundamental period between deep minima was approximately 90 days. As was mentioned previously, they also noted two "Algol-like" fades on JD 2444837.22 and 2444865.17 of approximately 0.15 V magnitude. These fades appear as single data points on their light curve of RS Sge, and measurement of the eclipse width and depth is somewhat uncertain. It is solely from these two reported fades that the apparent eclipse period for RS Sge is given as 27.95 days. This short term variability and the apparent eclipses are shown in Figure 2.

A query of the current ASAS project database, (Pojmański 2000), shows that more than 350 observations of RS Sge were made between 2003 and 2008. The long and short term variation of RS Sge from these ASAS observations is shown in Figure 3.

Likewise, a query of the AAVSO database (AAVSO 2011) returns a number of observations were made by both CCD and visual observers over a longer period, approximately twenty years. A corresponding graph of those observations shows a long term variation of RS Sge that is very similar to the ASAS light curve in Figure 3 (bottom).

A period analysis was conducted using the software package PERANSO (Vanmuster 2007) for both the AAVSO and ASAS observations of RS Sge, and this analysis indicates that the long period variation is 1193.49 ± 0.9 days, the fundamental period as 80.90 ± 0.7 days, and the half period as 40.55 ± 0.3 days. It does not reveal any significant period of approximately 28 days corresponding to the eclipse period reported by Kardopolov and Filip'ev (1985).

Self-correlation analysis, (Percy and Mohammed, 2004) also illustrates the approximately 40- and 80-day half and full period respectively (Figure 4, top), and an approximately 1,200-day long term variation (Figure 4, bottom). Similar to the period analysis, a self-correlation analysis does not indicate the presence of a twenty-eight day eclipse period for RS Sge in the ASAS and AAVSO data.

3. Current observations

For 2010 and 2011, observations of RS Sge were carried out using a number of telescopes:

- W28—a 28-cm Celestron, part of the AAVSOnet, located at the Astrokolkhoz telescope facility near Cloudcroft, New Mexico;
- W30—a 30-cm Meade LX200, part of the AAVSOnet, also located at the Astrokolkhoz telescope facility;
- SRO50—a 0.5-m telescope, part of the AAVSOnet, located at the Sonoita Research Observatory in Arizona;
- a 0.25-m Meade LX200, located in San Jose, California.

Depending on the specific instrument and filter, exposures ranging from 60 to 300 seconds were made using Johnson B, V, R, and Cousins I filters. Each recorded image was processed using established procedures. Photometric measurements were made using the AAVSO VPHOT application, using the corresponding AAVSO photometric sequence for RS Sge. The air mass for observations ranged from 2.17, for those few observations made earlier in the year, to 1.02, when RS Sge was at higher elevations during the night. Uncertainties for the photometric measurements averaged 0.08 mag. for B band, 0.03 mag. for V and R band, and 0.05 mag. for I band.

3.1. Light curves and color indexes

BVRI light curves from 2011 are shown in Figure 5. The overall variation for the B band is approximately 1.1 magnitude, and 0.6 for the other color curves. While the minima are fairly well aligned among the color curves, the maxima occur at different time periods, with the B-band maxima being well in advance of the V- or I-band maxima. The color indexes from the 2011 observations are shown in Figure 6. Examination of the V–I and B–V color indexes shows that these color indices have a saw-tooth type pattern, with the index values rising to a sharp peak at the maxima, while the V–R color index shows a more rounded maxima. The largest range of differences occur in the B–V index, almost 0.6 magnitude, while the V–I and V–R indexes show range differences on the order of 0.4 magnitude.

3.2. Observed vs. calculated minima

Examination of the 2011 RS Sge light curves in Figure 5 shows the typical RV Tauri-type alternating deep and shallow minima in their light curves, (Pollard *et al.* 1996). For RS Sge, this effect is most pronounced in the V band, also shown in Figure 10, when one compares the minima at JD 2455763 (14.1 V mag.) , JD 2455820 (14.25 V mag.), and JD2455846 (14.08 V mag.).

Additionally, it is typical for RV Tauri stars to generally show random fluctuations in period from one cycle to the next, (Percy *et al.* 1997). RS Sge follows this tendency, as the difference between minima is not constant, and did vary by as much as twelve days during the 2010 and 2011 observations. It was noticed that RS Sge apparently also has short bursts of fairly regularly spaced minima. If the average magnitude of each minima cycle is calculated and subtracted from the magnitude of each data point, the long term variation can be extracted from the light curve and the minima of 2010 and 2011 can be directly compared. Additionally, using the half period, 40.55 days, obtained from the period analysis of the ASAS data for RS Sge, the observed vs. calculated minima from 2010 and 2011 can be graphed. As shown in Figure 7, RS Sge had a number of minima that closely match the calculated date for the minima in 2010 and 2011.

4. Evidence of eclipses

An important aspect of the RS Sge light curve is that the segments between maxima and minima are sections of time where the star's magnitude is changing very rapidly, at times more that 0.1 magnitude in a single day. While this change is small in comparison to other variable stars, such a change is sufficient to effectively mask an eclipse of 0.15 magnitude in depth over perhaps several days, as was reported for RS Sge (Kardopolov and Filip'ev 1985). One of the perhaps fortuitous aspects of the 1985 eclipses was that they happened during a relatively slow period of change in RS Sge's light curve, as seen in Figure 2.

The challenge then, in finding evidence of eclipses in the current set of data from 2010 and 2011, is to separate where possible, any effects from an eclipse from the overall long and short term variability of RS Sge.

4.1. Eclipse evidence from 2010

Although the ASAS data are generally too sparse to use for eclipse detection, certain segments are useful for light curve comparisons. If a comparison is made for RS Sge between a segment of ASAS data from 2007, Figure 8 (top), and the other 2010 data, in Figure 8 (bottom), it can be noted that almost every cycle is fairly smooth, with a rapid rise to maxima, then a more gradual decline to the minima. In the 2010 data, Figure 8 (bottom) a discrepancy is noted around JD 2455370, in that after reaching the maxima, the light curve immediately drops 0.15 magnitude, then has a short segment of minor variability before resuming the normal gradual decline at JD 2455380.

If it assumed that this maximum around JD 2455370 has been altered by an eclipse, it is possible to recalculate the star's light curve for this segment. By also assuming that the light curve should have been following a more constant slope between JD 2455370 and 2455410, a possible eclipse can be revealed by subtracting out the expected slope of the light curve for this segment. The result of modifying the observational data in such a manner is shown in Figure 9. This residual light curve shows good evidence of an eclipse centered on JD 2455376.81393, which is also 377 27.95-day cycles from the first 1985 eclipse. This eclipse is approximately 0.15 V mag., in depth, and occurs over multiple days. In examining both the residual and the observed light curve for 2010 in Figures 8 and 9, there is additional evidence of eclipses at JD 2455321 and 2455404, which are multiples of this same 27.95 day cycle, prior to, and after the JD 2455375 event, although these eclipses appear more shallow.

4.2 Eclipse evidence from 2011

The light curve from 2011, shown in Figure 10, also shows evidence of an eclipse around JD 2455763, which is fourteen 27.95-day cycles from the 2010 eclipse at JD2455375. In this case, the eclipse appears to last approximately five days and reaches a depth of at least 0.11 V mag. In examining the overall light curve for 2011 in Figure 10, there is additional evidence of an eclipse around JD 2455848, also separated by multiples of 27.95 days, from the other 2011 eclipse event. The apparent eclipse at JD 2455848 is definitely shallower, only about 0.04 V mag. in depth.

4.3 Eclipse discussion

This evidence, the case of the presence of more shallow eclipses, is slightly different than what was reported by Kardopolov and Filip'ev (1985). In examining their light curve in Figure 2, it can be noted that the second eclipse at JD 2444865.17 is only partially recorded. Plus, its overall depth is even more uncertain than the first eclipse at JD 2444837.22, so the interpretation that there were two similar "Algol-like" fades in 1985 may be incorrect.

Additionally, while there is evidence of eclipse activity happening in multiples of approximately twenty-eight days for RS Sge, this difference in depth raises the possibility that the actual eclipse period might actually be approximately 56 days. The difference in depth obviously could represent a primary and secondary eclipse. In fact, if a period analysis is performed on the RS Sge 2010 and 2011 data, there is a small, but apparently significant period found in the PERANSO (Vanmunster 2007) period diagram corresponding to 55.86 ± 0.54 days, which is very close to twice the 27.95 period from 1985. The theta value, or calculated Schwarzenberg-Czerny value from the ANOVA analysis method (Schwarzenberg-Czerny 1996) is 11.53 for this 55.86-day period. This compares to a theta value of 28.12 for an ANOVA analysis of the 40.55-day half period, and 37.4 for the 80.9-day full period of RS Sge from the ASAS data.

5. System modeling

There is some concern that despite some observational evidence, the fact that RV Tauri stars are supergiant stars (Jura 1986), the corresponding stellar radius of such a star might make the existence of such a stable eclipsing system with an orbital period of 27.95 or 55.86 days, with eclipses lasting multiple days, somewhat improbable.

5.1. Astrophysical considerations

A simple astrophysical calculation can be performed to test the orbital possibilities of such an RS Sge system. It can be assumed that RV Tauri stars have luminosities (L_{RV}) of 10^3 to 10^4 $L_\odot$ (Fokin 1994) and RV Tauri stars vary from F to G, or G to K (Samus *et al.* 2011). This corresponds to a T_{eff} range of 4800–6500 K, so it is possible to calculate a range of possible stellar radii (R_{RV}) for RV Tauri stars by using the formula for stellar luminosity:

$$L = 4\pi R^2 \sigma T^4 \tag{1}$$

Using the luminosity of an RV Tauri star, L_{RV}, then dividing by the luminosity of the sun, $L_\odot$, and cancelling the constants, this becomes:

$$L_{RV} / L_\odot = T^4_{RV} R^2_{RV} / T^4_\odot R^2_\odot \tag{2}$$

Utilizing the range of T_{eff} and luminosities for RV Tauri stars, the range of possible radii is then:

$$R_{RV} = 15 - 100\ R_\odot \tag{3}$$

In terms of Astronomical Units (A.U.), this range is: $R_{RV} = 0.07 - 0.46$ A.U.

For an eclipse period of 27.95 days, Kepler's Third Law gives us the semi-major axis of a possible secondary component of RS Sge as:

$$a = 0.18 \text{ A.U.} \tag{4}$$

A companion star is possible if the luminosity of RS Sge is constrained to the lower end of the assumed range. If the primary eclipse period is closer to 56 days, the size of the semi-major axis is of course correspondingly larger, as is the possible range of luminosities.

5.2. Binary stellar modeling

A more rigorous method of modeling the RS Sge system is possible through an examination of the RS Sge light curves via a binary star modeling program such as PHOEBE (Prsa and Zwitter 2005), which utilizes the methods of the Wilson-Devinney code (Wilson 1994).

A difficulty in using such a modeling program like PHOEBE for RS Sge is that the star exhibits complex light curve changes outside of any possible eclipse activity. The net effect is that different eclipse events, on approximately 28-day centers, happen at very different magnitudes, ranging from approximately 11.5 to 14.0 V magnitude. While filtering for these eclipse data, some care must be taken to minimize any data selection bias, and these data, must, in turn, be converted to a common base magnitude so that the PHOEBE program can make sense of them. Nonetheless, as the JD 2455763 eclipse is the best defined, prior to input into PHOEBE, the magnitude of all eclipse V-band data from 2010 and 2011 was re-scaled to that JD 2455763 magnitude base of 14.02 V mag.

The best fit for the 2010 and 2011 RS Sge V-band data from PHOEBE is shown in Figure 11. This fit is for a detached binary system, based upon a 55.33-day orbital period with both primary and secondary eclipses, of 0.14 and 0.05 V magnitude, respectively. While the data are a good fit to the primary eclipse, there is some scatter about the secondary eclipse. The corresponding modeling of the RS Sge system is listed in Table 1.

The outputs from the binary model for RS Sge are consistent with the previous astrophysical calculations, in terms of stellar radius and effective temperature of RS Sge. The orbital period from the PHOEBE model is shorter than the one from the 2010 and 2011 period analysis, by about a half a day, but within the degree of uncertainty (0.54 day). It is also important to point out that because of limitations in the accuracy of the photometry, the small amount of eclipse data, and the inherent limitations of the binary models, the results offered here are from simply one solution, consistent with the available observational data, but it is not necessarily a mathematically unique solution.

6. Conclusions

This paper has reviewed previous and recent observations of RS Sge, including BVRI light curves, color indexes, period and self-correlation analyses, and an examination of observed versus calculated minima. There is good verification of the classification of RS Sge as a RVb-type variable star. The half-period of RS Sge was found to be 40.55 days, while the full period between the deep minima is 80.9 days. As is typical for RV Tauri stars, RS Sge shows some cycle-to-cycle variations in the timing of the minima. The long term variation of RS Sge was found to be 1193.5 days and spans more than 3.0 V magnitudes.

There is evidence of eclipse activity for RS Sge in the 2010 and 2011 data, seemingly confirming the eclipses first published in 1985. Because in some cases, the eclipse data are wrapped within the overall complex variation of this RV Tauri-type star, this confirmation is not totally unambiguous. Additional observations are needed to gather additional data and refine the nature of the RS Sge eclipses. Binary modeling of the current data does show a reasonable fit to a system with an orbital period of 55.33 days, with both primary and secondary eclipses being present.

7. Acknowledgements

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Table 1. Output from PHOEBE for the RS Sge data from AAVSOnet and the author's observations in 2010 and 2011.

Parameter	*Value*
Mass Ratio: q	0.95999
Primary Radius: R_p	13.02 $R_\odot$
Secondary Radius: R_s	5.92 $R_\odot$
Primary T_{eff}	6400 K
Secondary T_{eff}	5020 K
Semi-major axis: a	76.0 $R_\odot$
Inclination: i	81.1°
Eccentricity: e	0.05
Period: p	55.33 d
Epoch (HJD)	2455765.1008

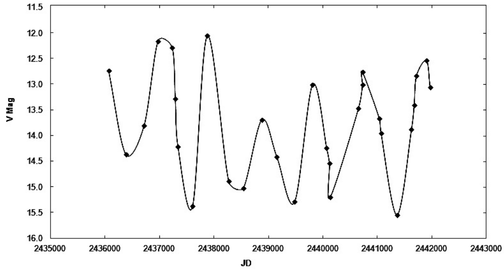

Figure 1. Long-term variability of RS Sge. From observations by Tsessevich (1977).

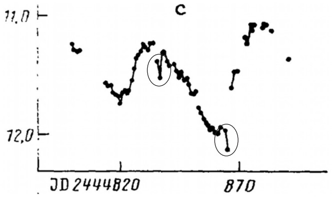

Figure 2: Short-term variability of RS Sge. The Algol-like fades are identified with a circle. From photoelectric observations by Kardopolov and Filip'ev (1985); light curve published in Kardopolov and Filip'ev (1988).

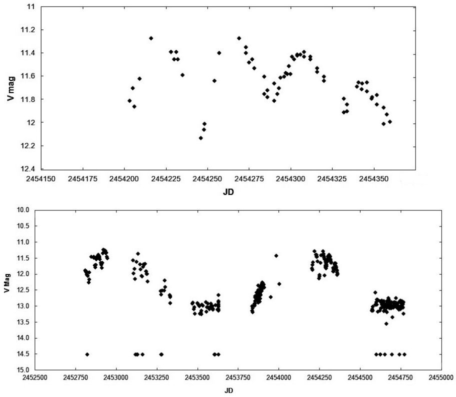

Figure 3. Short-term, April–September 2007 (top graph, black dots), and long-term (bottom graph, black dots) variability of RS Sge. From ASAS observations 2003–2008.

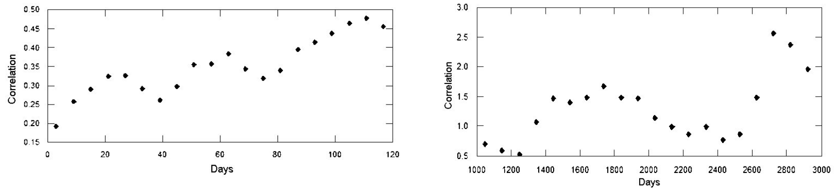

Figure 4: Short period (left graph, black dots) and long period (right graph, black dots), self-correlation analysis of the ASAS Data. From ASAS observations 2003–2008.

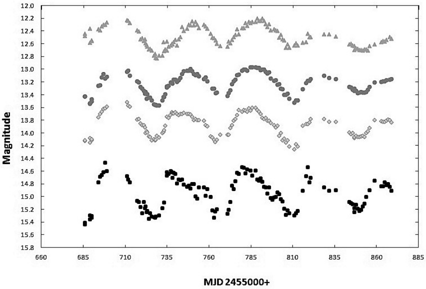

Figure 5: BVRI magnitudes of RS Sge (top to bottom: B, gray squares; V, gray diamonds; R, black dots; I, light gray triangles). From AAVSOnet and the author's observations in 2011.

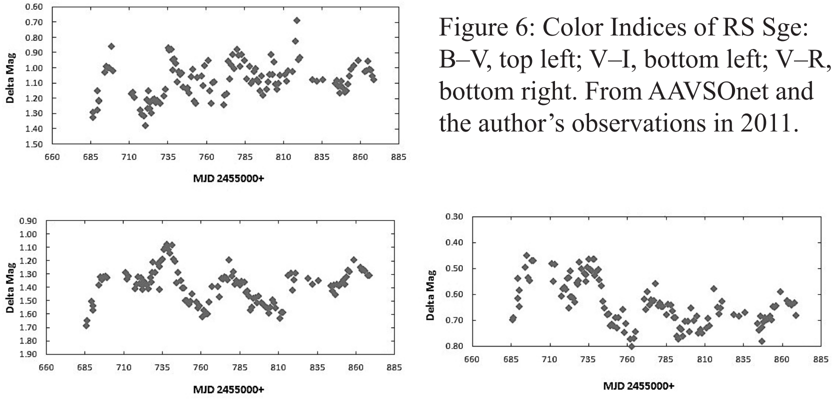

Figure 6: Color Indices of RS Sge: B–V, top left; V–I, bottom left; V–R, bottom right. From AAVSOnet and the author's observations in 2011.

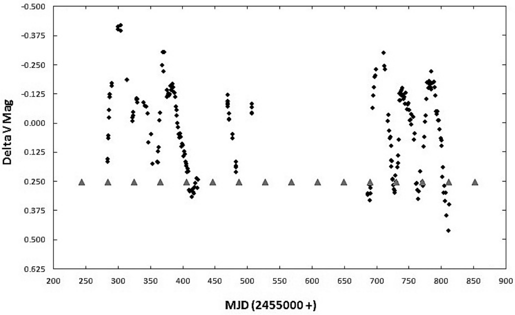

Figure 7: Calculated light curve (gray triangles) using a period of 40.55 days, and observed (black diamonds) minima for RS Sge. From AAVSOnet and the author's observations in 2010 and 2011.

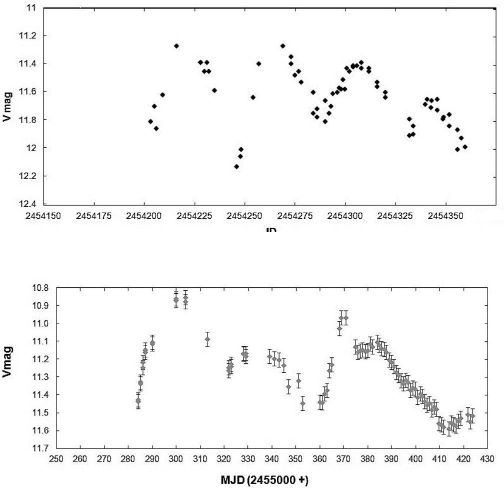

Figure 8: A comparison of RS Sge short term variability from ASAS data in 2007 (top graph) and from AAVSOnet and the authors observations in 2010 (bottom graph).

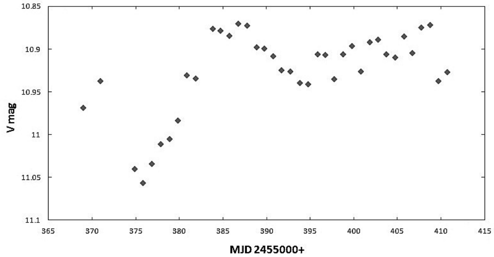

Figure 9: A residual light curve of RS Sge from AAVSOnet and the author's observations in 2010.

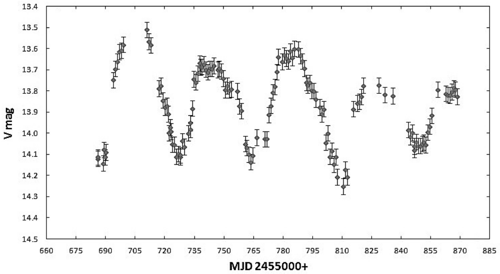

Figure 10: The V-band light curve of RS Sge from AAVSOnet and the author's observations in 2011.

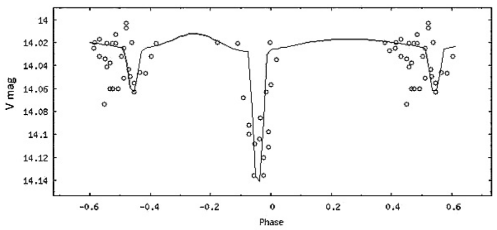

Figure 11: The calculated V-band light curve (line) from PHOEBE and the observed eclipse data of RS Sge from AAVSOnet and the author's observations in 2010 and 2011.

Intensive Observations of Cataclysmic, RR Lyrae, and High Amplitude δ Scuti (HADS) Variable Stars

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Abstract An intensive observing campaign is ongoing to study cataclysmic, RR Lyrae (with and without Blazhko effect), and High Amplitude δ Scuti (HADS) variable stars. These observations are based on requests and in collaboration with different organisations (CBA, VSNET, GEOS) and individuals. Observations are taken from my private observatories in Belgium, Chile, and through shared use of an observatory belonging to the AAVSOnet in New Mexico. Examples of individual stars intensively followed-up on are: CD Ind and BW Scl, two cataclysmic variables; NU Aur, an RR Lyr star with strong Blazhko effect; and GSC0762-0110, a HADS star. Many publications in different journals including *Astronomy and Astrophysics* have already emerged from this research.

1. Introduction

For the past couple of years I have been changing my interest in amateur astronomy, focussing towards variable star observations. Coming from "pretty picture" imaging and with my scientific background I have now fully dedicated my equipment and efforts towards following intensively short period variable stars like RR Lyr stars, Cataclysmic variables (CV), and High Amplitude Delta Scuti (HADS) stars. My roll-off observatory in my backyard has grown in recent years to house several telescopes dedicated to variable star observations. In Belgium, I observe mainly CV's in collaboration with the Center for Backyard Astrophysics (CBA) based on requests via the CBA e-mail alert list. Also, outburst observations of CV's are performed based on VSNET alerts and data are sent to Kyoto for further analysis. The telescopes used are nowadays a C14, a C11, and a Meade 14-inch, all equipped with SBIG CCD's and photometric filters. Parts of the data shown in Figures 1 and 5 have been taken with those telescopes. As the weather in Belgium is mostly cloudy, I have joined forces with AAVSO and share one of AAVSOnet telescopes (W30) with fellow AAVSOnet observers. With this telescope and the much better weather conditions in New Mexico most of the data from Figures 1 and 2 have been acquired. In addition, since mid-2011 I have found the ultimate observing site in the Atacama Desert in Chile. Since August 2011 a remote telescope (40 cm *f*/6.8 Optimized Dall Kirkham (ODK) from Orion Optics, UK) is operational utilizing an FLI ML16803 CCD with Astrodon photometric filters. The data shown in Figures 3 and 4 have been acquired remotely. In the following some explanations about the variable type and some examples of observational results acquired at the different sites mentioned above are given.

2. RR Lyr stars

This type of variable star is named after the prototype, the variable star RR Lyrae in the constellation Lyra. RR Lyr stars are pulsating horizontal branch stars with a mass of around half of our Sun's. They are thought to have previously shed mass and, consequently, they were once stars with similar or slightly less mass than the Sun, around 0.8 solar mass. RR Lyr stars pulsate in a manner similar to Cepheid and δ Scuti variables, so the mechanism for the pulsation is thought to be similar, but the nature and histories of these stars is thought to be rather different. In contrast to Cepheids, RR Lyr stars are old, relatively low mass, metal-poor so-called "Population II" stars. They are much more common than Cepheids, but also much less luminous. Their period is shorter, typically less than one day.

The RR Lyr stars are conventionally divided into three main types based on the shape of the stars' brightness curves:

1) RRab, the majority type, which display steep rises in brightness;

2) RRc, a type with shorter periods and more sinusoidal variation; and

3) RRd, a rare type of double-mode pulsators.

RRab types are fundamental mode pulsators, RRc types are pulsating in the first overtone, and RRd are a combination of both modes.

My interest in observing RR Lyr stars is on one hand due to the short period of those stars: Within one night you can see already quite a change in brightness. On the other hand the stars also show brightness modulation which is known as the Blazhko effect. In 1907, S. Blazhko observed this effect for the first time on the star RW Dra (Smith 2004). The Blazhko effect is, to date, not really understood. Recently, thanks to the Kepler and CoRoT satellite missions, more insight into this phenomenon has been gained as the satellites can of course observe the stars continuously, which is impossible for Earth-bound observations (Kolenberg 2011). Nevertheless, observations from Earth are also very valuable as can be seen in many publications on this subject in the astronomical literature.

Examples of RR Lyr stars showing Blazhko effect are given in Figures 1 and 2. Both NU Aur and VY CrB are RRab types with a rather strong modulation of the light curve due to the Blahzko effect. Both the maximum brightness and the time of maximum are changed.

3. Cataclysmic variables

Cataclysmic variable (CV) stars undergo large brightness increases of several magnitudes which last for a few days and then they drop back to a quiescent state. The stars are novae, dwarf novae, or closely related objects which undergo these outburts in a regular or semiregular way. They are normally interacting binaries of which one star is a white dwarf and the second star is closer to the main sequence. The latter star loses matter in the direction of the white dwarf, usually forming an accretion disk. The repetitive outbursts are most probably due to material from the accretion disk accumulating on the white dwarf and causing, for example, a thermonuclear reaction. CVs are subdivided into several classes, for example, those which have strong magnetic fields are called polars, an example of which is CD Ind.

I came to this sort of object by subscribing to different variable star mailing lists and by my recent participation in the SAS meeting in Big Bear in 2009, where I joined the CBA (Center for Backyard Astronomy) group. There was a meeting adjacent to the SAS meeting in Big Bear, and I met Joe Patterson in person. Since then I have been contributing my observations to the CBA data repository as well as the AAVSO International Database. Also, through T. Kato's VSNET alerts, I get information about interesting CV's in outburst, which can be followed up on.

Some examples of Cataclysmic Variables are given in Figures 3 and 4 (CD Ind and BW Scl). The most recent outburst and the first ever detected was for BW Scl. Due to my remote observatory I could follow this star during the pre-outburst period nearly until the writing of this paper, over a period of more than two months. I just missed the rise to outburst. Figure 4 shows the observed light curve.

4. High Amplitude δ Scuti (HADS) stars

δ Scuti stars exhibit both radial and non-radial luminosity pulsations. Non-radial pulsations are when some parts of the surface move inwards and some outward at the same time. Radial pulsations are a special case, where the star expands and contracts around its equilibrium state by altering the radius to maintain its spherical shape. Throughout their lifetime δ Scuti stars exhibit pulsation when they are situated on the classical Cepheid instability strip. They then move across from the main sequence into the giant branch.

I have been observing this kind of star for a couple of years based on a collaboration with Patrick Wils and the Flemish Association of Variable Stars. This group has an intensive CCD campaign in following up on HADS stars. The list of stars is provided by P. Wils and can be accessed at the following URL:

http://www.vvs.be/werkgroepen/werkgroep-veranderlijke-sterren/over-werkgroep-veranderlijke-sterren/de-werkgroep/hads-0#overlay-context=werkgroepen/werkgroep-veranderlijke-sterren/hads-waarnemingen

Wils collects the data and analyzes them in terms of determining the epoch and period of the star over a longer time span of several years to look for variations in these parameters. Occasionally, multi-periodic stars are also found in the list. They are then more intensely observed by several observers distributed around the globe to get a continuous capture of the light curve and its variations due to multiple periods. Those stars are of course the more interesting ones, as the light curve changes from night to night. An example, the HADS star GSC0762-0110 (Wils *et al.* 2008), is given in Figure 5.

5. Acknowledgements

The Wikipedia online free encyclopaedia is used for the introductory explanations to RR Lyrae, Cataclysmic, and HADS variable stars. I would like to thank Patrick Wils for valuable comments on the manuscript.

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Smith, H. A. 2004, *RR Lyrae Stars*, Cambridge Univ. Press, Cambridge, 103.

Wils, P., Rozakis, I., Kleidis, S., Hambsch, F. -J., and Bernhard, K. 2008, *Astron. Astrophys.*, **478**, 865.

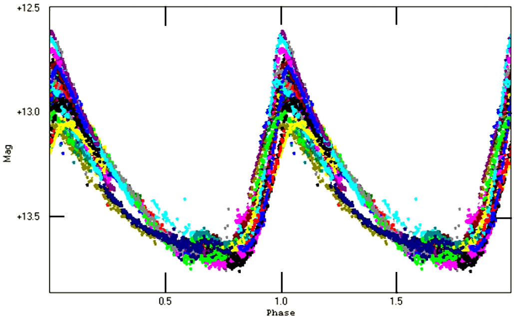

Figure 1. Phase diagram of NU Aur, a RR Lyr star with a strong Blazhko effect, which not only changes the maximum brightness but also the time of maximum. Data were taken from the author's backyard observatory and via the AAVSOnet scope W30 in New Mexico. The colors indicate different nightly runs.

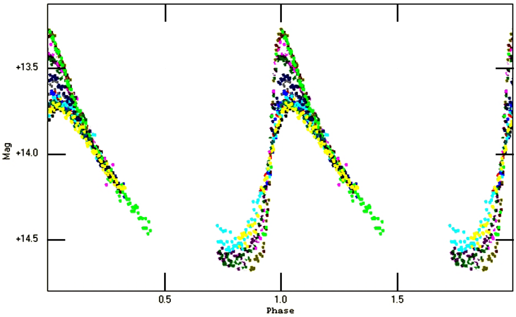

Figure 2. Phase diagram of VY CrB another example of a RR Lyr star showing the Blazhko effect. Data are via the AAVSOnet scope W30 in New Mexico. The colors indicate different nightly runs.

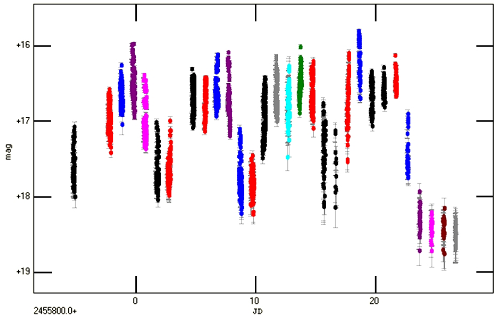

Figure 3. Example of an CV which showed several changes of about 1 mag in brightness during about three weeks of observations. Data were taken remotely from the author's observatory in Chile. The colors indicate different nightly runs.

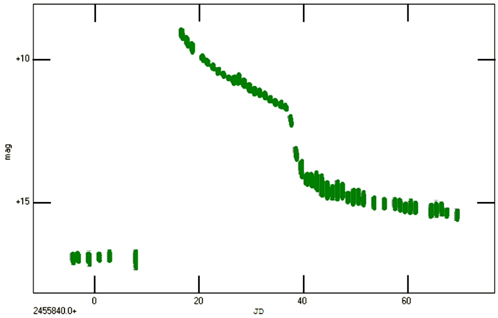

Figure 4. BW Scl showed its first ever detected outburst of more than 6 magnitudes and could be followed in its brightness decrease over more than two month. Also data before the outburst have been acquired. All data were taken remotely from the author's observatory in Chile.

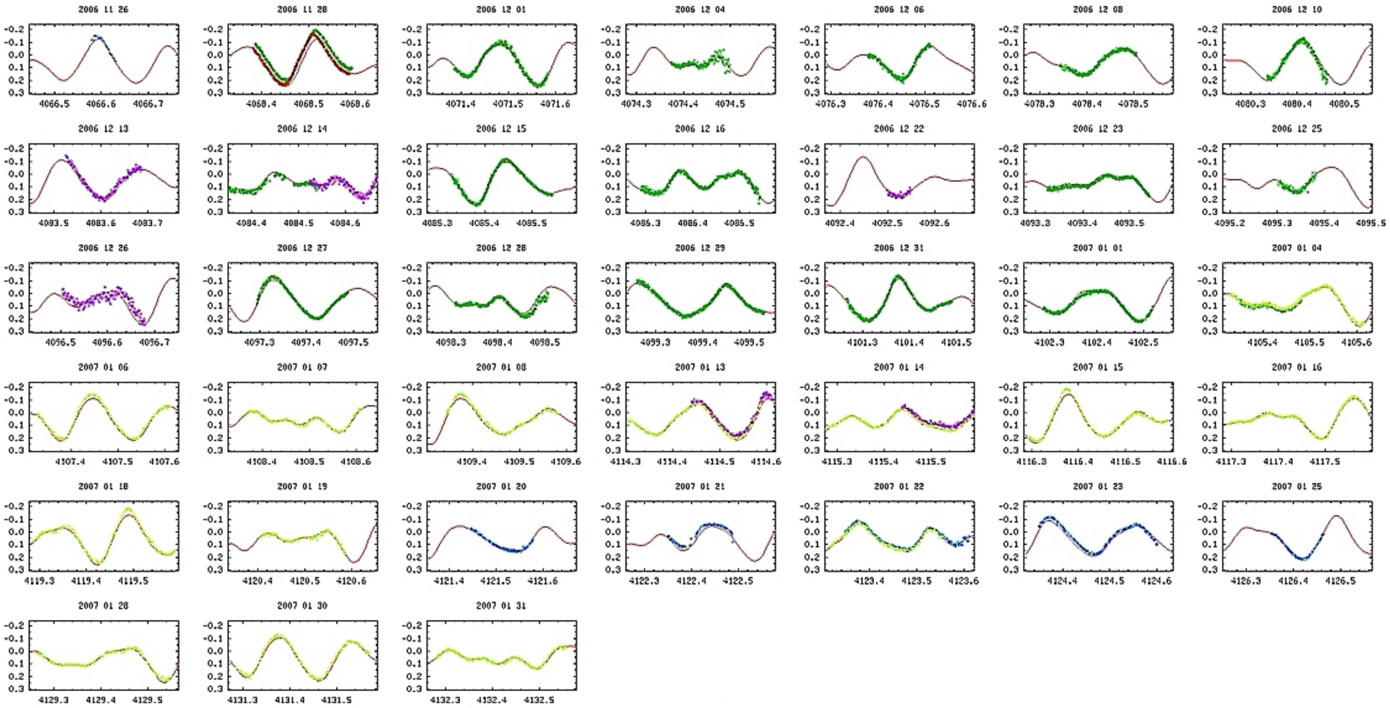

Figure 5. Example of a multi-periodic High Amplitude Delta Scuti (HADS) star, observed during several weeks by several observers. Data were taken from multiple sites by different observers including the author's backyard observatory in Belgium. (Wils *et al.* 2008).

A Study of the Orbital Periods of Deeply Eclipsing SW Sextantis Stars

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Abstract Results are presented of a five-year project to study the orbital periods of eighteen deeply eclipsing novalike cataclysmic variables, collectively known as SW Sextantis stars, by combining new measurements of eclipse times with published measurements stretching back in some cases over fifty years. While the behavior of many of these binary systems is consistent with a constant orbital period, it is evident that in several cases this is not true. Although the time span of these observations is relatively short, evidence is emerging that the orbital periods of some of these stars show cyclical variation with periods in the range 10–40 years. The two stars with the longest orbital periods, V363 Aur and BT Mon, also show secular period reduction with rates of -6.6×10^{-8} days/year and -3.3×10^{-8} days/year. New ephemerides are provided for all eighteen stars to facilitate observation of future eclipses.

1. SW Sex stars

SW Sex stars are an unofficial sub-class of cataclysmic variables (CVs), not in the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2012), which was first proposed by Thorstensen *et al.* (1991) with the comment "… these objects show *mysterious* behavior which is however highly *consistent* and *reproducible*." They are classified in the GCVS as novalike variables. The four prototype SW Sex stars were PX And, DW UMa, SW Sex, and V1315 Aql, which all appeared to share a common set of unusual properties (see below). Since then this class has expanded to include around fifty members of which about half are definite members and the others either probable or possible based on their observed characteristics. Don Hoard maintains an on-line list of SW Sex stars (Hoard *et al.* 2003).

These SW Sex stars have bright accretion disks, in some cases showing occasional VY Scl-type low states, but do not have the quasi-periodic outbursts seen in dwarf novae. They are often eclipsing systems with periods mostly in the range 3–4 hours. They may exhibit either positive or negative superhumps or both. Spectroscopically they show single-peaked Balmer and HeI emission lines, not double peaked lines as expected in high inclination CVs. Superimposed on the emission lines is a transient narrow absorption feature around phase 0.5. Phase offsets are observed between the radial velocity and eclipse ephemerides. Some systems exhibit modulated circular polarization indicating magnetic accretion onto the white dwarf. There is much variation in detail between individual systems and current models of SW Sex stars have difficulty explaining all of their observed properties. The general consensus seems to be that SW Sex stars contain accretion discs which are maintained in a bright state by a high, sustained mass-transfer rate and that these discs are complex in structure and may be variously eccentric, precessing, warped, tilted, or flared at the edge. The inner edge of the disc may also be truncated if the white dwarf is magnetic. For more information, see for example Hellier (1999), Gänsicke (2005), Rodriguez-Gil (2005), Rodriguez-Gil *et al.* (2007a), and Rodriguez-Gil *et al.* (2007b). Recently it has been claimed that the majority of novalike variables in the 3–4 hour orbital period range exhibit SW Sex-like properties to some extent (see Schmidtobreick *et al.* 2011). If true, this suggests that the SW Sex phenomenon may be a normal stage of CV evolution.

However, the bottom line at the moment seems to be that we really don't have a full understanding of the mechanisms which operate in SW Sex stars, and how they relate to other CVs with similar periods. But, as they appear to constitute the majority of CVs with orbital periods in the range 3–4 hours, they are important and need further study.

2. Aims of the project

This project was suggested to me in early 2007 by Boris Gänsicke at Warwick University who was interested to find out if studying eclipses of SW Sex stars would reveal evidence of changes in their orbital periods. Several of these stars had not been observed systematically for many years and were in need of new observations. The idea was therefore to combine published data on eclipse times going back in some cases over fifty years with new eclipse measurements to investigate the stability of their orbital periods.

The aims of the project were, for each star:

- to research all previously published eclipse times;
- to measure new eclipse times;
- to look for evidence of a change in orbital period;
- if found, to investigate its nature;
- to update ephemerides to aid future observations.

The eighteen SW Sex stars in Hoard's list which are deeply eclipsing, observable from the UK, and bright enough to yield accurate eclipse times with amateur-sized telescopes are the subject of this project. They are listed in

Table 1 in order of increasing orbital period (P_{orb}) along with the numbers of eclipse times found in the literature and new measurements reported here.

3. Previously published eclipse times

Eclipse times of minimum of these stars were discovered in over twenty different publications. For each star a list of published eclipse times obtained photographically (PG), photoelectrically (PE), or using CCD cameras was assembled along with corresponding cycle (orbit) numbers. As far as possible all times were confirmed to be in Heliocentric Julian Date (HJD). A very small number of visual eclipse times were also found but after careful consideration it was decided not to use these in this analysis because of their significantly larger and generally unknown uncertainties. In total 740 published eclipse times were located for these eighteen stars. Limitation on space prevents listing previously published eclipse times here. These are available through the AAVSO ftp site at ftp://ftp.aavso.org/public/datasets/jboydd401.txt.

Many published eclipse times did not specify errors. By examining the scatter in eclipse times obtained photographically their error was estimated to be, on average, 0.005d and this value was assigned to all photographic times. For photoelectric and CCD measurements published without errors each published set of data was considered separately and the root-mean-square (rms) residual of all the times in that set calculated with respect to a locally fitted linear ephemeris. This value was then assigned as an error to all the times in that set. These errors were typically in the range 0.0004d to 0.001d. In cases where the errors quoted appeared to be unrealistically small, more realistic errors were estimated by the same method. Each published time of minimum was given a weight equal to the inverse square of its error.

4. New measurements of eclipse times

Eclipses were observed using either a 0.25-m or 0.35-m telescope, both equipped with Starlight Xpress SXV-H9 CCD cameras, located at West Challow Observatory near Oxford, UK. Image scales were 1.45 and 1.21 arcsec/pixel, respectively. All measurements were made unfiltered for maximum photon statistics. Images were dark subtracted and flat fielded and a magnitude for the variable in each image derived with respect to between three and five nearby comparison stars using differential aperture photometry.

The dominant light source in these systems is the bright accretion disk, and its progressive eclipse by the secondary star results in eclipse profiles which are generally V-shaped with a rounded minimum. A quadratic fit was applied to the lower part of each eclipse from which the eclipse time of minimum and an associated analytical error were obtained. The magnitude at minimum was also obtained from this fit, enabling eclipse depths to be estimated. Some of these stars exhibit relatively large random fluctuations in light output which can persist during eclipses, indicating the source of these fluctuations has not been eclipsed. This can result in significant distortion of their eclipse profiles and consequently larger scatter in their measured times of minimum. In general it was found that the analytical errors from the quadratic fits underestimated the real scatter in eclipse times. By examining this scatter for each star over a short interval during which the eclipse times were varying linearly, a multiplying factor was found which was then applied to the analytical errors. For stars with the smoothest eclipses, a factor of 3 gave errors consistent with the scatter of eclipse times while for the most distorted eclipses a factor of 7 was required. Each measured time of minimum was given a weight equal to the inverse square of its associated error. All new times of minimum were converted to HJD. As shown in Table 1, 298 new eclipse times were measured, increasing the number of available eclipse times for these stars by 40%.

Initially a constant orbital period for each star was assumed and a linear ephemeris computed based only on published eclipse times. Predictions were then made of the expected times of future eclipses. Although in some cases these predictions were found to be inaccurate by up to an hour, in all cases it was possible to project the historical cycle count forward and unambiguously assign cycle numbers to new eclipses as they were observed.

For each star we now had the HJD of the time of minimum for every measured eclipse plus an error and a corresponding cycle number. New eclipse times measured for the eighteen stars in the project are listed in Table 2.

5. O–C analysis

For each star a constant orbital period was assumed and a weighted linear ephemeris was calculated based on all available eclipse times, both published and new. O–C (Observed minus Calculated) values for the time of each eclipse with respect to this linear ephemeris were calculated and an O–C diagram generated for each star. O–C values following the horizontal line at O–C = 0 would confirm that the orbital period was indeed constant. O–C values following an upwards curve would indicate that the period was increasing while a downwards curve would indicate that the period was decreasing. Sinusoidal behavior would indicate that the orbital period was varying in a cyclical way, alternately increasing and decreasing.

6. Eclipsing SW Sex stars with orbital periods less than 4 hours

Most of the thirteen eclipsing SW Sex stars with orbital periods less than 4 hours have O–C diagrams which appear to be consistent with having a constant orbital period over the time span covered by the available observations, in some cases more than thirty years. However, in a few cases there is an indication of possible non-linear behavior. This was investigated by applying a weighted sine fit to their O–C values using PERIOD04 (Lenz and Breger 2005) and comparing the rms residuals of linear and sinusoidal ephemerides. The conclusion was that ten of the thirteen stars were consistent with having linear ephemerides and therefore a constant orbital period while three, SW Sex, LX Ser, and UU Aqr, gave at least 20% smaller rms residuals for sinusoidal ephemerides indicating possible cyclical variation of their orbital periods.

Linear ephemerides for these thirteen SW Sex stars are given in Table 3. These should provide an accurate basis for predicting the times of future eclipses. Table 4 lists the parameters of possible cyclical variation and rms residuals of sinusoidal and linear ephemerides for SW Sex, LX Ser, and UU Aqr.

Figure 1 shows O–C diagrams for the ten SW Sex stars with orbital periods less than 4 hours which are consistent with linear ephemerides. Previously published observations are marked as black dots and new eclipse times as light-colored squares in this and subsequent figures. The larger scatter for some stars is primarily due to the less regular shape of their eclipses as noted above. Figure 2 shows O–C diagrams for SW Sex, LX Ser, and UU Aqr with dashed lines representing their sinusoidal ephemerides.

Given the length of their cyclical periods relative to the observed coverage and their relatively small amplitudes, more data are required to substantiate these cyclical interpretations. We do, however, note that similar behavior has been recorded in several other eclipsing CVs, see for example Borges *et al.* (2008) and references therein.

7. Eclipsing SW Sex stars with orbital periods greater than 4 hours

Five of the SW Sex stars have orbital periods longer than 4 hours: RW Tri, 1RXS J064434.5+334451, AC Cnc, V363 Aur, and BT Mon. For all these stars the eclipse times appear, to varying degrees, to be inconsistent with the assumption of a constant orbital period. Each of these stars is now considered individually.

7.1. RW Tri

A total of 115 published and 21 new eclipse times are available for RW Tri starting in 1957. The O–C diagram for RW Tri representing the residuals to a linear ephemeris with long-term average orbital period 0.231883193(2) day is shown in Figure 3a. The scatter in the data is sufficiently large that a time calibration problem with some of the published times must be considered a possibility. We decided to exclude the eleven eclipse times around HJD 2449600 from subsequent analysis as their O–C values were more than 5 minutes larger than those before and after. Between approximately HJD 2442000 and HJD 2450000 the period slowly decreased. It then started to increase and is currently longer than the long-term average. Taken as a whole, the data suggest cyclical variation of the orbital period. A weighted sine fit to the O–C data using PERIOD04 gives the results listed in Table 5 and shown as a dashed line in Figure 3a. Also listed in Table 5 are the rms residuals of sinusoidal and linear fits indicating that sinusoidal interpretation is statistically favored. However, given the large scatter in the data and the fact that just over one possible cycle has been observed, a convincing analysis will require data over a much longer time span. An earlier analysis by Africano *et al.* (1978) suggested sinusoidal variation with a period of either 7.6 or 13.6 years but with the addition of more recent data neither of these periods survives.

A linear ephemeris fitted to the data over the past seven years which should be useful for predicting eclipses in the near future is given in Table 3.

The out-of-eclipse magnitude of RW Tri, including early measurements reported by Walker (1963), observations from the AAVSO International Database and from ASAS (Pojmański *et al.* 2005), and new observations reported here, is plotted in Figure 3b. This shows a slight brightening around HJD 2450000 but otherwise little change. Eclipse depth has remained approximately constant over the observed time span (Figure 3c). Table 6 lists measurements of eclipse depth for the five stars with long orbital periods.

7.2. 1RXS J064434.5+334451

Twenty unpublished eclipse times for 1RXS J064434.5+334451 from 2005 to 2008 were kindly provided by David Sing and Betsy Green, who first identified this star as a CV (Sing *et al.* 2007). The first times reported here were in 2010 and these were consistent with those of Sing and Green, giving the orbital period 0.26937447(4) day and the linear eclipse ephemeris given in Table 3.

Surprisingly, eclipses in March 2011 were about three minutes late relative to this ephemeris. This behavior has since continued with most eclipses occurring between two and four minutes later than expected assuming a linear ephemeris based on observations up to and including 2010 (HJD < 2455500—see Figure 4a). Since March 2011 the mean orbital period has been slightly shorter at 0.2693741(2) day. The out-of-eclipse magnitude experienced a rise prior to, and a dip following, the O–C discontinuity (Figure 4b). Eclipses became, temporarily, about 10% deeper after the O–C discontinuity (Figure 4c and Table 6).

7.3. AC Cnc

For AC Cnc, forty-six published and eleven new eclipse times are available and fitting a linear ephemeris to these gives the O–C diagram shown in Figure 5a. Times measured before 1980 are photographic and have a large scatter. Using the more precise photoelectric and CCD measurements since 1980 (HJD > 2444000) gives an orbital period of 0.30047738(1) day and the linear eclipse ephemeris given in Table 3.

A recent paper by Qian *et al.* (2007) argues for a decreasing orbital period and also proposes a third body in the system causing sinusoidal modulation in the O–C diagram. A quadratic ephemeris calculated using the more reliable photoelectric and CCD measurements following HJD 2444000 and including the new times reported here gives a rate of period change of $2.1(2.2) \times 10^{-9}$ days/year, considerably smaller than the rate of $12.4(4.4) \times 10^{-9}$ days/year found by Qian *et al.* and consistent with no secular period change. However, there is an indication of cyclical behavior in the O–C diagram in Figure 5a. A weighted sine fit to the O–C data after HJD 2444000 gives the results listed in Table 5 and shown as a dashed line in Figure 5a. This is a shorter period and smaller amplitude than proposed by Qian *et al.* Observations over a much longer period are required to establish the reality and true parameters of this modulation. With few measurements available, there is little indication of variation in either the out-of-eclipse magnitude of AC Cnc (Figure 5b) or the eclipse depth (Figure 5c and Table 6).

7.4. V363 Aur (also known as Lanning 10)

The data for V363 Aur comprise eighteen published and twenty-seven new eclipse times and show a significant curvature in the O–C diagram with respect to a linear ephemeris, indicating a reducing orbital period (Figure 6a). A quadratic ephemeris, shown as a dashed line in Figure 6a, gives a mean rate of period change of $dP/dt = -6.6(2) \times 10^{-8}$ days/year over the thirty-one years covered by the data. The O–C residuals to this quadratic ephemeris (Figure 6b) show an apparently cyclical variation. A weighted sine fit to the residuals of the quadratic ephemeris gives the results listed in Table 5 and shown as a dashed line in Figure 6b, but these results must be considered speculative as only one cycle has been observed.

Over the past six years the mean orbital period has been 0.32124073(3) day and the eclipse times are well fitted by the linear ephemeris given in Table 3.

Figure 6c shows the out-of-eclipse magnitude of V363 Aur obtained from the AAVSO database plus our new measurements. Although the scatter is large, there appears to have been a slight dip centred around HJD 2449000. Figure 6d and Table 6 show the depth of eclipses of V363 Aur over the same interval. Although there are little data in the early years, recently there has been a progressive reduction in eclipse depth.

7.5. BT Mon

BT Mon is the progenitor system of a classical nova outburst observed in 1939. There are eight published eclipse times plus fourteen new times covering a thirty-four year time span. An O–C diagram with respect to a linear ephemeris shows significant curvature indicating a reducing orbital period (Figure 7a). A quadratic ephemeris, shown as a dashed line in Figure 7a, gives a mean rate of period change of $dP/dt = -3.3(2) \times 10^{-8}$ days/year. The O–C residuals to this quadratic ephemeris are shown in Figure 7b along with a dashed line indicating the results of a weighted sine fit whose parameters are listed in Table 5. This sinusoidal ephemeris is marginally favored over the quadratic ephemeris although, as before, this conclusion must remain tentative until more data are available.

Published eclipse times are scarce in the middle of this time span. Magnitude measurements of BT Mon obtained with the Roboscope system (Honeycutt 2003) between 1991 and 2005 were kindly provided by Kent Honeycutt. The Roboscope data were divided into two groups, before and after the start of 1999. By adopting mean orbital periods from the above quadratic ephemeris for each of these time intervals, two additional eclipse times have been synthesised using the Roboscope data. These have larger errors than directly measured eclipse times and are shown as triangles in Figures 7. They were not used in the above analysis but are consistent with its results and slightly favor the sinusoidal interpretation.

Over the last seventeen years the mean orbital period has been 0.33381322(2) day and eclipse times in the near future may be represented by the linear ephemeris given in Table 3.

Plotting out-of-eclipse magnitudes from Roboscope together with our new data (Figure 7c), we see a noticeable dip around HJD 2451000 followed by a gradual increase. Although there are little data, the eclipse depth shows a slowly decreasing trend over the same interval (Figure 7d and Table 6).

8. Conclusions

When this project started, most published analyses of SW Sex stars concluded that they had constant orbital periods. While the new data confirm that this is true for many of these stars, for some it is clearly not the case. There is a significant difference between the behavior of stars with orbital periods below and above 4 hours. Below 4 hours, ten of the thirteen stars appear to have constant orbital periods with three showing possible signs of low amplitude cyclical variation. The longer period stars all show more dynamic behavior with either a sudden change of orbital period or larger amplitude cyclical variation, either with or without a secular period change.

Eclipse times for all these stars will continue to be monitored to see if those with constant periods maintain this behavior and in the other more interesting cases with longer orbital periods to discover what light further data will shed on the tentative interpretations presented here.

9. Acknowledgements

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Table 1. Eclipsing SW Sex stars studied in this project.

Name	P_{orb} *(hrs)*	*Previously published eclipse times*	*New eclipse times reported here*
HS 0728+6738	3.21	14	24
SW Sex	3.24	32	11
DW UMa	3.28	176	20
HS 0129+2933 = TT Tri	3.35	27	11
V1315 Aql	3.35	71	16
PX And	3.51	38	22
HS 0455+8315	3.57	5	15
HS 0220+0603	3.58	13	13
BP Lyn	3.67	16	13
BH Lyn	3.74	29	16
LX Ser	3.80	50	10
UU Aqr	3.93	50	15
V1776 Cyg	3.95	12	17
RW Tri	5.57	115	21
1RXS J064434.5+334451	6.47	20	22
AC Cnc	7.21	46	11
V363 Aur = Lanning 10	7.71	18	27
BT Mon	8.01	8	14
Total	—	740	298

Table 2. Eclipse times for stars measured in this project with errors and corresponding cycle numbers.

Star/Eclipse time of minimum (HJD)	*Error (d)*	*Cycle number*
HS 0728+6738		
2453810.40077	0.00041	13539
2453836.45653	0.00024	13734
2453851.42254	0.00023	13846
2453853.42648	0.00013	13861
2454174.51418	0.00022	16264
2454181.32859	0.00025	16315
2454185.33706	0.00025	16345
2454186.40643	0.00024	16353
2454473.42029	0.00023	18501
2454493.33001	0.00023	18650
2454507.35967	0.00039	18755
2454835.39541	0.00032	21210
2454891.38182	0.00010	21629
2454895.39084	0.00009	21659
2454907.41644	0.00022	21749
2455188.41832	0.00021	23852
2455191.35834	0.00014	23874
2455200.31029	0.00019	23941
2455515.38459	0.00024	26299
2455520.32865	0.00038	26336
2455533.42346	0.00028	26434
2455889.38551	0.00036	29098
2455891.39036	0.00024	29113
2455893.39432	0.00019	29128
SW Sex		
2454185.43702	0.00044	72965

table continued on following pages

Table 2. Eclipse times for stars measured in this project with errors and corresponding cycle numbers.

Star/Eclipse time of minimum (HJD)	*Error (d)*	*Cycle number*
2454186.38145	0.00029	72972
2454553.41407	0.00048	75692
2454564.34410	0.00020	75773
2454906.41325	0.00019	78308
2454907.49269	0.00019	78316
2455260.35696	0.00018	80931
2455278.43821	0.00012	81065
2455630.35814	0.00026	83673
2455660.44910	0.00014	83896
2455662.33853	0.00028	83910
DW UMa		
2454181.41978	0.00019	58214
2454185.38111	0.00030	58243
2454224.45051	0.00044	58529
2454473.34780	0.00038	60351
2454564.46466	0.00020	61018
2454580.44785	0.00033	61135
2454580.58433	0.00027	61136
2454588.37104	0.00029	61193
2454588.50711	0.00019	61194
2454593.42488	0.00022	61230
2454596.43092	0.00034	61252
2454884.39723	0.00025	63360
2454892.32009	0.00025	63418
2455239.30026	0.00022	65958
2455263.34322	0.00015	66134
2455270.31000	0.00014	66185
2455278.37037	0.00017	66244
2455627.39978	0.00017	68799
2455628.35604	0.00020	68806
2455629.31205	0.00030	68813
HS 0129+2933 = TT Tri		
2454061.46332	0.00014	10892
2454081.29219	0.00016	11034
2454086.45848	0.00008	11071
2455106.37036	0.00038	18375
2455188.47729	0.00030	18963
2455191.27007	0.00019	18983
2455460.49099	0.00013	20911
2455533.38206	0.00022	21433
2455827.45860	0.00014	23539
2455835.41776	0.00016	23596
2455836.39518	0.00010	23603
V1315 Aql		
2454272.50437	0.00018	59916
2454306.44865	0.00027	60159
2454313.43262	0.00072	60209
2454651.48330	0.00048	62629
2454670.48100	0.00046	62765
2454810.31097	0.00082	63766
2455004.47952	0.00029	65156
2455006.43480	0.00049	65170
2455038.42351	0.00055	65399
2455052.39293	0.00070	65499
2455463.36184	0.00047	68441
2455464.33978	0.00036	68448
2455490.32143	0.00026	68634
2455777.38468	0.00040	70689
2455783.39087	0.00040	70732
2455903.24546	0.00047	71590
PX And		
2454318.44729	0.00051	34708
2454319.47234	0.00046	34715
2454325.47261	0.00036	34756
2454448.40773	0.00061	35596
2454473.28943	0.00051	35766
2454503.29163	0.00022	35971
2454761.45718	0.00049	37735
2454770.38547	0.00069	37796
2455064.40680	0.00108	39805
2455066.45577	0.00069	39819
2455173.29503	0.00032	40549

table continued on following pages

Table 2. Eclipse times for stars measured in this project with errors and corresponding cycle numbers, cont.

Star/Eclipse time of minimum (HJD)	*Error (d)*	*Cycle number*
2455186.32065	0.00020	40638
2455188.36884	0.00125	40652
2455191.29553	0.00055	40672
2455201.24653	0.00014	40740
2455460.43876	0.00028	42511
2455495.26963	0.00061	42749
2455515.46733	0.00025	42887
2455795.43984	0.00024	44800
2455819.44115	0.00069	44964
2455823.39248	0.00044	44991
2455901.25250	0.00064	45523
HS 0455+8315		
2454061.40139	0.00016	14807
2454063.48351	0.00020	14821
2454078.35643	0.00014	14921
2454112.41335	0.00017	15150
2454114.49593	0.00023	15164
2454115.38831	0.00017	15170
2454895.44552	0.00018	20415
2454906.45070	0.00013	20489
2454907.34318	0.00026	20495
2455065.43666	0.00029	21558
2455495.39753	0.00032	24449
2455519.49112	0.00017	24611
2455526.48082	0.00018	24658
2455835.38030	0.00021	26735
2455850.40114	0.00018	26836
HS 0220+0603		
2454061.32109	0.00048	10038
2454081.31479	0.00032	10172
2454081.46403	0.00018	10173
2454086.38783	0.00026	10206
2455156.35608	0.00028	17377
2455188.43603	0.00027	17592
2455200.37262	0.00034	17672
2455490.43180	0.00028	19616
2455495.35697	0.00031	19649
2455515.34977	0.00031	19783
2455533.40410	0.00029	19904
2455867.48013	0.00024	22143
2455884.48964	0.00012	22257
BP Lyn		
2454186.44462	0.00069	41257
2454891.36892	0.00095	45870
2454906.49781	0.00084	45969
2455239.32473	0.00058	48147
2455260.41122	0.00042	48285
2455263.31415	0.00049	48304
2455571.38461	0.00074	50320
2455594.30701	0.00042	50470
2455619.52087	0.00059	50635
2455914.44759	0.00041	52565
2455930.34125	0.00063	52669
2455932.32762	0.00066	52682
2455942.41314	0.00039	52748
BH Lyn		
2454181.48914	0.00029	44915
2454186.32132	0.00042	44946
2454199.41436	0.00053	45030
2454482.32954	0.00048	46845
2454834.45234	0.00046	49104
2454884.33284	0.00052	49424
2455247.36666	0.00027	51753
2455260.46000	0.00033	51837
2455267.31793	0.00059	51881
2455594.34608	0.00035	53979
2455628.32676	0.00041	54197
2455670.41251	0.00040	54467
2455675.40111	0.00031	54499
2455895.34197	0.00038	55910
2455902.35570	0.00039	55955
2455941.32605	0.00040	56205

table continued on following pages

Table 2. Eclipse times for stars measured in this project with errors and corresponding cycle numbers, cont.

Star/Eclipse time of minimum (HJD)	*Error (d)*	*Cycle number*
LX Ser		
2454316.41420	0.00032	63266
2454628.52570	0.00023	65236
2454976.44297	0.00038	67432
2454994.50414	0.00026	67546
2455001.47525	0.00033	67590
2455037.43960	0.00020	67817
2455662.45627	0.00040	71762
2455663.40637	0.00045	71768
2455672.43730	0.00041	71825
2455778.42860	0.00031	72494
UU Aqr		
2454323.44995	0.00046	48760
2454357.47405	0.00027	48968
2454365.48955	0.00036	49017
2454728.47437	0.00051	51236
2454735.34486	0.00034	51278
2454736.32601	0.00056	51284
2454789.32574	0.00032	51608
2455038.45994	0.00069	53131
2455059.39716	0.00052	53259
2455106.34585	0.00043	53546
2455469.49424	0.00052	55766
2455490.26865	0.00048	55893
2455778.49715	0.00019	57655
2455795.50952	0.00019	57759
2455893.33048	0.00019	58357
V1776 Cyg		
2454238.48406	0.00059	45659
2454254.46252	0.00044	45756
2454306.51977	0.00050	46072
2454314.42730	0.00053	46120
2454646.54029	0.00092	48136
2454668.44971	0.00092	48269
2454670.42804	0.00080	48281
2454770.42363	0.00115	48888
2454994.46940	0.00068	50248
2455037.46488	0.00052	50509
2455057.39969	0.00051	50630
2455176.34096	0.00062	51352
2455460.34923	0.00100	53076
2455494.45030	0.00101	53283
2455778.46040	0.00052	55007
2455849.46194	0.00052	55438
2455893.28160	0.00088	55704
RW Tri		
2454392.38737	0.00024	57197
2454419.51756	0.00027	57314
2454447.34346	0.00020	57434
2454789.37226	0.00041	58909
2454810.47333	0.00064	59000
2454835.28542	0.00050	59107
2455063.45767	0.00047	60091
2455106.35664	0.00047	60276
2455172.44338	0.00026	60561
2455487.34152	0.00042	61919
2455490.35562	0.00017	61932
2455533.48590	0.00023	62118
2455822.41233	0.00026	63364
2455828.44141	0.00023	63390
2455867.39741	0.00048	63558
2455881.31079	0.00014	63618
2455889.42621	0.00028	63653
2455914.23796	0.00028	63760
2455950.41154	0.00024	63916
2455953.42610	0.00051	63929
2455957.36910	0.00018	63946
1RXS J064434.5+334451		
2455307.42924	0.00074	7067
2455310.39210	0.00056	7078
2455313.35557	0.00049	7089
2455627.44814	0.00048	8255

table continued on next page

Table 2. Eclipse times for stars measured in this project with errors and corresponding cycle numbers, cont.

Star/Eclipse time of minimum (HJD)	*Error (d)*	*Cycle number*
2455629.33392	0.00043	8262
2455634.45149	0.00035	8281
2455655.46296	0.00045	8359
2455658.42635	0.00025	8370
2455682.39947	0.00042	8459
2455685.36351	0.00051	8470
2455850.48993	0.00045	9083
2455854.53082	0.00023	9098
2455891.43482	0.00015	9235
2455905.44214	0.00063	9287
2455914.33106	0.00043	9320
2455924.29847	0.00046	9357
2455932.37955	0.00032	9387
2455949.35041	0.00027	9450
2455953.38926	0.00037	9465
2455957.43085	0.00052	9480
2455959.31737	0.00024	9487
2455960.39430	0.00028	9491
AC Cnc		
2454199.45197	0.00026	32978
2454507.44198	0.00021	34003
2454891.45161	0.00036	35281
2454892.35306	0.00032	35284
2455260.43835	0.00023	36509
2455270.35440	0.00042	36542
2455619.50814	0.00082	37704
2455630.32565	0.00024	37740
2455675.39674	0.00047	37890
2455949.43118	0.00029	38802
2455959.34723	0.00034	38835
V363 Aur = Lanning 10		
2454181.39163	0.00043	29957
2454392.44674	0.00017	30614
2454447.37885	0.00024	30785
2454471.47221	0.00031	30860
2454473.39980	0.00037	30866
2454810.38137	0.00031	31915
2454827.40653	0.00042	31968
2454835.43772	0.00044	31993
2454891.33360	0.00054	32167
2454892.29747	0.00021	32170
2455188.48144	0.00054	33092
2455191.37255	0.00040	33101
2455200.36736	0.00026	33129
2455515.50429	0.00013	34110
2455516.46885	0.00021	34113
2455524.49896	0.00034	34138
2455526.42586	0.00026	34144
2455627.29626	0.00020	34458
2455634.36298	0.00020	34480
2455649.46157	0.00047	34527
2455854.41351	0.00026	35165
2455888.46463	0.00016	35271
2455891.35618	0.00021	35280
2455905.49122	0.00039	35324
2455914.48560	0.00015	35352
2455950.46438	0.00013	35464
2455954.31900	0.00028	35476
BT Mon		
2454447.47617	0.00043	32820
2454891.44778	0.00052	34150
2454892.44988	0.00045	34153
2455238.27878	0.00050	35189
2455239.28089	0.00082	35192
2455257.30609	0.00035	35246
2455260.31093	0.00041	35255
2455277.33531	0.00068	35306
2455571.42510	0.00058	36187
2455595.46030	0.00062	36259
2455600.46698	0.00093	36274
2455619.49354	0.00048	36331
2455960.31808	0.00089	37352
2455968.33013	0.00047	37376

Table 3. Linear ephemerides for the SW Sex stars in the project. For RW Tri, 1RXS J064434.5+334451, AC Cnc, V363 Aur, and BT Mon this linear ephemeris only represents behavior in the recent past. Over longer time intervals their behavior is more complex (see text).

Star	*Ephemerides*
HS 0728+6738	2452001.32739(8) + 0.133619437(4) E
SW Sex	2444339.64968(11) + 0.134938490(2) E
DW UMa	2446229.00601(8) + 0.136606547(2) E
HS 0129+2933 = TT Tri	2452540.53218(9) + 0.139637462(6) E
V1315 Aql	2445902.84037(10) + 0.139689961(2) E
PX And	2449238.83661(17) + 0.146352746(4) E
HS 0455+8315	2451859.24679(15) + 0.148723901(8) E
HS 0220+0603	2452563.57407(7) + 0.149207696(5) E
BP Lyn	2447881.85799(23) + 0.152812531(6) E
BH Lyn	2447180.33522(41) + 0.155875629(8) E
LX Ser	2444293.02345(18) + 0.158432492(3) E
UU Aqr	2446347.26651(6) + 0.163580450(2) E
V1776 Cyg	2446716.67956(27) + 0.164738679(6) E
RW Tri	2441129.35318(49) + 0.231883392(9) E
1RXS J064434.5+334451	2453403.75955(12) + 0.26937447(4) E
AC Cnc	2444290.30892(36) + 0.30047738(1) E
V363 Aur = Lanning 10	2444557.98318(89) + 0.32124073(3) E
BT Mon	2443491.72616(45) + 0.33381322(2) E

Table 4. Parameters of possible cyclical variation in orbital period for SW Sex, LX Ser, and UU Aqr.

Star	*Cyclical period (years)*	*Semi-amplitude (seconds)*	*Sinusoidal ephemeris rms residual*	*Linear ephemeris rms residual*
SW Sex	24.0(7)	69(5)	32.1	65.2
LX Ser	28(2)	48(6)	55.7	69.4
UU Aqr	20.3(6)	48(4)	34.9	43.6

Table 5. Parameters of possible cyclical variation in orbital period for RW Tri, AC Cnc, V363 Aur, and BT Mon.

Star	*Cyclical period (years)*	*Semi-amplitude (seconds)*	*Sinusoidal ephemeris rms residual*	*Linear ephemeris rms residual*	*Quadratic ephemeris rms residual*
RW Tri	36.7(4)	161(5)	80.8	128.0	—
AC Cnc*	13.5(3)	140(13)	106.8	141.3	139.5
V363 Aur	27.7(7)	119(6)	58.8	—	92.2
BT Mon	29(2)	113(15)	62.0	—	67.7

**Only including data after HJD 2444000.*

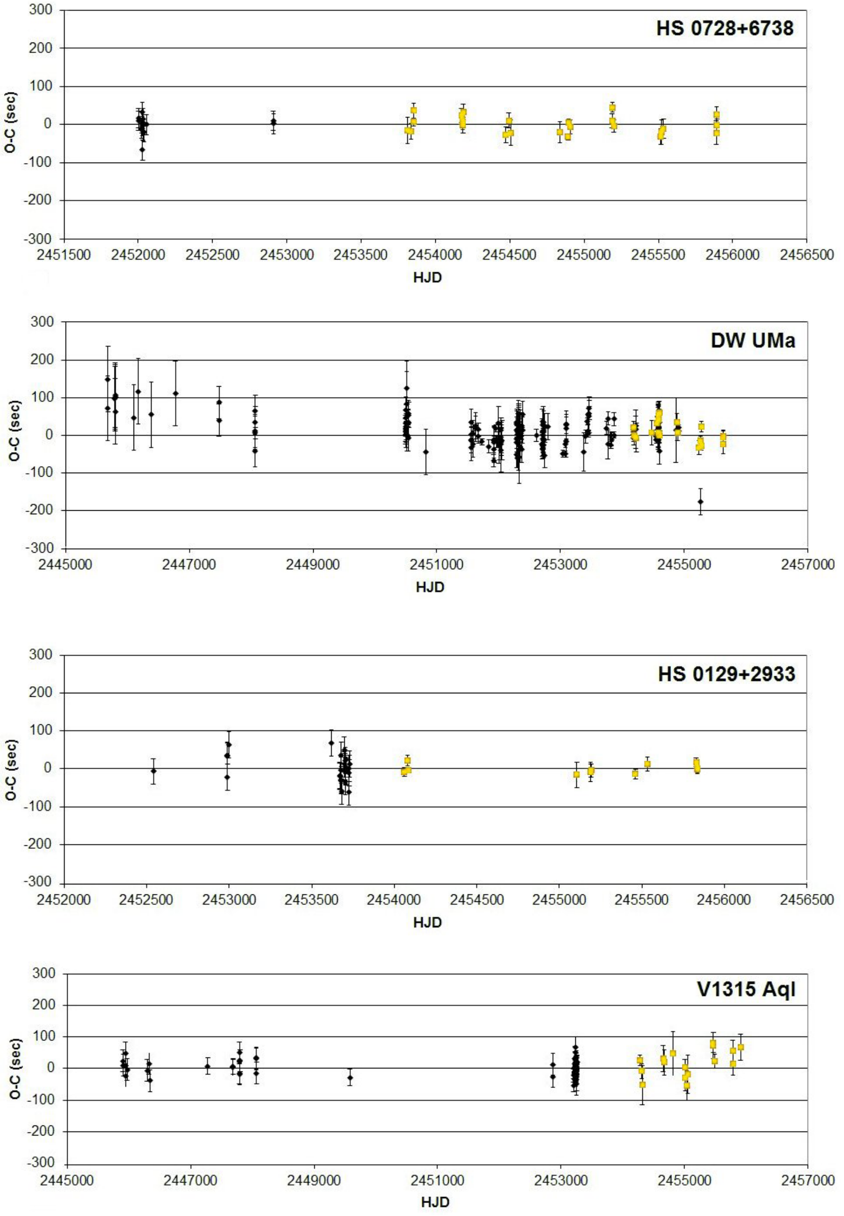
Table 6. Eclipse depth measured in this project for RW Tri, 1RXS J064434.5+334451, AC Cnc, V363 Aur, and BT Mon.

Eclipse time (HJD)	*Eclipse depth (magnitude)*
RW Tri	
2454392.38737	1.72
2454419.51756	1.84
2454447.34346	1.96
2454810.47333	1.84
2454835.28542	1.63
2455063.45767	1.76
2455106.35664	1.92
2455172.44338	1.89
2455487.34152	1.78
2455490.35562	1.71
2455533.48590	1.84
2455822.41233	1.62
2455828.44141	1.43
2455867.39741	1.59
2455881.31079	1.81
2455889.42621	1.89
2455914.23796	1.69
2455950.41154	2.06
2455953.42610	1.97
2455957.36910	1.56
1RXSJ064434.5+334451	
2455307.42924	1.13
2455310.39210	1.06
2455627.44814	1.26
2455629.33392	1.27
2455634.45149	0.90
2455655.46296	1.22
2455658.42635	1.29
2455682.39947	1.31
2455685.36351	1.23
2455850.48993	1.17
2455854.53082	1.11
2455891.43482	1.12
2455905.44214	1.13
2455914.33106	1.08
2455932.37955	1.14
2455949.35041	1.02
2455953.38926	1.07
2455957.43085	0.94
2455959.31737	0.97
2455960.39430	1.14
AC Cnc	
2454199.45197	0.96
2454507.44198	1.04
2454891.45161	0.94
2454892.35306	0.92
2455260.43835	1.00

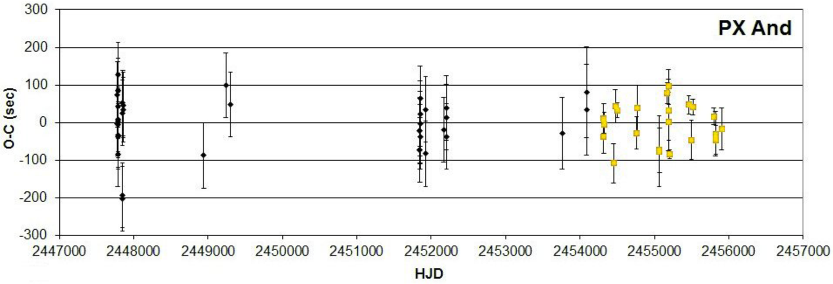
table continued on next page

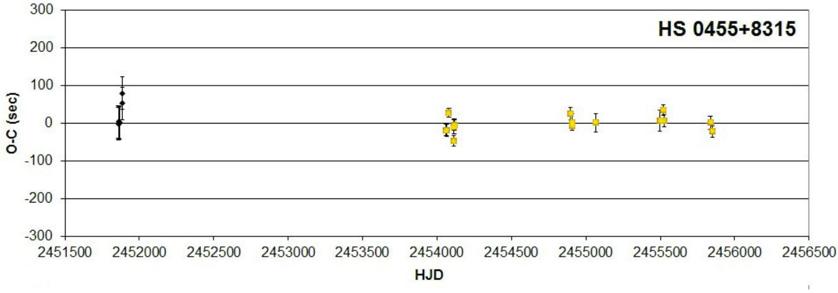
Table 6. Eclipse depth measured in this project for RW Tri, 1RXS J064434.5+334451, AC Cnc, V363 Aur, and BT Mon, cont.

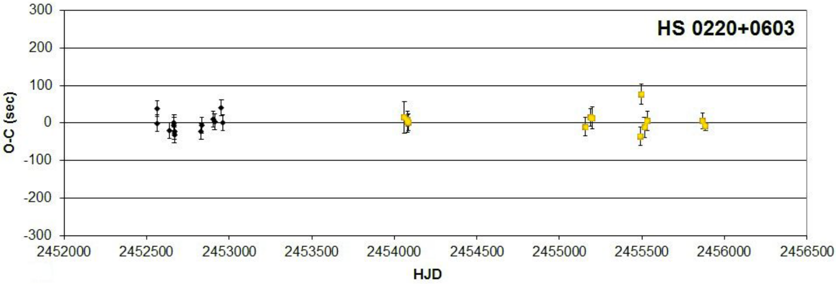
Eclipse time (HJD)	*Eclipse depth (magnitude)*	*Eclipse time (HJD)*	*Eclipse depth (magnitude)*
2455630.32565	0.87	2455634.36298	0.68
2455949.43118	1.14	2455649.46157	0.69
		2455854.41351	0.58
V363 Aur = Lanning 10		2455888.46463	0.53
2454392.44674	0.80	2455891.35618	0.62
2454447.37885	0.71	2455905.49122	0.65
2454471.47221	0.90	2455950.46438	0.71
2454473.39980	0.83		
2454810.38137	0.62	BT Mon	
2454827.40653	0.66	2454891.44778	1.74
2454835.43772	0.77	2454892.44988	1.82
2454892.29747	0.64	2455257.30609	2.01
2455191.37255	0.76	2455260.31093	1.90
2455515.50429	0.56	2455277.33531	1.96
2455516.46885	0.68	2455571.42510	1.61
2455524.49896	0.60	2455960.31808	1.49
2455526.42586	0.48	2455968.33013	1.62
2455627.29626	0.62		

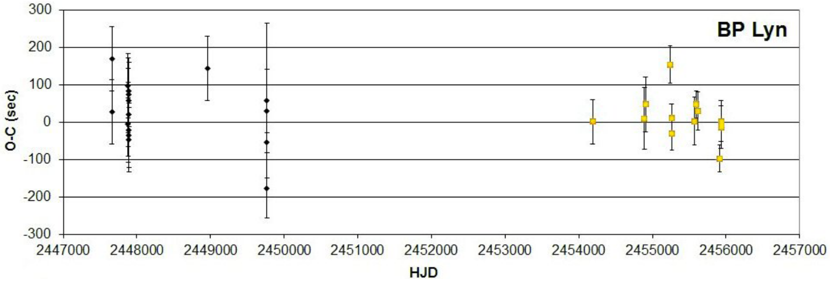


Figures 1a–j, O–C diagrams with respect to the linear ephemerides in Table 3 for those SW Sex stars with $P_{orb} < 4$ hours which are consistent with constant orbital periods. Previously published observations are marked as black dots and new eclipse times as light squares in this and subsequent figures (continued on next page).

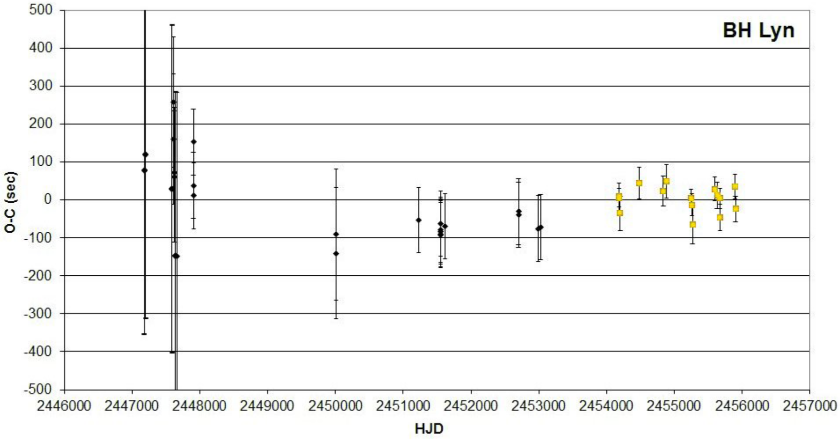


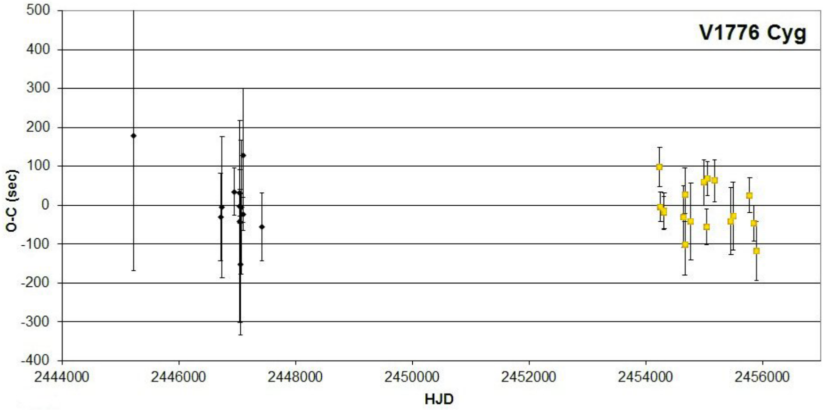






Figures 1a–j, cont. O–C diagrams with respect to the linear ephemerides in Table 3 for those SW Sex stars with $P_{orb} < 4$ hours which are consistent with constant orbital periods. Previously published observations are marked as black dots and new eclipse times as light squares in this and subsequent figures (continued on next page).





Figures 1a–j, cont. O–C diagrams with respect to the linear ephemerides in Table 3 for those SW Sex stars with P_{orb} < 4 hours which are consistent with constant orbital periods. Previously published observations are marked as black dots and new eclipse times as light squares in this and subsequent figures.

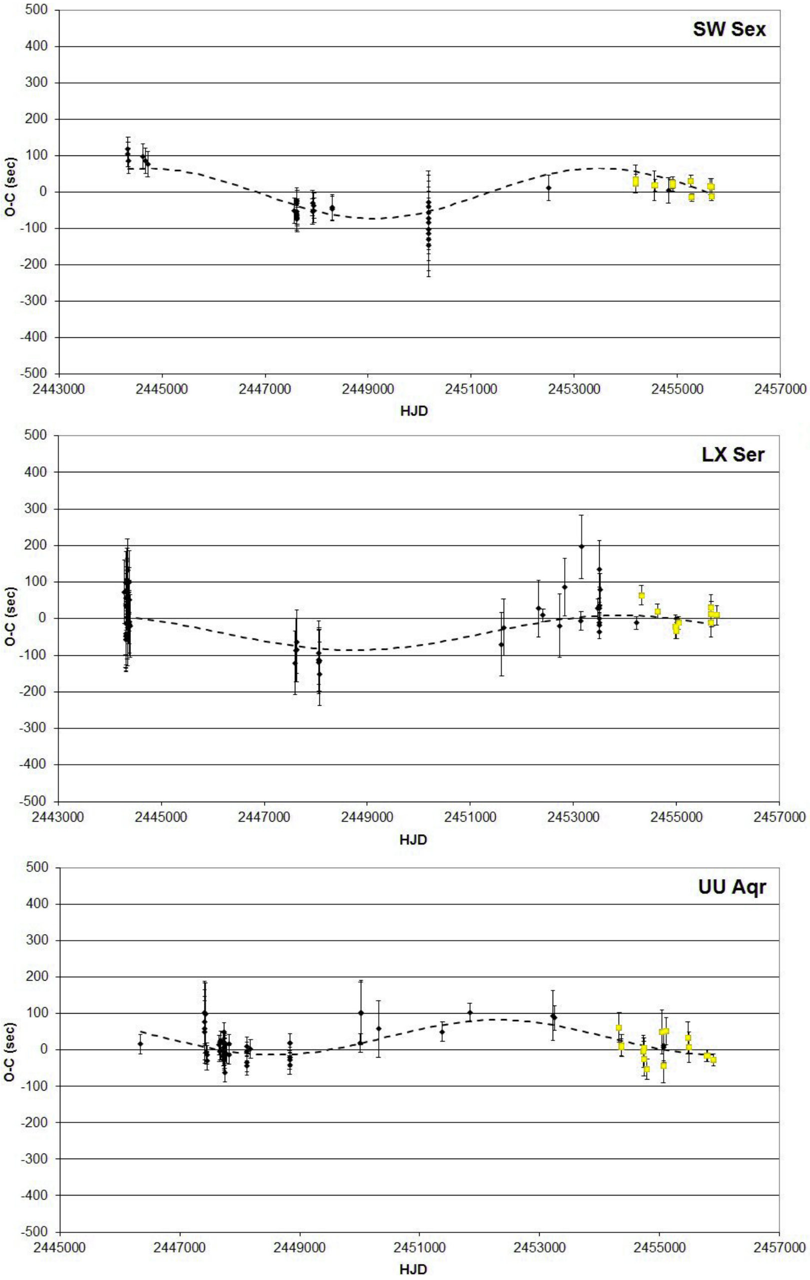


Figure 2. O–C diagrams with respect to the linear ephemerides in Table 3 for those SW Sex stars with $P_{orb} < 4$ hrs which show possible cyclical variation in orbital period (dashed lines).

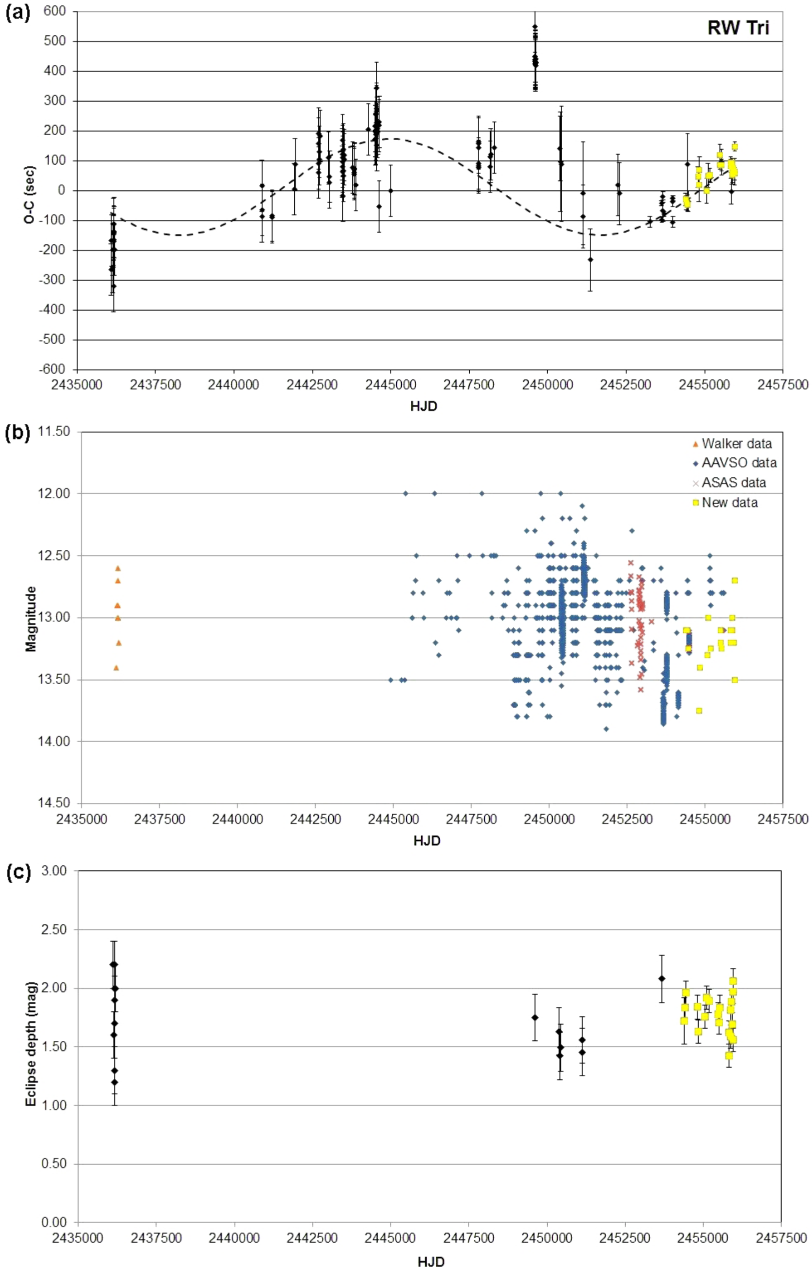


Figure 3. RW Tri: (a) O–C diagram with respect to a linear ephemeris showing a cyclical variation of orbital period (dashed line), (b) out-of-eclipse magnitude, and (c) eclipse depth.

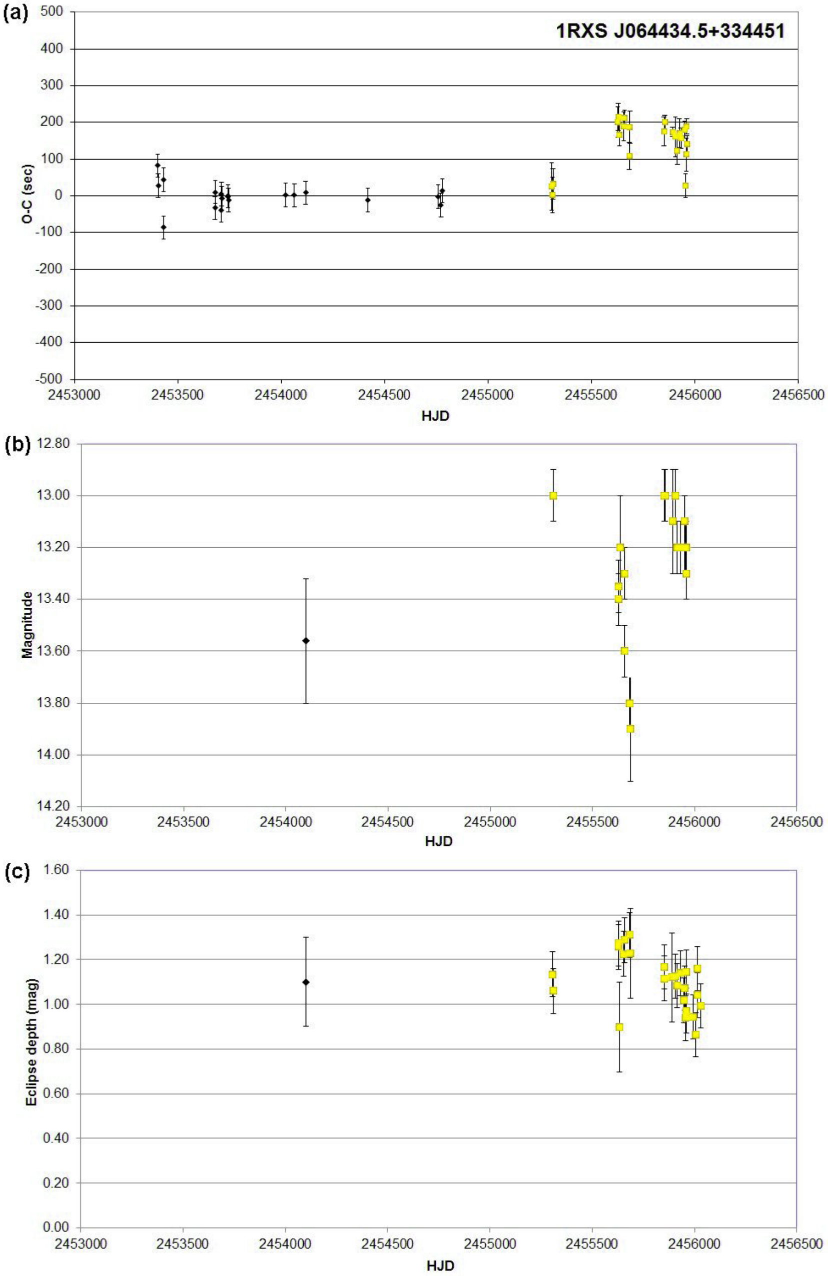


Figure 4. 1RXS J064434.5+334451: (a) O–C diagram with respect to a linear ephemeris for HJD < 2455500, (b) out-of-eclipse magnitude, and (c) eclipse depth.

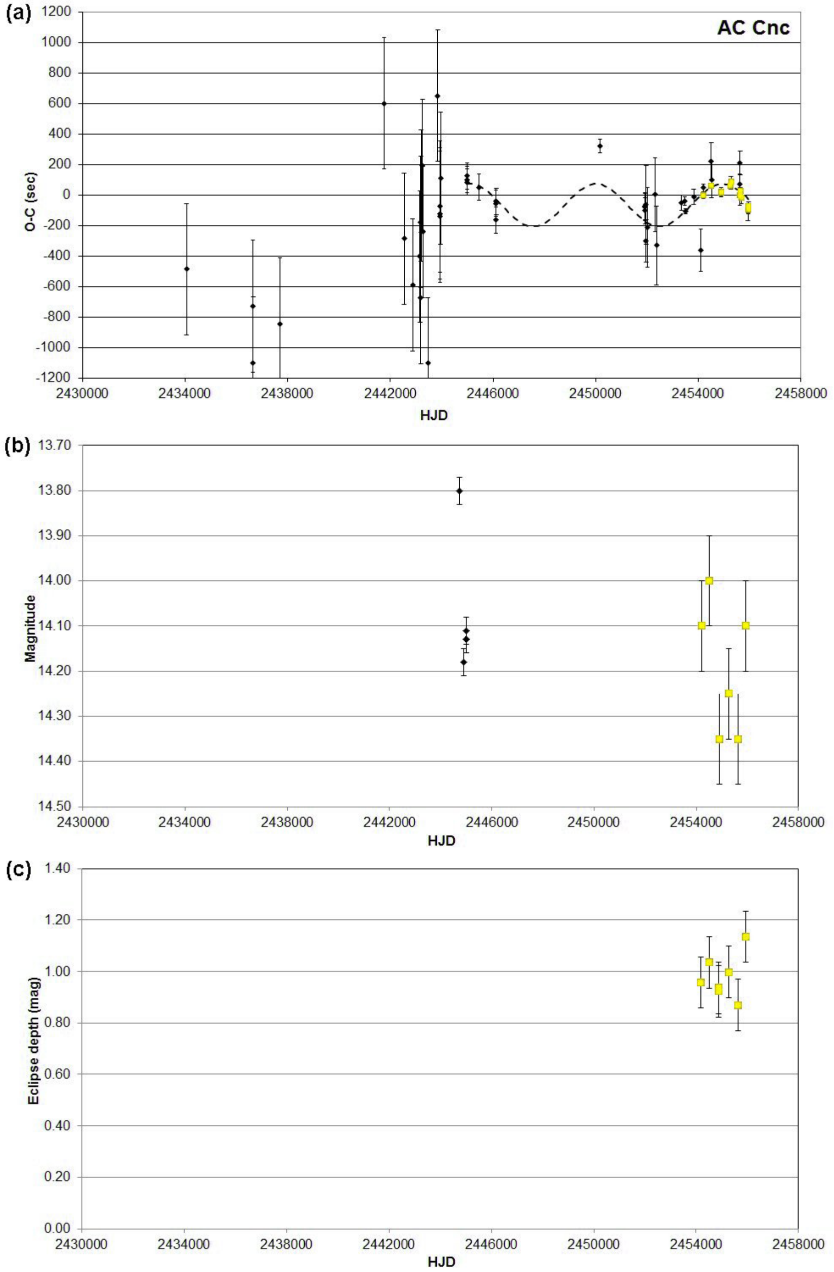


Figure 5. AC Cnc: (a) O–C diagram with respect to a linear ephemeris showing a cyclical variation of orbital period (dashed line), (b) out-of-eclipse magnitude, and (c) eclipse depth.

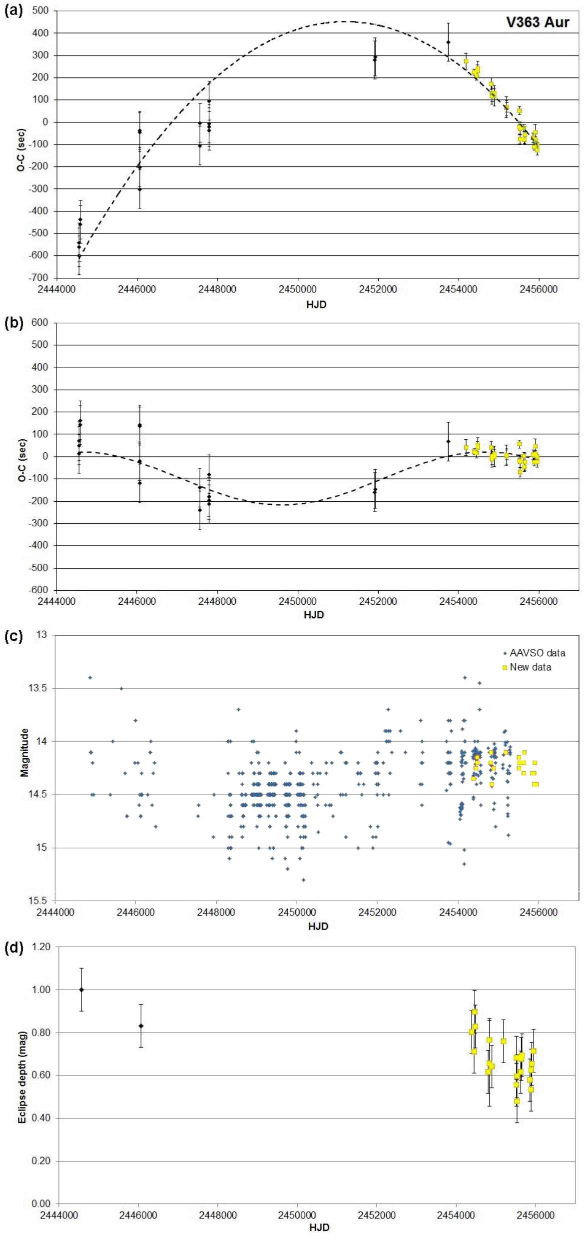


Figure 6. V363 Aur: (a) O–C diagram with respect to a linear ephemeris showing a quadratic ephemeris (dashed line), (b) O–C diagram with respect to a quadratic ephemeris showing a cyclical variation of orbital period (dashed line), (c) out-of-eclipse magnitude, and (d) eclipse depth.

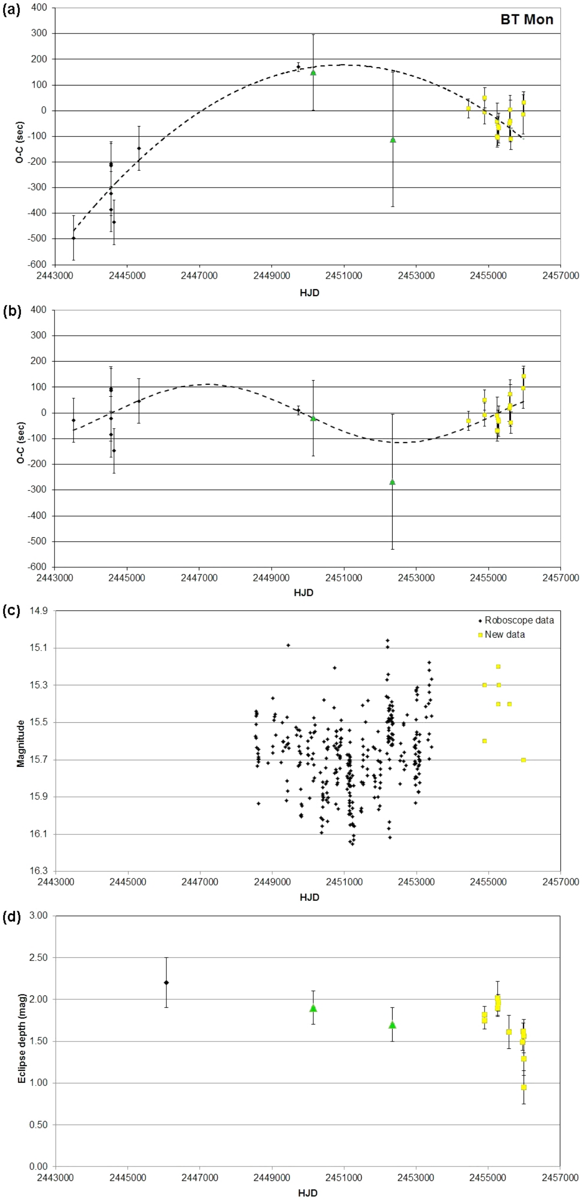


Figure 7. BT Mon: (a) O–C diagram with respect to a linear ephemeris showing a quadratic ephemeris (dashed line), (b) O–C diagram with respect to a quadratic ephemeris showing a cyclical variation of orbital period (dashed line), (c) out-of-eclipse magnitude, and (d) eclipse depth. Eclipses synthesised using Roboscope data are shown as triangles.

Hubble's Famous Plate of 1923: a Story of Pink Polyethylene

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Abstract On October 6, 1923, Edwin Hubble used the Mount Wilson 100-inch telescope to take a 45-minute exposure of a field in the Andromeda galaxy. This is the now-famous plate marked with his “VAR!” notation. I will discuss this plate and that notation. I will also tell the story of flying copies of that plate on the deployment mission for HST in 1990 as a Hubble memento and then locating those copies afterwards, and how copies were flown on Servicing Mission 4 on 2009 as well. This has led to an effort in which AAVSO members joined to identify and re-observe that noted star, arguably the most important object in the history of cosmology, but largely ignored since Hubble’s time.

1. Introduction—Hubble's discovery

On the night of October 6 (UT), 1923, Edwin Hubble took an astronomical photograph that is now famous (Figure 1). He used the 100-inch Hooker telescope on Mount Wilson to expose a 4 × 5-inch glass plate for 45 minutes under conditions of fair seeing. The object observed was the great nebula in Andromeda, M31. Standard practice with photographic plates was to use a dull pencil to write the plate number near the edge; the pressure activated the emulsion and caused the writing to show up when the plate was developed. Hubble wrote additional information on the emulsion side of the plate as well in ink (emulsion used, seeing conditions, and hour angle).

Hubble had been hired by the Director of Mount Wilson, George Ellery Hale, to do exactly what he was doing: to use the power of the world’s largest telescope to study the size and structure of our Universe. Hale himself is best known for his pioneering work in solar physics at Mount Wilson, but he knew talent when he saw it, and Edwin Hubble was a very capable young astronomer. Hale was a gifted impressario of astronomy who pursued ground-breaking work of his own (particularly on solar magnetism) and who could enlist the assistance of people like Andrew Carnegie, a major supporter of Mount Wilson and the institutions that succeeded it under the aegis of the Carnegie Institution of Washington.

Hubble was hoping to find Cepheids in M31 because that would make it possible to determine its distance. To understand why that mattered, you need to take yourself back to the early 1920s. The big event for astronomy was the

Curtis-Shapley debate, held at the Smithsonian Museum of Natural History, in Washington, D.C., in April 1920. Virginia Trimble (1995) has written a particularly good account of the debate and its context that you should read in order to understand why Hubble made his observations. At the time, no one was sure how big our Galaxy is, where we are in it, or if there were other galaxies like ours.

Cepheids, of course, are variable stars of a particular type. They are intrinsically very bright, and so relatively easy to detect even in other galaxies. Also, the range of variation is a magnitude or more, also easily detectable even looking by eye at photographic plates. What makes them so valuable to cosmologists is that Cepheids are pulsating stars (as we know now) that have a definite relationship between the observed period and the star's intrinsic luminosity (the composition of the star also matters, but that wasn't known then). This period-luminosity relation for Cepheids had been measured by Henrietta Leavitt (Figure 2) at the Harvard College Observatory, using observations of the Magellanic Clouds. The distance to the Clouds wasn't known, but it was reasonable to assume all the stars were the same distance.

Leavitt's period-luminosity relation was published in 1912 (Leavitt and Pickering 1912) and was well known. A year later Ejnar Hertzsprung (1913) used observations of Cepheids in the Milky Way to calibrate the relationship so that absolute distances could be derived. If an object like M31 were indeed a separate, external galaxy and not part of the Milky Way (the crux of the debate), finding Cepheids was the way to do it, and only Hubble had the needed access to the telescope that could detect stars that faint.

Edwin Hubble's effort took years, being published in 1929. That was because he needed dozens of separate exposures well-spaced over time, followed by careful effort to determine magnitudes (Hubble 1929). But the critical first step was finding Cepheids to measure in the first instance, and that's why his excitement ("VAR!") showed.

2. The Hubble plate revisited

Why am I telling you this? The reason goes back more than twenty-five years for me. When I started working at the Space Telescope Science Institute, in May 1984, the launch of HST was scheduled for 1986, and I was especially thrilled because a friend from graduate school, Steve Hawley, had been named to the astronaut crew that would deploy the telescope on that flight of the space shuttle. It occurred to me that it would be a nice thing to carry something along on the deployment mission that would tie Hubble the man to Hubble the telescope: a memento. The first thing that came to mind in thinking about Hubble the man was his pipe (Figure 3), which seems to show up in almost every photo of him. I contacted Allan Sandage, himself an observational cosmologist and a protege of Edwin Hubble in the early 1950s at Mount Wilson. Sandage was probably the one person most familiar with Edwin Hubble and his work, and he suggested the photographic plate shown in Figure 1. Indeed, it is pretty much the perfect Hubble memento: It was taken with Hubble's own hands and it embodies both the key science he pursued in his career and one of the primary goals for building the Space Telescope that was named after him, and it marked a key moment in modern science history.

I arranged to borrow the 4 × 5-inch original plate from the Mount Wilson archives (by then part of The Observatories, in Pasadena, California, and now known as the Carnegie Observatories), and a first question I asked myself was: Should we fly the original plate, or a copy of it? David De Vorkin at the Smithsonian's Air and Space Museum answered by noting that flying the original plate didn't really add to its historical value, and it's an important artifact in its own right, one worth preserving. Given that, and the likely reluctance of NASA to have something made of glass on the space shuttle, I opted to make film copies. Our staff photographer at STScI, John Bedke, had himself worked for years with Sandage in Pasadena and had helped to preserve many of Hubble's original plates by reprocessing them (Hubble was impatient and would pull plates from the fixer prematurely).

But why? Why do this at all? My idea at the time was that I would arrange to fly about ten copies of Hubble's plate, and, once they were returned, we'd have prints made from each, nicely matted and framed. Then we'd give these to the institutions that had played key roles in the development, construction, and launch of HST and send an astronomer to those places to say thanks for building us such a wonderful instrument, and here are some of the things we're doing with it. In other words, the idea was to reach back to the people who built HST.

But could you just ask NASA to fly something like that on the shuttle? Well, yes, actually you could. When a NASA facility like the Marshall Space Flight Center (MSFC), in Huntsville, Alabama, used the space shuttle to launch a mission that it had developed, they got to put on board something called the Official Flight Kit (OFK; you knew we were going to get into the three-letter abbreviations, right?). Also, the astronauts for a given flight got to take along personal items that could include just about anything, subject to size and weight limits. I could have given one of the film copies of Hubble's plate to Steve Hawley, but it didn't seem reasonable to ask him to take ten, and besides, I wanted to do this through official channels.

Once I had the copies of the plate I contacted the HST Project Manager at MSFC, Fred Wojtalik, and explained what I wanted to do. He agreed to include the film copies in the MSFC OFK, and so I sent them off to him. That gets us to the end of the beginning of this story.

Those of you of a certain age will recall vividly that after HST was launched it quickly became clear that Hubble's primary mirror was highly flawed and had significant spherical aberration. Instead of being an object of great pride, Hubble turned into a huge embarrassment for NASA. Going to parties and seeing neighbors was an exercise in damage control, combined with a bit of spin ("It's not that bad." It really was that bad.). Nevertheless, I contacted Mr. Wojtalik at MSFC to get the flown negatives returned. He requested a description of how they would be used, given that they were now official NASA materials, and I provided that. But the negatives didn't come. Under the circumstances, my immediate enthusiasm for the project had diminished and I didn't ever get them (I should have tried harder). Over the subsequent years I would make inquiries of NASA people I would meet who might have information, all without success.

That gets us to the beginning of the end. In 2006, new NASA Administrator Mike Griffin reinstated Servicing Mission 4 (SM4) for HST. The history of servicing Hubble with the space shuttle involves lots of stories waiting to be told, but one particular aspect of SM4 was that NASA declared that it would be the last shuttle mission to the observatory, period. Obviously I had to find those missing negatives because if I could, and if I could refly them on SM4 then we would achieve a rare case of cosmic symmetry: artifacts flown on missions that bookended Hubble's connection to human spaceflight.

I called and e-mailed lots and lots of people, many involved in the HST project in the 1980s. I found lots of new friends—every single person I talked to was enthusiastic about what I was trying to do—but I never found the negatives. Over many months new leads would pop up, but all proved futile. At one point I ran into Steve Hawley while he was here at STScI attending a conference and we talked. He mentioned that there was a person at Johnson Space Center, in Houston, who was the OFK Coordinator, Ms. Abby Cassell. I called her in May, 2008, and explained why. I knew that the items flown in MSFC's OFK in 1990 had been returned to Marshall, and she confirmed that, noting that their OFK included a plaque, 7,000 American flags, and ten negatives. I at least had proof my negatives had flown! I asked her if something flown in an OFK would be recognizable if it were sitting on a shelf somewhere, and she said "Yes, we shrink-wrap everything in pink polyethylene before it's put on board the shuttle." But then a thought came to her and she asked me to wait while she looked in her vault. She came back in a few minutes to tell me that back in 1990, when the negatives were flown, they would have been shrink wrapped in lavender polyethylene. That is probably a completely useless piece of information, yet I treasure it.

By that time in 2008, the launch of SM4 was only months away and there was no longer time to go through the effort of including the negatives even if I found them. I had to give up. But I still had five copies left, and so this time I made sure that there was redundancy. I gave one to John Grunsfeld for him to carry personally as a member of the SM4 crew, and another to Dave Leckrone, the HST Project Scientist at Goddard Space Flight Center, for him to include in GSFC's OFK. I got both of them back, the first from John Grunsfeld (Figure 4); I was a happy guy.

3. The Hubble discovery reaffirmed

Once they were returned an obvious question came to mind: Had HST ever observed that Cepheid that Edwin Hubble discovered back in 1923? That star could be called the most significant object in the history of cosmology because of its key role in establishing the cosmic distance scale. But how could I tell? A blue-sensitive plate from 1923 can look a lot different from a modern digital sky image, and Hubble's published coordinates were rough. I could tell that Hubble's plate included M31's nucleus, but it was hard to say just what the scale or orientation was. Photographic plates do not come with World Coordinate System headers! Fortunately, here at STScI we have Tom Brown, an astronomer who has studied M31 extensively, particularly its outer regions. It was easy for him to pinpoint the coordinates and so we could then see that several recent HST/WFPC2 exposures were very close to Hubble's Variable no. 1, but not on it.

The Hubble Heritage Program here at STScI helped by using some of their HST time to observe the star and its field with the new WFC3 camera on HST. Hubble Heritage is well known for their extraordinary images that have captured the public's attention and delight. We wanted to catch the Cepheid both when it was near its brightest and faintest, but the star had not been observed in a very long time (since the 1960s) and so the phase was unknown. That's when the AAVSO stepped in to help by providing ground-based observations of the field to re-establish the light curve (Templeton *et al.* 2011; NASA 2011).

The result was released at the May 2011 joint meeting of the AAVSO and the American Astronomical Society (AAS) held in Boston. One poignant aspect to me is that in the 21st century, citizen-scientists have access to and can afford the means to put telescopes and instruments in their backyards that can do better than Edwin Hubble could with the world's largest telescope in 1923. We have come so very far.

So that's the story, pretty much to its end. Despite initial setbacks, HST has been an enormous success and continues to advance astronomy in ways that amaze. We now use it in ways its original proposers could not even conceive of, answering questions they could even yet ask. It deserves commemoration.

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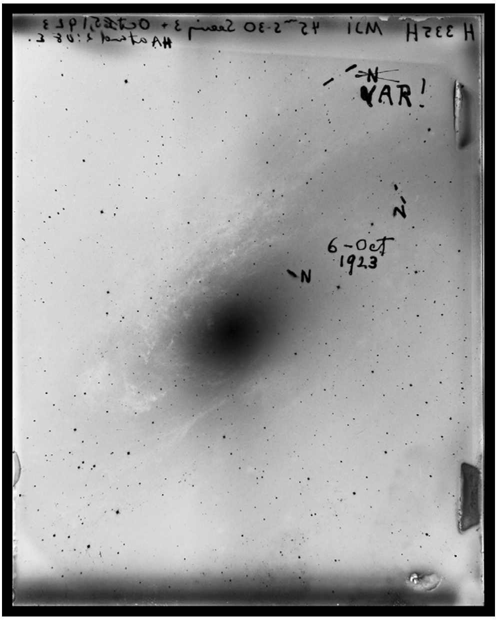

Figure 1. Hubble's plate of 1923.

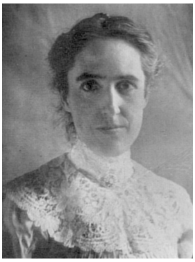

Figure 2. Henrietta S. Leavitt.

Figure 3. Edwin Hubble and his pipe.

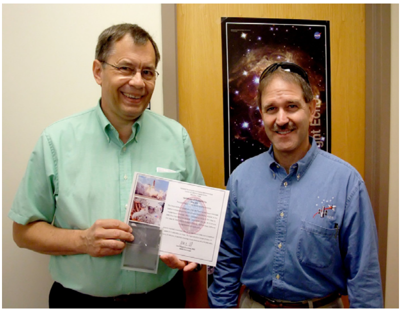

Figure 4. The author (left) and astronaut John Grunsfeld after one of the negatives was returned to me.

Things We Don't Understand About RR Lyrae Stars

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Abstract RR Lyrae stars have been identified as a distinct class of variable star for slightly longer than the century the AAVSO has existed as an organization. Although considerable progress has been made in understanding RR Lyrae variables over the past century, several aspects of their pulsation remain puzzling. This paper reviews some of the more poorly understood properties of these pulsating variable stars, with emphasis on the contributions that might be made by observers associated with the AAVSO and similar organizations.

1. RR Lyrae stars

Although RR Lyrae itself, the brightest known member of its namesake type of variable star, was discovered by Williamina Fleming at the end of the 19th century (Pickering 1901), it was through observations of globular clusters that the properties of these short period variables were first defined. Solon Bailey and his associates identified numerous variable stars in their photographic studies of globular clusters during the 1890s and early 1900s. Most of these variables had short periods, between 0.2 and 0.9 day, and are what we should today call RR Lyrae stars. However, so closely were these short period variables associated with globular clusters that they were often called "cluster variables" until the 1950s (Smith 1995). Bailey (1902) divided RR Lyrae stars into subclasses based upon the periods and light curve shapes of variables in the globular cluster ω Centauri. Originally three in number, types a, b, and c, these Bailey types are now usually condensed to two varieties, type ab and type c. RRc variables have shorter periods than RRab stars, and usually have smaller amplitudes as well. Because of the smaller amplitudes, RRc stars are often more incompletely discovered than RRab stars in variable star surveys. It was later realized that RR Lyrae of type ab are pulsating in the fundamental radial mode, whereas those of type c are pulsating in the first overtone radial mode. Because of this, RRab stars are sometimes called RR0 stars, while RRc variables are RR1 stars. Double mode RR Lyrae stars (RRd or RR01 stars) have also been discovered, which pulsate simultaneously in the fundamental and first overtone modes. The existence of RR Lyrae variables pulsating in the second overtone mode, RRe stars, remains more controversial (Kovacs 1998).

Shapley (1918) realized that RR Lyrae stars were important standard candles for measuring the distances to globular clusters, and they remain among the main objects for determining the distances to very old stellar populations. RR Lyrae stars are relatively low mass ($\approx 0.6-0.8M_{\odot}$) stars that are undergoing core helium burning on the horizontal branch in the HR diagram. The very existence of RR Lyrae variables in a stellar system is indicative of a stellar population older than about 10 Gyr (Smith 1995; Percy 2007).

Despite the progress that has been made in understanding RR Lyrae stars, there are important questions that remain unanswered. The solutions to some of these questions probably will fall to professional astronomers. For example, accurate parallaxes for RR Lyrae stars are needed to calibrate their absolute magnitudes (Benedict *et al.* 2011), and space-based efforts such as the GAIA mission (de Bruijne 2012) may be needed fully to resolve that issue.

However, other open questions are more amenable to being tackled by amateur observers, or by amateurs and professionals working in tandem. These areas where ignorance continues are the focus of the remainder of this paper.

2. Long term period changes

Eddington (1918) posed an important observational question regarding the period changes of Cepheid variable stars that applies equally to RR Lyrae variables: "It would be of great interest to determine the change in period (if any) of these stars, some of which have been under observation for many years; because this would give a means of measuring a very slight change of density, and so determine the rate of stellar evolution and the length of life of a star." The connection of period changes to density changes comes via the basic pulsation equation: $P\sqrt{\rho} = Q$, where P is the pulsation period, ρ is the mean density of the star, and Q is the so-called pulsation constant.

Stellar evolution theory predicts that there ought to occur slow changes in the period of an RR Lyrae star as it gradually fuses its central helium into carbon and oxygen. These changes are predicted to occur at a small and nearly constant rate during the span of a century or two (Koopmann *et al.* 1994), though the rates of period change can become larger as the RR Lyrae star begins to exhaust its core helium. To test these predictions, photometry of RR Lyrae stars is needed extending over as long a time interval as possible. For some RR Lyrae variables, the observational record already spans more than a century.

While there are indeed some RR Lyrae variables for which the observed rates of period change are small and nearly constant, consistent with the predictions of stellar evolution theory, others present challenges to the theoretical framework. More RR Lyrae stars show large period changes than would be expected from their theoretical rates of period change. Moreover, some RR Lyrae stars have been observed to swing between period increases and period decreases on a timescale of a few years, something not predicted by stellar evolution theory. XZ Cygni, one example of such a misbehaving variable, is an RR Lyrae star to which AAVSO observers have devoted particular attention. Discovered in 1905, XZ Cyg showed only a modest decrease in period during the first half century that it was observed (Klepikova 1958). However, beginning in 1965, the period of XZ Cyg declined steeply in several steps before sharply increasing again in 1979 (Baldwin and Samolyk 2003).

Thus, RR Lyrae stars appear to show some sort of period noise on top of any long term evolutionary period changes. Some have hypothesized the existence of short term instabilities that produce this period change noise but which, when observed long enough, would average out to the period change rate expected from stellar evolution theory (Sweigart and Renzini 1979).

Continued monitoring of the long term period behavior of field RR Lyrae stars is thus necessary to resolve several outstanding problems relating to period changes. Over the long term, will the period changes of all RR Lyrae stars fall into line with the predictions of stellar evolution theory? If so, how long do we have to watch an RR Lyrae star before the noisy observed period changes average out to the evolutionary rate? How often do episodes of large period change occur in a star like XZ Cygni?

In the 1960s Marvin Baldwin pioneered long term monitoring of the period changes of RR Lyrae stars by the AAVSO. Targeted RR Lyrae stars were at first observed visually but more recently almost entirely with CCD cameras (Baldwin 2011). The determination of the period changes of RR Lyrae variables has also been a major focus of the GEOS RR Lyrae survey (Le Borgne *et al.* 2011). All-sky surveys, such as ASAS (Pojmański 1998), are also useful for monitoring RR Lyrae period changes. It is important that these efforts continue long into the future if the questions associated with period changes are to find answers.

3. The Blazhko effect

Some RR Lyrae stars have light curves that repeat very precisely from one cycle to the next. That is not true of all RR Lyrae stars. Some exhibit periodic changes in light curve shape on a time scale typically of tens of days to hundreds of days—the Blazhko effect (Percy 2007; Smith 1995). Although the Blazhko effect was discovered a century ago, our understanding of what causes the phenomenon remains incomplete.

There has, nonetheless, been recent progress in several aspects of our understanding of the Blazhko effect. Smith (1995) stated that almost all of the Blazhko effect stars known at that time were RRab stars, and that perhaps 15–20% of all RRab variables showed the Blazhko effect. More recent researchers have upped that percentage nearer to 50% for RRab stars while more RRc variables have also been found to exhibit the Blazhko effect. This increase is attributable to high precision CCD photometry of RR Lyrae stars obtained from the ground (Jurcsik *et al.* 2009), and also to the monitoring of RR Lyrae variables from space by the Kepler mission (Benkő *et al.* 2010). The Blazhko effect is thus something that occurs in many RR Lyrae variables, if they are watched carefully enough to detect it (Figure 1).

Recent observations with the Kepler mission (Szabó *et al.* 2010; Kolenberg *et al.* 2011) have shown that alternate peaks in the primary light cycle of at least some Blazhko effect stars can differ in brightness (Figure 2). The size of the difference is not the same for all Blazhko stars, and even changes over time for a single star. In studying this so-called period doubling, the Kepler mission has the advantage of being able to continuously observe its targets, without a dirunal gap in the observations. Successive peaks of a half-day period variable star are difficult to observe from a single ground-based location because of the interference of daylight unless the observer is so fortunate (if that is the right word) as to be observing during winter in the arctic or antarctic.

Although the primary light cycle of an RR Lyrae star may be only half a day, the Blazhko periods are many times longer. Determining the period of the Blazhko effect in RR Lyrae stars requires many observations over a time span considerably longer than the Blazhko period itself. Accomplishing that is not a project for one night or even a few nights of observing. Thus, there are RR Lyrae stars for which the primary pulsation period is known, and for which it is suspected that the Blazhko effect exists, but which do not have well determined Blazhko periods. Intensive CCD observations of such stars are needed to establish definitively whether or not the Blazhko effect exists and, if so, to determine the Blazhko period and the manner in which the primary light curve changes over the longer Blazhko cycle. This can be done by observers at a single longitude, but, as Doug Welch has noted (http://www.aavso.org/now-less-mysterious-blazhko-effect-rr-lyrae-variables), observers spread around the world at different longitudes potentially have the ability to detect the recently discovered differences in alternate maxima. The study of CX Lyr by de Ponthiere *et al.* (2009) illustrates the type of study that can be carried out to determine the Blazhko period of an RR Lyrae star, and also some of the complications that can make fixing that period difficult.

Much is unknown about the long term stability of the Blazhko effect and its relationship to changes in the primary pulsation period. Some well-known Blazhko variables, such as RR Lyrae itself, have been studied for several decades. The type of light curve changes that occur during the Blazhko cycle sometimes have been observed to themselves vary on a timescale of years, perhaps in some cases indicating a cycle even longer than that of the Blazhko effect itself (Szeidl and Kolláth 2000). Monitoring of Blazhko effect stars over a span not just of years but of decades is needed to keep track of these very poorly understood long term changes. XZ Cyg again affords an example of a study of this type (LaCluyzé *et al.* 2004). Not only have the amplitude and period of the Blazhko effect changed over time for this star, but at least some of the changes appear to be coincident with changes in the primary pulsation period.

4. Double-mode RR Lyrae stars

Double-mode RR Lyrae stars are rarer than those for which a single pulsation mode is dominant. Are these double-mode stars in the process of switching from one main pulsation mode to another, and, if so, on what timescale does the shift occur? By obtaining photometry of these stars over a timescale of years, one can determine whether the relative amplitudes of the fundamental mode and first overtone mode pulsations are changing. If they are observed to change, are the changes all in one direction (i.e. does the fundamental mode amplitude increase while the first overtone mode decreases, or vice versa) or does the direction of change itself switch over time? It is also perhaps noteworthy that, so far as I am aware, no one has yet detected the Blazhko effect in a double-mode RR Lyrae star. A good example of the type of work that can be done along these lines is the study of the double-mode RR Lyrae star NSVS 5222076 by Hurdis and Krajci (2010, 2011).

5. RR Lyrae stars in globular clusters

The AAVSO RR Lyrae program and the GEOS project have focused upon RR Lyrae stars in the field of the Galaxy, rather than those that are members of globular clusters. This is understandable. Many field RR Lyrae stars are brighter than their cluster counterparts. Moreover, magnitudes of field RR Lyrae stars can usually be obtained from CCD observations with aperture photometry, whereas observations of globular cluster RR Lyrae stars often require the more complicated methods of profile fitting photometry (Stetson 1987) or image differencing (Alard 2000). Nonetheless, RR Lyrae stars in a number of globular clusters are within the reach of modest telescopes equipped with CCD cameras, and observing clusters does have the advantage that many RR Lyrae stars can be recorded on a single image. The unknowns relating to RR Lyrae stars mentioned above apply to cluster as well as field stars (Jurcsik *et al.* 2012) and, in the future, more amateurs may decide to attempt observations of cluster variables.

6. The long haul

A theme that recurs in the discussions above is the need for observations of RR Lyrae stars that span years and decades. I don't know how much time will pass before all of these things we don't understand about RR Lyrae stars become things we do understand. I suspect that decades will go by before the answers to some of the questions posed are fully known. Who is going to provide those observations over such a timescale? An individual observer might be active for only a few years, or perhaps a few decades. However, the AAVSO is now into its second century, and it, and organizations like it, can be key to organizing and encouraging observational programs that continue beyond the lifetimes of any individual observer.

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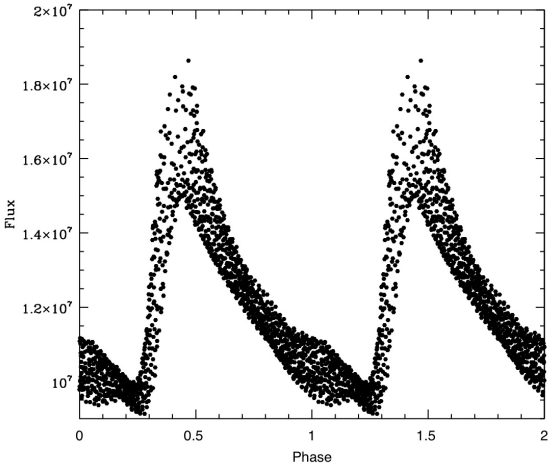

Figure 1. The Blazhko effect is shown in this light curve of RR Lyrae itself, based upon Kepler mission long cadence data. The data are folded with a primary period of 0.566868 day.

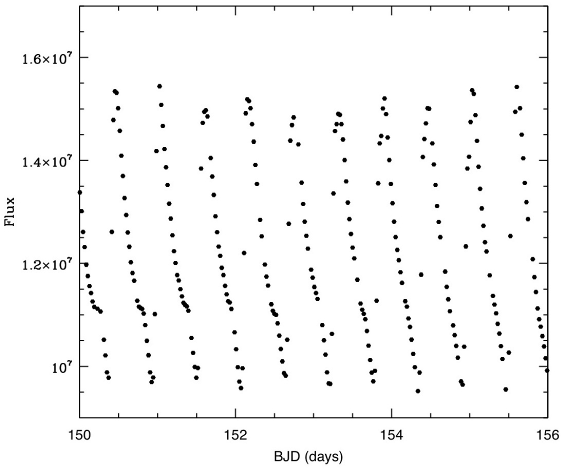

Figure 2. A portion of the Kepler data used to construct the light curve in Figure 1 is plotted against baryocentric Julian date.

The Usefulness of Type Ia Supernovae for Cosmology—a Personal Review

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Abstract We review some results of the past twelve years derived from optical and infrared photometry of Type Ia supernovae. A combination of optical and infrared photometry allows us to determine accurately the extinction along the line of sight. The resulting distance measurements are much more accurate than can be obtained from optical data alone. Type Ia supernovae are very nearly standard candles in the near-infrared. Accurate supernova distances, coupled with other observational data available at present, allow us to determine the matter density in the universe and lead to evidence for the existence of Dark Energy. We can now address some questions on the grandest scale such as, "What is the ultimate Fate of the universe?"

1. Introduction

The basic supernova (SN) classification scheme stipulates that supernovae (SNe) with hydrogen emission in their spectra are called Type II SNe, and those without hydrogen are called Type I SNe (Minkowski 1941). For more than twenty years we have delineated subclasses. Type Ia SNe show absorption due to singly ionized silicon. The key line has a rest wavelength of 6355Å (Filippenko 1997). As it is observed at roughly 6150Å at the time of maximum light, this signifies that a typical outflow velocity at maximum light is about 10,000 km s^{-1}.

It is generally believed that a Type Ia SN is caused by the explosion of a carbon-oxygen white dwarf (WD) star (in a close binary system) which has approached the Chandrasekhar limit of $1.4\,M_{\odot}$. Two possible scenarios are envisioned. Either the WD gains mass from a nearby donor star (a main sequence star or a giant), or the explosion results from the merging of two white dwarfs.

In Figure 1 we show a schematic diagram of the light path from a SN to a telescope on the Earth. At maximum light (roughly 19 days after the explosion) the size of the expanding fireball is ~100 AU. Light is possibly scattered by circumstellar material near the SN (Wang 2005; Goobar 2008). The light may be dimmed by dust in the host galaxy. The light waves are shifted towards longer wavelengths owing to the expansion of the universe, given the redshift of the host galaxy. The light is dimmed by dust in the Milky Way galaxy. Finally, the light passes through the Earth's atmosphere, is reflected and/or transmitted by the optical elements of the telescope, is spread out into a spectrum or passes through one of several broad band filters, and hits the light detector in our spectrograph or CCD camera, the quantum efficiency of which is a function of wavelength. Thus, the SN light is affected by many factors, and if we are to understand SNe well, we must standardize our spectra and broad band photometry.

Phillips (2012) has written an excellent review of the near-infrared (IR) properties of Type Ia SNe. We can hardly improve on his article. Here we shall emphasize our contributions over the past dozen or so years. One topic we shall not discuss here is the morphology of Type Ia SN lightcurves. We refer the reader to Hamuy *et al.* (1996), Riess *et al.* (1996), Kasen (2006), Jha *et al.* (2007), and the relationship between the B-band decline rate parameter and the strength of the I-band secondary maximum shown in Figure 17 of Krisciunas *et al.* (2001). Mandel *et al.* (2009) and Mandel *et al.* (2011) give sophisticated analysis of optical and near-IR light curves.

2. Standardizable candles and standard candles

In order to determine the distance to an astronomical object we make use of the standard relationship between absolute magnitude (M), apparent magnitude (m), and distance (d) in parsecs:

$$M = m + 5 - 5 \log (d), \tag{1}$$

where the apparent magnitude is corrected for any dust extinction along the line of sight. A century ago Henrietta Leavitt discovered that Cepheids with longer periods are brighter than those with shorter periods (Leavitt and Pickering 1912). This is the famous period-luminosity relation. In short, its significance is that while Cepheids do not all have the same intrinsic brightness, those of a given stellar population type show a specific linear relation between the logarithm of the period in days and the mean absolute magnitude. Thus, they are standardizable candles. The brightest Cepheids are more than 10,000 times more luminous than the Sun. By contrast, RR Lyrae stars of a particular metallicity pulsating in the fundamental radial mode have mean visual absolute magnitudes of about +0.7 (Layden *et al.* 1996). They are standard candles—all exhibit the same luminosity, like 100-watt light bulbs only much brighter. RR Lyr stars are roughly forty times more luminous than the Sun. Type Ia SNe are very useful for extragalactic astronomy because at maximum light they are four billion times more luminous than the Sun; they can be detected halfway across the observable universe with a 4-meter class telescope.

Baade (1938) first suggested that Type I SNe may be useful for measuring accurate cosmic distances. (The subclass of Type Ia SNe was first identified by Elias *et al.* (1985).) Kowal (1968) made the first test of the usefulness of these objects as distance indicators. Phillips (1993) discovered the "decline rate relation" and established the usefulness of the parameter $\Delta m_{15}(B)$, which is the number of *B*-band magnitudes that a Type Ia SN declines in the first 15 days after *B*-band maximum; a typical value is 1.1 magnitudes, but the range is from 0.68 (Krisciunas *et al.* 2011) to 1.93 or so (Garnavich *et al.* 2004). As with Cepheids, the absolute magnitude is related to another observable. The most slowly declining Type Ia SNe are about 2.5 magnitudes more luminous in the *B*-band at maximum light than the fast decliners. The steepness of the decline rate relation becomes shallower as we proceed to longer wavelength bands (see Figure 2). Thus, at optical wavelengths, Type Ia SNe are standardizable candles.

Meikle (2000) presented a very useful compilation of IR photometry of Type Ia SNe published up to that time. Of particular note are the two papers of Elias *et al.* (1981, 1985); the latter paper presented the first IR Hubble diagram of Type Ia SNe, using the *H*-band magnitudes at 20 days after maximum light. Meikle (2000) also showed, on the basis of a small number of objects, that Type Ia SNe at ~14 days after maximum light may be standard candles. Krisciunas *et al.* (2003) also showed that Type Ia SNe might be standard candles in the near-IR. We based this on a sample of Type Ia SNe only slightly bigger than that of Peter Meikle, on the basis of their *H*-band (1.65 micron) magnitudes 10 days after *B*-band maximum.

One might ask why there are so many fewer near-IR data compared to optical photometry. Near-IR chips have fewer pixels than optical CCD cameras. A small field of view makes it more difficult to make mosaic images, as there would be fewer field stars of appropriate brightness near any SN. This is particularly important for images taken on non-photometric nights. Also, there are few telescopes systematically used for near-IR observations of SNe. Amongst them are the CTIO 1.3-meter telescope, the Las Campanas 1.0-meter and 2.5-meter telescopes, a 1.3-meter telescope at Mt. Hopkins, Arizona, and the Liverpool JMU 2-meter telescope at La Palma.

3. Uniformity of color curves for determining extinction

I began observing Type Ia SNe early in 1999 using the Apache Point Observatory 3.5-meter telescope. My collaborators were Gene Magnier, Chris Stubbs, and Alan Diercks of the University of Washington. (Stubbs and Diercks were members of the High-Z Supernova Team, whose highly cited paper (Riess *et al.* 1998) garnered a Nobel Prize in physics for Brian Schmidt and Adam Riess.) We published a paper (Krisciunas *et al.* 2000) which had two primary results, one dealing with color curves, the other dealing with unusual dust properties.

We found that Type Ia SNe whose decline rate parameter $\Delta m_{15}(B)$ was in the middle range delineated uniform optical vs. infrared color curves. This follows up a suggestion by Elias *et al.* (1985) that *V–K* colors of Type Ia SNe may be quite uniform. An example of *V–K* color curves of Type Ia SNe is shown in Figure 3. Using our data of SN 1999cp and data of SNe 1972E, 1980N, 1983R, 1981B, and 1981D (see Elias *et al.* 1981, 1985, and data and references given by Meikle 2000) we constructed a "zero reddening" locus. Optical and IR data for SN 1998bu (Suntzeff *et al.* 1999, Jha *et al.* 1999, Hernandez *et al.* 2000) show the same basic color curve shape, but reddened in the *V–K* color index by nearly 1 magnitude. (The *UBVRIYJHK* bands are at 0.36, 0.44, 0.55, 0.65, 0.80, 1.03, 1.25, 1.65, and 2.2 microns, respectively.) Our observations of SN 1999cl (Krisciunas *et al.* 2000, 2006) show that this object was reddened even more.

We can parameterize dust reddening as follows. Say we somehow know the unreddened *B–V* color of a star or SN. The difference of the observed color and the unreddened color is the color excess E(*B–V*). The *V*-band extinction is related to this color excess as follows:

$$A_V = R_V E(B–V). \tag{2}$$

The standard value of $R_V = 3.1$ is for Milky Way dust (Cardelli *et al.* 1989), but this value can range from 1.5 to 5 depending on the line of sight in our Galaxy.

Extinction by interstellar dust is diminished at longer wavelengths. An analog of Equation 2, but using the *V*- and *K*-bands, is as follows:

$$A_V = \alpha\, E(V–K). \tag{3}$$

where parameter α is in the range 1.08 to 1.14.

Even for a wide range of dust grain size and composition the scaling parameter in Equation 3 has a very small range. Thus, if one can obtain a *V–K* color excess, increasing that by ten percent gives us the *V*-band extinction. How much extinction one expects for that SN in other bands can be obtained using the coefficients calculated by Jose Prieto and given in Table 8 of Krisciunas *et al.* (2006).

Krisciunas *et al.* (2004b) present coefficients to generate the *V–H* and *V–K* color curves of the mid-range decliners, and the *V–J*, *V–H*, and *V–K* color curves of the slowly declining Type Ia SNe. This paper also gives the coefficients to generate *JHK* light curve templates valid from 12 days before the time of *B*-band maximum until 10 days after T(B_{max}). While the fast-declining Type Ia SNe are considerably redder than more slowly declining objects of this type around maximum light, from 30 to 80 days after T(B_{max}) Type Ia SNe of all decline rates show a certain uniformity in the *V–H* and *V–K* color indices (Krisciunas *et al.* 2009b). (In optical bands researchers make use of the "Lira Law." It relates to the uniformity of the unreddened *B–V* colors of Type Ia SNe from 32 to 92 days after T(B_{max}) (Lira 1995, Phillips *et al.* 1999).) The uniformity of *V–H* and *V–K* colors of Type Ia SNe is backed up by modeling calculations by Peter Hoeflich and shown in Figure 12 of Krisciunas *et al.* (2003).

Our observations of SN 1999cl (Krisciunas *et al.* 2000, 2006) indicated that $R_V \approx 1.55 \pm 0.08$ for the host galaxy dust. Since then a small number of highly reddened Type Ia SNe have been observed, amongst them SN 2002cv (Elias-Rosa *et al.* 2008), 2003cg (Elias-Rosa *et al.* 2006), and SN 2006X (Wang *et al.* 2008). As Wang (2005) and Goobar (2008) point out, the light of a highly dimmed and reddened object can suffer from extinction and scattering. What the balance is of these processes is not understood at this time. With intrinsic color variations, which are expected for any group of cosmic objects, we thus have three sources of color effects.

Suffice it to say that adopting standard Galactic reddening of $R_V = 3.1$ for all Type Ia SNe is just wrong. The host of SN 1999cl, for example, is M88 in the Virgo cluster. Adopting $R_V = 3.1$ for the dust that affected SN 1999cl gives us a distance value that is halfway to the center of the Virgo cluster. Thus, either M88 is by chance in the same direction as the Virgo cluster, but not in it, or we need to adopt the value of R_V derived from a combination of optical and IR data.

4. Clones

Krisciunas *et al.* (2007) found that, for all intents and purposes, SN 2004S was a clone of the well studied object SN 2001el (Krisciunas *et al.* 2003). Since the former is essentially unreddened in its host, we can correct both objects for a small amount of Milky Way dust extinction and determine that the host galaxy dust of SN 2001el was characterized by $R_V = 2.15 \pm 0.24$ and that SN 2001el suffered 0.47 ± 0.03 magnitude more *V*-band extinction than SN 2004S (see Figure 4). This result exploits the advantage of using a combination of optical and infrared photometry of Type Ia SNe. Previously, if we were limited to using only *B*- and *V*-band photometry, the uncertainty in distance to a reddened SN might have been ±20 percent, but by using optical and IR data the uncertainty of the extinction corrections leads to uncertainties in distance that can be as small as the random errors of the photometry, a few percent. This is a considerable improvement!

Type Ia SNe are not the only exploding stars that show certain uniformities of their lightcurves and color curves. The Type II-P SNe 1999em and 2003hn were found to be near-clones of each other. This allowed us to use the optical and IR photometry to calculate that SN 2003hn was dimmed by 0.25 ± 0.03 magnitude more in the *V*-band than SN 1999em (Krisciunas *et al.* 2009a).

5. The first Hubble diagram of Type Ia SNe at maximum light in the near-IR

Our light curve templates for the near-IR *JHK* bands (Krisciunas *et al.* 2004b, Table 12) allowed us to derive the maximum magnitudes of Type Ia SNe as long as there were some observations between twelve days prior to $T(B_{max})$

and ten days afterward. We used our *V* minus near-IR color curves to correct these apparent magnitudes at maximum light for extinction along the line of sight. This led to the first Hubble Diagram of Type Ia SNe at maximum light in the IR (Krisciunas *et al.* 2004a) (see Figure 5). The fact that the data fit the three straight lines like beads on a string means two things. One is not a surprise, that light intensity decreases as the square of the distance. But the other will be significant for all future surveys of Type Ia SNe, namely that they are better than standardizable candles in the IR. This sample of objects shows that they are standard candles. Of course, one wants a sample bigger than sixteen objects, but this was a good start.

The scatter in the near-IR Hubble diagrams obtained so far is about ± 0.15 magnitude, comparable to what one finds for *BVRI* Hubble diagrams. However, as we push out into the Hubble flow (that is, redshift $z > 0.01$) we can expect the near-IR Hubble diagrams to have tighter fits because of the minimal systematic errors in the extinction corrections and the diminished effect of the peculiar velocities.

6. Deviations from uniform standard candle nature

In Figure 5 if there were any points above the lines, that would indicate SNe intrinsically fainter than the rest, and points below the lines would indicate SNe intrinsically brighter. More information on the standard candle nature of Type Ia SNe can be gleaned from a plot of the absolute magnitudes at maximum brightness vs. some other parameter. Figure 6 is a plot from Krisciunas *et al.* (2011), but we have added three regression lines to subsets of the data. Figure 6 shows that Type Ia SNe are (nearly) perfect standard candles in the near-IR. SN 2009dc may have been a "super-Chandra" event, rather than a more standard Type Ia SN that produces roughly 0.5 $M_\odot$ of ^{56}Ni. In our paper on SN 2003gs (Krisciunas *et al.* 2009b) we also used data of SN 1986G (Frogel *et al.* 1987) and four objects from the Carnegie Supernova Project (Contreras *et al.* 2010) to show that there is a bifurcation in the absolute magnitudes at peak brightness of the fast decliners. At the right hand side of Figure 6 the diamond shaped symbols correspond to objects that peaked in the near-IR after $T(B_{max})$. We have excluded these points and SN 2009dc from the regression lines shown in Figure 6. These lines have non-zero slopes only at the 1.3- to 2.2-σ levels of significance. (A 3-standard deviation result is usually the criterion for statistical significance. For a random sample of data this would occur only 0.5 percent of the time.) The data indicate that Type Ia SNe with $\Delta m_{15}(B) = 1.4$ are roughly 0.10–0.15 magnitude fainter in the near-IR than those with $\Delta m_{15}(B) = 0.8$. This is comparable to the uncertainties of the absolute magnitudes shown in Figure 6.

Folatelli *et al.* (2010, Figure 17) showed that there may be a non-zero slope to the *J*-band decline rate relation. More extensive data from the Carnegie

Supernova Project (Kattner *et al.* 2012) indicate non-zero slopes at the 2-σ level for the *YJH* bands.

Suffice it to say that Type Ia SNe at maximum brightness are excellent objects for determining extragalactic distances. They are nearly perfect standard candles in the near-IR. Excluding possible super-Chandra events and late-peaking subluminous objects, the slopes of the regression lines in Figure 6 are not statistically significantly different than zero.

7. Hubble Diagrams and evidence for Dark Energy

We do not have the space here to review the subject of high redshift SNe and the discovery of the acceleration of the universe. For a cosmology primer see the article "Fundamental cosmological parameters" (Krisciunas 1993, and references therein); also the discussion of "luminosity distances" in the Introduction to Krisciunas *et al.* (2005).

Two fundamental parameters used by observational cosmologists are the mean density of matter in the universe compared to the critical density, Ω_M, and the Dark Energy density parameter, Ω_Λ. If these two parameters sum to 1.00, then the geometry of the universe is flat. In Figure 7 we show the "distance modulus" (or $m-M$ from Equation 1) as a function of the logarithm of the redshift. Different models of the universe are shown. The "empty universe" has $\Omega_M = 0.0$, $\Omega_\Lambda = 0.0$. The "Einstein-de Sitter universe" (or critical density model) coasts to a stop after an infinite amount of time and has $\Omega_M = 1.0$. Prior to 1998 the expectation was that high redshift Type Ia SNe would show that $\Omega_M = 0.3$, $\Omega_\Lambda = 0.0$; this we call the "open model", as it would lead to the perpetual expansion of the universe even without a positive Cosmological Constant.

Figure 8 is a "differential Hubble diagram." We take the empty universe model from Figure 7 as a reference and plot the differences of the other loci with respect to the empty universe model. What Riess *et al.* (1998) and Perlmutter *et al.* (1999) found was that the high redshift SN data do not fall along the locus of the "open" model. Instead the SNe are "too faint" by about 0.19–0.25 magnitude from redshift 0.4–0.8. Possible explanations are: 1) that some kind of gray dust is dimming the light but not reddening it; 2) Type Ia SNe at this lookback time are inherently dimmer than nearby, more recent, Type Ia SNe; or 3) the SNe are further away than we would expect, given their redshifts, which is evidence for repulsive Dark Energy.

Riess *et al.* (2004) used the Hubble Space Telescope to find Type Ia SNe at even greater redshifts and found that the SNe at $z > 1.3$ were "too bright" compared to the empty universe model. This means that they looked far back enough in time to see the universe when it was small enough and dense enough that the gravitational attraction of matter on all other matter was stronger than any repulsive effect of a positive Cosmological Constant. At a redshift beyond 1.3 the universe is observed to be decelerating. The findings of Riess *et al.*

(2004) also proved that the faintness of Type Ia SNe at redshift ~0.5 was not due to some weird kind of gray dust.

We note that SN data alone do not give us enough leverage to determine the most accurate values of Ω_M and Ω_Λ. Wood-Vasey *et al.* (2007) and others used SN data combined with information from "baryon acoustic oscillations" (Eisenstein *et al.* 2005). The flatness of the geometry of the universe is best demonstrated from the characteristic angular size of the warmer and cooler spots of the Cosmic Microwave Background (CMB) radiation, such as shown by the analysis of seven years of data from the Wilkinson Microwave Anisotropy Probe (WMAP) by Komatsu *et al.* (2011).

Once we know the matter and Dark Energy content of the universe, we can determine the expansion history of the universe (Figure 9). The universe was dense enough for the first seven billion years that the gravitational attraction of all the matter caused the expansion to be decelerated. After that the effect of repulsive Dark Energy has caused an acceleration of the expansion.

8. Future analysis required

Hicken *et al.* (2009) presented data for 185 nearby Type Ia SNe observed by astronomers from the Harvard-Smithsonian Center for Astrophysics. Only thirty-one of them have values of $\Delta m_{15}(B)$, maximum U-band magnitudes, and are at a redshift greater than $z = 0.01$ (which is regarded to be the beginning of the smooth Hubble flow). The U-band data show a scatter of ± 0.25 magnitude for a decline rate relation graph or a Hubble diagram, which is almost twice the scatter one sees in other photometric bands. Some of this extra scatter may be due to a viewing angle effect (Maeda *et al.* 2010). It is known that some Type Ia SNe are polarized, implying that the explosions are not spherically symmetric. Since the U-band light is dimmed more than the longer wavelength bands, this could increase the scatter of the derived U-band absolute magnitudes.

The other factor affecting the U-band data is the perennial challenge to correct the photometry for differences in the effective bandpasses used for all the observations from all telescopes for a given SN. Using lab data obtained by us, or provided by manufacturers, and spectra of the SN themselves, the method of spectroscopically-derived corrections (the so-called "S-corrections") allows us to resolve this problem, in principle. The method was originated by Stritzinger *et al.* (2002), who applied it to SN 1999ee, and by Krisciunas *et al.* (2003), who applied it to SN 2001el. Other papers written by us show photometric corrections to optical and IR photometry of many objects (Candia *et al.* 2003, Krisciunas *et al.* 2004b, 2004c, 2007, 2009b, 2011).

Our paper on SN 2003gs (Krisciunas *et al.* 2009b), however, did not include U-band S-corrections, and we chose at that time not to publish U-band photometry from one telescope because it was systematically 0.4 magnitude brighter at one month after maximum light compared to data from two other telescopes. We now have worked out corrections and can reconcile the otherwise discordant *U*-band data of SNe 2003gs and 2003hv obtained with three telescopes. This is a step in the right direction. Details will be published in a separate paper.

Why are the *U*-band data so important? Both the Sloan Digital Sky Survey supernova search (Kessler *et al.* 2009) and the CFHT Legacy Supernova Survey (Conley *et al.* 2011) discovered systematic errors in the distance moduli of high-redshift SNe when anchored with *U*-band photometry of nearby objects. Both projects decided to eliminate from the analysis data that originated in the restframe *U*-band. (For example, a SN at redshift 0.7 observed in the *R*-band gives us photons emitted in the *U*-band.) To utilize fully the SN surveys of the future such as the Dark Energy Survey and data from the Large Synoptic Survey Telescope we need to fix the old *U*-band photometry (which may be impractical or impossible), or we have to restrict ourselves to data obtained with a minimum number of telescopes and cameras, such as the Carnegie Supernova Project (Hamuy *et al.* 2006).

Until recently the effective filter profiles for S-corrections were obtained using laboratory data for the transmissions and reflectances of all the optics in a telescope and camera, then multiplying all these functions of wavelength together. This allowed us to reconcile previously discordant data obtained with cameras having significantly different filters. Stubbs *et al.* (2007) and Rheault *et al.* (2010) have shown the way to the future for SN calibration. They designed two systems to measure the effective filter profiles in situ. Stubbs *et al.* used a tunable laser and Rheault *et al.* use a "monochromator" to scan the transmission throughout the whole system from the ultraviolet through the near-IR.

9. Conclusions

Data obtained over the past decade have confirmed the suggestion of Elias *et al.* (1985) that optical minus infrared colors of Type Ia SNe are uniform within certain ranges of the *B*-band decline rate. A combination of optical and near-IR photometry allows us to determine the amount of extinction very well, and allows us to determine the reddening parameter R_V (Krisciunas *et al.* 2007). The suggestion of Meikle (2000) and Krisciunas *et al.* (2003) that Type Ia SNe are nearly standard candles in the near-IR has been borne out by subsequent analysis of the absolute magnitudes at maximum light (Krisciunas *et al.* 2004a, Wood-Vasey *et al.* 2008, Kattner *et al.* 2012). The goal of future photometry of Type Ia SNe will be to obtain well calibrated data at ultraviolet, optical, and IR wavelengths for nearby SNe and also for SNe out to redshift $z = 2$. Some of these observations must be made from space, such as with the satellites Euclid, WFIRST, or the James Webb Space Telescope. Infrared data in particular, whether in the observer's frame or the restframe, will be very important for observational cosmology.

10, Acknowledgements

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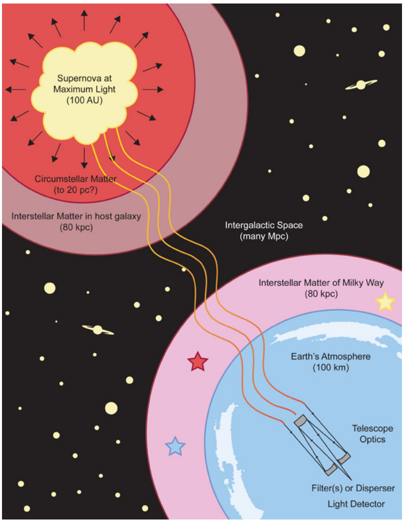

Figure 1. Schematic diagram of the light path of a Type Ia supernova to a telescope situated on the Earth. Figure by Elisabeth Button.

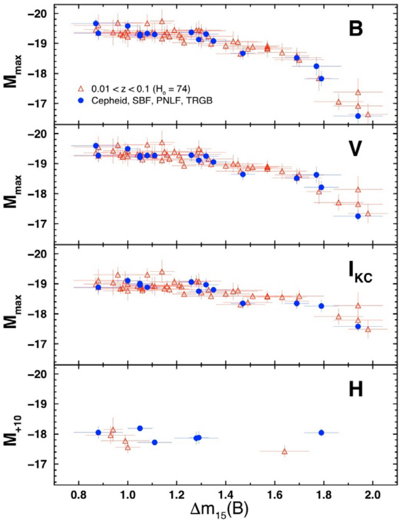

Figure 2. Decline rate relations of Type Ia SNe for the BVI and H-bands (Krisciunas et al. 2003). The x-axis parameter is the number of B-band magnitudes that a Type Ia SNe declines in the first 15 days after the time of B-band maximum. For BVI the absolute magnitudes are the maximum brightness values. For the near-IR H-band the absolute magnitudes are measured at 10 days after T(Bmax). Figure by Mark Phillips.

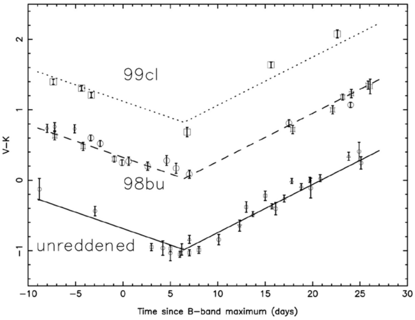

Figure 3. *V–K* colors of Type Ia SNe unreddened in their host galaxies (lowest locus) and for two reddened objects. Based on data discussed by Krisciunas *et al.* (2000).

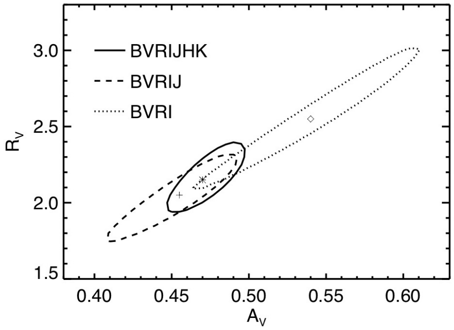

Figure 4. Reddening parameter R_V as a function of the difference of the amounts of *V*-band extinction suffered by SN 2001el and its clone SN 2004S (Krisciunas *et al.* 2007). Figure and analysis method by Peter Garnavich.

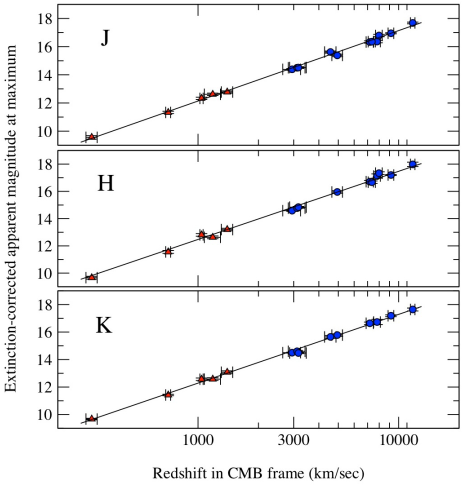

Figure 5. Infrared Hubble diagrams of Type Ia SNe at maximum brightness (Krisciunas *et al.* 2004a). If these objects are standard candles, then from Equation 1 it follows that the y-axis values are a simple function of the logarithm of the distance in parsecs. The slope of the line is fixed at 5.

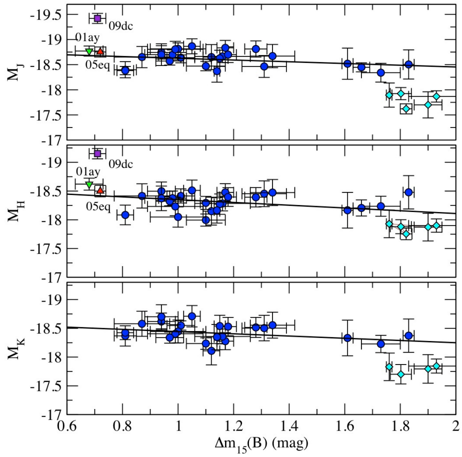

Figure 6. Near-IR absolute magnitudes of Type Ia SNe at maximum brightness, as a function of the *B*-band decline rate parameter (Krisciunas *et al.* 2011).

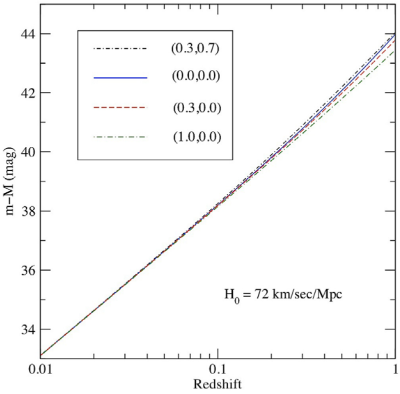

Figure 7. Theoretical Hubble diagram for various combinations of the mass density parameter Ω_M and the Dark Energy density Ω_Λ. The modern "concordance model" of the universe has $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$ and a Hubble constant ~ 72 km s^{-1} Mpc^{-1} (Freedman *et al.* 2001). Note that one only starts to detect evidence of Dark Energy from SN photometry at redshift greater than about $z \sim 0.2$.

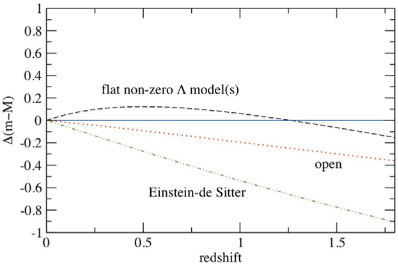

Figure 8. A differential Hubble diagram. We take the "empty universe model" as the reference from Figure 7. Prior to 1998 the expectation was that the data would lie along the "open" line: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.0$. Data of Riess *et al.* (1998) and Perlmutter *et al.* (1999) showed that at redshift ~ 0.5 Type Ia SNe were "too faint" by about 0.2 mag compared to the open model.

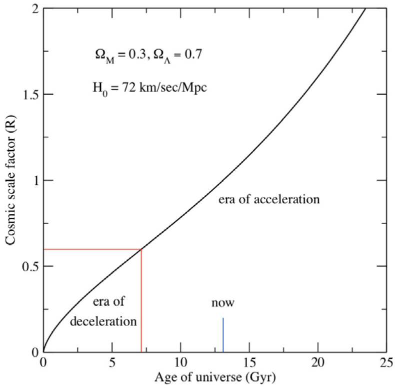

Figure 9. The expansion history of the universe. The y-axis is the cosmic scale factor, effectively the average distance between galaxies.

Amateur Observing Patterns and Their Potential Impact on Variable Star Science

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Abstract In this paper I highlight some trends seen in amateur observations submitted to the AAVSO over the past fifty years. Some systematic trends are noted in both the amount of data submitted and the frequency with which stars are observed. Two trends are evident: the decreasing number of days per year when individual stars are observed, and the overall decreasing number of visual observations submitted. The former is shown through an analysis of data submitted for a number of subclasses of cataclysmic variable, while the latter is generally evident across all variable star types through our overall annual totals. A decrease in nightly coverage may impact the kinds of science that can be done with AAVSO light curves. The decrease in visual observing may result in a loss of long-term coverage that impacts the usability of long-term light curves. I discuss possible impacts on the kinds of science that can be done with AAVSO data and long-term light curves, and suggest ways to address this issue.

1. Introduction

The AAVSO International Database (AID) contains over 20 million observations of thousands of individual stars. The data are a mix of both visual magnitude estimates and instrumental photometry, with visual data making up the vast majority of all data submitted prior to 1995. Instrumental observations now account for more than eighty percent of all data submitted to the AAVSO every year. Prior to 1995, most observations of variables were nightly or weekly visual observations, and the goal was to monitor these objects for phenomena that occurred on timescales from days to years. Now, a much larger fraction of data submitted consists of instrumental time-series of short-term phenomena (Figure 1). This shift in focus has drawn a number of observers away from long-term monitoring observations toward these more focused, short-term projects. It has also brought about a shift in observing method from visual to CCD; while the number of visual observers still numbers around 800 (Figure 2), the number of visual observations of all variable stars submitted per year is now about half the number submitted in the mid-1990s. When visual observers do observe, they do not do so in the numbers they once did.

The question of whether long-term visual observation of variable stars should be encouraged is an important one. Underlying this question is a more fundamental one of whether the scientific questions that long-term monitoring of variable stars can answer are ones that are still of interest to the scientific community. Any observational program must be motivated by the pursuit of valid scientific questions in order to be relevant to astronomical research. This is as true of instrumental observations as visual ones. In order to motivate a discussion of this question, I present a simple study of the daily observational coverage of cataclysmic variable stars to quantify the shift in focus from long-term monitoring to more intensive short-term observations.

2. Selection of CV data sets for examination

To examine trends in long-term coverage, we searched the AID for observations of CVs of several important subclasses. We selected stars based upon the following criteria:

- star is classified as NL or UGx;
- at least 1000 observations/500 days covered since 1961;
- observations counted: visual, and (B,V, unfiltered) CCD;
- we are not counting the total number of observations, but *the number of days they were observed at least once.*

The last bullet is critical: this study aims to address not the raw number of observations made per year, but the daily coverage of individual stars. The number of days observed per year is a better indicator of how useful a light curve will be in performing studies of long-term behavior, potentially yielding information about mean light levels, outburst frequency, and outburst duration among other things.

3. Results

There are between two and three dozen stars among each of the NL, UGSS, UGSU, and UGZ types that meet these criteria. The results for each of these four subsets are as follows:

UGSS-type—See Figure 3. Many of these stars have been observed for many decades, with the longest-observed star being SS Cygni itself (SS Cyg is one of the best-observed stars in the AID, with nearly 365 days of coverage per year). Among the twenty best-observed stars, only SS Cyg has retained a near continuous level of daily coverage. The remainder of the twenty show declines in coverage of varying degree. Coverage slowly increased through the mid- to late-1990s, and then began to decline across the board. Some declines have been dramatic (a factor of two or more), but others show less of a decline. In most cases, the onset of declines appear to be in the late 1990s to early 2000s.

UGSU-type—Most of these stars show significant declines in coverage starting in 2000, with some well-known and observed stars (like SU UMa itself) losing nearly half of their daily coverage since 2000. Others have been even more precipitous, with southern stars in particular showing losses in daily coverage of greater than fifty percent (for example: TU Men, WX Hyi, Z Cha, and OY Car). For some stars, daily coverage has declined to levels not seen since 1970.

UGZ-type—Z Cam itself is well observed but as with the UGSS stars, the UGZs show generally declining coverage in the past five to ten years. Some of the small number of stars that first came under observation in the 1970s and 1980s (for example: EM Cyg, AT Cnc, BI Ori, VW Vul, and V344 Ori) have leveled off in coverage. EM Cyg is covered for around sixty percent of the nights per year, but the more equatorial sources have coverage only about one-third of the year, while the more southerly star TT Ind is hardly observed anymore—only around twenty percent of the nights per year have at least one observation.

Novalikes and UGWZ-types—It is difficult to make any blanket assessments of their long-term coverage. Few of these stars have been extensively observed for many decades, although UZ Boo (UGWZ) appears to receive consistent coverage for about seventy-five percent of the nights per year. Coverage of UGWZ stars with marginally predictable recurrence times may decline outside of expected outburst windows; WZ Sge itself is now only observed about 125 nights per year, about the same as in 1980. Among the novalikes only V Sge has good coverage throughout the fifty-year span of this study, and the vast majority of these objects were discovered within the past fifty years. Observations of these sources peaked in the 1990s, probably due to the interest generated from space-based X-ray observations in the 1970s–1990s. TT Ari has had consistent coverage of about 200 nights per year since the mid-1980s, around the time it returned from its previous deep fade (circa 1985).

4. Overall trends

Most of the objects under consideration here have shown some decline in coverage since the 1990s when interest in cataclysmic variables first peaked. While the trends show declines in the number of days covered, many of these stars also show declines in the number of observations made per year, despite the consistent increase in the total number of observations of all variable stars made per year. Figure 4 shows the number of observations submitted per year for six well-known dwarf novae. Although the totals for individual stars are occasionally punctuated by years with substantial time-series data, in general the number of observations per year per star is declining.

5. Time-Series versus long-term monitoring

The annual total of all observations submitted to the AAVSO includes several hundred thousand data points of time-series observations of a small number of stars. Often, these observations are of interest to that particular observer during a small window of time (for example: a study of an eclipsing binary or outbursting cataclysmic variable). In such cases, the total number of submitted data points is large, but the time-span of the data is very small—often days, weeks, or months—and the star may not be observed again. While the overall number of observations being submitted to the AAVSO is increasing, the coverage and quality of our long-term light curves is not keeping pace with this increase. For many important stars, coverage is in decline.

6. The roles of amateur monitoring and robotic surveys

There are several robotic surveys in existence whose purpose is to conduct nightly monitoring of the visible night sky. Surveys like the All-Sky Automated Survey (ASAS; Pojmański 2002), the Northern Sky Variability Survey (NSVS; Wozniak *et al.* 2004), and the Catalina Real-Time Transient Survey (CRTS; Drake *et al.* 2009) provide a possible means for overcoming the declining numbers of amateur observations of stars with long-term light curves. As of today there is no universally agreed-upon process by which survey data are guaranteed to remain publicly available beyond the lifetime of the individual project, and thus the long-term survivability of robotic survey data is unclear. It is not difficult to ensure that such data be preserved.

There is clearly room for both human and robotic observation of variable stars, and the benefits of both methods are numerous. They should be considered as complementary rather than conflicting. The variable star community needs to address both the declining long-term coverage by the amateur community, and the organized care and maintenance of large and valuable databases created by robotic surveys. Without such a discussion, there is a chance that the scientific value of long-term light curves such as those held by the AAVSO will no longer grow with time.

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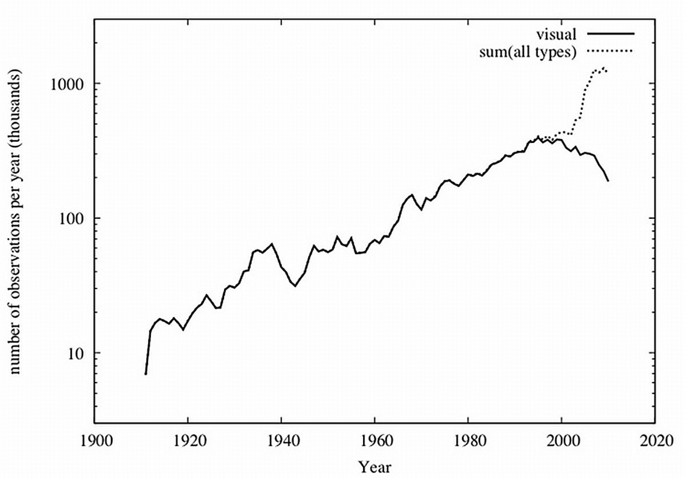

Figure 1. The number of observations per year found in the AAVSO International Database (AID): solid line, visual data; dotted line, all data. These numbers include data from the AFOEV and RASNZ. Beginning around the year 2000, CCD observations became the majority of observations submitted per year. The number of visual observations has been in decline since its historical maximum in 1995.

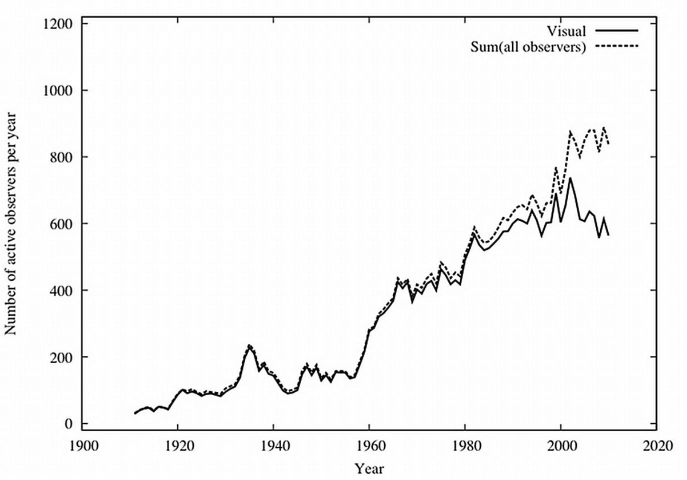

Figure 2. The number of observers whose data are submitted to the AID per year: solid line, visual data; dotted line, all data. Visual observers—including those who also observe with a CCD part of the time—still represent a majority of observers. Recent trends suggest the number of observers is holding steady or declining slightly.

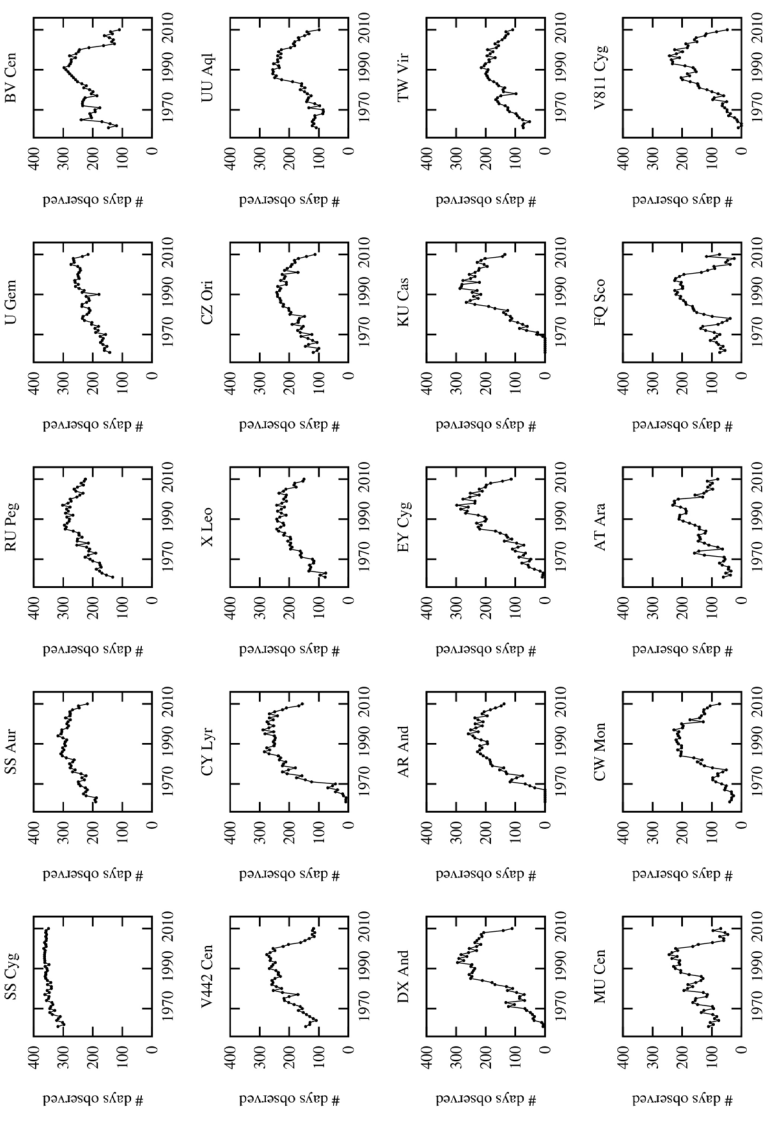

Figure 3. Daily coverage: The twenty best-observed dwarf novae of type UGSS (SS Cyg-type).

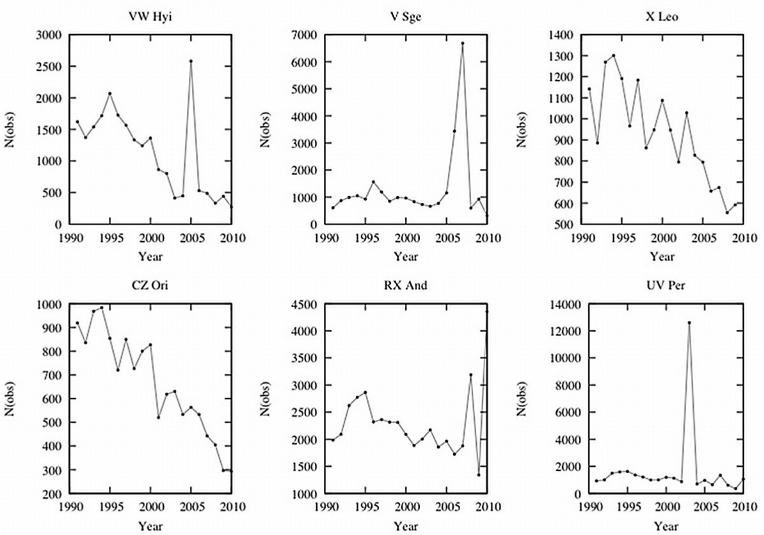

Figure 4. Yearly totals for six dwarf novae, 1991–2010. Coverage of these stars is declining, with some declines (especially CZ Ori, X Leo, and VW Hyi) being especially dramatic. With fewer observations and fewer days per year, it becomes increasingly difficult to study long-term changes in these stars.

The Acquisition of Photometric Data

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Abstract The planning and execution of a typical observing run will be outlined. Particular attention will be addressed to details which aid in the acquisition of quality photometry.

1. Introduction

The astronomical literature utilizes a number of terms which describe the kind of photometry undertaken for a given project. A description of the terminology is in order.

Relative photometry is the kind of photometry which most observers, and certainly virtually all AAVSO observers, do in their studies. It is photometry tied into sets of standard stars established around the sky, with zero points which can be traced back through photometric history. Such measurements are not tied into any laboratory system, but are related to nearby standard stars, in a variety of photometric standard systems. Examples of such photometric systems are the UBVRI system of Johnson, Kron and Cousins, the Stromgren four-color (uvby) system, and the Sloan u'g'r'i'z' photometric system.

Absolute photometry is based on spectrophotometry, or photometry tied to a laboratory source, such as a black body cavity, or something similar, all as an integral part of the data acquisition process. Absolute photometry is based on physical units. In spite of the terminology used on occasion in some of the recent literature, only a small number of astronomers (for example, Art Code, James Gunn, Bev Oke, and Don Hayes) ever have done absolute photometry.

Differential photometry is the direct comparison of two or more stellar images, historically done using a photographic plate, or a photomultiplier, but now best done with CCD imaging. Many stellar images are obtained on the same photograph, or CCD image (frame), and hence can be measured, intercompared, with high precision because the air masses essentially are identical. (This is not necessarily a true statement for some of the large CCD arrays.) One directly compares the intensities of two nearby images, determining the difference in intensity, and perhaps then plotting the result versus time to search for a light variation of the object under study. Most of the observing done by AAVSOers is this kind of photometry.

Be aware that all sky photometry does *not* lead to absolute photometry!

2. Interesting history and useful references

There appeared in the literature some decades ago an interesting series of papers by Weaver (1946a–f, 1962). He summarized therein a review of the history of astronomical photometry up to the beginning of the photoelectric photometry era. An excellent history of astronomical photometry was published by Hearnshaw (1996), covering the development of astronomical photometry from the times of the ancients to the beginning of the current epoch of charge-coupled devices (CCDs) as the detector of choice. A discussion of the most used photometric system over the past sixty years, the Johnson-Kron-Cousins UBVRI photometric system, appeared in Landolt (2007a, 2011).

Along with the history of actually completing photometric observations, it is of interest to review the accuracies achieved by the techniques available over the decades. Most photometry was accomplished in the first half of the twentith century either using the human eye, or photography. Early attempts to do what we now call photoelectric photometry included, for example, observations by Stebbins (1910). Also read chapter 9 in Hearnshaw (1996). Photometric accuracies which were achieved over time have been on the order of and have improved from 0.25 magnitude for the human eye (under controlled conditions, the accuracy is under 0.1 magnitude; see Williams and Saladyga (2011)), to 0.02 magnitude for photographic plates, to 0.005 magnitude for all sky photoelectric and CCD photometry, 0.0005 magnitude for CCD derived differential photometry. Space-based instrumentation, such as the Kepler spacecraft, can do an order of magnitude better in accuracy.

The AAVSO photometrists have at their disposal a number of books which describe procedures in data acquisition and analysis. Four such books, listed in order of publication date, are by Henden and Kaitchuck (1982), Sterken and Manfroid (1992), Howell (2006) with particularly useful references in his Appendix A, and Warner and Harris (2006). A new book on CCD photometry is in preparation (Henden 2012). The different viewpoints and approaches are a positive in understanding and in aiding observers in defining an approach with which they are comfortable.

3. Thoughts on observing

The two photometric filter systems of most interest to AAVSO members are the UBVRI Johnson-Kron-Cousins system, and the Sloan u'g'r'i'z' filter system. These two filter systems have the advantage that both are broad band filter systems. Both tie into a huge history of data (UBVRI) and as a tie into recent sky survey projects (Sloan Digitial Sky Survey = SDSS). The AAVSO has taken advantage of these facts in its APASS (AAVSO Photometric All Sky Survey) sky survey, using the Johnson B and V filters, plus the g'r'i' filters from the Sloan system.

It is *most* important to use a filter if at all possible! An observer will not be able to reach as faint magnitudes when using a filter, but the resulting measurement will have more lasting scientific value. That is because an image through a standard filter, say Johnson V, is more easily compared to other observers' data. The transformation relations between the data sets have a better likelihood of being linear, of being a straight-line relation, of being better correlated.

Unfiltered images may be used to determine times of maxima or minima for variable celestial objects. However, one cannot as easily relate unfiltered data to other data sets. The relation between an unfiltered image formed from photoms from across the spectrum and an image resulting from a filtered image defined by a filter's band width, is not cleanly, linearly, defined.

While there is no one precisely correct way to observe, one that has proved fruitful has been described in some detail by Landolt (2007a). More specific situations are covered in several of his papers which provide standard stars for calibration of data taken using the UBVRI photometric system filters (Landolt 1983, 1992, 2007b, 2009; Landolt and Uomoto 2007). Much of what follows will be based upon this material, particularly from Landolt (2007a). No matter the observing program in which one uses CCDs as the detector, one has to obtain dark frames, bias frames, and dome flats or sky flats, for *each* night's observing in order to obtain the most accurate results. The dark and dome flat frames can be obtained during the afternoon. Suggestions may be obtained from AAVSO manuals and from books such as Howell (2006) and Henden (2012). Comparison stars should approximate the variable star as closely as possible, both in magnitude and color index.

A night's observing plan depends upon the program, of course. The most rewarding program is one which incorporates good science and is fun to pursue. So find a star, or a class of variable star, and observe and learn about them! If the need, or sky conditions, demand or allow differential photometry only, then one need know only the coordinates of the object or objects to be observed that night. The assumption is that the comparison stars exist in the field of the program object. They should approximate the brightness and color index of the variable star to provide the most consistent results. If non-photometric skies persist, one must ensure that the photometric measures, the CCD frames, will include the appropriate stars, in brightness and color index, which will permit good differential photometry to be done. The AAVSO chart and photometric sequence team in many instances will have provided an appropriate comparison star sequence. If the observer happens to be blessed with a proper astronomical environment, that is, a clear and photometric sky with some regularity, then the opportunity exists for the observer to establish a photometric sequence. For the majority of AAVSO observations, the observer will take a series of exposures of sufficient length to provide a good signal to noise ratio for the program object.

Since AAVSO members primarily are interested in variable stars, the observer must time observations as accurately as possible. The time at which each frame, each image, was exposed, must be recorded. The shorter the period of the variable star, the more accurate must be the timing measure. The time of the final magnitude determination should be taken as the central time of the exposure. The central time of the exposure should be converted to the Heliocentric Julian Day (HJD). An AAVSO data submittal form can accept either the Julian Day (JD), that is the barycentric Julian Day, or the HJD. The HJD is the more accurate number, and especially is needed, is a must, for the short period variables. The JD is usable for the long period variable stars since their periods are long. Long term, though, even data for stars of long period benefit if the timings of observations are given in HJDs.

On the other hand, on photometric nights when the observational program involves standardization work, or all sky relative photometry, then the observer needs to plan more carefully. A sufficient number of appropriately placed, during the night, measures of extinction and transformation stars need to be observed (see Figures 4 and 5 in Landolt (2007a), together with the associated discussion). One must realize that extinction can and does vary throughout the night (see Landolt 2007a, Figure 8 and page 41). Although an observer can record images of fainter objects if a filter is not used, it is important to realize that photometric results have enhanced value if a filter is used in the light path. A Johnson V filter is preferred; its use will allow the best tie-ins to the AAVSO sequences and to most photometric systems, and hence enhances the value of the data.

When doing all sky relative photometry, an observer will want to intersperse standard star images with program star images with standard star images, and so on. This procedure is repeated throughout a night, the number of repetitions depending upon the length of the night. It is useful to observe in a pattern, like VBUUBV, so that one can average measures, images, frames, around a common air mass. This procedure works best for short exposures and when the CCD has a short read-out time.

In either situation an observer must keep good notes, an informative log book, so that during analysis one can recover and remember sky conditions, equipment behavior, and so on. State the size of the aperture used during data reductions. One must use the same size aperture for standard stars and for program stars in all sky photometry, and for the variable star and the comparison star(s) when doing differential photometry. Such information particularly is important during attempts to understand errant (outlying) data points. Such information is crucial for future users of the data, either the observer who by that time has forgotten just what happened at the telescope, or the person who downloaded the data, and now needs to understand how to meld the observer's measurements with data from other sources.

Given a "raw" CCD data frame, one immediately can difference the signal between a variable star and a comparison star, then add that difference to the comparison star's known magnitude, and get the magnitude of the variable at the moment of exposure. However, to get the best accuracy, the most accurate final magnitude for the variable object, whether or not the data were taken under a photometric sky or through cirrus, say, one first should subtract the bias frame and divide out the flat frame. One should apply extinction corrections, too. Here, on a non-photometric night, is the one time when it is useful to use "mean extinction coefficients." The observer is encouraged to reference the detailed explanations in the *AAVSO CCD Observing Manual* (AAVSO 2011), as well as the reference books cited earlier.

Final results from all sky photometry will include magnitudes, color indices, and HJDs. Final results for differential photometry obtained under non-photometric skies, will include HJDs and associated differential magnitudes.

4. Acknowledgements

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Digital Archiving: Where the Past Lives Again

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Abstract The process of digital archiving for variable star data by manual entry with an Excel spreadsheet is described. Excel-based tools including a Step Magnitude Calculator and a Julian Date Calculator for variable star observations where magnitudes and Julian dates have not been reduced are presented. Variable star data in the literature and the AAVSO International Database prior to 1911 are presented and reviewed, with recent archiving work being highlighted. Digitization using optical character recognition software conversion is also demonstrated, with editing and formatting suggestions for the OCR-converted text.

1. Introduction

When AAVSO Science Director Dr. Matthew Templeton initiated the Harvard Annals Digitization Project in August of 2010, archival digitizing activity at the AAVSO had been going on for some time. AAVSO Technical Assistant Dr. Michael Saladyga has, for example, digitized over 94,000 variable star observations of the late AAVSO member Wayne Lowder. Since October 2009, the Eggen Digitization Team (George Silvis and others) has begun to capture hundreds of thousands of photoelectric observations of Olin Eggen from the 1950s into the 1990s. Brian Skiff of the U.S. Naval Observatory in Flagstaff, Arizona, has digitized past visual and photoelectric data from the literature. Recently, Bob Stine, Christian Fröschlin, Hunter Johnson, Andrew Rupp, and this author have contributed numerous pre-1911archival observations to the AAVSO International Database (AID). This paper was written to aid in the future research into and archiving of older variable star observations.

Digital archiving is the process of capturing and recording past variable star observations from the literature and from archival sources, culminating with the entry of data into the AID. Digital archiving either involves the manual entry of data into a spreadsheet or using optical character reading (OCR) software to convert image data into text. Digitization using OCR conversion requires additional editing and not all sources of archival variable star data are appropriate for this methodology. Manual data entry and OCR digitization are discussed in later sections.

The archiving of older variable star observations has many benefits. In addition to completing the record of historical observations, it also allows for astrophysical studies to be performed on long timescales. It provides historical data sets for important variable stars (Figure 1), class prototypes, and novae, sometimes dating back to just after discovery (Figure 2). It also allows for the study of variable star evolution, helping to document phenomena such as changes in period, amplitude, or rates of mass transfer.

2. The archiving process

The digital archiving process consists of the following steps:

- Select your project.
- Check for existing data in the AID.
- Locate and download your data using NASA ADS (for papers) or Google Scholar (for books).
- Obtain AAVSO observer codes for observers in your data set.
- Create your spreadsheet template and then digitize your data.
- Proofread the spreadsheet and email it to the AAVSO.
- The spreadsheet will be converted into a version of the AAVSO Extended Visual ASCII format and entered into the AID by the AAVSO staff.

Variable star data in the literature usually exist in four different forms. In most references (including most of the *Harvard Annals* data), the Julian dates (JDs) are given and the magnitudes exist in reduced format (Figure 3). In older references, the magnitude estimates may exist as unreduced "step" or "step pair" data and calendar dates are given with no JD conversion (Figure 4). In very rare cases, magnitude estimates may exist as "decimal step" or "grade" data (Figure 5). Decimal step data divide the interval between two comparison stars into a number of steps and record just a single observation, i.e. "a6.5b." When working with grade data, magnitudes must then be derived by regression of magnitude versus grade (tables of magnitudes and grades of the comparison stars are usually given within the paper). Photoelectric data for variable stars also exist in the literature from the late 1940s to the 1990s (no example shown) and may provide additional archival material.

3. The spreadsheet template

The main spreadsheet template is shown in Figure 6. It consists of twelve columns (nine of which are kept) and may be up to several thousand rows deep. The key columns are labeled Observer (C), Type (D), Star (E), Julian Day (F), Fainter than (G), Magnitude (H), Comment Codes (I), Uncertain (J) and

Comments (K). Columns C through K are the portions of the spreadsheet which are kept and emailed to AAVSO Headquarters. Columns A and B are the partial JD columns which are summed in Column G. Splitting the JDs and using cell addition can save valuable keystrokes. The Observer Code goes in Column C. Visual observations are denoted with a "V" in Column D. Observations that are "fainter than" or "uncertain" are denoted with a "1" in Columns G and J, respectively. Column K is the Comments column, where the reference for each observation is noted in NASA ADS format with the year, journal, volume number, and page number indicated, along with the digitizer's observer code. Column L is an error check column, where for a given JD, the previous JD is subtracted. A progression of positive numbers downward indicates error-free JD entry. When the spreadsheet data entry is finished, be sure to "Highlight" all of the summed JDs in Column F and do a "Paste Special" and "Values" over the same highlighted contents to preserve the numerical JD values and hit "Save." After a final error check, delete Columns A, B, and L, "Save" the Spreadsheet Template, and email it to AAVSO Headquarters for uploading to the AID.

4. Excel-based archival tools

4.1. A step magnitude calculator

In many cases in the literature, the magnitude of an archival observation is not reduced but is commonly given as a "step" estimate using two comparison stars. In the example shown in Figure 7, an estimate for the Mira variable R Leonis is given as "n5R" and "R2l"—n5R2l—where R represents R Leonis. R Leonis is five steps fainter than comparison star "n" and is two steps brighter than comparison star "l". When the magnitudes of comparison stars "n" and "l" are known, the resultant magnitude is equal to the fractional ratio of the step range to the true magnitude range of the comparison stars. The magnitude for R Leonis can be calculated by the following equation:

$$\mathrm{mR} = (\mathrm{Steps\ (n\ to\ R)} / (\mathrm{Steps\ (n\ to\ R)} + \mathrm{Steps\ (R\ to\ l)}) \times (\mathrm{l} - \mathrm{n})) + \mathrm{n}, \quad (1)$$

where mR is the magnitude estimate for R Leonis, Steps (n to R) and Steps (R to l) are the step parts of the magnitude, and l and n are comparison star magnitudes for l and n, respectively.

The solution for the magnitude for R Leonis is:

$$\mathrm{mR} = (5 / (5 + 2) \times (6.48 - 5.84)) + 5.84 = 6.30 \quad (2)$$

The construction of this step magnitude spreadsheet is straightforward. Enter the comparison star names (Columns A and I) and sequence magnitudes (Columns B and H). Follow the instructions and enter the equations given in Figure 7. When step numbers (dark green) are entered in Columns D and F, the magnitudes of the comparison stars (light green) and step numbers are displayed in the Logic Columns C and G and in row 14. The final reduced magnitude (yellow) is displayed in Cell E16.

4.2. An Excel Julian date calculator

In other instances, archival variable star data may give the dates of the observation in calendar format, commonly with GMT times. In these cases, the Julian date (JD) will need to be calculated. A JD with no heliocentric correction is calculated by the equation:

$$\text{JD (referenced from October 15, 1582)} = 367 \times \text{Year} - \text{INT}\,(7 \times \text{Year} + \text{INT}\,((\text{Month} + 9) / 12)) / 4) - \text{INT}\,(3 \times (\text{INT}\,((\text{Year} + (\text{Month} - 9) / 7) / 100 + 1) / 4 + \text{INT}\,(275 \times \text{Month} / 9) + \text{Day of the Month} + 1721028.5 + \text{UTC Hr.} / 24 + \text{UTC Min.} / 1440 + \text{UTC Secs.} / 86400 \tag{3}$$

As opposed to using another software package to compute the JD, it can be calculated in Excel by using the equation given above, where the year, month, day of the month, and GMT times in hours, minutes, and seconds become specific cell inputs in Columns A through F, respectively, as shown in Figure 8. In this screen shot of the Excel spreadsheet, Cell J2 is highlighted and the Excel version of the JD equation is shown in the function window and here as Equation 4; the JD (Excel equation to be entered for Cell J2, [all numbers and text between the parentheses]):

“=367*A2-INT(7*(A2+INT((B2+9)/12))/4)-INT(3*(INT((A2+(B2-9/7)/100+1)/4)+INT(275*B2/9)+C2+1721028.5+D2/24+E2/1400+F2/86400” (4)

Otherwise, this JD-calculating spreadsheet template in Figure 8 is similar to its counterpart shown in Figure 6.

When you are finished digitizing, be sure to “Highlight” all of the calculated JDs in Column J and do a “Paste Special” and “Values” over the same highlighted contents to preserve the numerical JD values and hit “Save.” Columns A, B, C, D, E, F, and O can then be deleted, the spreadsheet template can then be edited, “Saved”, and emailed to AAVSO Headquarters for uploading to the AID.

5. Digitizing suggestions and guidelines

Listed below are a list of suggestions and hints for digitization by spreadsheet entry:

- Research the AID and literature thoroughly.
- Correspond with AAVSO Headquarters (Dr. Matthew Templeton) before selecting of your project; digitize a complete paper, as opposed to doing partial digitization of a given reference.

- Obtain or request necessary AAVSO observer codes beforehand.
- Use a computer with a full-sized keyboard and keypad; use of an all-in-one generic laptop is not recommended.
- Use the “Copy” and “Paste” functions to create and fill the Spreadsheet Template.
- Review your archival article to understand the used of italics, observer abbreviations, and special symbols for “not seen” and “fainter than” observations.
- Record all data as presented in the journal or article.
- Omit “fainter than” and “not seen” observations if no comparison star data are given.
- Determine the photometric system of your paper, as the AAVSO uses the Harvard Photometric system; some papers or archival sources may use Schonfeld, Hagen ASV, or Potsdam photometric sequences; make a comment if the magnitude estimates are not on the Harvard system and enter the “Comment code” “K.”
- Average multiple estimates made on the same JD (where no times are given) and make a note in the Comments column.
- Use the “additive columns” method to minimize JD keystrokes.
- Remember to “Copy,” “Paste Special,” and “Values” for saving JD’s derived from mathematical cell operations.
- Check for errors in JD, magnitude, observer, star name, and page number.
- “Save” your work often and take breaks as needed to reduce fatigue.
- Enter Comments codes (Fainter than, Uncertain, etc.) as required.
- In the Comments column, enter the paper reference in ADS format with the page number (if the paper in listed by the ADS, otherwise use the standard AAVSO references format for books and other non-ADS references), your AAVSO observer code, and other comments.
- Run a JD-subtraction quality check to detect possible JD errors.

6. Review of variable star observation in the literature and archival sources

In 1890, Pickering presented and analyzed 125,720 variable star observations from the literature and those sent to Harvard College Observatory between 1837 and prior to 1888 from thirty-one worldwide observers and institutions (Pickering 1890). The observers and institutions identified in that paper included: *Argelander, Backhouse, Baxendell (Sr. and Jr.), Chandler*, Duner, *Eadie*, Espin, *Harvard College Observatory*, Gore, Hartwig, *Hagen, Heis, Knott*, Lawrence, Markwick, National Observatory in Cordoba, Argentina, Oudemanns, Peck, Plassman, *Parkhurst, Schonfeld*, Sarafik, Shearman, *Sawyer, Schmidt*, Upton, Webb, Wilsing, *Zwack*, and *Zaiser* (observers in Table 1 are indicated here in italics). Until very recently, few observations prior to 1888 existed in the AID. Pickering (1890) is a key reference for variable star observations prior to 1888 and may be an important source for researching additional archival variable star observations.

Table 1 lists a number of variable star observation collections prior to 1911. A total of thirty-one individual sources from the literature and the AAVSO Archives are identified and summarized in the table. The individual columns going from left to right are: the paper, book or archival source; the observer(s); the number of observations (estimated observations are noted); the number of individual stars documented; the magnitude reduction status; the Julian Date conversion status, and the AAVSO digitization status as of this writing. All listed sources are detailed in the reference list. The variable star data sources that have been digitized and are currently in the AID are given in italics.

Table 1 represents over an estimated 222,000 variable star observations prior to 1911, of which over an estimated 39,000 have been digitized up to the present time. Of the 125,720 variable star observations known by Pickering to exist prior to 1888, over 100,000 remain to be digitized and an estimated 98,000 observations from 1888 to 1911 also remain to be digitized. Further research may yield tens of thousands of additional variable star observations.

Additional sources of variable star data include papers in journals of the past: *Astronomische Nachrichten, Astronomical Journal, Monthly Notices of the Royal Astronomical Society, The Observatory,* and others. While this paper mainly concerns itself with the pre-1911 observations, other sources of variable star data are equally important, including unpublished observations in Ph.D. dissertations, photoelectric observations in the literature from the late 1940s to the 1990s, and private collections of individual observatories and archives.

7. Digitization using optical character reading (OCR)

After the presentation of this paper at the AAVSO's Annual Meeting in 2011, the author began to investigate OCR digitization with the freeware program "FreeOCR Version 3.0", which is based on the Tesseract OCR engine. This Windows-based software shows promise with increased digitizing efficiency and accuracy relative to the previously described manual spreadsheet entry method. However, the resulting OCR converted text will have to be edited and formatted within Excel. Figure 9 shows a small highlighted selection of variable star data of RR Andromedae from Campbell and Pickering (1912; left) and the corresponding OCR output (right) using this software.

Several important points about OCR-converted text are noted:

- The thin vertical column lines of the source .pdf file do not affect the resulting OCR text output.
- Text conversion accuracy appears to be high, between 90 and 95%.
- The two-digit year data are offset from the remaining variable star data of the scanned output text; this is not a problem, since the text may be edited within Excel after "Copying and "Pasting."
- Some errors will result from the OCR-conversion process: the bold vertical column lines may introduce spurious text; some italicized and regular text may not be converted properly (C's may become G's, c's may become 0's, 3's or 6's may become 8's or 0's, etc.), decimal points may be skipped or converted to commas and blemishes on the original text file may result in spurious converted text.

The following steps are required to edit the OCR-converted text and to enter it into the standard spreadsheet template (Figure 6):

- Highlight and OCR-convert one column of variable star data at a time; trying to OCR convert an entire page of variable star data at once complicates the editing process.
- "Copy" data from the OCR text window and "Paste" the OCR text in column N or higher in the standard Excel spreadsheet template; the columns of the OCR-converted text should be automatically parsed into columns and rows of data in Excel.
- Edit the rows and columns of new OCR text in Excel as necessary, removing the spurious data, correcting errors, and maintaining the JDs, magnitudes, and observers in their respective columns.
- "Copy" and "Paste" your desired columns of data to their proper positions within the standard Spreadsheet Template as required.
- Use the cell-addition method to complete the JDs and replace any improvised observer abbreviations with their correct AAVSO Observer Code.
- Edit the "Fainter than" (usually expressed as italicized magnitude values) and "Uncertain" observations and cite the paper reference and submission details in the Comments column.
- Delete the originally "Pasted" OCR converted data within Excel and repeat the process.

The author has noted a potential 35% increase in efficiency in using OCR software for digital archiving when compared to manual spreadsheet entry, even with the additional editing steps. Corrections are readily made in Excel. The use of OCR digitization and the standard spreadsheet template following the suggestions and guidelines previously described are highly recommended on large data sets where JD's and magnitudes are already converted.

8. Conclusions

The archiving process, a spreadsheet template, suggestions, and Excel-based data tools have been reviewed and presented. Thirty-one sources of variable star data prior to 1911 have been identified and presented in tabular form. Of the 125,720 observations known to Pickering prior to 1888, over 100,000 observations still remain to be located and digitized. Over 98,000 archival observations from 1888 to 1911 have been identified and also remain to be digitized. Spreadsheet entry of data is not tedious by using the methods described. Digitization by optical character reading conversion is a very promising alternative to manual spreadsheet entry, but additional editing and formatting are required to get the variable star data into the standard spreadsheet template. However, manual spreadsheet entry of archival data needs to be used in cases when the conversion of calendar dates to JDs and/or step magnitudes are required. All archival variable star data have value, if we can locate and can capture them. This paper attempts to clarify the where and how of the digital archiving process.

9. Acknowledgements

The author would like to thank all of the past observers for their observations and past authors for their papers, publications, and books. Dr. Matthew Templeton of the AAVSO is acknowledged for his guidance and suggestions. Elizabeth O. Waagen of the AAVSO is recognized for her uploading of the archival observations to the AID and providing new observer codes. A special thanks goes to Michael Saladyga for his help in the preparation of this paper and providing AAVSO Archives information. The author also recognizes Robert Stine, Andrew Rupp, Christian Froschlin, and others for their efforts in digitization of variable star observations prior to 1911. The SAO/NASA Astrophysics Data System Abstract Service and Google Scholar were used for the online searching and retrieval of digitized papers, journals, and books which exist in the public domain.

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Pickering, E. C. 1900b, *Ann. Harvard Coll. Obs.*, **33**, 29.

Pickering, E. C. 1900c, *Ann. Harvard Coll. Obs.*, **33**, 75.

Pickering, E. C. 1900d, *Ann. Harvard Coll. Obs.*, **33**, 95.

Pickering, E. C. 1903, *Ann. Harvard Coll. Obs.*, **46**, 39.

Pickering, E. C. 1904, *Ann. Harvard Coll. Obs.*, **46**, 120.

Pickering, E. C. 1918, *Ann. Harvard Coll. Obs.*, **79**, 35.

Pickering, E. C., and Wendell, O. C. 1890, *Ann. Harvard Coll. Obs.*, **24** 1.

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Table 1. A selection of variable star observations in the AAVSO Archives and in literature prior to 1911. Data sources in italics have been digitized and are currently in the AID.

Source[1]	*Observer(s)*	*No. Observations*	*No. Stars*	*Magnitude Reduced*	*JD Converted*	*Status*
Sawyer (1877–1892)[2]	Sawyer	5000[3]	unknown	no	no	not digitized
Chandler (1883–1884)[2]	Chandler	700[3]	unknown	yes	no	not digitized
Parkhurst (1883–1885)[2]	Parkhurst, J.	2000[3]	unknown	no	no	not digitized
Eadie *et al.* (1884–1885)[2]	Eadie, Hagen, Zaiser	1000[3]	unknown	no	no	not digitized
Eadie (1884–1890)[2]	Eadie	2000[3]	unknown	no	no	not digitized
Yendell (1888–1918)[2]	Yendell	30000[3]	unknown	mixed	mixed	not digitized
Pickering and Wendell (1890)	Pickering and Wendell	1057	165	yes	no	digitized by Paxson
Townley (1892)	Townley	1085[2]	37	yes	no	digitized by Paxson
Parkhurst and Pickering (1893)	Eadie and Parkhurst, H.	4800[3]	135	yes	no	not digitized
Pickering (1900a)	various	6300[3]	17	yes	yes	not digitized
Turner (1899)	Knott	6683	23	yes	no	digitized by Paxson
Pickering (1900b)	Argelander	4290	16	yes	yes	digitized by Paxson
Pickering (1900c)	Schonfeld	1535	31	yes	yes	digitized by Paxson
Pickering (1900d)	Schmidt	7070	5	yes	yes	digitized by Paxson
Valentiner (1900)	Schonfeld	37000[3]	118	no	no	not digitized
Hagen (1901)	Hagen *et al.*	3000[3]	52	no	no	not digitized
Guthnick (1901)[4]	various	6200[3]	1	no	no	not digitized
Wendell and Pickering (1902)	various	4400	58	yes	yes	digitized by Rupp and Fröschlin

[1] See reference list for more information. [2] In AAVSO Archives. [3] Estimated. [4] Observations of Mira only.

Table continued on next page

Table 1. A selection of variable star observations in the AAVSO Archives and in literature prior to 1911. Data sources in italics have been digitized and are currently in the AID, cont.

Source[1]	*Observer(s)*	*No. Observations*	*No. Stars*	*Magnitude Reduced*	*JD Converted*	*Status*
Hagen (1903)	Heis and Krueger	8500[3]	61	no	yes	not digitized
Pickering (1903)	various	3346	1	yes	no	digitized by Stine
Daniel and Reid (1903–1904)[2]	Daniel and Reid	500[3]	unknown	yes	no	not digitized
Pickering (1904)	Wendell	5000[3]	150	yes	yes	not digitized
Turner (1905)	Peek and Grover	4133	22	yes	yes	not digitized
Backhouse (1905)	Backhouse	2300[3]	49	no	no	not digitized
Campbell and Pickering (1907)	various	8400[3]	75	yes	yes	not digitized
Brook (1908)	Pogson	4210	31	yes	yes	digitized by Paxson
Wendell (1909)	Wendell	6900[3]	44	yes	yes	not digitized
Campbell and Pickering (1912)	various	21,950[2]	328	yes	yes	digitized by Paxson
Blagg, Turner (1912–1924)[5]	Baxendell	6953	30	yes	yes	digitized by Paxson
Fleming and Pickering (1912)	Fleming	20000[3]	107	yes	yes	not digitized
Furness (1913)	various	4800[3]	101	yes	yes	not digitized

[1] See reference list for more information. [2] In AAVSO Archives. [3] Estimated. [4] Observations of Mira only. [5] Includes Turner (1912), Turner and Blagg (1914–1918), and Blagg (1924).

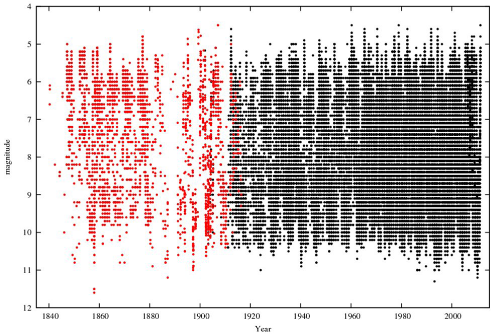


Figure 1. R Leonis observations in the AAVSO International Database. Black dots are data in AID prior to digitization project; red dots are observations digitized by the author to extend the light curve back to 1840.

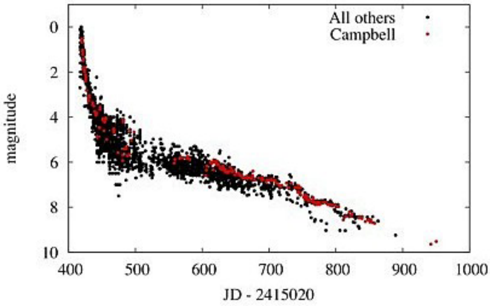
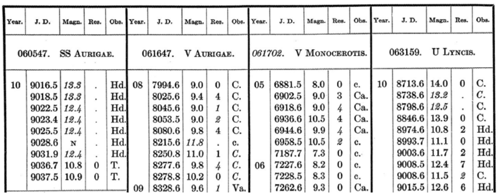
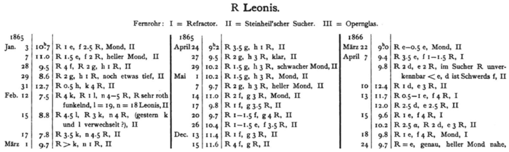


Figure 2. AAVSO light curve of Nova Persei 1901 No. 2 (GK Persei) digitized by Bob Stine from Pickering (1903). Black dots are pre-existing data; red dots are Stine-digitized data added to the AID.



Year.	J. D.	Magn.	Res.	Obs.	Year.	J. D.	Magn.	Res.	Obs.	Year.	J. D.	Magn.	Res.	Obs.	Year.	J. D.	Magn.	Res.	Obs.
060547. SS Aurigae.					061647. V Aurigae.					*061702.* V Monocerotis.					063159. U Lyncis.				
10	9016.5	*13.3*	.	Hd.	08	7994.6	9.0	0	C.	05	6881.5	8.0	0	c.	10	8713.6	14.0	0	C.
	9018.5	*13.3*	.	Hd.		8025.6	9.4	4	C.		6902.5	9.0	3	Ca.		8738.6	*13.2*	.	*C.*
	9022.5	*12.4*	.	Hd.		8045.6	9.0	*1*	C.		6918.6	9.0	*4*	Ca.		8798.6	*12.5*	.	C.
	9023.4	*12.4*	.	Hd.		8053.5	9.0	*2*	C.		6936.6	10.5	4	Ca.		8846.6	13.9	0	C.
	9025.5	*12.4*	.	Hd.		8080.6	9.8	4	C.		6944.6	9.9	*4*	Ca.		8974.6	10.8	2	Hd.
	9028.6	N	.	Hd.		8215.6	*11.8*	.	c.		6958.5	10.5	*2*	c.		8993.7	11.1	0	Hd.
	9031.9	*12.4*	.	Hd.		8250.8	11.0	1	*C.*		7187.7	7.3	0	c.		9003.6	11.7	2	Hd.
	9036.7	10.8	0	T.		8277.6	9.8	*4*	*C.*	06	7227.6	8.2	0	c.		9008.5	12.4	7	Hd.
	9037.5	10.9	0	T.		8278.8	10.2	0	*C.*		7228.5	8.3	0	c.		9008.6	11.5	*2*	C.
					09	8328.6	9.6	*1*	Va.		7262.6	9.3	0	Ca.		9015.5	12.6	6	Hd.

Figure 3. Typical *Harvard Annals* format with JDs, reduced magnitudes, and observer identification (Campbell and Pickering 1912).



R Leonis.

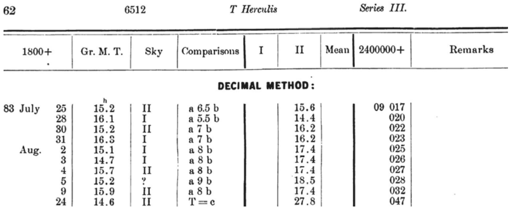
Fernrohr: I = Refractor. II = Steinheil'scher Sucher. III = Opernglas.

1865			
Jan.	3	$10^{\mathrm{h}}.7$	R 1 e, f 2.5 R, Mond, II
	7	11.0	R 1.5 e, f 2 R, heller Mond, II
	28	9.5	R 4 f, R 2 g, h 1 R, II
	29	8.6	R 2 g, h 1 R, noch etwas tief, II
	31	12.7	R 0.5 h, k 4 R, II
Feb.	12	7.5	R 4 k, R 1 l, n 4–5 R, R sehr roth funkelnd, l = 19, n = 18 Leonis, II
	15	8.8	R 4.5 l, R 3 k, n 4 R, (gestern k und l verwechselt ?), II
	17	7.8	R 3.5 k, n 4.5 R, II
März	1	9.7	R > k, n 1 R, II

1865			
April	24	$9^{\mathrm{h}}.2$	R 3.5 g, h 1 R, II
	27	9.5	R 2 g, h 3 R, klar, II
	29	10.2	R 1.5 g, h 3 R, schwacher Mond, II
Mai	1	10.2	R 1.5 g, h 3 R, Mond, II
	7	9.7	R 2 g, h 3 R, heller Mond, II
	14	11.0	R 2 f, g 3 R, Mond, II
	17	9.8	R 1 f, g 3.5 R, II
	20	9.7	R 1–1.5 f, g 4 R, II
	26	10.4	R 1–1.5 e, f 3.5 R, II
Dec.	13	11.4	R 1 f, g 3 R, II
	15	11.6	R 4 f, g R, II

1866			
März	22	$9^{\mathrm{h}}.0$	R e–0.5 e, Mond, II
April	7	9.4	R 3.5 e, f 1–1.5 R, I
		9.8	R 2 d, e 2 R, im Sucher R unverkennbar < e, d ist Schwerds f, II
	10	12.4	R 1 d, e 3 R, II
	13	11.7	R 0.5–1 e, f 4 R, I
		12.0	R 2.5 d, e 2.5 R, II
	15	9.6	R 1 e, f 4 R, I
		10.2	R 2.5 α, R 2 d, e 3 R, II
	18	9.8	R 1 e, f 4 R, Mond, I
	24	9.7	R = e, genau, heller Mond nahe,

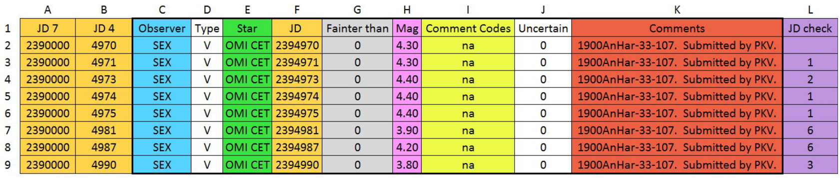
Figure 4. Step magnitude data of Schonfeld with calendar dates and times, but with no JD conversion (Valentiner 1900).



62 6512 *T Herculis* *Series III.*

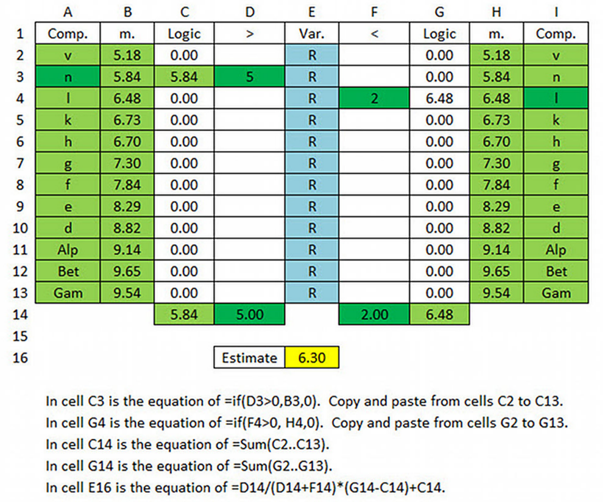
1800+			Gr. M. T.	Sky	Comparisons	I	II	Mean	2400000+	Remarks
					DECIMAL METHOD:					
83	July	25	$15^{\mathrm{h}}.2$	II	a 6.5 b		15.6		09 017	
		28	16.1	I	a 5.5 b		14.4		020	
		30	15.2	II	a 7 b		16.2		022	
		31	16.3	I	a 7 b		16.2		023	
	Aug.	2	15.1	I	a 8 b		17.4		025	
		3	14.7	I	a 8 b		17.4		026	
		4	15.7	II	a 8 b		17.4		027	
		5	15.2	?	a 9 b		18.5		028	
		9	15.9	II	a 8 b		17.4		032	
		24	14.6	II	T = c		27.8		047	

Figure 5. An example of decimal step data (in the Comparisons column) and grade data (in Column II) with calendar dates and JDs being given (Hagen 1901).



	A	B	C	D	E	F	G	H	I	J	K	L
1	JD 7	JD 4	Observer	Type	Star	JD	Fainter than	Mag	Comment Codes	Uncertain	Comments	JD check
2	2390000	4970	SEX	V	OMI CET	2394970	0	4.30	na	0	1900AnHar-33-107. Submitted by PKV.	
3	2390000	4971	SEX	V	OMI CET	2394971	0	4.30	na	0	1900AnHar-33-107. Submitted by PKV.	1
4	2390000	4973	SEX	V	OMI CET	2394973	0	4.40	na	0	1900AnHar-33-107. Submitted by PKV.	2
5	2390000	4974	SEX	V	OMI CET	2394974	0	4.40	na	0	1900AnHar-33-107. Submitted by PKV.	1
6	2390000	4975	SEX	V	OMI CET	2394975	0	4.40	na	0	1900AnHar-33-107. Submitted by PKV.	1
7	2390000	4981	SEX	V	OMI CET	2394981	0	3.90	na	0	1900AnHar-33-107. Submitted by PKV.	6
8	2390000	4987	SEX	V	OMI CET	2394987	0	4.20	na	0	1900AnHar-33-107. Submitted by PKV.	6
9	2390000	4990	SEX	V	OMI CET	2394990	0	3.80	na	0	1900AnHar-33-107. Submitted by PKV.	3

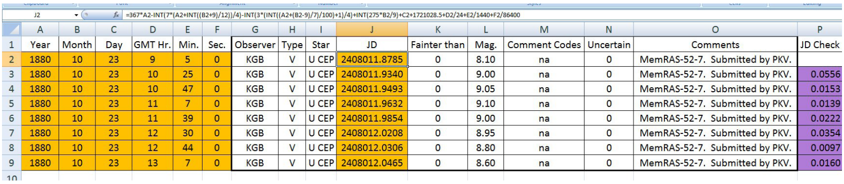
Figure 6. The standard spreadsheet template for capturing archival variable star observations. Columns C–K are sent to the AAVSO. Data for observer Julius Schmidt (observer code SEX) are shown.



	A	B	C	D	E	F	G	H	I
1	Comp.	m.	Logic	>	Var.	<	Logic	m.	Comp.
2	v	5.18	0.00		R		0.00	5.18	v
3	n	5.84	5.84	5	R		0.00	5.84	n
4	l	6.48	0.00		R	2	6.48	6.48	l
5	k	6.73	0.00		R		0.00	6.73	k
6	h	6.70	0.00		R		0.00	6.70	h
7	g	7.30	0.00		R		0.00	7.30	g
8	f	7.84	0.00		R		0.00	7.84	f
9	e	8.29	0.00		R		0.00	8.29	e
10	d	8.82	0.00		R		0.00	8.82	d
11	Alp	9.14	0.00		R		0.00	9.14	Alp
12	Bet	9.65	0.00		R		0.00	9.65	Bet
13	Gam	9.54	0.00		R		0.00	9.54	Gam
14			5.84	5.00		2.00	6.48		
15									
16				Estimate	6.30				

In cell C3 is the equation of =if(D3>0,B3,0). Copy and paste from cells C2 to C13.
In cell G4 is the equation of =if(F4>0, H4,0). Copy and paste from cells G2 to G13.
In cell C14 is the equation of =Sum(C2..C13).
In cell G14 is the equation of =Sum(G2..G13).
In cell E16 is the equation of =D14/(D14+F14)*(G14-C14)+C14.

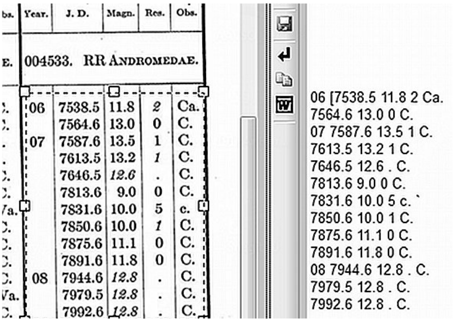
Figure 7. A Step Magnitude Calculator. Reduction of the step values "n5R" and "R2l" gives an estimated magnitude of 6.30.



J2 =367*A2-INT(7*(A2+INT((B2+9)/12))/4)-INT(3*(INT((A2+(B2-9)/7)/100)+1)/4)+INT(275*B2/9)+C2+1721028.5+D2/24+E2/1440+F2/86400

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Year	Month	Day	GMT Hr.	Min.	Sec.	Observer	Type	Star	JD	Fainter than	Mag.	Comment Codes	Uncertain	Comments	JD Check
2	1880	10	23	9	5	0	KGB	V	U CEP	2408011.8785	0	8.10	na	0	MemRAS-52-7. Submitted by PKV.	
3	1880	10	23	10	25	0	KGB	V	U CEP	2408011.9340	0	9.00	na	0	MemRAS-52-7. Submitted by PKV.	0.0556
4	1880	10	23	10	47	0	KGB	V	U CEP	2408011.9493	0	9.05	na	0	MemRAS-52-7. Submitted by PKV.	0.0153
5	1880	10	23	11	7	0	KGB	V	U CEP	2408011.9632	0	9.10	na	0	MemRAS-52-7. Submitted by PKV.	0.0139
6	1880	10	23	11	39	0	KGB	V	U CEP	2408011.9854	0	9.00	na	0	MemRAS-52-7. Submitted by PKV.	0.0222
7	1880	10	23	12	30	0	KGB	V	U CEP	2408012.0208	0	8.95	na	0	MemRAS-52-7. Submitted by PKV.	0.0354
8	1880	10	23	12	44	0	KGB	V	U CEP	2408012.0306	0	8.80	na	0	MemRAS-52-7. Submitted by PKV.	0.0097
9	1880	10	23	13	7	0	KGB	V	U CEP	2408012.0465	0	8.60	na	0	MemRAS-52-7. Submitted by PKV.	0.0160

Figure 8. The spreadsheet template modified for Julian date calculation. See text for calculation equation.



Year.	J. D.	Magn.	Res.	Obs.
004533. RR ANDROMEDAE.				
06	7538.5	11.8	*2*	Ca.
	7564.6	13.0	0	C.
07	7587.6	13.5	1	C.
	7613.5	13.2	*1*	C.
	7646.5	*12.6*	.	C.
	7813.6	9.0	0	C.
	7831.6	10.0	5	c.
	7850.6	10.0	*1*	C.
	7875.6	11.1	0	C.
	7891.6	11.8	0	C.
08	7944.6	*12.8*	.	C.
	7979.5	*12.8*	.	C.
	7992.6	*12.8*	.	C.

```
06 [7538.5 11.8 2 Ca.
7564.6 13.0 0 C.
07 7587.6 13.5 1 C.
7613.5 13.2 1 C.
7646.5 12.6 . C.
7813.6 9.0 0 C.
7831.6 10.0 5 c. `
7850.6 10.0 1 C.
7875.6 11.1 0 C.
7891.6 11.8 0 C.
08 7944.6 12.8 . C.
7979.5 12.8 . C.
7992.6 12.8 . C.
```

Figure 9. A comparison of RR Andromedae variable star data (Campbell and Pickering 1912) in an image file (left) versus its equivalent OCR converted output (right).

The Effect of Online Sunspot Data on Visual Solar Observers

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Abstract Solar observing affords opportunities for amateurs and students to contribute to the AAVSO. This study explores the use of online solar data and photographs in training solar observers, and the bias effects such data can have when not used judicially.

1. Estimating Sunspot Activity

As noted on the AAVSO's Solar Section web page (http://www.aavso.org/solar), solar observing is one way that amateur astronomers with relatively small telescopes can (with a proper white light filter) contribute useful data. The AAVSO's Solar Section aggregates and reduces the data contributed by its observers and publishes a monthly bulletin containing the Relative American Sunspot Number R_a for each day of that month (http://www.aavso.org/solar-bulletin). Since solar observing can be done during normal school hours and with modest equipment, it is an easy way to include telescopic observing in astronomy classes (both at the high school and college level) and introduce students to both the AAVSO and the collection and importance of individual astronomical observations.

There are a number of different organizations that collect and aggregate sunspot observations; each organization produces its own sunspot number or index. Each index is based on the Wolf index (developed by Rudolf Wolf in 1848), calculated as $R=10g + s$, where g is the number of sunspot groups (areas of sunspot activity) and s is the number of individual spots included in all the groups. Three commonly cited indices are the Boulder Index (computed at the NOAA Space Environment Center in Boulder, Colorado), International Index (computer by the Solar Influences Data Center in Belgium), and the aforementioned American Index (computed by the AAVSO Solar Section). Each uses data from a different set of observers/observatories, and each aggregates the data in a slightly different way. Because observers have a tendency to underreport the number of sunspots (due to differences in instrumentation, experience, and visual acuity), there will be a range of R values reported on any given day (Schaefer 1993, Foster 1997). In addition, observers will vary in the way they distinguish between different groups, and how well he or she can distinguish a pore from a sunspot (Schaefer 1993, Schaefer 1997). In order to compensate for these differences, it has become customary to assign each observer a K-factor which is multiplied by his or her R value to correct for these differences. (For more information about the K-factor and how the AAVSO computes its values see Foster 1997, Schaefer 1997, and Feehrer 2000.) This "personal equation" is not uncommon in the aggregation and comparison of astronomical data. The term "personal equation" dates back to the nineteenth century, when astronomers discovered that their individual measurements of transit times for the same object/event differed (Schaffer 1988). Today each sunspot index uses a different technique to assign K-factors to contributing observers. The result is the values reported by each index will differ from one another.

One relatively simple way to introduce students to the concept of the sunspot cycle is through the Spaceweather website (www.spaceweather.com). This resource hosts on its main page a daily picture of the near-side of the sun from the Solar Dynamics Observatory and identifies some of the sunspot groups by number. The site also includes an overall Boulder sunspot number from the past twenty-four hours. While the Boulder index differs from R_a by a significant factor (Feehrer 2000), the beginning student solar observer does not need to delve into these subtleties from the onset. Also, since the AAVSO data are released after the fifteenth of the following month, students do not have real-time access to this data. Real-time photographs and sunspot indices can be helpful for visual sunspot observers who are just beginning to learn the techniques of careful visual sunspot counts (for example, how to identify complex groups and how to carefully examine the limb of the sun), but the "power of suggestion" these data might have on an observer cannot be ignored. An observer can check his or her observations against this "standard" and may be tempted to alter their data to conform to what he or she considers to be a more reliable standard. For example, while the AAVSO Solar Section includes the SOHO website real-time image (http://sohowww.nascom.nasa.gov/data/realtime/hmi_igr/512/) as one of its recommended resources for solar observers, and recommends an observer consult such a site when one has a break in observing (in order to follow the evolution of groups), an important caveat is included within the recommendation: "DO NOT use these resources to 'scale' your own observations. Most sources available via this medium use equipment and procedures that are different from the ones you use and can be expected to achieve different results" (Beck 2010). The study described in this paper first examined the effects of the Spaceweather site on a class of college students just beginning to learn white light solar observing, and then compared the results of a more experienced solar observer (the faculty course instructor) with the Spaceweather data. In no case was biased data submitted to any agency or organization.

2. Introducing Students to Sunspot Observing

In the middle of the Fall 2010 semester, twelve students in ESCI 278 (Observational Astronomy) at Central Connecticut State University were taught how to solar observe with a 6-inch *f*/1 1525 mm Schmidt-Cassegrain telescope, Thousand Oaks glass filter, and 35mm *f*/1 eyepiece. Students had been using other telescopes for night observing for six weeks beforehand and were therefore familiar with basic telescope usage and observing techniques. Solar activity was very low during this time; therefore, the instructor consulted the Spaceweather website before each sunny class period and observations were made only on days on which there were sunspots to observe. Each student individually observed the sun, drew a sketch, and estimated his or her observed sunspot number $R=10g + s$. Afterwards each student checked his or her sketch against the Spaceweather.com picture, observed a second time and drew a second sketch, noting if he or she could see all the areas of activity visible on the website. Students were aware of the fact that the posted R on the website was the previous day's data, and therefore concentrated on the actual photograph (which was on average several hours old).

There were 37 sets of before/after observations. In 19 cases the students could not see additional activity after viewing the photograph, while in 13 instances students were able to view additional activity afterwards. Sample comments from this latter group of observations include the following:

> "Without looking at the internet I observed two elliptical shaped sunspots making a group. After looking online I noticed that with the two sunspots I saw above are several more smaller spots but I couldn't divide them in the scope."
>
> "After I could see more spots in the lower group—about 2 more. Also, I could see one more spot in the higher group."
>
> "After looking at the computer I see a few more in the center."
>
> "For some reason after looking at the computer I was able to see two 'sets' of spots with a multitude of spots to be seen the second time. However, the spots seemed to be perforated."
>
> "When I observed I could not see anything. Image was fuzzy, could see a minimum of four spots (went back to look after seeing computer)."

Consulting the online photograph was therefore successful in prompting the students to both look more carefully at the groups they had seen in order to count small spots and look at all areas of the sun more carefully to pick up small spots/groups. In the case of one student, it also reinforced an important lesson of observing in general: "One of the pieces of 'dirt' (on the eyepiece) turned out to be a group of sunspots."

Several student comments also raised important red flags, including the following (made by two different students):

> "After I think I might see one. But I'm not sure. It's hard for me to see anything. I could be making it up again."
>
> "I still can't see anything, including the one I made up before. The image seemed shakier than before."

The fact that students had (apparently) included spots in their logbooks that they had not seen speaks directly to the admonition of the AAVSO website and raises questions as to whether students felt they would either be graded lower or otherwise displease the instructor if they could not see spots (although they had been unequivocally advised otherwise). The honesty of the students is laudable, but reflects one of the dangers in utilizing such photographs or standardized data when instructing beginning observers—the tendency toward bias is powerful. Although students were often and firmly admonished never to change their original observation based on what their classmates saw, or what they saw on the website, this was clearly not followed. Even if the Spaceweather site was not used in this study, it is suggested that general peer pressure would have been sufficient to tempt some students to "make it up." While keeping one's observations secret from one's classmates may have stopped this, the need to improve one's technique (and attention to detail), and the ability to do this by sharing and consulting other sources, outweighs the downfalls *if* the students do not attempt to submit their data until they are confident enough in their own abilities to avoid such biases.

Even after viewing the Spaceweather picture, some of the students still could not see activity that his or her classmates could see, leading to some frustration (and possibly explaining the previously noted instances of "making spots up"). One student in particular—a science major—had difficulties on all four dates:

> "There were, supposedly, other sunspots found besides the ones I saw but I was unable to find them even after I saw their position online."
>
> "I was not able to make out any spots today even though there was at least one spot other people found. I was only able to see the yellow sun."

> “This whole semester I have had trouble with noting the sunspots. It was hard to see with my glasses and sun shining at me but it would also be difficult for me to focus clearly on the sun so I could see the spots. The spot on the top left is only a smudge on the eyepiece.”

This particular student also had issues with some night observations as well, and began wearing her contact lenses to class near the end of the semester (after the solar observing had concluded) in order to help with her observations (with some success). It would be interesting to explore whether the use of glasses versus contact lenses affects the acuity of solar observers (although astigmatism should be compensated for by refocusing the telescope).

The general conclusions of this portion of the study are as follows:

1) Integrating Spaceweather.com’s real-time sun pictures can aid students in taking care to look more carefully when solar observing.

2) Beginning observers can be tempted to “invent” sunspots if they know they are missing something that others can see. Students must be reminded on numerous occasions of the ethics involved in contributing individual data to collecting organizations.

3) By sharing their observations and noting the differences, students came to an understanding of the importance of the K-factor in solar data aggregation.

For a future extension of this study, it would be interesting to explore whether using the posted sunspot counts (posted on the next day) and the labeling of certain sunspot groups by number on the posted photo aid students in identifying individual groups in times of higher solar activity (as suggested by the AAVSO Guidelines for Solar Observers (http://www.aavso.org/solar-guidelines)).

3. Online Sunspot Counts as an Aid for Experienced Sunspot Observers

In the second portion of this study, the faculty instructor used the same equipment to observe the sun ten times (approximately once a week) from March 1 through May 1. The separation between observations was selected to avoid bias from previous observations. In each case, the Spaceweather.com photograph was consulted after the initial observation and a second observation was then commenced to note if additional activity could be seen. The observer’s results were consistent with the AAVSO sunspot index R_a published in the following month (Howe 2011) and were (as expected) generally significantly lower than the Boulder index reported on the Spaceweather website. The most important outcome was the fact that in all cases, any additional activity visible in the photograph but not seen in the initial observation was not seen in a second observation, confirming that the observer was consistently observing to the limits of her instrumentation, eyesight, and seeing (Schaefer 1993). The conclusion of this portion of the study is that Spaceweather.com and other similar websites are valuable to more seasoned observers as well as beginners in order to make sure one is taking care to view all spots visible to his or her limitations and not rushing through an observation or being sloppy. Again, the AAVSO's admonition to avoid bias is key. One can consult a website after concluding one's observation; if sunspots are found to be missing, one should never add to his or her data afterwards. If differences in the number of areas of sunspot activity had been found by the author in this study, those observations would not have been sent to the AAVSO, but instead used as practice. Similarly, the students in the first portion of this study did not submit their data to the AAVSO, and the consultations with the Spaceweather site were done to aid the students in improving his or her own ability, with the goal to become a competent solar observer.

4. Conclusion

In conclusion, both the AAVSO Solar Section's inclusion of such websites in its recommended resources for observers and the accompanying admonition are confirmed as appropriate (and necessary) for beginning observers and their more seasoned colleagues who wish to improve their solar observing technique. However, in order to prevent bias, these sources of information should be used for training purposes only, and in no case should an observer's report to the AAVSO (or any other organization) be anything other than his or her individual observations.

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Adverse Health Effects of Nighttime Lighting

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Abstract The effects of poor lighting and glare on public safety are well-known, as are the harmful environmental effects on various species and the environment in general. What is less well-known is the potential harmful medical effects of excessive poor nighttime lighting. A significant body of research has been developed over the last few years regarding this problem. One of the most significant effects is the startling increased risk for breast cancer by excessive exposure to nighttime lighting. The mechanism is felt to be by disruption of the circadian rhythm and suppression of melatonin production from the pineal gland. Melatonin has an anticancer effect that is lost when its production is disrupted. I am in the process of developing a monograph that will summarize this important body of research, to be presented and endorsed by the American Medical Association, and its Council of Science and Public health. This paper is a brief overall summary of this little known potential harmful effect of poor and excessive nighttime lighting.

1. Introduction

The following is a brief summary of a longer monograph that will be presented by me to the American Medical Association (AMA) in June of 2012, written with contributions by Dr. Richard Stevens, Dr. David Blask, Dr. Steven Lockley, and Dr. George Brainard.

2. Human health issues

Since the introduction of electricity a little over a century ago, lighting the night has become a priority of modern societies due to many perceived advantages including for commerce and social activity. However, in the past two decades there has emerged a realization that with these benefits have come detriments, some of which may be substantial. The dialogue on electric light in the environment has focused on four topics: 1) esthetics, or loss of the starry night sky, 2) the energy cost of unnecessary electric light, especially at night, 3) the impact of the evolutionarily novel light at night on animal and plant life, and 4) impact of electric lighting on human health, primarily through disruption of circadian biological rhythms.

The Milky Way is no longer visible to the majority of people in the modern world. As societies have increasingly used electricity to light the night, it has become difficult to see more than a few stars from Earth's surface. Though the major impact of electric light at night is in major metropolitan areas, even the once pristine nights of the U.S. National Parks are beginning to be degraded, more rapidly in the East but also in parks in the West as well.

Electric lighting accounts for about 19% of electricity consumption worldwide and costs about $360 billion annually (OECD/IEA 2006). Much of the light that is produced is wasted, for example by radiating up into space away from the task or environment intended to be illuminated. Estimates of how much is wasted vary; one estimate from the International Dark-Sky Association is 30% in the United States. Such a percentage worldwide would account for an annual cost of about $100 billion.

The 24-hour solar cycle of light and dark is ancient, and all life on the planet has evolved to accommodate it. Human imposition of light at night is a dramatic change in the environment but has only recently begun to attract the attention it deserves. Study of the effects of light at night on animal and plant life is in an early stage but already suggests major impacts on the entire spectrum of life including animal, plant, insect, and aquatic. Electric light at night disrupts the solar light cycle, and can be expected to have impact on any life form that is exposed to it.

About 30% of all vertebrate species and 60% of invertebrate species on Earth are nocturnal, and depend on dark for foraging and mating. Documented wildlife destruction by light at night has been evident on bird species and migrating amphibians. The most studied case is of sea turtle hatchlings on the coast of Florida which historically have scurried from their nest directly to the ocean; with increased development along the coast, and attendant increased electric lighting at night, these hatchlings become confused and often migrate away from shore to the lights. Hundreds of thousands of hatchlings are believed to have been lost as a result of this stray electric lighting at night in Florida.

The circadian biology of plants is as robust as animals, and the impact of light at night on plant life may also be considerable due to the role of light in photosynthesis and the fact that many plants are pollinated at night. In addition, light at night as a vector attractant for diseases such as malaria is beginning to be evaluated.

3. Disability glare and discomfort glare

Disability glare is unwanted and poorly directed light that blinds, causes poor vision by decreasing contrast, and creates an unsafe driving condition, especially at night. Disability glare is a particular problem on the older aging eye. Many older drivers have a difficult time driving at night, unaware of the etiology of their poor night vision, which is, in part, the result of badly engineered lights. A proper understanding of the human eye physiology would allow for engineering safer and better designed street lighting. There are natural causes of disability glare, such as solar glare at sunset on a dirty windshield. We have all experienced such glare, and attempt to minimize its effects with sunglasses or a cleaning of the windshield. Unfortunately, glare at night while driving is not so easily remedied. Its cause is generally overly bright and unshielded or poorly directed light that enters the eye and then scatters off of eye structures resulting in diminished contrast and impeded vision. Such effects become dramatically worse as the human eye ages due to aging eye structures. As the human eye cannot be so easily fixed as cleaning a dirty windshield it thus behooves us to thus engineer our street lighting to minimize the effects of disability glare.

Disability and Discomfort in the nighttime driving environment have long been a topic of research. Disability glare has been fairly well defined based on the physiology of the human eye and behavior of light as it enters the ocular media. However, discomfort glare has been less defined. Discomfort glare is not based on a physical response but rather a psychological response. This means that the basis of the two responses is fundamentally different and the research into each of the effects is also fundamentally different.

Disability glare is, as the name implies, glare which limits the ability of the driver to see. Disability glare has a direct link to the physiology of the eye and has been researched for many years. The process which causes disability glare was originally discovered by Holladay (1927) and was determined to be light scatter from the ocular media in the eye. As light enters the eye, it collides with components of the ocular media such as the cornea, lens, and the vitreous humor. At each collision, photons scatter and cast a veil of light across the retina. According to Vos *et al.* (1964) and Boyton and Clark (1962) 25–30% of the stray light is from the cornea, approximately the same amount is from the lens, and the rest is scattered in the retina itself. Later measurements showed that much of the scattering also occurs in the vitreous humor. The veil of light has the effect of reducing the contrast of the object which the driver is trying to see which would have the same effect as raising the background luminance of the object.

This veiling light can be modeled and is represented by the term veiling luminance. Many equations have been developed over time, however, the same general form of the equation is used. Originally proposed by Holladay, the relationship is that veiling luminance is directly related to the illuminance of the light source and inversely related to the square of the angle of eccentricity of the light source with an age-dependant multiplier across the entire equation.

Discomfort glare is by far less defined than disability glare. Discomfort glare is defined as a glare source which causes the observer to feel uncomfortable. The definition of discomfort is not precise and some research has shown that a person's response to a glare source is based more on their emotional state than on the light source itself. Discomfort glare is based primarily on the observer's light adaptation level, the size, number, luminance, and location of the light sources in the scene. Models of Discomfort glare have been developed and rely on the illuminance of the light source on the eye. These models continue to need development and the overall impact of discomfort on fatigue and user safety remains an issue. Both discomfort and disability glare have specific impacts on the user in the nighttime environment. Research has shown that both of these glare effects occur simultaneously. Research also shows that the effects of the glare are cumulative, meaning that the glare from two light sources is the sum of the glare from the individual light sources. As a result, every light source within the field of view has an impact on the comfort and visual capability of the driver.

For overhead roadway lighting, design standards include a methodology for controlling the disability glare through a ratio of the eye adaptation luminance to the veiling luminance caused by the light source. As the veiling luminance is related to the illuminance of the light source at the eye, a roadway luminaire which directs light horizontally has a much greater effect on the driver than a light source that cuts off the horizontal light. A trend towards flat glass luminaires which provide a cut-off of light at horizontal angles provides a lower level of both disability and discomfort glare.

Decorative luminaires such as those called acorn or drop lens luminaires have a high level of horizontal light, and the visible portion of the luminaire provides a different situation. Here, these luminaires are typically used for areas where pedestrians are the primary roadway users. The horizontal light in this situation is useful for facial recognition of a pedestrian but it limits the driver in their ability to perceive other objects in the roadway. As a result, many cities are designing and installing two lighting systems, one for the pedestrian and one for the roadway.

The final issue with glare from overhead lighting is the cyclic nature of the impact. Bennett found that as a driver passes through a roadway, they typically go from one luminaire to another. The glare experience will increase as they approach the luminaire and then fall off as they pass the luminaire. While typically not an issue for disability glare, this is a discomfort issue and can be quite fatiguing.

4. Importance of circadian biological rhythms

From the beginning, the solar cycle of light and dark has provided one of the essential bases for life on Earth. Adaptation to the solar cycle has resulted in fundamental molecular and genetic processes that are aligned to an approximately 24-hour period (the circadian biological rhythm) in virtually all life on the planet. The endogenous nature of this circadian rhythm was realized when researchers studied life forms, plant and animal, in laboratory environments devoid of any time cues. Previously it was assumed that plants and animals only responded to the sun rather than anticipated its cycle. It has now become clear that the circadian genetic clock mechanism is ubiquitous and intimately involved in many, if not most facets of cellular and organism function. It has also become clear that although capable of a self-maintaining rhythm, the master circadian clock in mammals (including humans) responds to light through a novel photoreceptive system in the retina. This tandem development of an endogenous rhythm and a sensitivity of it to light were presumably designed by nature to allow for a precise 24-hour regulation of rest and activity, and for adapting to seasonal changes in day-length, while maintaining the advantages of a physiology that anticipates day and night. Understanding how these endogenous rhythms work at the molecular and physiological level and how light is communicated to this system have together become one of the hot topics in the life sciences today.

Biological adaptation to the Sun has evolved for a very long time. In the last hundred years, however, bright light increasingly invades the night as human societies gain industry, technology, and wealth; lighting of the night took a major turn for the brighter as the world began to use electricity. At the same time, ever greater numbers of people work inside buildings under electric lighting. This lighting is vastly dimmer than sunlight, and it provides a very different spectral irradiance; whereas daylight is strong at all visible wavelengths peaking in the blue region, electric lighting has extreme characteristic wavelength peaks (fluorescent) or monotonic increases in irradiance as wavelength lengthens (incandescent). Much of the modern world now lives in a murky cloud of dim light throughout the day and night in isolation from the sun; it is remarkable how little sun people get even in such sunny environments as San Diego.

It is imperative to determine if there are adverse health consequences of our electric lighting practices in the human environment, and if so, the mechanisms underlying these effects. Effective interventions could then be identified that would mitigate the downsides of suboptimal light exposure. Society will not go back to life before electricity, and light during the night is required for our way of life. However, there are undoubtedly ways of lighting the night that are less disruptive than others to our well-being. Considerations in this regard are light spectrum, intensity, duration, and timing during the day and night, all of which determine the effect of light on physiology.

As the research on the biology of circadian rhythms has advanced, the range of potential disease connections has expanded. The first focus was breast cancer, but many more are now being pursued as well such as other cancers (such as prostate cancer), obesity, and diabetes.

5. Light at night, cancer, and importance of melatonin

The first step in determining whether electric lighting affects human health is to understand the impact of light on human physiology. The endogenous human circadian rhythm is complex. Perhaps the most studied aspect of that rhythm is the hormone melatonin, both as a marker of the rhythm and also as an important modulator of the rhythm. There is scientific evidence in humans that support the following features of the impact on electric light exposure on melatonin production, and by extension to the circadian rhythm. The biology of phototransduction continues to be unraveled, and will undoubtedly yield further insights into potential health impacts of electric lighting.

Epidemiological studies are a critical component of the evidence base required to assess whether or not light-at-night (LAN) affects disease risk, including cancer. However, these studies are necessarily observational and can rarely provide mechanistic understanding of the associations observed. For this reason, a robust body of basic scientific studies is also needed before causal inference can be pursued. Only carefully designed and controlled basic laboratory studies in experimental animal models of cancer have the potential to provide the empirical support for a causal nexus between light at night and elevated cancer risk as well as for a plausible biological mechanism to explain such a connection.

The preponderance of experimental evidence supports the hypothesis that under the conditions of complete darkness, high circulating levels of melatonin during the night not only provide a potent circadian anticancer signal to established cancer cells but help protect normal cells from the initiation of the carcinogenic process in the first place. It has been postulated that disruption in the phasing/timing of the central circadian pacemaker in the brain's suprachiasmatic nucleus (SCN), in general, and the suppression of circadian nocturnal production of melatonin, in particular, by light at night (LAN), may be an important biological explanation for the observed epidemiological associations of cancer risk and surrogates for LAN (such as night shift work, blindness, reported hours of sleep, and so on).

The majority of earlier studies in experimental models of either spontaneous or chemically-induced mammary carcinogenesis in mice and rats, respectively, demonstrated an accelerated onset of mammary tumor development accompanied by increased tumor incidence and number in animals exposed to constant bright fluorescent LAN as compared with control animals maintained on a strict LD12:12 light/dark.

More recent work, however, has focused on the ability of light at night to promote the growth progression and metabolism in human breast cancer xenografts. Blask and co-workers (2005) assessed the dose-response effects of light exposure during darkness on the growth of tissue-isolated human breast cancer xenografts in nude female rats; these human tumors are estrogen receptor negative (ER–) and depend on the essential polyunsaturated fatty acid linoleic acid for their growth. Both ER– and ER+ human breast cancer xenografts are highly sensitive to the direct growth and linoleic acid metabolic inhibitory effects of nocturnal concentrations of melatonin. Five different groups of xenograft-bearing rats were each exposed to one of five increasing intensities of white, fluorescent polychromatic light, ranging from very dim to very bright, during the dark phase of each LD 12:12 cycle beginning two weeks before tumor implantation and continuing thereafter until the end of the tumor growth experiment; a sixth control group of tumor-bearing rats was exposed to complete darkness during the dark phase of each LD 12:12 cycle. Following several weeks of exposure of rats to increasingly brighter light during the dark phase there was a dose-dependent increase in the percent suppression of peak nocturnal serum melatonin levels. There was also an accompanying marked, dose-related increase in tumor metabolism of linoleic acid and the rate of tumor growth as light intensity during the night increased and the nocturnal amplitude of blood melatonin levels decreased. A particularly important aspect of this study was that exposure to even the very dimmest intensity of LAN (0.2 lux), which induced approximately a 65% suppression of the nocturnal peak of circulating melatonin levels, resulted in a marked stimulation in the rates of tumor growth and linoleic acid metabolic activity that was nearly equivalent to that observed in constant bright light-exposed tumor-bearing rats in which there was complete melatonin suppression. Furthermore, as little as a 15% suppression of nocturnal melatonin levels, in response to an extremely low intensity of LAN, was required to elicit a small but significant increase in xenograft growth and linoleic acid metabolism. This finding suggested that even a seemingly marginal suppression of the nocturnal circadian melatonin signal induced by exposure to extremely dim LAN could translate into a significant stimulation of human breast cancer growth and metabolism.

Similar findings were also obtained by this group on the growth and linoleic metabolism of a highly melatonin-sensitive rat hepatoma in male rats exposed to the same increasing intensities of light at night. The stimulatory effects of dim LAN (0.2 lux) observed in rat hepatoma and human breast cancer xenograft growth were subsequently and independently corroborated with respect to the growth of DMBA-induced mammary carcinomas in female rats by Cos *et al.* (2006). They documented a significant decrease in nighttime urinary excretion of the main liver metabolite of melatonin, 6-sulfatoxymelatonin, in animals exposed to dim LAN as well as a marked increase in serum estradiol. More recently, Dauchy *et al.* (1997) reported high tumor growth and linoleic acid metabolic rates and completely suppressed nocturnal melatonin levels in rats bearing human breast cancer xenografts or rat hepatomas as a result of their initial exposure to LAN (24.5 lux). However, as the amount of LAN exposure was subsequently and sequentially reduced to zero, there was a gradual restoration of circulating melatonin concentrations to high nocturnal peak levels accompanied by a marked reduction in tumor growth and linoleic acid metabolic activity to baseline rates.

In the same investigation by Blask and colleagues cited above, important new relationships between circadian biology, the endogenous nocturnal melatonin signal, and its suppression by LAN, relative to human breast cancer risk were uncovered using a unique experimental strategy that combined blood collection from human subjects, exposed to either complete darkness or light at night, and the direct perfusion of human breast cancer xenografts with the resulting blood samples. The linoleic acid metabolic and growth activity of ER– (and ER+) human breast cancer xenografts (growing in nude rats) directly perfused in situ with whole blood collected during completely dark nights from young, healthy premenopausal female subjects (high melatonin), was markedly reduced as compared to when the xenografts were perfused with blood collected during the daytime (low melatonin). Following dark exposure, the exposure of the same subjects to bright (such as 2800 lux), polychromatic, white fluorescent light during the night reduced their melatonin levels almost to daytime concentrations and extinguished the tumor and metabolic inhibitory activity of their blood.

That this effect was achieved via LAN-induced melatonin suppression was supported by the fact that addition of a physiological nocturnal concentration of melatonin to blood collected from light-treated subjects (low melatonin) restored the tumor inhibitory activity to a level comparable to that observed in the melatonin-rich blood collected at night during total darkness. Moreover, the addition of a melatonin receptor antagonist to the blood collected during darkness (high melatonin) completely eliminated the ability of the blood to inhibit the growth and metabolic activity of perfused tumors. Therefore, melatonin is the first soluble, nocturnal anticancer signal to be identified in humans that directly links the central circadian clock with some of the important mechanisms regulating breast carcinogenesis.

These findings provide the first definitive nexus between the exposure of healthy premenopausal female human subjects to bright, white LAN and the enhancement of human breast oncogenesis via circadian disruption (that is, suppression) of the nocturnal, anticancer melatonin signal.

6. Light-at-night and sleep disruption

As alluded to above, in addition to light-at-night suppression of the nocturnal melatonin signal, another type of circadian disruption can be caused by chronically advancing the phasing of light exposure (chronic jet lag). Filipski and co-workers (2004, 2005) maintained male mice in either an alternating LD12:12 light/dark cycle or exposed them to experimental chronic jet lag (through serial eight-hour advances of LD12:12 cycles every two days) in order to disrupt the rest-activity circadian rhythm. Ten days after the start of the light-dark cycle advances, animals in both groups were implanted with mouse osteosarcoma. In the mice undergoing "jet-lag" via repeated advances in circadian phase, tumor growth progression, during a narrow window of time between days 8 and 11 after tumor transplantation, was modestly but significantly faster as compared with that in mice kept in LD12:12. Although circulating melatonin levels were not assessed in the two groups, it is important to note that the specialized strain of mice used in this study exhibits an abnormal melatonin profile with highest levels of melatonin occurring during the light phase rather than during the dark phase. Nevertheless, this study indicated that in addition to light-at-night-induced melatonin suppression, circadian disruption induced by chronic phase advances in light exposure may represent another biological mechanism for increased cancer growth.

The human evidence, primarily from epidemiological studies, is indirect. The greatest amount of evidence so far is on cancer risk, particularly of breast.

Among the potential health effects of circadian disruption from electric lighting, the development of breast cancer has received the most attention. The idea that the increasing use of electricity to light the night might explain a portion of the high breast cancer risk in the industrialized world, and the increasing incidence and mortality in the developing world, was first articulated in 1987 by Stevens. The idea was originally based on suppression of the normal nocturnal rise in circulating melatonin, but has since expanded to include impact on circadian gene function. From this theory came a series of predictions, including that non-day shift work would raise risk, blind women would be at lower risk, reported sleep duration (as a surrogate for hours of dark) would be inversely associated with risk, and that population nighttime light level would co-distribute with breast cancer incidence worldwide. The most studied of these predictions is that non-day shift work would be associated with increased risk. Based on studies of non-day shift occupation and cancer (mostly breast cancer) published through 2007, the International Agency for Research on Cancer (IARC) concluded "shift-work that involves circadian disruption is probably carcinogenic to humans (Group 2A [level of confidence of carcinogenic potential])." The detailed review of the individual studies is also available (IARC 2010).

Since the IARC evaluation was conducted, several new studies of breast cancer have been published. Lie *et al.* (2011) conducted a large case-control study of nurses in Norway and found a significantly elevated risk in subjects with a history of regularly working five or more consecutive nights between days off. Hansen and Stevens (2011) evaluated the impact of type of shift (such as evening, night, rotating) and found a roughly increasing risk as the expected disruptiveness of the shift increased. Each of these studies has strengths and limitations common to epidemiology, particularly in exposure assessment and appropriate comparison groups; that is to say, no woman in the modern world is unexposed to light-at-night but quantifying that exposure is difficult. However, on balance the new evidence is consistent with the elevated risk from the previous studies evaluated by IARC.

Four case-control studies have now reported an association of some aspect of nighttime light level in the bedroom and breast cancer risk. The elevated risk estimate was statistically significant in two of them. As case-control designs, in addition to the limitation of recall error there is also the potentially severe limitation of recall bias. Despite the difficulty of gathering reliable information on bedroom light level at night, the possibility that even a very low luminance over a long period of time might have an impact on cancer risk is important. It is not yet clear what is the lower limit of light level that could, over a long time period, affect the circadian system.

Until 1980 when Lewy and colleagues (1980) published in *Science* magazine that bright light can suppress circulating melatonin concentration, it was thought that humans were insensitive to light. Since that time, the intensity believed to be adequate to inhibit melatonin production has steadily declined. In pioneering work, Brainard and colleagues (1988) have shown that very low monochromatic photon flux density can have an effect which is wavelength dependent. And it has now been reported that the lighting typical in bedrooms in the evening after dusk (but before bedtime) can also suppress melatonin and delay its nocturnal surge.

After lights out for bedtime, it is not yet clear whether the ambient background light from weak sources in the bedroom or outside light coming through the window could influence the circadian system; a brief exposure at these levels may not have a detectable impact in a laboratory setting though long-term chronic exposure might. In the modern world few people sleep in total darkness. When eyelids are shut during sleep, only very bright light can penetrate to lower melatonin, and this in only some people. However, it is normal to awaken in the middle of the night as most people do, and there is often the need to use the facilities, which increases as people age. Therefore the potential for low level light in the bedroom to affect human health by disrupting the circadian system should be a research priority.

The modern world has an epidemic of obesity and diabetes that may in part be due to lack of sleep, lack of dark, and/or circadian disruption. The circadian rhythm and sleep are intimately related but not the same thing. It has long been known that non-day shift workers are at greater risk of diabetes and obesity. Epidemiological studies also show associations of reported sleep duration and risk of obesity and diabetes. Circadian disruption may be a common mechanism for these outcomes. This is based on the rapidly emerging understanding of the link between the circadian rhythm and metabolism.

Adequate daily sleep is required for maintenance of cognitive function, and for a vast array of other capabilities that are only partially understood. Sleep is not, however, required for maintenance of the endogenous circadian rhythm (such as melatonin cycling), whereas dark is required. The epidemiological and laboratory research on sleep and health cannot entirely separate effects of sleep duration from duration of exposure to dark, so that this work can be difficult to interpret. The distinction is quite important because a requirement for a daily and lengthy period of dark to maintain optimal circadian health has different implications than a requirement that one must be asleep during this entire period of dark; it may be normal to experience a wakeful period in the middle of a dark night.

Light during the night will disrupt circadian function as well as sleep, and the health consequences of short sleep and of chronic circadian disruption are both now the subject of intense research. There is a growing number of both observational and clinical studies of sleep and metabolism which suggest an alarming and important impact of short sleep on health; however it is not yet clear that sleep and dark have been entirely disentangled in these studies. An example of the difficulty of interpretation of the "sleep" studies is the carefully conducted study of Taheri *et al.* (2004), who reported that sleep duration, as verified by polysomnography, was associated with morning blood levels of leptin in a sample of 1,024 adults in Wisconsin. However, in the same analysis, the duration of typical sleep reported by each subject was more strongly associated with leptin level. Mean verified sleep was 6.2 hours, whereas mean reported sleep was 7.2 hours, a full hour different. Reported "sleep" duration probably means the difference in time when a person turns out their light for bed, and when they get up in the morning; or actual hours of dark. An important question is: what portion of health effects of dark disruption is due to sleep disruption and what portion is due directly to circadian impact of electric light intrusion on the dark of night?

7. Conclusion

It is clear now that light-at-night has profound effects on human physiology, and many of these effects are just now becoming known. These effects have spawned a burgeoning field of research that shows how profoundly both humans and life on earth are affected by the loss of the dark at night. Light-at-night affects more than just our views of the night sky.

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Star Watching Promoted by the Ministry of the Environment, Japan

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Abstract In 1987 the author suggested to Japanese government authorities to promote star watching as a means of campaigning for the prevention of air pollution. The "Star Watching" program still continues today. Recently, it became a campaign not only for the prevention of air pollution, but also a campaign to educate about light pollution, energy-saving, and the reduction of greenhouse gas. This paper summarizes twenty years of activity in the "Star Watching" program.

1. Introduction

For variable star astronomers, the visibility of faint stars is an important concern. I made a study of the visibility of stars in the Tokyo city district, derived from observations of the members of the Japan Astronomical Study Association. Simply, it is an index of visibility based on the difference of magnitudes between the faintest comparison star and the calculated limit depending on the diameter of the telescope used. The results show that the visibility of stars in Tokyo since 1952 (Sakuma 1956) has been becoming rapidly poor. Because Japan's environment problem became serious, an "Environment Agency" (later, the Ministry of Environment) was established in 1971.

In the 1980s, traffic and diesel engines caused severe air pollution. Under these circumstances, the Environmental Agency carried out a campaign for pollution prevention, with regard to air pollution—visibility (in the meteorological sense) observation by elementary school children, and water pollution—making 100 selections of clear fountains and streams. I suggested to the government authority to promote "Star Watching" as their next campaign in 1986. Recently, the astronomical part became a campaign not only for the prevention of air pollution but also light pollution, energy-saving, and the reduction of greenhouse gas.

2. Star watching

The outline of a method had been introduced by Isobe and Kosai (1991), Kosai and Isobe (1991), Kosai, Isobe, and Nakayama (1992), and Crawford and O'Meara (1991), early enough to be of use. I also introduced my "Star

Watching" project in the *AAVSO Newsletter* (Sakuma 1987, 1989). The method is as follows: Visual observations are carried out on a moonless night about one hour after sunset during January and August. Observers try to find the Milky Way in the constellations of Perseus, Gemini, and Monoceros in winter, and Cassiopeia, Cygnus, and Sagittarius in summer. Use of 7 × 50 binoculars is recommended for star counting in an area encircled by six bright stars in the Pleiades cluster in winter, and in an area of the triangle formed by α Lyr (Vega), ε Lyr, and ζ Lyr. I consult the AAVSO's charts for these areas (BU Tau, AY Lyr, and LL Lyr) to obtain the magnitudes of stars in the target area. The positions of stars which one sees are then drawn in a notebook.

The Photographic method is carried out by a camera with a focal length of 50 to 55 mm, an *f*-ratio brighter than 2.0, and a reversal color film with a speed of ISO 400. The camera is fixed on a tripod and is set in the center of the α Tau field in winter, α Lyr in summer. Three exposures of 80, 150, and 300 seconds without guiding are carried out after setting the *f*-ratio at 3.5 or 4.0. Three exposed films are used to measure the density of the sky background relative to standard stars in that field using a densitometer. This method will be adapted to the use of a digital single lens reflex (DSLR) camera this summer.

3. Summary of results

The number of observer groups in the project has kept steady at more than 300 through most of its twenty-year history (Figure 1). In summer 2010, there were 6,786 observers in 418 groups; in winter 2011, 3,033 observers in 313 groups contributed.

Binocular observation results (Figures 2 and 3) in winter show limiting magnitudes slightly down (brighter). Judging from the results of twenty-three fixed points (Figures 4 and 5), the background brightness of the sky does not change over the past 20 years.

Japan's northeastern area was attacked by an earthquake and tsunami on March 11, 2011. Power plants were destroyed. To avoid a total shutdown of electricity, a projected, or programmed, power failure was carried out for four months, until, oil- and coal-burning power plants could restart. This summer, the Ministry restricted heavy users of power by 15%, and recommended that citizens save as much power as possible. Consequently, the visibility of stars during this summer became better than in the past. The results of "Star Watching" of this summer were not announced until now.

4. Future development

The Ministry of Environment enacts a positive policy for the prevention of light pollution. A "Guideline for prevention of light pollution" was established by the Ministry in 1998 and revised in 2006. A "lights down" campaign was carried out when comet Hyakutake approached the earth on March 23–27, 1996, and when comet Hale-Bopp appeared on April 1–6, 1997. Such campaigns as star watching and lights down are becoming more and more important all over the world. For example, Dr. Kelly Beatty, of the International Dark Sky Association (IDA), at Kitt Peak proposed a "Great World Wide Star Count"; The British Astronomical Association's Centre for Dark Skies proposed a "Christmas and New Year Star Count"; and Dr. Mario Motta of the AAVSO gives talks on light pollution and adequate lighting. International cooperation can be expected the more that public awareness grows.

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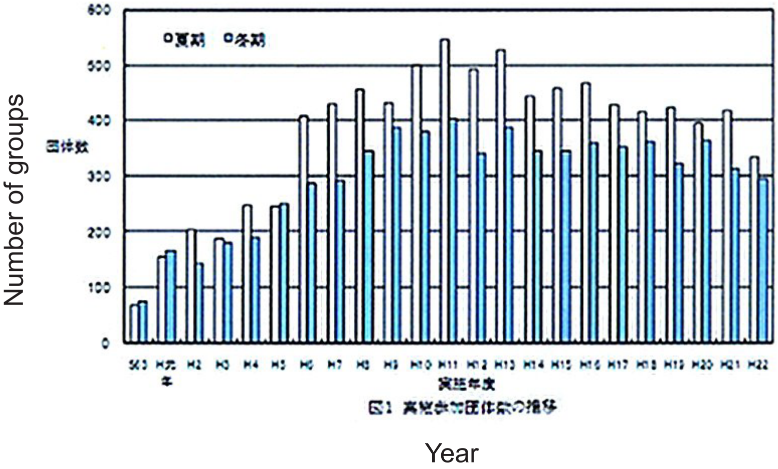

Figure 1. Growth in number of observer groups in the "Star Watching" project from 1988 to 2010. The number of groups has kept steady at more than 300 through most of its twenty-year history.

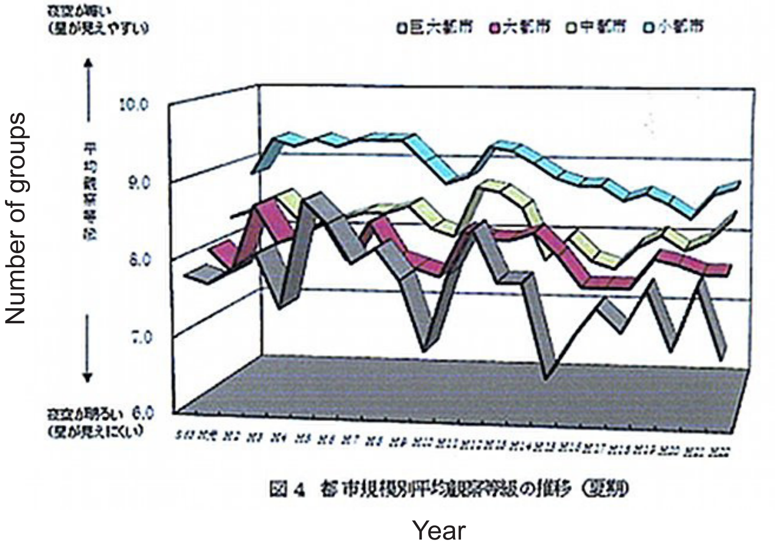

Figure 2. Binocular observation results 1988–2010, showing limiting magnitudes observed during winter seasons.

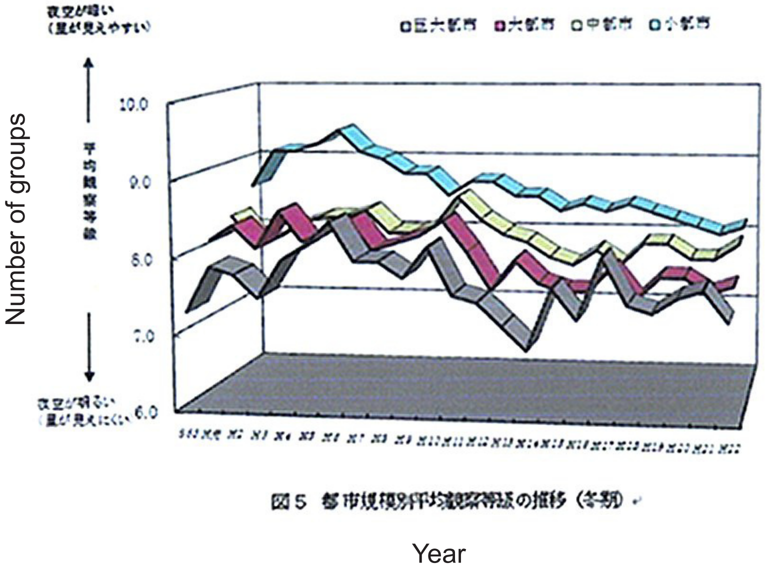

Figure 3. Binocular observation results 1988–2010, showing limiting magnitudes observed during summer seasons.

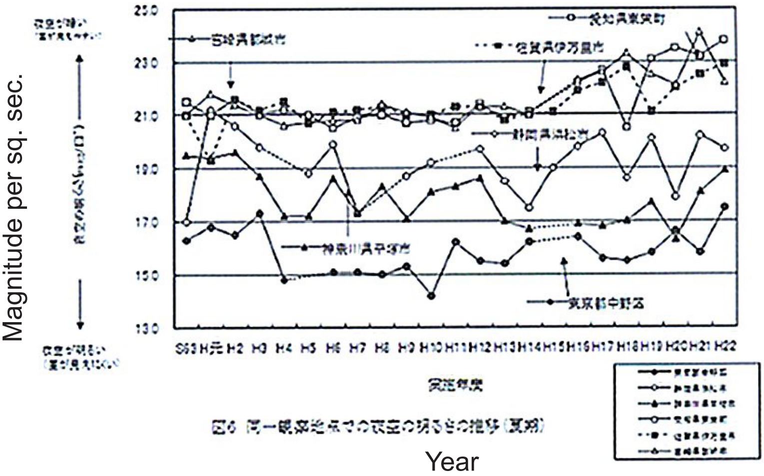

Figure 4. Results of photographic observations 1988–2010, summer seasons, showing magnitude per square second at several fixed points.

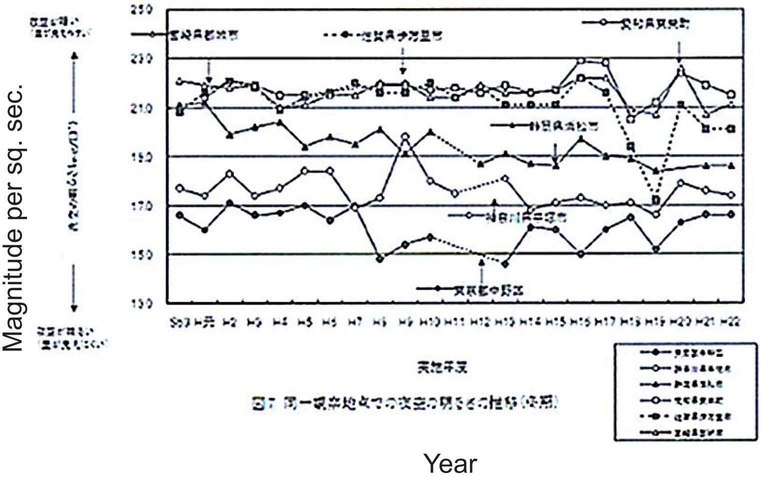

Figure 5. Results of photographic observations 1988–2010, winter seasons, showing magnitude per square second at several fixed points.

Progress Report for Adapting APASS Data Releases for the Calibration of Harvard Plates

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Abstract The Digital Access to a Sky Century @ Harvard (DASCH) has scanned over 19,000 plates and developed a pipeline to calibrate these plates using existing photometric catalogues. This paper presents preliminary results from the use of the AAVSO Photometric All-Sky Survey (APASS) catalogue releases DR1, DR2, and DR3 for DASCH plate calibration. In the optimum magnitude 10–12 range of the DASCH patrol plates, the median light curve RMS with APASS calibration is 0.10–0.12 magnitude, an improvement from the 0.1–0.15 magnitude median light curve RMS with GSC 2.2.3 calibration.

1. Introduction

The Harvard College Observatory plate collection consists of approximately 525,000 photographs produced by over eighty telescopes spanning over 100 years from about 1885 to 1992. The goal of the Digital Access to a Sky Century @ Harvard project (DASCH; Grindlay 2009; see http://hea-www.harvard.edu/DASCH/) is to digitize this entire collection and provide photometry measurements for all objects. With the successful completion of a high speed plate digitizer (Simcoe *et al.* 2006) we have digitized over 18,000 plates and and used the SExtractor program (Bertin and Arnouts 1996) to extract an average of 90,000 objects per plate.

One of the primary goals of this project is to extract photometric data from these plates. The DASCH pipeline presented in Laycock *et al.* (2010) creates a calibration curve for each plate by using robust locally weighted scatterplot smoothing to match SExtractor isophotal magnitudes to magnitudes in a standard catalogue. The choice of a standard catalogue has been a continuing project issue because the catalogue must be all-sky and must match the magnitude 4–17 range of the plate collection. We are currently using the *Guide Star Catalog* version 2.3.2 (GSC 2.3.2; Lasker *et al.* 2008). The relatively poor photometric accuracy of the *Guide Star Catalog* is balanced by a good overlap in magnitude range with the Harvard plate collection and all-sky coverage. However, DASCH team member Sumin Tang reports that light curve searches using the *Kepler Input Catalog* (KIC; Brown 2011) for calibration showed less error contamination. This paper introduces a new metric, the normalized outlier count, in an attempt to quantify the relative value of calibration catalogues with respect to such light curve searches.

Fortunately, the American Association of Variable Star Observers (AAVSO) has similar requirements for a bright star photometric catalogue and we welcome the initiative of AAVSO to produce the AAVSO Photometric All-Sky Survey (APASS; AAVSO 2009; see http://www.aavso.org/apass). We appreciate the willingness of the AAVSO to provide preliminary releases of their data and recognize that all results reported in this paper are preliminary until the final release of the APASS catalogue. Catalogue calibration of the APASS data for 18,308 plates takes 1.7 days on our current cluster configuration. Database entry is single threaded and takes an additional 3.3 days for the 16,640 plates that produce valid data with the APASS DR3 release. Because of these long processing times, the continued scanning of new plates, and the evolution of the pipeline algorithms, the design of strictly controlled experiments is not easily achieved.

The Harvard plate collection has full sky coverage, but we have been concentrating on the regions of the sky shown in Table 1. As a result, the current DASCH sky coverage from scanned plates is shown in Figure 1.

The first APASS data release (DR1) covered primarily regions North of +40 degrees declination and matched only the Northern part of our Kepler field for which we already had calibration magnitudes available from the *Kepler Input Catalog*. The second APASS data release (DR2) (Figure 2) provided a good match with our LMC field for which we had only GSC 2.3.2 calibration magnitudes. We began our tests with the APASS DR1 and DR2 releases and then migrated to the APASS Data Release 3 (DR3) as soon as it became available in August 2011. This paper discusses our experience with the DR1 and DR2 releases and the changes implemented with the DR3 release.

2. APASS DR1 and DR2 releases

For maximum performance, the calibration catalogues are reformatted into compact binary files sorted by "gsc_bin_index" which is a simple spatial hash index consisting of 1/64 degree declination bands beginning at the celestial South pole. Within each declination band, stars are sorted by right ascension into an integral number of bins approximately 1/64 degree wide. Although there is no closed form mathematical solution for the bin layout, a lookup table provides quick conversion of RA and Declination to one of the 168,966,386 gsc_bin_index values.

Figure 3 shows the steps for reformatting the calibration catalogue. Since APASS objects currently have no catalogue identification number, these objects are given a designation similar to the SDSS designations: "APASS Jhhmmss.s+ddmmss" where the J2000 Right Ascension is hh:mm:ss.ss and and the declination is +dd:mm:ss in sexagesimal format. The DASCH pipeline requires two magnitudes, a primary magnitude close to the blue spectral range where the

Harvard plates are most sensitive, and a secondary magnitude used to calculate plate-specific color corrections. With the GSC 2.3.2 catalogue, DASCH uses photographic blue and red (IIIaJ and IIIaF) magnitudes and for the KIC, SDSS g and r magnitudes. For DR1 and DR2 releases, the current study selected the APASS g and r magnitudes.

It is necessary to filter the entries for accuracy. Previous experience with KIC calibration of the DASCH plates show that the best accuracy produced by the DASCH photometric pipeline is about 0.1 magnitude RMS. Therefore, the combined APASS catalogue uses only observations for which more than one measurement is available for the SDSS g and r magnitudes and the magnitude error of each measurement is less than 0.1 magnitude. (Because of a software bug, the preferred filtering on color errors added in quadrature was not implemented in the DR1/DR2 phase of this study.) We also use a color check to filter out g-r colors which are not in the range of –1.0 and 2.5 mag. Of the 8,702,597 entries on the DR1 and DR2 releases, there are 7,173,325 entries between magnitudes 7 and 19 which meet the above criteria.

Because APASS DR1 and DR2 have overlapping fields on the celestial equator, the question arises as to whether the combined catalogue contains any duplicate objects. Matching the combined DR1 and DR2 catalogue against itself produced 79,173 matches, the majority of which were within the stated accuracy of 0.25 magnitude and 2.5 arcsec pixel size of the APASS telescopes. Before writing out the contents of a gsc_bin_index, a search for matches within a 1.0 arcsec radius accepts only the matching entry that has the lowest RMS of the magnitude accuracies added in quadrature. For the DR1 and DR2 combined catalogue, a total of 68,510 entries were rejected.

Because the earliest DASCH scanned plate to date was exposed on January 24, 1886, there is a need to correct all catalogue positions for proper motion. The final step is to match the combined the APASS catalogue with the UCAC3 catalogue (Zacharias 2010) and add the UCAC3 proper motions to the APASS data. Using the same search algorithm described above, there were 6,231,923 UCAC3 matches for the 7,104,815 APASS entries.

3. APASS DR1 and DR2 results

Figure 4 shows that the coverage of the APASS-calibrated stars is most complete in the LMC region and the Northern half of the Kepler region. There was also some coverage near the equator for the M44 and 3c273 regions. Table 2 shows that 68% of the plates which yielded data for the GSC 2.3.2 catalogue also yielded data for the APASS catalogue, and about 25% of the stars that provided good data with GSC 2.3.2 also provided good data with APASS.

Three important metrics of DASCH photometry quality are derived from light curves which have at least ten points and pass all of the DASCH quality checks. Figure 5 shows the DASCH pipeline yield as a function of magnitude for all of the calibration catalogues. A major deficiency with the DR1 and DR2 combined release is its ninth magnitude limit for bright stars. Figure 6 shows the median RMS of DASCH light curves as a function of magnitude. By plotting the median RMS, this figure excludes variable stars. The best accuracy of DASCH light curves comes in two ranges, magnitude 9 to 12 and magnitude 15 to 17, because of the different types of telescopes used to generate the Harvard plate collection. Most of the plates that we scan are patrol plates with small aperture objectives which have a limiting magnitude of 13 to 14. Magnitudes dimmer than 15 are covered by a smaller collection of plates produced by telescopes with larger objectives. For objects dimmer than 11th magnitude, there is little differentiation among the various catalogues, suggesting that errors in the plates dominate. Brighter than 11th magnitude, the combined DR1 and DR2 catalogue is comparable to the KIC and noticeably better than GSC 2.3.2. The third metric shown in Figure 7 reflects the use of of the DASCH database to search for new variable stars. For this search, Sumin Tang (2012) defined a series of light curve parameters which show promise in identifying flares and other unusual variability. One such parameter is “nburst3” which is the number of points in a light curve that are at least 0.4 magnitude brighter than the median magnitude of the light curve. Figure 7 shows a “normalized nburst3” which is the sum of nburst3 for all light curves that have valid values of nburst3 divided by the number of light curves that have valid values of nburst3. For stars dimmer than magnitude 12 the three catalogues produce comparable results, although the APASS catalogue produces the highest outlier rate around magnitude 14. For stars brighter than magnitude 12, the APASS calibration is significantly better. These results should be taken with some caution: A problem with the “normalized nburst3” metric is that it does not reproduce Sumin Tang’s qualitative assessment that the KIC produces fewer false outliers than the GSC 2.3.2 catalogue.

4. APASS DR3 release

Figure 8 shows that release of the APASS DR3 dataset in August 2011 provides expanded coverage in the Southern celestial hemisphere to include more of the DASCH M44, 3C273, and LMC fields. Since this release incorporates the DR1 and DR2 releases, there was no need to combine DR3 with the previous releases. This new release provided an opportunity to make four changes in the reformating of the APASS catalogue shown in Figure 9. First, the search radii for duplicates was expanded from 1 to 2 arcsec. Second, objects rejected for photometry use are now retained in the calibration catalogue to avoid confusion in searching for novae and other uncatalogued objects. These rejected objects are flagged as “variable” so that the pipeline code does not use them for plate calibration, but does assign a DASCH magnitude from the calibration data. Third, the DR3 release was merged with the *Tycho-2* catalogue (Høg 2000) as described below to improve coverage in the magnitude 4 to 9 range. Fourth, a bug was corrected in which not only individual magnitude uncertainties greater than 0.1 magnitude were rejected, but the sum of these uncertainties added in quadrature were rejected. Correction of this bug, however, did not occur until the final processing run involving B and V Johnson magnitudes.

The *Tycho-2* catalogue was first filtered to reject B and V RMS values greater than 0.1 magnitude. While this step rejected nearly 60% of the stars, Figure 10 shows that most of the stars rejected were dimmer than 10th magnitude and would have been replaced by APASS stars.

The next step was to transform the *Tycho-2* magnitudes into the SDSS color system. Because the KIC also incorporates Tycho-2 stars, we used equations 6a and 6b in Brown *et al.* (2011) which are repeated below:

$$g = 0.54B + 0.46V - 0.07 \tag{1}$$

$$r = -0.44B + 1.44V + 0.12 \tag{2}$$

Since there was time for another photometry processing iteration, this iteration used the Johnson B and V data available with the APASS release. Høg (2000) says that the *Tycho-2* magnitudes are "close to Johnson B and V" and recommends that transformations not be used because these transformations are dependent on the luminosity class and reddening of each star. Since there are 55,718 direct matches between *Tycho-2* and APASS positions, these matches can be used to derive a transformation. However, the resulting transformation shows a standard deviation of 0.45 magnitude and is valid over only a 1- to 2-magnitude range. Consequently we followed the recommendation of Høg (2000) and used no transformation of the *Tycho-2* B–V data.

In combining *Tycho-2* with APASS DR3, there were 1,103,581 duplicates in 21,418,221 records. Preference was given to the object with the lowest magnitude error and to APASS stars as shown in Table 3.

The final step of matching the combined catalogue with the UCAC3 catalogue to obtain proper motions proceeded as described above. For the 20,434,140 objects in the combined SDSS g-r catalogue, we found UCAC3 proper motions for 16,671,675 stars. For the 20,314,720 objects in the combined Johnson B–V catalogue, we found UCAC3 proper motions for 16,580,857 stars.

Because refinements in object positions between DR2 and DR3 may cause the APASS designation to change, it is important to flush the photometry database of all references to the earlier APASS catalogue. This flushing is accomplished by a version ID which is incremented whenever new results for the same plate are inserted into the photometry database.

5. APASS DR3 results

When compared with Figure 4, Figure 11 shows expanded coverage of APASS-calibrated stars South of 30 degrees declination. Table 4 must be interpreted with caution because it reflects *Tycho-2* calibrated stars as well as APASS calibrated stars. The new results are presented in the previously discussed Figures 5, 6, and 7. These figures contain data for both the APASS Johnson B and V calibration and the APASS SDSS g and r calibration.

Interpretation of these figures must recognize several underlying variables which may skew the results. First, there are the variations in coverage of the three catalogues which may produce systematic errors dependent on sky conditions. The GSC 2.3.2 catalogue may also have systematic variations between the different plate series used for the Northern and Southern hemispheres and for the Magellanic clouds. Experiments with subsets of Figure 6 show that there is indeed a large effect of sky position on the median RMS values between magnitudes 5 and 9. RMS values for Large Magellanic Cloud stars are higher than for Kepler satellite field stars. Second, there is the use of the *Tycho-2* catalogue to fill in the three calibration catalogues. Where APASS and *Tycho-2* overlap, most stars brighter than magnitude 9 have *Tycho-2* calibrations. Where there is no overlap, the *Tycho-2* calibrations can extend to magnitude 12. Our version of the GSC 2.3.2 catalogue uses independently derived transformations from *Tycho-2* to SDSS magnitudes. We learned that the KIC does not use a similar tranform. (According to Monet (2011), equations 6a and 6b in Brown *et al.* (2011) were used only for the calculation of the effective KIC magnitude.) Finally, there is the division of the DASCH data into patrol and deep-field telescopes. Each telescope is good for an optimum range of magnitudes, but this range is also a function of the exposure time for each individual plate and emulsion type.

Given the above uncertainties and the fact that both DASCH and APASS are continuing works in progress, the author can draw only limited conclusions at this stage. Except for the magnitude 13 to 15 range, the APASS calibration catalogue provides better results than the GSC 2.3.2 and KIC catalogues. The APASS B and V data produce comparable results to the APASS g and r data, though the former produce slightly fewer outliers over a large magnitude range. Finally, the attempt to merge in the *Tycho-2* catalogue should be abandoned in favor of a smaller but better-behaved dataset between magnitudes 8 and 11. Since we currently process every newly scanned plate with both the GSC 2.3.2 and the APASS catalogues, researchers seeking coverage for brighter stars should use the GSC 2.3.2 calibrated data. Subsequent to the processing of the APASS DR3 data, the DASCH team implemented a proposal by Sumin Tang to improve saturated star calibration, but the results from this change are not yet available. We are also interested in testing the new UCAC4 catalogue as a photometry calibration catalogue when it becomes available.

6. Acknowledgements

Thanks to the other members of the DASCH photometry team, principal investigator Prof. Jonathan Grindlay, Sumin Tang, and Dr. Mathieu Servillat for their advice and comments. Additional contributors to the DASCH project are the Harvard College Plate Stacks Curator, Alison Doane; hardware engineer, Robert Simcoe; and our transcribers, plate cleaners, and scanners. Arne A. Henden of AAVSO provided us with early releases of the APASS data. Both Arne Henden and the anonymous reviewer provided valuable comments on the drafts of this paper. This work was supported in part by NSF grants AST0407380 and AST0909073 and now also the Cornel and Cynthia K. Sarosdy Fund for DASCH. The AAVSO APASS project was made possible with funding by the Robert Martin Ayers Sciences Fund.

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Table 1. DASCH Primary Coverage Regions.

Region	*R.A. (2000.0)* *h m*	*Dec. (2000.0)* *° ′*
M44	08 40	+19 41
3C273	12 30	+02 03
Baade's Window	18 03	–29 00
Kepler Satellite	19 20	+45 00
Large Magellanic Cloud	05 23	–69 45

Table 2. Photometry Pipeline Output for APASS DR1 and DR2.

Catalogue	*Plates*	*Magnitudes*	*Stars Matched*	*Light curves**
GSC 2.3.2	15,942	1,566,000,000	72,411,000	4,307,000
KIC	3,673	322,733,487	3,978,000	533,000
APASS DR1 and DR2	10,853	812,740,385	2,834,509	1,115,651

**The light curve contains at least two points that match all of the DASCH acceptance criteria.*

Table 3. Truth Table for Star Selection Between *Tycho-2* and APASS Stars Within 2 Arcsec. There are sixteen possible combinations of catalogue source and RMS level. The note marks show the preferred entry.

Matches (g–r)	*Matches (B–V)*	*First Duplicate Source*		*Second Duplicate Source*	
3956	3137	Tycho-2	RMS < 0.1[b]	Tycho-2	RMS < 0.1[b]
1505	1706	Tycho-2	RMS < 0.1[a]	Tycho-2	RMS > 0.1
31	25	Tycho-2	RMS > 0.1	Tycho-2	RMS < 0.1[a]
484	956	Tycho-2	RMS > 0.1[b]	Tycho-2	RMS > 0.1[b]
74787	55740	Tycho-2	RMS < 0.1	APASS	RMS < 0.1[a]
53171	37827	Tycho-2	RMS < 0.1[a]	APASS	RMS > 0.1
222573	264450	Tycho-2	RMS > 0.1	APASS	RMS < 0.1[a]
38373	30812	Tycho-2	RMS > 0.1	APASS	RMS > 0.1[a]
105587	81575	APASS	RMS < 0.1[a]	Tycho-2	RMS < 0.1
293755	346859	APASS	RMS < 0.1[a]	Tycho-2	RMS > 0.1
85118	63032	APASS	RMS > 0.1	Tycho-2	RMS < 0.1[a]
51744	44900	APASS	RMS > 0.1[a]	Tycho-2	RMS > 0.1
25800	87652	APASS	RMS < 0.1[b]	APASS	RMS < 0.1[b]
29950	34671	APASS	RMS < 0.1[a]	APASS	RMS > 0.1
25337	26382	APASS	RMS > 0.1	APASS	RMS < 0.1[a]
91410	23777	APASS	RMS > 0.1[b]	APASS	RMS > 0.1[b]

Notes: a: Selected candidate. b: Selected candidate has the lowest RMS.

Table 4. Photometry Pipeline Output for APASS DR3.

Catalogue	*Plates[a]*	*Magnitudes*	*Stars Matched*	*Light curves[b]*
GSC 2.3.2	16989	1,666,000,000	76,209,000	4,325,000
APASS DR3 g–r	16642[c]	1,282,000,000	8,109,840[c]	3,052,942[c]
APASS DR3 B–V	16640	1,291,720,897	8,323,460	2,618,816

Notes: a: These totals reflect the additional 1,188 plates of the LMC scanned during August, 2011. b: The light curve contains at least two points that match all of the DASCH acceptance criteria. c: These numbers may include stale entries from previous processing iterations.

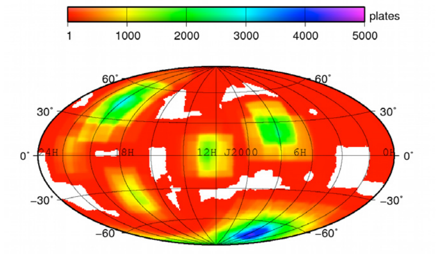

Figure 1. Current DASCH sky coverage from scanned plates.

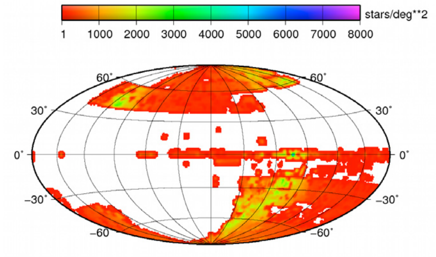

Figure 2. Coverage of APASS Data Releases 1 and 2.

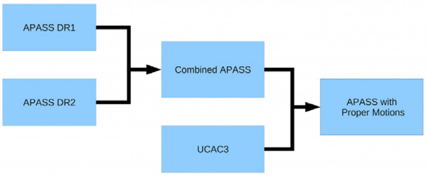

Figure 3. Preparation of DASCH/APASS DR1 and DR2 calibration catalog.

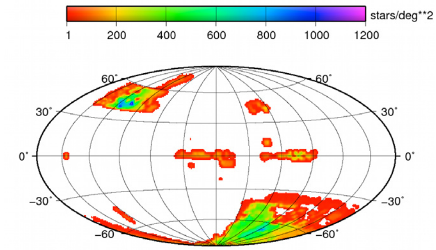

Figure 4. Coverage of APASS DR1 and DR2 calibrated plates.

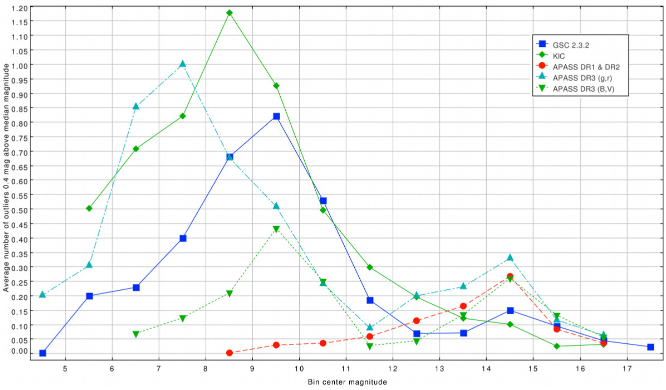

Figure 5. Number of DASCH light curves with at least ten good points after photometric processing.

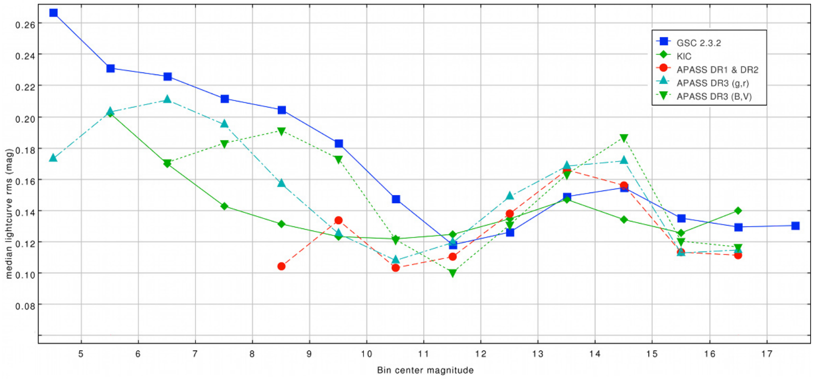

Figure 6. Median RMS of DASCH light curves with at least ten good points after photometric processing.

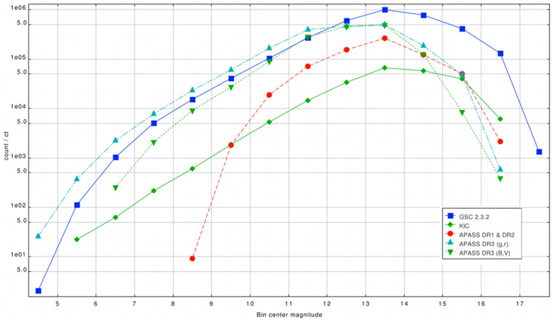

Figure 7. Average count light curve outliers: points 0.4 magnitude above the median light curve magntiude.

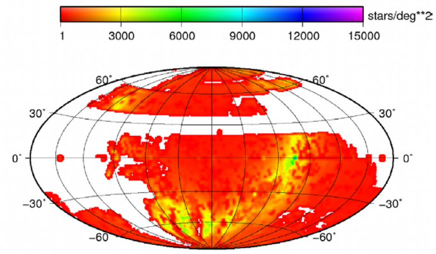

Figure 8. Coverage of APASS Data Release 3.

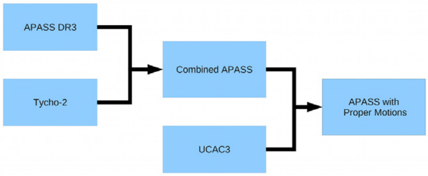

Figure 9. Preparation of DASCH/APASS DR3 calibration catalog.

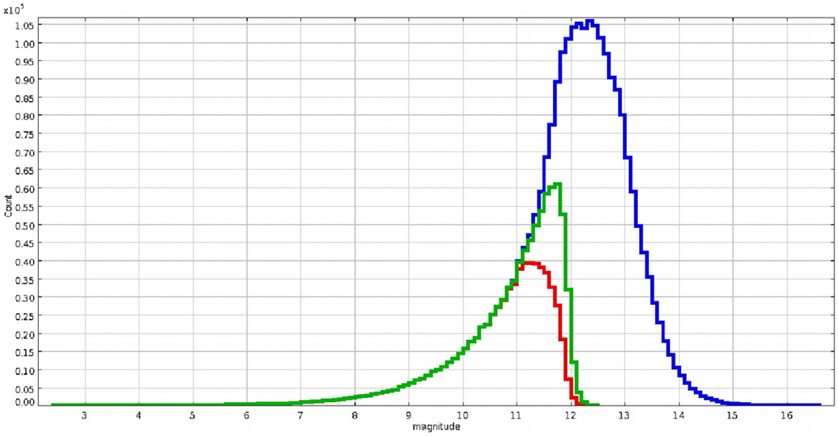

Figure 10. Magnitude Distribution of the Tycho2 Catalog. The full dataset (blue) contains all objects with valid magnitudes. The next most inclusive dataset (green) contains all objects with individual magnitude RMS values less than 0.1 mag. The most restricted dataset (red) contains objects with magnitude uncertainties added in quadrature less than 0.1 mag.

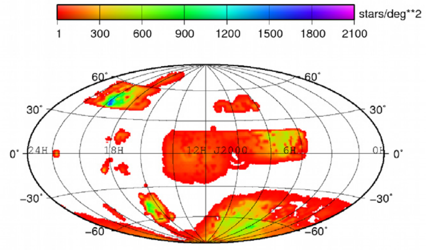

Figure 11. Coverage of APASS DR3 calibrated plates.

Flares, Fears, and Forecasts: Public Misconceptions About the Sunspot Cycle

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Abstract Among the disaster scenarios perpetrated by 2012 apocalypse aficionados is the destruction of humankind due to solar flares and coronal mass ejections (CMEs). These scenarios reflect common misconceptions regarding the solar cycle. This paper (based on an annual meeting poster) sheds light on those misconceptions and how the AAVSO Solar Section can address them.

1. Introduction

Despite the fact that the current 2012 end-of-the-world hysteria is usually (and correctly) disparaged for needlessly scaring members of the general public, the silver lining is that it offers a unique opportunity for educators and scientists to peer into the minds of the same science-phobic public. What is discovered is a plethora of misconceptions about science in general, and astronomy in particular. One of the most commonly touted apocalypse scenarios centers around the sunspot cycle; therefore a careful survey of the claims put forth by proponents of this "sun fries the earth" cataclysm affords solar observers and educators the opportunity to learn about what the public does and does not know about the sun and its cycles, and then attempt to turn those fears and misconceptions into a more healthy interest in and respect for our nearest star and its variability. This paper surveys some of the common misconceptions the public has concerning solar activity and offers suggestions as to how the AAVSO in general and the AAVSO Solar Section in particular could aid in the education of the general public in these matters.

2. Misconceptions, pseudoscience, and scientific illiteracy

Numerous studies have shown that the scientific literacy of the American public has stagnated at about 60% in recent decades—a grade of D-minus (National Science Board 2010). It is not merely a lack of knowledge that educators and scientific organizations have to worry about, however, but rather the prevalence of misconceptions about scientific concepts. These erroneous ideas are often deeply ingrained in a person's personal view of the world around them, and can be difficult to dislodge (Mestre 1991). Adding to this is the general inability of many Americans to distinguish science from pseudoscience (explaining the tenacity of astrology in modern culture, for example) (Shermer 1997). Finally, the general public misinterprets the healthy professional debate that takes place between scientists (as they continue to investigate natural phenomena and the causal connections between them) as a sign of weakness: if science isn't absolutely certain, then any other suggested answer may be considered to be just as valid. The result is a general public that is easily swayed by purveyors of pseudoscience and conspiracies, especially in the age of the Internet. Without the ability or willingness to consider claims made by nonscientists with skepticism, the general public has fallen prey to a series of increasingly alarmist claims about the upcoming solar maximum, often perpetrated by adherents of the so-called 2012 apocalypse hoax—the claim that the end of the world (or at least the end of human civilization) will occur on December 21, 2012.

3. Misconceptions about the sunspot cycle

According to a lengthy list of astronomical misconceptions collected by University of Maine astronomy professor Neil Comins, the following are some of the misconceptions concerning the solar cycle:

- sunspots are regions of soot on the sun;
- sunspots occur on an Earth-based cycle;
- sunspots are places on the sun that have run out of fuel to burn;
- sunspots are hotter places on the sun;
- sunspots are permanent;
- sunspots are where meteors crashed (or are craters);
- sunspots are optical illusions due to staring at the sun;
- the sun does not rotate;
- the sun does not have a magnetic field;
- sunspots are volcanic in nature. (Comins, undated)

These misconceptions (and others) are addressed by Dooling and Kneale (1997), O'Neill (2008), International Solar Terrestrial Physics (ISTP) (Anon. 2012), and 2012Hoax (Anon. 2010). A related misconception that crops up in discussions of the 2012 apocalypse hoax is a belief that solar activity can affect volcanic activity on earth. For example, it appears in a thread of comments on the 2012Hoax webpage devoted to debunking a viral email/blog entitled "Seven Reasons Why the World Will End in 2012—Proven Scientifically." An example is an October 24, 2011, post by Cern: "What is this I hear about a super-volcano forming in Bolivia? ...seems to coincide with the giant sun spots lately…. As the activity increases so will this volcanoes [sic]?" (Anon. 2009).

The existence of these misconceptions suggests that some among the general public lack basic knowledge concerning sunspots and their cycle. The result is that while members of the public may have heard of sunspots, they know little about them. Thus, when an item comes up in the press about sunspots, they may listen (after all, they know that sunspots must be somehow important because they have at least heard of them), but do they really hear what is being said? Unfortunately, the press capitalizes on the situation with sensational titles, such as:

- "Space Weather: Worse Than Hurricane Katrina" (New Scientist);
- "Huge Solar Flares Could Spell Catastrophe for Earth" (Forbes);
- "Sun unleashes huge solar flare towards Earth" (BBC).

The reader who ventures no further than the title will certainly be left with serious misconceptions. However, even those who read the entire article may leave with little more than a lingering impression from the title. Hence this author encourages science journalists and scientific agencies to think long and hard as they craft press releases and articles on the solar cycle that will be seen by the general public. The point is not that the information is being released, but rather how it is released. For example, Somerville and Hassol (2011) note that "Scientists typically fail to craft simple, clear messages and repeat them often…. We encourage them to speak in plain language and choose their words with care." They also offer that "By failing to anticipate common misunderstandings, scientists can inadvertently reinforce them." Their article also includes a useful chart that shows the differences between scientific terms and the way the public interprets them.

4. Misuse of scientific information: 2012

Like other scientific discoveries, those surrounding the sun have been used by groups and individuals to foster their own agendas. For example, earnest scientific studies as to the impact of solar activity on Earth's climate have routinely been used by global warming deniers to attempt to exonerate humanity from responsibility for changes in the environment. However, pseudoscience and conspiracy theory proponents have gone even further, using science in service to their desire to scare the general public into buying their survival guides or subscribing to their for-profit websites. The most important recent example is, of course, the 2012 apocalypse hoax.

For those few fortunate astronomers who have not yet come face to face with this rampant pseudoscience, in a nutshell (pun intended) the idea is that the Maya calendar (and/or Nostradamus, the Bible Code, etc.) predicts that the world will end on December 21, 2012, by asteroid impact, creation of an earthsucking black hole by the Large Hadron Collider, alignment with the black hole at the center of the Milky Way, flipping of Earth's poles (magnetic or otherwise), solar flares, or other catastrophe. The viral email/blog message "Seven Reasons Why the World Will End in 2012—Proven Scientifically" summarizes much of this hysteria, with the following in particular said about the sun:

> Solar experts from around the world monitoring the sun have made a startling discovery: our sun is in a bit of strife. The energy output of the sun is, like most things in nature, cyclic, and it's supposed to be in the middle of a period of relative stability. However, recent solar storms have been bombarding the Earth with so much radiation energy, it's been knocking out power grids and destroying satellites. This activity is predicted to get worse, and calculations suggest it'll reach its deadly peak sometime in 2012. (Anon. 2008)

A probable source of this exaggeration is a 2006 study by the National Center for Atmospheric Research (NCAR 2006) that suggested that the next solar maximum would be "30–50% stronger than the last one" and posited a peak in 2012.

A number of 2012 apocalypse proponents have twisted this prediction into a certain prophecy of doom, declaring that the largest solar flare on record will fry Earth (along with the electric grids and satellites). This is why NASA and other organizations should be mindful of the wording of their statements when releasing scientific data on the interactions between the sun's magnetic phenomena and terrestrial systems—the pseudoscientists are lurking in the shadows, ready to say "See! We told you!" As the Social Issues Research Centre/Amsterdam School of Communication Research (SIRC/ASCOR 2006) report on communicating science to the general public warns, "While there are numerous examples of how the media have 'hyped' science stories…there are equal examples of where scientists have communicated, say, data relating to risks in such a manner that public misunderstandings have been almost inevitable." As is commonly the case with pseudosciences, subsequent evidence provided by scientists attempting to clarify or update the situation is either ignored, or declared part of a conspiracy to withhold the truth from the general public. Thus subsequent announcements from various scientists about updated predictions for the peak of Cycle 24 (now to occur in 2013, after the world will have presumably ended) have largely gone ignored in the 2012 hoax community.

5. What the general public is reading and saying

One can rightly ask just how widespread these misconceptions and misrepresentations of the solar cycle are on the Internet. The answer is that they are far too prevalent. For example, Mitch Battros, an acupuncturist and trauma resolution therapist, asserts in the books *Solar Rain* and *Cosmic Rain* (and their promotional websites) that the following original "equation" explains what we will expect to see in 2012:

> Sunspots → Solar Flares → Magnetic Field Shift → Shifting Ocean and Jet Stream Currents → Extreme Weather and Human Disruption (Battros, undated)

In his mind, since extreme weather is presumed to be caused by sunspots, the coming apocalypse will center around sunspots triggering weather catastrophes on Earth.

Michael E. Sallas, Ph.D. (who neglects to inform readers of his website that his degree is in Government Studies, not Astronomy) claims on his "Zero Sunspots, Global Consciousness, Solar Activity and 2012" website that not only is Battros's "theory" correct, but that he can use the model to explain the unusually low sunspot counts seen until recently as "due to changes in global consciousness brought about by the harmonizing of human interests and activities through the internet" (Sallas 2008). Thus, he reasons, Cycle 24 will be "unremarkable" as "changes in global consciousness produce greater planetary cooperation and harmony" over the next few years. If this is true, then why is self-described "student of consciousness and libertarian decentralist pacifist activist, writer, songwriter, and video producer" Carol Moore (2011) claiming on her website "Sunspot Cycles and Activist Strategy" that the upcoming cycle maximum will coincide with "mass demonstrations, riots, revolutions and wars"? The answer, of course, is that none of this is scientific. However, with all involved using the same sunspot cycle charts from NASA and NOAA, and "equations" to bolster their cases, does the general public understand the difference? Unfortunately not. The following are a handful of posts from the "Seven Reasons" website posted at buburuza.net (typos original):

> "the sun is dieing as we know it and by the tie there is the storm it wont be big enough."
>
> "yes the sun is becoming closer…."
>
> "No, the world will end after 1 billion years because the hydrogen at the sun will disappear."
>
> "volcanoes are going to happen because of the sun storms."

Clearly more needs to be done to educate the general public concerning the sunspot cycle, solar activity, and its influence on Earth. This certainly falls within the purview of the AAVSO's Mission Statement.

6. Conclusion

Various authors have sounded the call to action for a number of communities to come forward and aid in the debunking of the 2012 hoax, including AAS members (Manning 2009), ASP members (Morrison 2009), amateur astronomers (Larsen 2010a, 2010b), geologists (Larsen 2010c), science teachers (Larsen 2010d), planetarium professionals (Larsen 2010e), and the AAVSO in general (Larsen 2009). Astrobiologist David Morrison has been an eloquent leader in the effort to debunk the 2012 apocalypse hoax, as have archaeoastronomer E. C. Krupp (2009), solar physicist Ian O'Neill (2008), and amateur astronomer Bill Hudson and his army of volunteers at the 2012Hoax website (Anon. 2009, 2010). In this spirit, this author makes the following claim: the AAVSO's Solar Section has a unique opportunity to join in the stamping out of misconceptions surrounding solar activity, and at the same time possibly generating interest in solar observing. Some of those who are interested in solar activity (and think that scientists are "hiding" information) may be motivated to take part in safe solar observing; thus effort should be taken to educate these individuals on solar activity and how they could gather more data for the AAVSO Solar Section. An encouraging development in this vein can be seen on the comments section to the 2012Hoax webpage on solar flares, where posters have discussed following the current solar cycle on the www.spaceweather.com website. For example, in a March 5, 2011, post, DieselHorseLAW admits, "I have become somewhat addicted to www.spaceweather.com and I notice the day to day sun spot number fluctuates a lot." Elsgeorge answers the following day: "So have I, I even downloaded their 3D Sun app" (2012Hoax, Anon. 2010).

On the down side, others may decide to take matters into their own hands and unsafely observe the sun. Well-meaning individuals can also convey erroneous information, opening up the possibility of unsafe observing. For example, a reply by obaeyens to DieselHorseLAW dated March 6, 2011, correctly advises that a pinhole projector could be safely used to see sunspots, as well as using binoculars to project an image. The author also correctly warns the readers to never look at the sun directly using a telescope or binoculars. However, the author incorrectly adds, "You can also look at the sunspots when the sun is about to go below the horizon for a short time." Therefore it is recommended that the AAVSO Solar Section capitalize on the current interest in the solar cycle and provide a valuable public service by both publicizing the need for new solar observers AND stressing the proper methods of solar observing. Having public demonstrations of the use of sunspotters and simple projection methods would serve dual purposes. It is also recommended that the AAVSO Solar Division be a model of best practices in terms of communicating with the general public, both through its website and bulletin, and as individual members discuss their solar observing (and its importance) with the general public. Campbell (2008) warns that "We may believe that data speaks for itself, but data is also subject to interpretations, including by laypersons, that are completely valid though not in line with the conclusions of scientists." Collecting sunspot data for the scientific community is an important function of the AAVSO Solar Division. Explaining to the general public how we collect these data, what value the data have, and what is and is not predicable about the solar cycle despite the amount of data collected should also be central to the Solar Division's mission.

David Morrison (2009) has often noted that one of the "worst long-term consequences of the 2012 doomsday hoax" could be what he terms "cosmophobia," a fear of "astronomy and the universe." This can be seen in a January 4, 2001, post by Andrew Maxwell to the buburuza.net "Seven Reasons Why the World Will End in 2012—Proven Scientifically" webpage: "i'm terrified of the sun." Rather than merely trying to get rid of the lemons of misconceptions, solar observers can use the interest in solar activity spawned by purveyors of the 2012 apocalypse hoax to create lemonade, in the form of new solar observers (and interest in solar observing in general). As Manning (2009) notes, "This is a teachable moment. So let us teach." Let's change fear to awe, respect, and knowledge, one prospective solar observer at a time.

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AAVSO Estimates and the Nature of Type C Semiregulars: Progenitors of Type II Supernovae *(Abstract)*

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Abstract The nature of the variability in the M supergiant type C semiregular (SRC) variables is examined using new and archival spectroscopic and spectrophotometric observations of the stars phased according to AAVSO magnitude estimates. SRC variables appear to be more regular than sometimes suggested, although the nature of their pulsation remains unclear in some cases. Some SRCs appear to undergo irregular fading episodes that may result from dust ejection. But recent light curves of the stars display large scatter that hinders reliable determination of their cycle lengths, a problem that needs to be addressed to improve the usefulness of AAVSO data for learning more about massive stars as they approach the terminal stage of their evolution as Type II supernovae.

Preliminary Analysis of MOST Observations of the Trapezium *(Abstract)*

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Abstract We present our first assessment of light curves of the Trapezium stars obtained by the MOST satellite in early 2011. The data sets consist of four stars of the θ^1 Ori system (A, B, C, and D), along with 34 GSC stars in the field nominally used for guiding. The photometry of the brightest stars is sufficient to detect variability at a level well below one mmag, while photometry of the fainter guide stars has not yet been assessed. An early look at the data indicates intrinsic signals are clearly present; non-trivial systematics also related to the spacecraft and sampling are also present, and we discuss potential means for dealing with these issues. We will also discuss our plans for analyzing the data and deriving physical information on these stars.

High School Students Watching Stars Evolve *(Abstract)*

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Abstract Some stars pulsate (vibrate). Their pulsation period depends primarily on their radius. The pulsation period changes if the radius changes, due to evolution, for instance. Even though the evolution is slow, the period change is measurable because it is cumulative. The observed time of maximum brightness (O) minus the calculated time (C), assuming that the period is constant, is plotted against time to produce an (O–C) diagram. If there is a uniform period change, this diagram will be a parabola, whose curvature—positive or negative—is proportional to the rate of period change. In this project, we study the period changes of RR Lyrae stars, old sun-like stars which are in the yellow giant phase, generating energy by thermonuclear fusion of helium into carbon.

We chose 59 well-studied stars in the GEOS database, which consists of times of maximum measured by AAVSO and other observers. We included about a dozen RRc (first overtone pulsator) stars, since these have not been as well studied as the RRab (fundamental mode) stars because the maxima in their light curves are not as sharp. We will describe our results: about 2/3 of

the stars showed parabolic (O–C) diagrams with period changes of up to 1.0 s/century, some with increasing periods and some with decreasing periods. The characteristic times for period changes (i.e. period divided by rate of change of period) were mostly 5–30 million years. These numbers are consistent with evolutionary models. Some stars showed too much scatter for analysis; we will discuss why. A few stars showed unusual (O–C) diagrams which cannot be explained simply by evolution.

This project was carried out by coauthors MacNeil, Meema-Coleman, and Morenz, who were participants in the prestigious University of Toronto Mentorship Program, which enables outstanding senior high school students to participate in research at the university. We thank the AAVSO and other observers who made the measurements which were used in our project.

Eclipsing Binaries That Don't Eclipse Anymore: the Strange Case of the Once (and Future?) Eclipsing Binary QX Cassiopeiae *(Abstract)*

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Abstract We report on the cessation of eclipses of the former 6.005-day eclipsing binary QX Cas. This 10th-magnitude star is a member of the young open cluster NGC 7790; in 1954 QX Cas (B1 IV–V + B3 V) was discovered by Erleksova (1954: *Astr. Circ.* 155) to be an eclipsing binary. Subsequently Sandage (1958: *ApJ*,128,150) and Sandage and Tammann (1969: *ApJ*, 157, 683) obtained accurate photometry of QX Cas that confirmed its eclipsing nature and provided accurate measures of UBV magnitudes and colors. The early light curves display two narrow eclipses with depths of ~ 0.32 magnitude and ~0.28 magnitude, respectively. Moreover the Min II occurs at 0.37 P—indicating an moderately eccentric orbit. To secure modern light curves, we have carried out UBVRI photometry using the 0.8-m Four College Automatic Photoelectric Telescope (FCAPT). Photometry was conducted on >110 nights and the observations now cover all the orbital phasespace of the binary. However, this photometry (and overviews of all recent photometry) show no evidence of eclipses. Thus QX Cas is no longer an eclipsing binary! QX Cas joins another former eclipsing binary—SS Lac—that over twenty years ago also ceased eclipsing.

We present the analysis of previous light curves and the analysis of recent spectroscopy and HST observations of QX Cas to determine its orbital and physical properties. We discuss the reasons that could cause QX Cas to stop eclipsing. These include binary system disruption or an impulsive orbital change from a close encounter with another cluster star or (most likely) from orbital perturbations from a putative bound tertiary companion.

QX Cas and other related eclipsing binaries that stopped eclipsing or show changes in their eclipse depths could be interesting targets for AAVSO members to monitor using CCD or photoelectic photometry. In addition, the changing orbital inclination of QX Cas and other similar, previous eclipsing binaries can be studied with spectroscopic radial velocity observations which are dependent on the star's orbital inclination. This research is supported by NSF/RUI Grants AST05-07536 as well as NASA Grant HST-GO 10116 which we gratefully acknowledge.

High Speed UBV Photometry of ε Aurigae's 2009–2011 Eclipse *(Poster abstract)*

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Abstract We present rapid cadence U, B, and V photometry of ε Aurigae during its 2009–2011 eclipse. Data are analyzed to look for both periodic and random variation. Observations are presented from two observers. The first is from Rockyford, Alberta, Canada, and used a ST-7 and ST-8XME with 50mm and 135mm lenses, respectively. This observer recorded continuous filtered time series up to 11 hours long. The second is in Hereford, Arizona, and used a ST-10XME with a 0.36-m SCT.

δ Scorpii 2011 Periastron: Visual and Digital Photometric Campaign *(Poster abstract)*

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Abstract Approximately a hundred observations of δ Scorpii, from April to September 2011, made for the AAVSO visually and digitally with a commercial CMOS camera, have been plotted. The three most luminous pixels either of the target star and the two reference stars are used to evaluate the magnitude through differential photometry. The main sources of errors are outlined. The system of δ Sco, a spectroscopic double star, experienced a close periastron in July 2011 within the outer atmospheres of the two giant components. The whole luminosity of δ Sco increased from about Mv = 1.8 to 1.65, peaking around 5 to 15 July 2011, but there are significant rapid fluctuations of 0.2–0.3 magnitude occuring over 20 days that seem to be real, rather than a consequence of systematic errors due to the changes of reference stars and observing conditions. This method is promising for being applied to other bright variable stars like Betelgeuse and Antares.

Bright New Type-Ia Supernova in the Pinwheel Galaxy (M101): Physical Properties of SN 2011fe From Photometry and Spectroscopy *(Poster abstract)*

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Abstract We report on the preliminary multi-wavelength photometry and spectroscopy of SN 2011fe, a bright, new Type-Ia supernova (SN Ia) that

occurred in the spiral galaxy M101 (Pinwheel Galaxy). One of the closest and brightest SN Ia in the last forty years, the supernova was discovered on August 24, 2011, by the Palomar Transient Factory during the star's initial rapid rise (Nugent *et al.* 2011). SN Iae occur in binary systems in which a degenerate white dwarf component accretes mass from its companion star (or undergoes a merger with another white dwarf), overcomes the Chandrasekhar limit, and deflagrates in a spectacular explosion. The peak brightnesses of most SN Iae are remarkably similar. This allows SN Iae to be used as accurate cosmic distance indicators and thus they are crucial to understanding cosmology, dark energy, and inflation. SN 2011fe is being extensively observed over a wide range of wavelengths by both amateur and professional astronomers (including several AAVSO members). The UBVRI photometric observations discussed here are being carried out with the 1.3-meter Robotically Controlled Telescope (RCT) located at Kitt Peak National Observatory. The RCT data show a peak apparent magnitude of mV (max) ~ +10.0 mag, in agreement with other measures. Using the M 101 distance modulus of (mV – MV)0 = 29.04 (~21 million LY) as determined by Shappee and Stanek (2011), and assuming interstellar reddening of AV = 0.03 (from E(B-V) = 0.008) toward the objects in SN 2011fe's neighborhood, we estimate the absolute magnitude in the V band of SN 2011fe to be MV = –19.07 mag, which appears to be slightly under-luminous than the SN Iae average of <MV> = –19.30 (Hillebrandt and Niemeyer 2000). Visual and IR spectroscopic data gathered from Buil and Theirry (2011) show strong absorption features, especially those of Co II ~ 3995 Å, Si II ~ 6150 Å, Fe II/Mg II blends ~ 4500 Å, and the Ca II near-IR triplet ~ 8250 Å. Crucially, the spectrum shows no hydrogen and helium lines, which, coupled with the strong Si lines, means that SN 2011fe is a Type-Ia SN. Constraints on the progenitor system (for a single degenerate model) by Li *et al.* (2011) rule out bright red-giant mass donors, but do not rule out faint secondaries. SN 2011fe is important because of its relatively high brightness and early detection in a nearby, well-studied, face-on galaxy with a good distance determination and little ISM extinction. The prodigious amount of data that continues to be gathered will lead to exciting opportunities in the future that include further study of the spectral time series evolution, Δm15(B) relation, and Hubble Constant calibration. In this poster, we discuss the up-to-date physical and photometric properties of this SN and compare them to those of other Type-Ia supernovae.

This research is supported, in part, by NSF/RUI grant AST1009903 and NSF/RUI grant AST0507542. We also gratefully thank both the RCT Consortium and AAVSO members for the photometric data.

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The World's Strangest Supernova May Not Be a Supernova At All *(Abstract)*

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Abstract SN 2008ha is the least luminous supernova ever to be observed. It is unclear what caused this obscurity to occur. For the last three years I have been doing independent follow-up research on SN 2008ha.

SN 2008ha is believed to be 100 times brighter than a nova, but 1,000 times dimmer then a supernova. The spectrum to some degree was classic Type Ia supernova because of the lack of hydrogen and abundance of silicon, but there are many other factors to be considered. SN 2008ha had a short rise time of only 10 days (typical Type Ia is 19.5 days). It has low expansion velocities of only 2,000km compared to the typical Ia with very small kinetic energy per unit mass of ejecta. Although some elements of the spectrum are consistent with those of a Type Ia, narrow lines were observed. This is just one of several characteristics that SN 2008ha shares with the "SN 2002cx-like class" of supernovae. SN 2008ha is believed to be the most extreme of this sub-class of supernovae with the smallest amount of space between lines, 5 days shorter rise time, being significantly fainter, and having lower velocities. With all these things considered, it does make classification as a Type Ia questionable. In fact it is even questionable if this is a supernova at all, and not just an "imposter." This may have just been a "star burp" which means that the supernova may have failed, resulting in some parts of the star being left, maybe even enough remains to explode again as seen in the case of SN 2006jc. This may have occurred because the explosion was not deep enough in the core of the star, and only eliminating some or all of the hydrogen envelope and leaving behind the carbon and oxygen inner layers, instead resulting in a Type Ic supernova. It would be interesting to see what, if anything is left of the star; this could make it a possible Hubble candidate. The idea that it may "burp" again makes it especially important.

An Amateur-Professional International Observing Campaign for the EPOXI Mission: New Insights Into Comets *(Abstract)*

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Abstract Comets are leftovers from the early solar system and may have played a role in delivering water and organics to the prebiotic Earth. Because comets may preserve a record of the early solar system conditions, they are the focus of small body missions. The EPOXI (Extrasolar Planet Observation and Characterization (EPOCh) + Deep Impact Extended Investigation (DIXI) = EPOXI) flyby of the nucleus of comet 103P/Hartley 2 provided us with physical properties of the nucleus and clear evidence of chemical heterogeneity with CO_2-driven jets as a dominant volatile loss mechanism at perihelion compared to subsurface water-ice sublimation. An international Earth-based observation campaign played a complementary role to the in-situ data, providing recovery images of the comet at large distances, physical information about the nucleus size, and from a coordinated multiwavelength program nearly continuous coverage from August 2010 through encounter on 4 November 2010. From the Earth-based campaign it was clear that comet Hartley 2 had a small nucleus (0.57 km radius), with a rotation period near 16.4 hours prior to the onset of activity. As the activity developed the periodicity was found to change significantly over a period of months. The highly active nucleus had long- and short-term gas production variability with peak activity shortly after perihelion. The comet's activity has been photometrically monitored (as scattered light from the dust coma) from the time of recovery to the present, and the nearly continuous coverage of the comet from August 2010 into 2011 would not have been possible without the amateur contributions. Using these brightness data, we have developed an ice sublimation model to estimate the amount of dust emitted from the comet (and hence the total scattered light) as a function of heliocentric distance as it is driven by a gas flow. The model includes nucleus ices: H_2O, CO_2, CO, and H_2O sublimating from the large chunks seen both from the EPOXI spacecraft and the Arecibo radar observations (Harmon *et al.* 2011). The model indicates that like other comets, water-ice sublimation began to create an observable dust coma/tail near 4–4.4 AU as the comet approached the sun, but that near perihelion, strong CO_2 outgassing in the form of jets (as seen by the spacecraft) was responsible for lifting large ice/dust grains from the surface. CO_2 is likely a strong contributor to activity on the outbound leg of the orbit. The models show that the fractional active nucleus area is small for water production (typical of other comets) and that at perihelion most of the water production is likely from the ice grain halo. Sublimation from deeper CO_2 reservoirs is

likely an important driver of activity for this comet, including out to and beyond aphelion, and this may be a characteristic of unusually active comets—relating to differences in chemistry from either formation or subsequent evolution. This paper will present mission highlights, and emphasize the important role that the amateur observations has in understanding the behavior of this comet.

Light Curve of Minor Planet 1026 Ingrid *(Poster abstract)*

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Abstract We have imaged minor planet 1026 Ingrid over the time period of July 29, 2011, to late September 2011, using the Wheaton College 0.25m telescope at Grove Creek Observatory in Australia via internet access. This telescope is equipped with a Santa Barbara Instrument Group STL-1001E CCD Camera, used with a clear filter. Over 1,000 30-second images were obtained and imported into the MPO Canopus software package for light curve analysis. Our preliminary estimate of the rotation period of 1026 Ingrid is 5.390 ± 0.001 hours, which is consistent with the previous estimate of 5.3 ± 0.3 hours (Székely, P., *et al.* 2005, *Planet. Space Sci.*, **53**, 925).

Membership of the Planetary Nebula Abell 8 in the Open Cluster Bica 6 and Implications for the PN Distance Scale *(Poster abstract)*

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Abstract The potential link between the newly discovered open cluster Bica 6 and the planetary nebula (PN) Abell 8 (PN G167.0-00.9) proposed by Bonatto *et al.* (2008) is confirmed on the basis of new UBVRI CCD photometry for the cluster and spectroscopic observations of its brightest stars, in conjunction with an analysis of 2MASS data for the cluster. The reddening, estimated distance, and radial velocity (+58 ± 6 km/s) of Abell 8 are a close match to the parameters derived for Bica 6: E(B–V)(B0) ≈ 0.40, d = 1.6 kpc, Vr = +57 ±4 km/s (11 stars). The radial velocity match is particularly interesting given that the velocities are more than 50 km/s larger than expected for Galactic orbital motion at l = 167°. The cluster age of 1 billion years implies a mass of –2.5–3 $M_\odot$ for the planetary nebula progenitor star, although the picture is complicated by a few blue stragglers as likely cluster members. The central star of the PN is an optical double in the 2MASS survey, with the companion indicated to be a cluster M dwarf. Abell 8 is a highly evolved PN containing a low luminosity central star (Mv ≈ +8), with a distance implied by cluster membership favoring the short PN distance scale.

What Mass Loss Modeling Tells Us About Planetary Nebulae *(Abstract)*

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Abstract Planetary nebulae are the result of mass loss from an AGB star (specifically, a Mira variable or post-Mira infrared source) that is swept up by a later fast wind and/or ionized when the central star becomes hot. The central stars of planetary nebulae are the naked cores of the former AGB star. Not all AGB stars form PNe, however, and the ones that do may be mostly binary

star systems. Using both a large grid of detailed mass loss models and some simple analytical mass loss formulae we can relate observations of PNe and their nuclei to the character of the late AGB (Mira stage) mass loss.

Stars, Planets, and the Weather: If You Don't Like It Wait Five Billion Years *(Abstract)*

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Abstract Over the last decade realization has grown that high-energy phenomena such as X-ray and EUV radiation, winds, and coronal mass ejections exhibited by stars like our own Sun have an importance far beyond local "stellar weather." From the stormy magnetic extremes of stellar youth to the gentle breeze of stellar middle age and beyond, I describe how stellar weather is now central to problems as diverse as the evolution of supernova Type Ia progenitor candidates, planet formation, and the development and survival of life in planetary systems.

The Hunt for the Quark-Nova: a Call for Observers *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 21, 2011

Abstract A Quark Nova is the explosive transition from a neutron star to a quark star that is theorized to take place days or weeks after a small fraction of "normal" Type II supernova events. The Quark Nova signature is the delayed brightening of the new object by about five magnitudes. The proposed close

long-term monitoring of Type II supernova events should reveal the presence or absence of the signature double-hump of a Quark Nova and allow us to estimate the frequency or upper limit to the rate of such events. Normal supernova search techniques and follow-up activities may miss the subsequent brightening that takes place during the Quark Nova event. We seek CCD-equipped observers with modest-sized telescopes to join a collaborative effort to search for these events. Your job would begin after Type II supernovae are discovered by others. You, with a team of other observers, would follow all new Type II discoveries for about one to two months looking for the signature "double-bump." As there are not many known Type II supernovae active at any given time, the observational commitment is not expected to exceed about one hour per night. We have set up an on-line database to manage the process and record the observations and a communications forum to provide support to the observers and structure to the project (see http://quarknova.ucalgary.ca). The confirmation that these objects exist will be a significant event in supernova research.

Collaborative Research Efforts for Citizen Scientists *(Poster abstract)*

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Abstract The AAVSO's Citizen Sky project encourages participants not just to collect and categorize data, but to critically analyze and publish research findings. Our participants form teams of different yet complementary skills that work together towards a common goal. Each team has a leader and a professional astronomer assigned to act as an advisor. In this work we explore the formation of teams, by what means they find research topics, and how they

manage their collaborations. We acknowledge support from the NSF Informal Science Education Division under grant DRL-0840188 to the AAVSO and the University of Denver.

Exploring the Breadth and Sources of Variable Star Astronomers' Astronomy Knowledge: First Steps *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract There is considerable interest related to the astronomy content knowledge of various groups, whether that group consists of 3rd graders who have just learned the phases of the moon, or astronomy graduate students who are working on original research. Similarly, the Center for Astronomy and Physics Education Research (CAPER) Team and the American Association of Variable Star Observers (AAVSO) are interested in the general astronomy content knowledge of the AAVSO members. To increase our understanding of the knowledge base of today's variable star astronomers, we asked a subset of members to respond to an online general astronomy content knowledge survey called the Test Of Astronomy Standards (TOAST). The TOAST is a twenty-nine-item, multiple-choice format assessment instrument which addresses the full range of topics commonly taught in an introductory astronomy survey course, and is criterion referenced aligned to the consensus learning goals stated by the AAS Chair's Conference on ASTRO 101, the AAAS Project 2061 Benchmarks, and the NRC National Science Education Standards. This paper presents preliminary results on this work to the AAVSO membership in the hope that the findings will begin a conversation about the kinds of experiences and education that are transformative for this important group of astronomy researchers.

Rasch Analysis of Scientific Literacy in an Astronomical Citizen Science Project *(Poster abstract)*

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Abstract We investigate change in attitudes towards science and belief in the nature of science by participants in a citizen science project about astronomy.

A pre-test was given to 1,385 participants and a post-test was given six months later to 165 participants. Nine participants were interviewed. Responses were analyzed using the Rasch Rating Scale Model to place Likert data on an interval scale allowing for more sensitive parametric analysis. Results show that overall attitudes did not change, $p = .225$. However, there was significant change towards attitudes relating to science news (positive) and scientific self efficacy (negative), $p = .001$ and $p = .035$, respectively. This change was related to social activity in the project. Beliefs in the nature of science exhibited a small but significant increase, $p = .04$. Relative positioning of scores on the belief items suggests the increase is mostly due to reinforcement of current beliefs.

The Citizen Sky Planetarium Trailer *(Poster abstract)*

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Abstract Citizen Sky is a multi-year, citizen science project focusing on the bright variable star ε Aurigae. We have developed a six-minute video presentation describing eclipsing binary stars, light curves, and the Citizen Sky project. Designed like a short movie trailer, the video can be shown at planetariums before their regular, feature shows or integrated into a longer presentation. The trailer is available in a wide range of formats for viewing on laptops all the way up to state-of-the-art planetariums. The show is narrated by Timothy Ferris and was produced by the Morrison Planetarium and Visualization Studio at the California Academy of Sciences. This project has been made possible by the National Science Foundation.

The World Science Festival *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 22, 2011

Abstract New York City in the late 20th century rose to be a planetary capital for the sciences, not just astronomy. This growth was mainly in the academic sector but a parallel growth occurred in the public and home field. With the millennium crossing, scientists in New York agitated for a celebration of the City as a place for a thriving science culture. In 2008 they began World Science Festival. 2011 is the fourth running, on June 1–5, following the AAVSO/AAS meetings. World Science Festival was founded by Dr. Brian Greene, Columbia University, and is operated through the World Science Foundation. The Festival is "saturation science" all over Manhattan in a series of lectures, shows, exhibits, performances. It is staged in "science" venues like colleges and musea, but also in off-science spaces like theaters and galleries. It is a blend from hard science, with lectures like those by us astronomers, to science-themed works of art, dance, music. Events are fitted for the public, either for free or a modest fee. While almost all events are on Manhattan, effort has been made to geographically disperse them, even to the outer boroughs. The grand finale of World Science Festival is a street fair in Washington Square. Science centers in booths, tents, and pavilions highlight their work. In past years this fair drew 100,000 to 150,000 visitors. The entire Festival attracts about a quarter-million attendees. NYSkies is a proud participant at the Washington Square fair. It interprets the "Earth to the Universe" display, debuting during IYA-2009. Attendance at "Earth..." on just the day of the fair plausibly is half of all visitors in America. The presentation shows the scale and scope of World Science Festival, its relation to the City, and how our astronomers work with it.

New Life for Old Data: Digitization of Data Published in the *Harvard Annals (Abstract)*

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Abstract We describe the volunteer-driven project to digitize published

visual observations found in the *Annals of the Harvard College Observatory*, the publication of record for Harvard's variable star data archives prior to the founding of the AAVSO. The addition of published data from the 19th and early 20th centuries to the AAVSO International Database has the potential to enable significant new science by extending long term light curves farther back in time with high-quality visual and photographic data. AAVSO volunteers working on this project have together digitized over well over 10,000 observations from the *Harvard Annals*, adding decades to the light curves of some stars. We highlight the work done so far, and show the potential to expand the project by both AAVSO Headquarters and by the volunteers themselves.

Data Release 3 of the AAVSO All-Sky Photometric Survey (APASS) *(Poster abstract)*

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Abstract APASS is an all-sky survey in five filters (B,V,g',r',i') covering the magnitude range 10–17. It is currently underway at two sites: Dark Ridge Observatory in New Mexico, and CTIO in Chile. The survey will take approximately two years to complete, and will provide a precision of 0.02 magnitude for well-sampled stars. This paper presents the current status of the project and provides the access methods to the catalog.

Data Evolution in VSX: Making a Good Thing Better *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract A review of the current status of the AAVSO International Variable Star Index (VSX) is presented. Starting with an heterogeneous set of catalogs automatically imported, the data included in VSX have been constantly evolving and the role of observers contributing their new discoveries or revising known variable stars is growing more important each day. Examples are given of the improvements made in several aspects of star data such as identification, classification, elimination of duplicate entries, and updates.

VSX: the Next Generation *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract The AAVSO International Variable Star Index (VSX), the most comprehensive and up-to-date assemblage of publicly-maintained variable star data on the planet, will be undergoing a major overhaul in the coming year to greatly improve the database design, as well as the Web-based user interface. Five years after its official launch, VSX has evolved into an essential component of the AAVSO enterprise information architecture, tightly integrated with many of the technical organization's other mission-critical processes. However, its unique configuration and functionality are largely based on decades-old data formats and outmoded Web methodologies which will generally not scale well under the anticipated deluge of data from large-scale synoptic surveys. Here, we present the justifications and vision for VSX 2.0, the next generation of this indispensable research tool, including overviews of the creation of a brand new, fully-normalized, database schema, and the ground-up redesign of the front-end Web interface.

AAVSOnet: the Robotic Telescope Network *(Poster abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011

Abstract AAVSOnet is the growing network of robotic telescopes owned and operated by the American Association of Variable Star Observers. With telescopes ranging from 60-mm to 0.61-m in aperture located around the globe, the network fulfills a multitude of science goals. The largest telescopes will be fitted with instruments capable of doing both spectroscopy and photometry. We have pairs of 20-cm telescopes in Chile and New Mexico conducting an all-sky photometric survey (APASS) from 10th to 17th magnitude. These pairs of telescopes monitor the sky in two filters simultaneously in Johnson B and V, as well as Sloan g, r, i, and z. There are telescopes in the 25–35-cm range available to conduct automated programs of stars selected by AAVSO members, and five small telescopes monitoring poorly studied stars brighter than 10th magnitude in both the southern and northern hemispheres. All the data for every star on every image are archived at AAVSO headquarters for future data-mining; images are uploaded to member accounts where they can be analyzed by a powerful suite of photometric tools and observations submitted to the AAVSO International Database.

Hα Emission Extraction Using Narrowband Photometric Filters *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 21, 2011

Abstract Maria Mitchell Observatory (MMO) has explored using Narrowband Photometric (<100Å) filters to substitute for spectroscopic observations. The method is thought to have significant signal-to-noise advantages over spectroscopic observations for small telescopes. These small telescopes offer advantages for projects requiring intensive monitoring where telescope time is limited on larger telescopes. RR Tau, a suspected UXOR, was intensively observed by the MMO 0.6-m Ritchey-Chrétien telescope in Nantucket, Massachusetts, and the 0.29-m W28 AAVSOnet telescope from Cloudcroft, New Mexico, during the 2010 Winter and Spring seasons. Observations were

made in Hα with 45Å and 100Å narrowband filters as well as the continuum at 6450Å with 50Å and 100Å filters. Hα emission was extracted with an error of 8% and compared to the change in the continuum. RR Tau exhibited a 30% change in emission while the continuum changed by over a factor of 5.

Automation of Eastern Kentucky University Observatory and Preliminary Data *(Poster abstract)*

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Abstract Eastern Kentucky University is a regional comprehensive institution located in Richmond, Kentucky. Its service area includes much of the eastern part of Kentucky, commonly referred to as Appalachia. As such, Eastern has truly been a “school of opportunities” for the region. We offer three astronomy courses and one of them, AST 135, has an outdoor lab component, in which the students observe the moon and the brightest planets using 6-inch SCT. To expand our offerings by adding advanced classes in observational astronomy, and with support from the University and a small grant from the AAS (Small Research Grants), we constructed a small observatory for that purpose.

We have a 14-inch telescope (C14 from Celestron), with a research grade mount (Paramount ME), housed permanently in a two-room facility. The telescope room has a retractable roof and the control room is insulated against the elements. The telescope is conveniently located near campus, in a location away from city lights and vehicular traffic, with access via a secure gate. The observatory is on a concrete pad poured directly onto the ground, to minimize vibrations. The instrument package consists of a SBIG STL-6303E CCD camera with filter wheel and full complement of photographic, narrow-band, and photometric filters (Hα and UBVRI). Courtesy of the AAS grant, we also have a temperature-compensated focuser (TCF-S3i), off-axis guider, and SBIG AO-L adaptive optics accessory.

Our first step has been the measurement of our CCD transformation parameters, to assess the capabilities of our telescope-camera combination. We imaged a standard photometric field from Landolt (1992) (R.A. $09^h\ 21^m\ 32^s$, Dec. $+02^\circ\ 47'\ 00''$ (J2000, Plate 38 of Landolt). Data were obtained with a time integration of 90 seconds, binned 2×2 (~1 arcsec/pixel) at air mass X = 1.31. We determined the CCD transformation parameter as described by the AAVSO

document "Computing and Using CCD transformation coefficients" (Cohen 2003). We obtained the following:

$$T_{bv} = 1.329;\ T_{vr} = 1.000;\ T_{ri} = 0.912;\ T_{v} = -0.065;\ T_{r} = -0.042$$

We estimate a 5% uncertainty in our measurements. This past summer, with student support, we were able to perform our first measurements of light curves, particularly of the AAVSO Short Period Pulsator Program—suggested δ Scuti star DY Her and the RR Lyrae stars UU Boo and XX Cyg. Our light curves (we have two complete BVRI sets for DY her) were not corrected using our transformation parameters, but just compared with the reference stars provided by AAVSO. We will present the data obtained and our current efforts in automation of the observatory operations. We have the necessary hardware to monitor the environment via video and remotely operate the roof and the telescope.

References

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Status of the USNO Infrared Astrometry Program *(Poster abstract)*

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Abstract The USNO Infrared astrometry program has been in a suspended state since a June 2006 cryogenic accident with our imaging camera. We describe the current status of bringing the program back to full operation. We expect to re-start an expanded astrometric program in the near future and present our initial list of targets. This will also provide an opportunity for the community to suggest potential cool, low-mass targets which are in need of high quality parallaxes and proper motions. We earlier published preliminary astrometric results for 40 L and T dwarf fields based on the first two years of observations (Vrba *et al.*, Astron. J., 127, 2948 (2004)). Those initial objects plus an additional nineteen fields added later comprise a total of one M dwarf, twenty-eight L dwarfs, and thirty-nine T dwarfs, including objects in binary systems. Final parallaxes and proper motions for these objects will be published later this year. The additional approximately four years of observations for the original forty objects improve the mean parallax errors orginially reported from 4.31 mas to 1.73 mas, with the best at 0.64 mas, and the mean proper motion errors from 6.56 mas/yr to 1.09 mas/yr.

Variable Star Observing With the Bradford Robotic Telescope *(Abstract)*

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Presented at the 100th Spring Meeting of the AAVSO, May 22, 2011

Abstract The Bradford Robotic Telescope (BRT) is a collection of telescopes and other instruments located on Mount Teide, Tenerife, Canary Islands; this resource is available to all for use at no cost (http://www.telescope.org/info/BRT_information). With the recent addition of Johnson *BVRI* filters on the BRT's 24 square arc minute camera, this telescope has become a resource to be considered when monitoring certain stars such as LPVs. This presentation will examine the mechanics of observing with the BRT and show examples of work that has been done by the author and how those data have been reduced using VPhot.

Solar Cycle 24—Will It Be Unusually Quiet? *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract For the last forty years or so all the AAVSO (American Association of Variable Star Observers) Very Low Frequency (VLF) Sudden Ionospheric Disturbance (SID) data have been sent to NGDC (National Geophysical Data Center). In this paper these data are put into a database and graphed in hopes of understanding these VLF SID submissions. The graphics show the NGDC accumulated Importance Rating (an index of the duration of solar flares) for all the AAVSO VLF SID submissions over the past forty years. And, if we compare these VLF SID data with the last three solar cycles of sunspot number counts compiled by the Solen group (Jan Alvestad: http://www.solen.info/solar/cyclcomp.html), it seems that the AAVSO VLF SID submissions to NGDC show our accumulated Importance Rating signals lag by 18 to 24 months after the start of each of the last three solar cycles! That puts our VLF radio's SID IR index measure at a point where it takes at least 100 sunspot counts per month before the VLF SID accumulated IR index even shows a signal through the noise floor of our ionosphere. The VLF observer's importance rating index is just monitoring the tip of these solar cycles with our VLF radios when compared to the sunspot number count indexes. And if the Solen sunspot predictions are right for Cycle 24, the solar sunspot peak won't even reach the 70 mark for this next cycle. So, our VLF SID IR index signal submissions may not even be detectable in Cycle 24!

A Generalized Linear Mixed Model for Enumerated Sunspots *(Abstract)*

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Presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

Abstract Monthly sunspot counts data from consistently submitting AAVSO observers were provided to determine monthly average sunspot numbers and the individual observer parameters that correct each observer's counts to the monthly average. The data span a fourteen-month period from May 2010 through June 2011. The parameters are determined from a mixed-effects, loglinear model constructed specifically from the fourteen months of Poisson-distributed sunspot numbers. This model differs in the treatment of the data distribution assumptions of the existing linear regression model developed by Shapley (1949). The loglinear model methodology exceeds the correction coefficient performance criteria set by Shapley, and provides a method for determining the relative sunspot number reported monthly by the American Association of Variable Star Observers Solar Section. Model improvements are discussed.

AAVSO 100th Annual Meeting After-Banquet Remarks

Centennial Highlights in Astronomy

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After-banquet remarks presented at the 100th Annual Meeting of the AAVSO, October 8, 2011

For many years Harlow Shapley, director of the Harvard College Observatory, eminent observer of variable stars, and patron of the AAVSO, delivered an annual after-dinner talk at the AAVSO meetings where he summarized the highlights in astronomy in the past year. In 1961, at the AAVSO's 50th anniversary, he expanded his talk, giving nineteen highlights from the previous half century, beginning with the founding of the AAVSO itself.

In following in Dr. Shapley's footsteps (and "Doctor Shapley" was how we always referred to him), I decided to divide the century into its ten decades and to select a single highlight from each ten-year interval. Please note that in many cases the highlight is an important theme for the decade, even though the actual initial discovery may have been made earlier; this is particularly true for the discovery of dark matter, placed in the 1980s decade. In the event, choosing a single highlight proved in many cases rather more difficult than it might appear at first glance. Let me demonstrate with the problems of choosing a single highlight from the years 1911 to 1920.

The teens were the decade of Einstein's general relativity and the critical eclipse test of 1919, but also Shapley's own pioneering work on the structure of the Milky Way and the sun's place within our galaxy. Curiously, Shapley didn't mention his own Milky Way work in his 1961 list, nor did he mention Hubble's work on galaxy distances in the next decade. But, anonymously, he cited the pulsation theory of variable stars in connection with Henrietta Leavitt's period-luminosity relation. Now, around this time, in 1959 or '60, he showed me the preliminary list of selections he was proposing for his *Source Book in Astronomy, 1900–1950*. I noticed that he included his 1914 paper on δ Cephei, where he showed that if this famous variable star were an eclipsing binary star, as many astronomers thought at the time, then the secondary star had to revolve inside the primary! In other words, δ Cephei had instead to be an intrinsic variable, probably explained by physical pulsations. Nevertheless, I thought it was a little idiosyncratic to choose this paper for inclusion, and I told him so.

Recently I stumbled on his letter in reply. "Young man, you weren't there in 1915!" is essentially what he said. In effect, his paper provided the credentials for Henrietta Leavitt's period-luminosity relation to be used as a distance indicator, for if Cepheids were simply eclipsing binaries, Miss Leavitt's relation was simply accidental.

That's the first half of this story. The second half is that Shapley's English contemporary Arthur S. Eddington also made a list of highlights, but much earlier, in 1920 for the centennial of the Royal Astronomical Society. The only highlight he included from the 1911–1920 decade was the measurement of the diameter of Betelgeuse, made by Michelson and Pease with an interferometer attached to the Mt. Wilson 100-inch Hooker reflector. Why was this so significant? Because it credentialed the implications of the to-become-famous diagram drawn by Henry Norris Russell and independently by Einar Hertzsprung.

In fact, the sorting of stars made possible by the H-R diagram held the key for using highly luminous stars, such as supergiants and Cepheids, as distance indicators. The understanding it provided concerning the diverse luminosities of stars laid the foundation for Shapley's work on the structure of our galaxy, and for Hubble's work in the following decade on the distances of galaxies. Ultimately the diagram would enable astronomers to get a grip on the life history of stars themselves, and the clusters in which they live.

Therefore, my choice for **highlight number one, for the 1911–1920 decade, is establishing the H-R diagram**.

As the decade waned, in April of 1920, there was a famous debate between Harlow Shapley, then from Mt. Wilson Observatory, and Heber D. Curtis, from Lick Observatory, on the scale of the universe. Everyone knows what Shapley got wrong. At the time he didn't believe that the spirals were extragalactic nebulae. But few people realize what Curtis got wrong. He apparently didn't believe in the period-luminosity relation of the Cepheids, nor appreciate the significance of dwarf and giant stars!

For 1921–1930: In 1921, by finding Cepheid variables in the Andromeda nebula, Edwin Hubble demonstrated its great distance and opened up the universe of galaxies. Before the decade was out Georges Lemaître found the distance-red shift correlation, later established more firmly by Hubble. **Highlight number two is Hubble's opening the realm of the galaxies and the explosive flight as the universe expands.**

For 1931–1940: Although Cecilia Payne got some hint of the high hydrogen abundance in her 1925 thesis, her method was novel, unsubstantiated, and in any event it referred only to the atmospheres of the stars. Additional evidence marshaled by Russell helped credential the early hint, and in the next decade stellar interior calculations by Bengt Strömgren and Eddington showed that stars could be primarily hydrogen all the way through. Before the decade was out, C. F. Von Weizsäcker and Hans Bethe showed that a nuclear carbon cycle could power stars. **The hydrogen composition of the stars and the nuclear fusion that powers them is highlight number three.**

For 1941–1950: Taking advantage of the dark skies provided by the wartime blackout of Los Angeles, Walter Baade probed the starry composition of the Andromeda galaxy and developed his idea of **stellar populations**. Not until the following decade did he identify the populations with the ages of stars, nor did he yet use the concept to double the accepted age of the universe.

For 1951–1960: The flowering of radio astronomy, and the discovery of the 21-cm line of hydrogen, led to the **delineation of the spiral structure of the Milky Way.**

For 1961–1970: New windows on the universe, epitomized by the discovery of quasars, pulsars, and X-ray sources, but above all for purposes of cosmology and the origin of the universe, the **discovery of the 3° background radiation.**

For 1971–1980: Recognition that our universe has an evolving history, brought about by studies of nucleosynthesis and by the cosmological distances of quasars.

For 1981–1990: The widespread appreciation that rather than hydrogen, mysterious **"dark matter" provided the overwhelming mass in the universe.** This had been suggested much earlier by Fritz Zwicky and in the 1970s advocated by Jan Oort, by Jerry Ostriker, James Peebles, and Amos Yahil, and observationally established by Vera Rubin and Kent Ford.

For 1991–2000: The Hubble Space Telescope decade, settling the much-debated age of the universe, but also **the discovery of the accelerating universe or dark energy.** A runner-up: the COBE mission and the Big Bang anisotropy, the "seeds" of galaxies.

And finally, for 2001–2011: The discovery of large numbers of exoplanets, and recognition of the long-term migration of planets. Another runner-up: WMAP, whose accurate measurements of the cosmic microwave background fluctuations not only demonstrated the cosmological flatness of our universe, but also showed within a few percent that non-baryonic "dark matter" is five times more abundant than the baryonic matter that makes up you, me, and the visible universe.

And now, through the looking glass: **A few predictions for 2012–2061!**

First, I predict the success of attempts to detect the gravitational waves, the ripples in space propagated from appropriate massive movements of material in the universe (sought by LIGO, the Laser Interferometer Gravitational-Wave Observatory and its successors). Second, the detection of non-equilibrium chemistry in the atmospheres of selected exoplanets (and I predict that the interpretation of the existence of life on distant planets will be highly controversial). I would also look forward to the clarification of two of the deepest mysteries now facing astrophysicists: the so-called dark energy and dark matter.

From the vantage point of 2011, with the world economy in confusion, it is difficult to predict the future of the giant James Webb space telescope. Let us hope it will be successfully launched, and that it will reap surprising, unpredicted new phenomena. Dare one predict unpredicted phenomena will be found? Such I predict! And I predict that the AAVSO, venerable by 2061, will still be collecting data, but in new and more efficient ways.

Invited review papers

Introduction: Variable Star Astronomy in the 21st Century

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The AAVSO has just celebrated an exciting and important milestone in its history—its centenary. At the age of 100, it is in excellent health (unlike most people), with a new(ish) home, an able and dedicated staff and council, a worldwide network of volunteer observers and friends, respect and support from professional astronomers, impressive technology, and a continuing mandate to engage in and facilitate research in variable star astronomy.

It therefore seems appropriate to review variable star astronomy in 2011–2012. Several years have gone by since my book (Percy 2007) attempted to review the field and, as in most areas of astronomy, much has happened in a short period of time. We therefore commissioned a set of short reviews of variable star types which are of special interest to AAVSOers by professional-astronomer friends of the AAVSO with special expertise on these topics. We thank them for taking the time, in their busy schedules, to provide these reviews.

We begin, appropriately, with a review of young stellar objects (YSOs) by Bill Herbst, Van Vleck Professor of Astronomy, Wesleyan University. Bill has been a leader in this field for many years, especially through international long-term photometric monitoring campaigns, and through mentoring undergraduate research students. Bill is the science advisor to the AAVSO's recently-formed YSO Section. He's also an award-winning teacher, active in public outreach, and a skilled tennis player!

Bryce Croll, NASA Sagan Fellow at the Massachusetts Institute of Technology (MIT), reviews exoplanet transits, one of the hottest fields in which amateurs can contribute. Exoplanets are planets around other stars. If they transit their star and dim its light, that variability can provide evidence for the exoplanet, and much information about its properties. Bryce recently completed a Ph.D. in the exoplanet group at the University of Toronto, studying the atmospheres and other properties of exoplanets. He also had several variable star publications, as an undergraduate, based on photometry with *MOST* (Microvariability and Oscillations of STars), Canada's "humble space telescope." At Toronto, he was a driving force behind our public outreach programs. And he's a triathlete.

Ed Guinan, Professor of Astronomy and Astrophysics, Villanova University, reviews eclipsing binaries. These provide fundamental and unique information about the properties and evolution of stars. Ed is an international leader in the study of stars and binaries, especially through the Variable Star Division of the International Astronomical Union (IAU). He is also a leader in international astronomy education and development; he chairs the IAU's Program Group on "Teaching for Astronomical Development," and works for astronomical education and development in many countries around the world. His research interests include pulsating stars, binaries, black holes, sun-like stars, robotic telescopes, and exoplanets. He has served on the AAVSO Council since 2008.

RR Lyrae stars, which provide essential information about the properties of the oldest stars in galaxies, are reviewed by Katrien Kolenberg, Harvard-Smithsonian Center for Astrophysics, on leave from the University of Leuven, Belgium. I first met Katrien in Leuven when she was a graduate student, at an IAU Colloquium on pulsating stars. There, she stood out as a result of both her scientific and her artistic talents. Much of her research focuses on one of the oldest and most puzzling mysteries in variable star astronomy—the nature and cause of the *Blazhko effect*. She is currently at CFA on a Marie Curie Scholarship, using *Kepler* data to study RR Lyrae stars in ways not previously possible.

Doug Welch, Professor at McMaster University, Hamilton, Ontario, reviews Population II Cepheids. Doug began his interest in astronomy as a keen amateur in Ottawa, survived two summers as my undergraduate research assistant, doing photometry of variable stars, and went on to a very successful career as a researcher, professor, administrator, and promoter of astronomy outreach. He served on AAVSO Council in 1995–1999 and 2007–2008, and has assisted the Association in many other ways, including establishing the on-line discussion group. His research interests are in pulsating stars and, more recently, light echoes from supernovae and other transients.

Cepheids are reviewed by Dave Turner, Saint Mary's University, Halifax, Nova Scotia. Dave's research encompasses star clusters, especially those which contain Cepheids. He also carries out long-term studies of period changes in Cepheids, which provide important and unique information about Cepheid evolution. He is also a long-time supporter of pro-am collaboration, both through the Royal Astronomical Society of Canada (RASC) (he served for many years as Editor of *JRASC*), through the AAVSO, in which he is currently a Councillor, and through his collaboration with amateurs in the Halifax area.

Lee Anne Willson, University Professor, Iowa State University, reviews Miras. Lee Anne and the AAVSO are a perfect fit: she is an expert in constructing and interpreting theoretical models of Mira pulsation, which AAVSO observers have studied productively for over a century. She has been deeply involved in the AAVSO, as a Councillor for many years, and as President in 1999–2001. She has been publishing in *JAAVSO* for over thirty years. As Vice-President of the American Astronomical Society, she recently facilitated the May 2011 joint AAVSO-AAS meeting, part of the AAVSO centenary. Her extra-curricular interests include being the Founding President of the Creative Artists' Studio of Ames, Iowa.

Non-Mira pulsating red giants are reviewed by Laszlo Kiss and me. Laszlo graduated from the University of Szeged, Hungary, and spent several years at the University of Sydney, Australia, before returning to the Konkoly Observatory in Hungary. He already has 380 publications in the ADS data system, partly because, in addition to his very productive professional career, he has been a very active participant and supporter of amateur astronomy, especially in Hungary. He is a member and good friend of the AAVSO. Professionally, he has a special interest in large-scale surveys of variable stars and, more recently, exoplanets (and exomoons), but he has made contributions to the understanding of many other types of variables as well.

Geoff Clayton, Ball Family Distinguished Professor of Physics at Louisiana State University, reviews R CrB stars, a field in which he has been a world leader for many years. He has written several comprehensive reviews of R CrB stars in the past, and we are honored that he has contributed his latest one to *JAAVSO*. He has served as an AAVSO Councillor and, like several of our reviewers, is a member of the Editorial Board of *JAAVSO*. For several years, he supervised summer undergraduate research students at the Maria Mitchell Observatory. His website is "The Centre for Fun Astrophysics; the home of 'Team Clayton'", expressing his enthusiasm for studying R CrB stars and interstellar matter.

The review of cataclysmic variables is contributed by Paula Szkody, Professor, University of Washington, and her colleague Boris Gaensicke. CVs have been a topic of great interest to AAVSO observers, especially since the dawn of the space age and high-energy astrophysics in the 1970s. Paula has been a user of AAVSO data for almost thirty years, a mentor to the Association and its observers and, more recently, a Councillor (2003–2009) and President (2007–2009). She has also served recently as Editor of *Publications of the Astronomical Society of the Pacific* (*PASP*). Boris Gaensicke is a professor in the Department of Physics, University of Warwick, UK, where he is engaged in a wide variety of projects on binaries containing white dwarf stars. He co-edits a *Newsletter on Interacting Binaries*.

Ulisse Munari, National Institute of Astrophysics INAF, Observatorio Astronomico di Padova, Italy, reviews the symbiotic stars, and also novae; we thank him especially for providing both these reviews. Symbiotic stars are among the most complex of all variables, since they vary on a wide range of time scales, for a wide range of reasons. And novae are the spectacular result of runaway thermonuclear reactions. Ulisse was the AAVSO's second Janet A. Mattei Research Fellow; he worked with Arne Henden to improve observer quality, to provide spectra of new transient objects to decipher their classification, and to provide calibrated photometric sequences for many variables. He will be returning to AAVSO Headquarters in fall 2012 to collaborate on the APASS photometric survey. He has over 500 publications listed on ADS!

Peter Garnavich, Professor of Astrophysics and Cosmology, Notre Dame University, reviews supernovae. Peter is a distinguished scientist. He shared the Gruber Prize in Cosmology in 2007, and was an integral part of the research that won the Nobel Prize in Physics in 2011 (and was invited to attend the Nobel Prize ceremony in Stockholm). Peter is keenly involved in communicating with the public and the media about the excitement of astronomy. He is also a great friend of the AAVSO, and served as Councillor from 1996 to 2000. His first publication was an *Information Bulletin on Variable Stars* (*IBVS*) with Janet Mattei and Lee Anne Willson, and his second publication was a sole-author paper in *JAAVSO*!

Other types of variable stars

There are other types of variable stars which are not included in the reviews. generally because they are less suitable for study by amateurs. Most of these types have small amplitudes, and are most often found as variable comparison stars for visual, PEP, or CCD photometry. They are "fair game" for skilled amateurs who can achieve millimag precision. Since many of them have periods of hours to days, joining a multi-longitude network of observers is often a good strategy. Here are short notes on some of those variable star types. Another useful resource is the 2012 triennial report of the IAU Commission on Variable Stars (Handler 2012). Other excellent resources are the AAVSO "Variable Star of the Season" articles (www.aavso.org/vsots_archive), especially the more recent ones, and the "For Observers" page (www.aavso.org/observers#sections) which contains links to the observing sections, including data mining, solar, and high energy network, which are not discussed explicitly in these short science reviews.

δ Scuti stars and γ Doradus stars These are A5-F2 stars, near the main sequence, which pulsate in a complex mixture of modes, with periods of a few hours to a few days. They are analogues of the Cepheids, in that they are driven by the same helium opacity mechanism. Most δ Scuti stars have very small amplitudes, but there are a few HADS—high-amplitude δ Scuti stars—which are amenable to visual observation. The most active work on δ Scuti stars continues to be: (1) detecting and studying them, especially with high-precision photometry from space; (2) interpreting the complex spectrum of periods with models, a process called *asteroseismology*. δ Scuti stars are radial pulsators, though many have non-radial modes as well; γ Doradus stars are pure non-radial pulsators. Both, through asteroseismology, provide important information about the interiors and evolution of these stars.

Pulsating B stars These include β Cephei stars, which have been known for a century, and Slowly Pulsating B (SPB) stars, which are a more recent discovery. Their pulsation is driven by a similar opacity mechanism as the Cepheids, but involving iron-group elements, rather than helium, deep within the star. There are many dozens of these among the naked-eye stars. These are complex, multi-mode pulsators. The β Cephei stars are primarily radial p-mode pulsators, with periods of a few hours; the SPB stars are primarily g-mode pulsators, with periods of hours to a day or two. However, there are stars which show both types of modes. The most important recent development has been the availability of ultra-precise photometry from space missions, *MOST,* *CoRoT*, and *Kepler*. But De Cat *et al.* (2011), in a recent review, end by saying that "there is still a clear need for ground-based follow-up observations." Another research frontier is the search for and study of magnetic fields in OB stars, which may explain some poorly-understood aspects of their behavior.

γ *Cas (Be) stars* These are non-supergiant B stars which have shown emission lines in their spectra on at least one occasion. They vary, photometrically and spectroscopically, on time scales from hours to years. They may brighten and fade unpredictably and, since there are about 200 among the naked-eye stars, they are well-suited for PEP and CCD monitoring. The emission lines and some of the photometric variability are due to an equatorial disc slowly moving away from the star. Now that spectroscopy of brighter stars is within the reach of suitably-equipped amateurs, Be stars can be monitored by amateurs using that technique as well. One of the most exciting new developments in Be star research is the ability, using optical interferometry, to image the discs of these stars.

A good place to learn about current research on Be stars is in the *Be Star Newsletter*, maintained by David McDavid at the University of Virginia: (http://www.astro.virginia.edu/$\sim$dam3ma/benews/ (click on "abstracts")).

Rotating variable stars and stellar activity Rotating variables are stars with non-uniform surfaces; their period of variability is their rotation period. Most have visual amplitudes less than 0.1 magnitude. They are of two types: (1) stars like the sun, or cooler, with starspots; and (2) peculiar A stars, with temperatures of typically 10,000K and strong global magnetic fields, inclined to the rotation axis ("oblique rotators"). Type (1) rotating variables are of current interest because they may host exoplanets. The rotational variability provides information on the rotation and activity of the star; it may also be confused with an exoplanet transit!

Related to the spotted rotating variables are the *flare stars* which, along with rotating variables, are the most numerous variable stars in our galaxy. That's because over ninety percent of stars are main sequence stars, like the sun or cooler, and virtually all of these rotate, have spots, and flare. Spots and flares result from magnetic fields, which are generated by rotation and convection. Papers on classical flare stars are still published, but stellar flares have become a standard, mainstream process in astrophysics—especially as similar processes occur on the sun.

Solar-type oscillations The sun vibrates in thousands of complex, non-radial modes, driven by convective motions in its outer layers, but these vibrations are so small that they require specialized observation techniques. On other stars, they are observable from the ground only with great difficulty, but they are most effectively observed with high-precision photometry from space, with *MOST, CoRoT*, and *Kepler*. As described in the Kiss and Percy review, they have been observed in many red giants, and are revolutionizing our understanding of the nature and structure of these stars.

RV Tauri and SRd stars These are mentioned briefly in Doug Welch's review, but I would like to highlight two continuing areas of interest in these stars: (1) the cause of the alternating deep and shallow minima in these stars—probably a combination of multiperiodicity, chaos, and convection effects—and (2) the nature of the long-period variability of the RVb stars—probably a result of binarity in a significant fraction of RV Tauri and other post-AGB stars.

Hypergiants The most luminous stars, of all temperatures, are unstable and variable in a variety of ways. Stars such as the hot P Cygni and the cooler ρ Cas are well-established targets for AAVSO observation, and there are current/recent AAVSO campaigns on the hot hypergiants S Dor (*AAVSO Alert Notice 453*) and on P Cygni (*AAVSO Alert Notice 440*). I was saddened, but also moved in a way to recently receive a copy of the last paper by Richard Stothers, who passed away in 2011, and who made important contributions to the theory and interpretation of stellar variability during his long career. His paper on "Yellow Hypergiants Show Long Secondary Periods?" (Stothers 2012) deals with the hypergiants ρ Cas and HR 8752—two of the first stars that I collaborated on with the AAVSO. It suggests that both show the mysterious "long secondary periods" found in pulsating red giants, red supergiants, and red hypergiants (see review by Kiss and Percy), and are regarded by some as being the most important unsolved problem in stellar pulsation theory. Stothers attributes these to the turnover of giant convection cells in the stars' convective envelopes.

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The Variability of Young Stellar Objects

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Abstract A brief review of the types and causes of the variability of young stellar objects (pre-main sequence stars) is given with an emphasis on what we do not yet understand and how amateur observers can continue to make important contributions to the field.

1. Introduction

Alfred H. Joy (1945) was the first to identify a class of eleven irregular variable stars with characteristics similar to his adopted proto-type T Tauri. The amplitude of the variability was large—typically several magnitudes—and irregular, with no evidence of periodicity and no discernible pattern. Some stars behaved erratically, changing brightness by a magnitude or more from night to night, while others were more quiescent. Individual stars went through active periods and quiescent periods, although some could be counted on to generally be more active than others. The close association of these stars with dark and bright nebulosity as well as their spectroscopic characteristics, including emission lines of CaII and HI, indicated that they might be very young stars, an hypothesis more or less proven by George Herbig (1960, 1962). There are now thousands of known T Tauri stars within reach of small telescopes. Many were discovered by their Hα emission and catalogued by Herbig and Bell (1988). Others were found in photometric studies, especially of young clusters such as the Orion Nebula Cluster (Herbst *et al.* 2002).

The range of spectral classes among the original eleven stars of Joy was rather narrow and did not extend later than G5. Today the typical T Tauri star is of K spectral class, while earlier-type counterparts are referred to as Herbig Ae/Be stars. T Tauri stars are the youthful versions of sun-like stars, with masses of a few tenths to a few times the mass of the Sun. Herbig Ae/Be stars are young stars of higher mass. T Tauri stars are further divided into two classes: classical T Tauri stars (CTTS) and weak-lined T Tauri stars (WTTS). The distinction is commonly, although not exclusively, made on the basis of the strength of the Hα emission line. If it exceeds about 10 Å in equivalent width the object is called a CTTS and if it is less than that amount, the object is called a WTTS. Since the strength of the Hα feature is now recognized as a proxy for the star's accretion rate, it is generally the case that CTTS are pre-main sequence stars that are still accreting from surrounding disks, while WTTS are only weakly accreting from their disks, if at all. We have learned that the presence or absence of an accretion disk is in fact the most important determinant of the observed characteristics of a young star, including the type of variability it exhibits.

2. The evolutionary status and structure of young stellar objects

2.1. Pre-main sequence stars

Stars form from interstellar clouds of gas and dust when parts of them become dense enough and cold enough that gravity overcomes random thermal motions and initiates the inexorable collapse that leads to a star. During this time, the radius of the sphere of matter that will become a star decreases by about a million fold! At the center, there quickly accumulates a protostar that is transforming the infalling energy of the accreting gas into thermal energy as it crashes into the central sphere. Within a hundred thousand years (or less for more massive stars) the central object has reached stellar temperatures at its surface, but is not quite hot enough at its center to initiate nuclear burning of Hydrogen. Such stars are easily visible, nonetheless, and make up the general class of variable stars known as young stellar objects discussed here. They are also referred to as pre-main sequence stars because they have not yet fully contracted to their main sequence size, where they will stabilize as their cores become hot enough to initiate the H-burning needed to stop the collapse. Pre-main sequence stars shine primarily by slowly shrinking, thereby converting gravitational potential energy to thermal energy, some of which is radiated away. It takes about 30 My for a sun-like star to reach the main sequence and finally turn on its core nuclear burning, but its T Tauri phase is much shorter than that, only the 1–10 My it takes to dissipate its accretion disk and organized surface magnetic fields. Older pre-main sequence stars are sometimes called post T Tauri stars (PTTS) and show little variability at optical wavelengths although they may still be strong X-ray sources.

2.2. Accretion disks

Anything that collapses by a million-fold will also spin up by a huge factor due to the well known phenomenon of conservation of angular momentum. A skater who brings her arms in close to her body spins noticeably faster even though the contraction in distance is only a few times, not a million times! It is not hard to show that even the slightest amount of spin expected to be present in an initial cloud would produce a protostar spinning faster than the speed of light if angular momentum were conserved. Exactly how forming stars rid themselves of this excess spin energy is complicated and unknown in detail, but it is clear that two things often result. First, binary stars are a common outcome of the star formation process and they can store a good deal of angular momentum in the orbital motion of the stars. A second common outcome is a single star with planetary system—again a good sink for angular momentum. Note that it is also possible and presumably common to have a binary system with planets, as recent observations with the Kepler satellite have demonstrated. Prior to forming individual planets, the systems collapse to a central pre-main sequence star (or binary) plus a disk. Spectacular Hubble Space Telescope images of the Orion Nebula Cluster, for example, have revealed these disks around many of the young stellar objects in that cosmic nursery.

Rapid rotation has a flattening effect on matter, as anyone who has watched pizza dough spun into a crust will recognize. Disks probably form around every young star although some may be disrupted by interactions with binary companions or neighboring stars within a cluster. The great success of the Kepler mission at finding planets shows that disks survive in most cases and planets form within them. Initially, however, the disks are primarily gaseous and have a viscosity that causes some matter to be driven inward towards the star. As the accreting matter reaches a distance of only a few stellar radii it encounters the star's magnetosphere, a region dominated by intense magnetic fields rooted at the stellar magnetic poles. Some of the incoming matter is caught in the rotating fields and ejected perpendicular to the disk, forming bipolar jets of outflowing material. The rest is funneled to the star's surface in the polar regions much like the solar wind is funneled into auroral rings on Earth (Hartmann 2001).

Figures 1 and 2 show the structure of a CTTS and a WTTS. In the CTTS the disk is more massive, composed of mostly gas and is still accreting onto the star, causing the irregular, large amplitude variability first noticed by Joy. In the WTTS there is still a disk, since planets have not yet formed, but the gas is largely gone and there is little or no accretion. Since the star still has a very strong surface magnetic field it still exhibits some variability due especially to its rotation and the presence of dark spots. A PTTS probably looks much like a WTTS except that the magnetic field has weakened or become more irregular so that the spots are more uniformly distributed around the star, resulting in less photometric variability.

3. Variability types among young stellar objects

While many different classification schemes have been used to characterize the sometimes bewildering observed phenomena, here we will follow the scheme proposed by Herbst *et al.* (1994) augmented by two types of eruptive variable described originally by George Herbig and a potential new form of variability signified by the unique behavior of KH 15D.

3.1. Periodic variables with cool spots (type I variables)

Most WTTS show regular, often nearly sinusoidal, variations of 0.1 to 0.3 magnitude in their optical light on time scales of 1 to 15 days. The largest amplitude example is V410 Tau (Herbst 1989). The shapes and amplitudes of these variations typically evolve on timescales of months or years but the periods remain stable, supporting the view that the cause of the variation is the rotation of a cool spotted surface. For many beautiful examples of such light curves see Grankin *et al.* (2008). The scientific interest in these stars is that they provide a handy and reliable method to measure the rotation period of pre-main sequence stars. They are not an easy target for amateurs since they tend to be relatively faint stars with fairly small amplitude variations. For advanced amateurs with CCDs who wish to commit many months of rather continuous observing time (they require nightly or even hourly observation) and can deal with the analysis issues (normally the period is only revealed by a rather sophisticated mathematical analysis such as a Fourier transform) the payoff is a rotation period for a young star. We now have such periods for thousands of young stars so the incremental value of another one is not so great. But there may still be interesting objects out there and the possibility of changing periods, perhaps caused by differential rotation on the surface of the star, as occurs on the Sun, remains open.

3.2. Mostly irregular variables with hot spots (type II variables)

Most CTTS show this kind of variability due to the irregular nature of the accretion heating. Just as auroral displays wax and wane with the solar wind, the brightness of CTTSs wax and wane irregularly with accretion rate changes. While interesting, it is hard to get too much useful science out of these changes which can be like trying to understand the comings and goings of clouds! But there are some interesting projects for amateurs here and some new techniques for extracting useful information (Percy *et al.* 2010a, b). The prototype for these stars is T Tauri itself and it had a sufifciently stable variation during one epoch of observation that we were able to determine its rotation period of 2.8 days (Herbst *et al.* 1986, 1987). This work was done with the collaboration of many astronomers including amateurs because we needed data to be obtained at many different longitudes. There are undoubtedly more CTTS that will show periodicity when enough data are accumulated on them.

On the longer term, the modulation of the irregular behavior in these stars is very interesting and something that AAVSO observers have contributed to and can continue to contribute to. For example, T Tauri has a very extensive data base in the AAVSO archives that shows it has gone through periods of great activity and periods of relative quiescence. The cause of these modulations is unknown but could have to do with companions orbiting it (Beck *et al.* 2001), either stars or perhaps protoplanets. Continuing to keep an eye on this object and similar ones is a task well suited to the AAVSO and of potentially great scientific importance, especially should some unexpected behavior occur.

3.3. Irregular variables suffering occultations (type III variables): UXors

Many Herbig Ae/Be stars and earlier type CTTS such as RY Tau and CO Ori undergo this type of variability. While its cause is still debated, it seems clear that these stars are irregularly occulted by circumstellar matter. The timescales are similar to, although perhaps a bit longer than, the Type II variables and there is probably a mixture of accretion-related heating and occultation going on in some sources. One characteristic of the class is that there can be rather sudden drops in the brightness of the star by one, two, or even three magnitudes followed by slower and often irregular recoveries. When very faint the stars are bluer and more polarized, indicating that scattered light by small grains is important (Voshchinnikov *et al.* 1988). A possible cause of the variations is obscuration of the photosphere by dusty accreting material. The interesting periodic star AA Tau may be of this type but apparently has the property that the occulting matter is confined to a warped disk rather than an accretion stream, leading to its periodicity (Bouvier *et al.* 1999, 2003). Alencar *et al.* (2010) have noted a number of AA Tau-like stars in young clusters that may be UXors. The prototype for the class is UX Orionis, hence the name.

The UXors probably represent the only major class of variable stars in which the exact mechanism of variability is still debated. As such they deserve all the observational attention they can get. The long records of the AAVSO are very important for understanding these variables and how they evolve. Since the occulting matter may, in some cases, be solids within protoplanetary disks there may be encoded in the variability information about the early stages of the formation of planets. As is often the case, data on these stars are of considerably more value if they are obtained at more than one wavelength. This allows astronomers to determine the optical properties of the occulting material, in particular whether it is the very small grains characteristic of the interstellar medium or larger solids expected to grow within disks during the first stages of planet formation. Many light curves of UXors can be seen in the paper by Herbst and Shevchenko (1999).

3.4. Large scale eruptive variables (FU Orionis stars): FUors

A few T Tauri stars are known to have gone through substantial eruptive events in which they brighten by several magnitudes and maintain their bright state for months or years. Their prototype is FU Orionis and the class was first proposed and discussed by Herbig (1977). While debate continues about the exact causes of this phenomenon it appears to be related to a rather abrupt increase in the accretion rate (Hartmann and Kenyon 1996). Such eruptive behavior in pre-main sequence stars, if common, could have substantial effects on forming planets, since the increased luminosity of the star would heat disk material well above what would be typical for a non-erupting T Tauri star.

The field of eruptive pre-main sequence stars is one which has benefitted from the participation of amateur astronomers and may continue to do so. Amateur astronomer J. McNeil discovered a new nebula that was produced as a result of a likely FUor outburst in 2004 (McNeil *et al.* 2004; Briceno *et al.* 2004). Regular patrolling observations of star forming regions may reveal such eruptions well before they are noticed by professional astronomers. It is interesting that most, if not all, FUors are found in relatively isolated star forming locales, not within the denser regions of the populous clusters such as the Orion Nebula Cluster, IC 348, and NGC 2264 where many professional survey programs are concentrated. The statistics of the FUor phenomenon are quite uncertain owing to the small number of definitive cases. This makes it difficult to assess how important the phenomenon is to star and planet formation in general.

3.5. Small scale eruptive variables (EX Lupi stars): EXors

Herbig (2007) described the behavior of another rather large amplitude T Tauri variable, EX Lup, and suggested it may represent a class of eruptive variables with similarity to the FUors but on a smaller scale. Unfortunately the class remains rather heterogeneous and ill-defined (Herbig 2008). Presumably these are stars also suffering enhanced accretion events but not to the extent of the FUors. It is unclear at present whether these are just extreme examples of the Type II variability characteristic of most CTTS or represent something distinctly different and perhaps related to the FUor phenomenon. Again, improving the statistics of light curve behavior among these large amplitude CTTS, especially ones that are not concentrated into the massive clusters that professionals prefer to monitor, is a field in which amateur astronomers could make major contributions.

3.6. Periodic variables of KH 15D type

Kearns and Herbst (1998) described a large amplitude, strictly periodic variable now known as KH 15D, in NGC 2264. Its behavior is unique and now understood as arising from a binary T Tauri star with a warped, precessing circumbinary disk (Chiang and Murray-Clay 2004; Winn *et al.* 2004; Hamilton *et al.* 2005). Other large amplitude, strictly periodic variables have been found that may, like KH 15D, be caused by circumstellar matter within a disk periodically occulting a single star or one member of a binary. Possible members of this class include V718 Per (HMW 15) (Grinin *et al.* 2008) and CHS7797 (Ledesma *et al.* 2012). AA Tau (Bouvier *et al.* 1999, 2003) also may meet this definition, perhaps creating a bridge to the aperiodic UXors. In any event, the discovery of additional cases of large amplitude, periodic occultations would be very interesting. Since most of the stars in this class appear to exhibit the periodicity only episodically, this is another area in which careful, long-term monitoring programs such as amateurs can carry out under the auspices of the AAVSO may yield substantial scientific payoffs.

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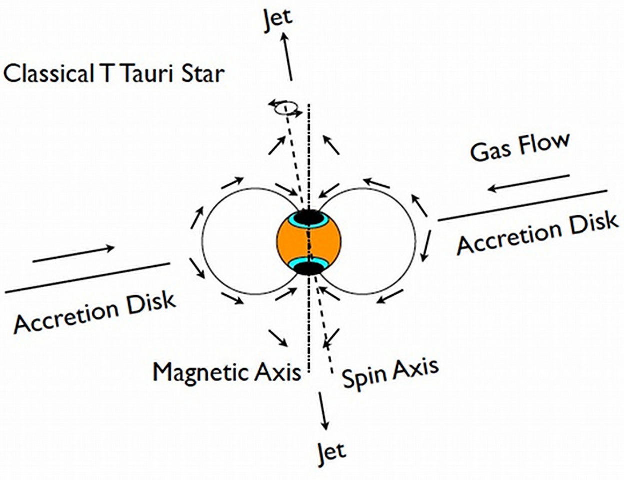

Figure 1. Schematic diagram of a CTTS showing the gas flows through the accretion disk and then into the jet or onto the star near the magnetic pole. The dark spots at the poles result from disruption of convective energy transport by the magnetic field, just like in sunspots. The bright rings around them represent parts of the photosphere heated by the accreting gas and are analogous to auroral rings on Earth. The small misalignment of the rotation and magnetic axes leads to periodic variability of the star as we view different parts of its inhomogeneous surface.

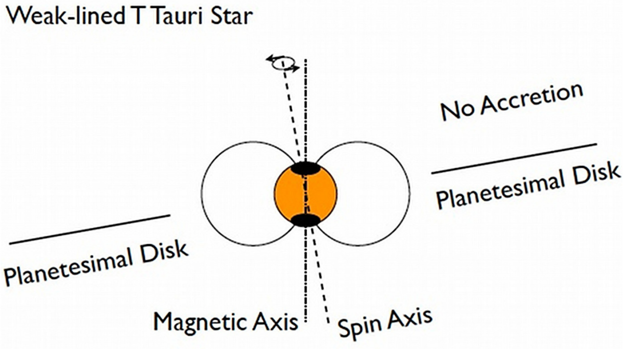

Figure 2. Schematic diagram of a WTTS showing that there is now little, if any, gas flow through the disk or accretion onto the star. Much of the irregular variability therefore disappears in these stars but they continue to show periodic variations of typically 0.1–0.3 mag. caused by the rotation of their spotted surfaces. For WTTS it is often possible to determine their rotation period since the surface spot distributions often remain stable for months or even years.

How Amateurs Can Contribute to the Field of Transiting Exoplanets

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Abstract In 1999 on two evenings in September, the first tell-tale dips of a transiting extrasolar planet passing in front of its star were detected with a 10-centimeter telescope that was set up in a parking lot beside a wooden shed. Although these observations were obtained by professional astronomers, their setup—a modest aperture telescope in an unassuming location—should sound familiar to many enterprising amateur astronomers. What should warm the heart of any amateur astronomer, while they man their telescope alone on a cold winter's eve, or as they gaze at the blinking glare of their computer monitor, is that there are still numerous avenues via which ambitious amateurs can significantly contribute to the evolving story of transiting extrasolar planets (exoplanets). In the brief review below, I'll summarize the current state of the field of transiting exoplanets, and then elucidate the ways that resourceful amateurs—those with and without access to telescopes—can contribute to the field, both in discovering new transiting exoplanets and in characterizing existing ones.

1. Transiting planets: the state of the field

The notion that we might be able to detect planets in other solar systems by the diminution of light when the planet passes in front of the star along our line-of-sight (a so-called transit) is not a new one. Struve (1952) presciently predicted that Jupiter-size planets should create transit dips on the order of a few percent more than half a century ago, and noted that the methods of the day even then were likely sufficient to achieve the precision necessary to detect these dips. The nearly half-century wait until the detection of a transiting exoplanet was not due to a lack of precision from observers, but mostly due to the fact that planetary theorists did not predict how odd the first exoplanets we detected around stars similar to our own would turn out to be. Although, Struve (1952) hypothesized that it might be possible for planets to exist a mere few stellar radii from their host stars, other planetary theorists were not so sanguine; they predicted that extrasolar systems would have orbital configurations similar to our own solar system, with Jupiter-mass planets in orbits of several years or more (Isaacman and Sagan 1977). Thus any aspiring transit observer faced the daunting prospect of hoping to detect a single transit only once every few years. As a result Struve's prescient suggestion remained largely forgotten for decades.

Although the credit for the discovery of the first exoplanet rightly goes to Wolszczan and Frail (1992), for their discovery of what would turn out to be three planets (Wolszczan 1994) in what can only be described as an extreme environment orbiting a millisecond pulsar (a so-called "dead" star that has burned its nuclear fuel and already gone supernova), the true imagination of the scientific community was not excited until the discovery of a planet, 51 Peg b, around a star similar to our own (Mayor and Queloz 1995). This first detection of an exoplanet around a sun-like star, made via the radial velocity (RV) technique, which indirectly reveals the presence of planets by the doppler shift in the stellar lines from the subtle tugging back and forth of the planet on the star, began the trickle that turned into a flood of exoplanet discoveries—at the time of writing the RV technique has confirmed the discovery of ~700 exoplanets in ~550 extrasolar systems (exoplanet.eu; accessed 23 March 2012).

For those of us who would eventually become enamoured with transiting planets, there was something else captivating about 51 Peg b—something that would reinforce the impressive foresight of Struve's (1952) prediction that planets might be able to survive close to their host stars. This planet was not the true Jupiter analog that planetary theorists were expecting, with a few-year orbital period; instead, it was a so-called hot Jupiter—a Jupiter-mass planet orbiting with a period of a mere few days and thus roasting near its star with an equilibrium temperature in excess of ~1000 K. For the subset of planets that transit their host star, this meant that rather than having to wait several years between transits, they would occur every few days. Also, the chance that the planet would actually transit its star would greatly increase for these close-in planets (for a planet to transit, the cosine of the orbital inclination, *cos i*, multiplied by the orbital distance during eclipse (the semi-major axis for a circular orbit), a, must be less than the radius of the star, R_*: $a \sin i < R_*$). The expected fraction of exoplanets that transit their stars is a healthy ~10% for hot Jupiters, and a much smaller fraction for planets of increasing orbital periods. It was this gift from nature—that these hot Jupiter planets exist and can survive, even briefly, roasting next to their host stars—that led to the explosion of interest in using transits to detect exoplanets, and as a result allowed the true potential of Struve's prescient prediction to be achieved.

The transition of this potential into reality started with the first detection of a transiting exoplanet in September 1999. From the unassuming location of a parking lot, using a size of telescope (10-centimeters) that even some amateurs might consider modest, Charbonneau *et al.* (2000) obtained photometry of a known RV-detected hot Jupiter, HD 209458, and observed the characteristic loss of light resulting from the planet transiting across its star (Figure 1; Charbonneau 2001; Jayawardhana 2011. Henry *et al.* 2000 would discover that HD 209458 transits its host star independently). Since that seminal discovery, ~230 planets in ~200 systems have been confirmed to transit their stars, while the Kepler space satellite has identified an additional ~2,300 likely candidates (although many of these systems will remain candidates for the near-term future, because they are not amenable to RV follow-up and confirmation, most of these candidates stand a very good chance of being bona fide planets (Morton and Johnson 2011)) ranging in size from larger than Jupiter to smaller than Earth (Batalha *et al.* 2012). This impressive wealth and diversity in the current sample of known transiting exoplanets offers a compelling opportunity for both professionals and amateurs alike in both adding to the sample by detecting transiting exoplanets especially around bright host stars (section 2), as well as characterizing the atmospheres and orbits of known transiting exoplanets (section 3).

2. How amateurs can assist in detecting new transiting exoplanets

2.1. Searching for transits of known RV detected exoplanets

Excitingly, the very same method that was used to discover the first transiting exoplanet is one that amateurs can continue to use to discover planets. The first transiting exoplanet was discovered by looking at a relatively bright star that was already known from the RV technique to harbor an exoplanet. Not only does the RV technique reveal the period, eccentricity, and the minimum mass of the planet, it also reveals when the planet is expected to pass in front of its star along our line of sight (with an uncertainty of tens of minutes to a few hours in the best cases). Many of these radial velocity stars are relatively bright, and the expected transit depths for giant planets (~1% percent typically) are achievable with modest, CCD-equipped, amateur telescopes from pristine sites. Thus, all that is required is for interested amateur astronomers to be convinced to look at specific stars at specific times and obtain and share the hopefully-resulting high quality light curves. This was exactly the motivation behind one website that is soon to be retired, and another, which is being routinely updated with new RV exoplanet discoveries, that should adroitly take its place. The soon to be retired website is *Transitsearch.org*, which details the following details of known planets detected via the RV method: the Right Ascension, declination, expected transit depth, estimated percentage chance that the planet will actually transit in front of its parent star, and lastly, and most importantly, the ephemerides of the predicted transit window around which interested amateurs are encouraged to search for the tell-tale dip that would indicate that the known RV-detected planet in fact transits its star. Luckily the functionality of *Transitsearch.org* has been included in the NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu/), which should allow interested amateurs to follow up on the latest RV discoveries.

A campaign organized by *Transitsearch.org* was exactly how one of the brightest transiting exoplanets that have been discovered to date was found; HD 17156b (Barbieri *et al.* 2007) was a known RV-detected exoplanet with a period of ~21.2 days and an eccentricity of *e* ~0.67. The orientation of its elliptical orbit compared to the Earth's line-of-sight was fortuitous such that, despite its longer period, it still had a relatively high chance (~13%) of transiting its parent star. Photometry obtained during the predicted transit window by a series of amateurs using telescopes that ranged in size from 0.18 m to 0.40 m revealed a ~1% dip, resulting in the confirmation of one of the brightest transiting planets discovered even to this day. This wasn't *Transitsearch.org*'s only success; another *Transitsearch.org* campaign assisted in the discovery that another bright RV-detected exoplanet (HD 80606b) transited its star (Fossey *et al.* 2009; Moutou *et al.* 2009; Garcia-Melendo and McCullough 2009).

With over ~230 confirmed transiting exoplanets, and Kepler's trove of an additional ~2,300 candidates, an additional transiting exoplanet, even if it is discovered by amateurs, may not seem especially significant. However, this is not the case. It may seem counterintuitive, but it is actually the brightest stars—the ones that amateurs can easily access—that have not been adequately searched by professional astronomers for transiting exoplanets. Many of the existing wide-field, ground-based efforts to detect transiting exoplanets examine fainter stars (V ~8 and fainter) so as to not saturate their detectors, and to allow a great number of stars to be observed simultaneously in the field-of-view of the telescope. However, planets orbiting brighter hosts will always be more favorable for follow-up solely due to the increased number of photons. There are several professional endeavors that seek to fill in this parameter space, by both following up known RV-detected planets—an example is the Transit Ephemeris Refinement and Monitoring Survey (TERMS; Kane *et al.* 2009)—and by searching for transiting planets around relatively bright hosts—examples include the ground-based KELT-survey (Pepper 2007) and the proposed space-based Transiting Exoplanet Survey Satellite (TESS; Ricker *et al.* 2010).

At the current juncture, there still could be at least a handful of RV detected planets that could prove to be a needle of a transiting exoplanet in the haystack of all the RV candidates to date. Even for a dedicated amateur, robustly detecting a 1% transit dip on stars with visual magnitudes on stars as faint as V~8 is not for the faint of heart (Bruce Gary's (2012) *Exoplanet Observing for Amateurs: Second Edition*, which is freely available for download, is an excellent resource that explains the challenges associated with and how to actually achieve such precision; http://brucegary.net/book_EOA/x.htm). However, for the especially dedicated, ambitious amateur, observing from a pristine site with an equally impressive amateur telescope, observing the RV targets listed in the NASA Exoplanet Archive at the specified times may be just the opportunity to add to the short list of RV-detected exoplanets that have been found by amateurs to transit their host stars.

2.2. Planet Hunters

For those amateurs who don't necessarily have access to a telescope, but do have access to a computer, time, and enthusiasm, there is a way they may still discover transiting exoplanets—that way is Planethunters: a citizen science project (http://www.planethunters.org/; Fischer *et al.* 2012) that allows amateurs to seach for planets using data from the Kepler space telescope. NASA's Kepler spacecraft is a 0.95-m telescope in an Earth-trailing orbit (Borucki *et al.* 2011) that is designed to provide ultraprecise photometry of 150,000 stars in a 115-square degree patch of the sky near the constellation of Cygnus; the goal is to discover exoplanets of varying sizes and with periods out to a year, and therefore to determine the frequency of Earth-like planets in the habitable zones of other stars. The Kepler photometry is indeed extremely precise (Borucki *et al.* 2009), but nonetheless it has a variety of noise sources that are both intrinsic (photon-noise), and instrument-related hiccups (systematic errors in astronomy "lingo"); to detect the transits of "wee" planets despite this noise, the Kepler team has developed a variety of algorithms to pick out the tell-tale dips in the light curve. However, those of us who have developed such computer algorithms to accomplish simple tasks know that the human eye and brain are often better at pattern recognition than any algorithm. Thus instead of a single computer algorithm looking for periodic transits in each of the 150,000 light curves that Kepler observed, what if a series of amateurs could be convinced to look at these 150,000 light curves? Would they be able to detect planets that the algorithms had missed? Or possibly, something even more interesting?

Planet Hunters—an interface that allows users to scroll through a great many of the 150,000 Kepler light curves and identify possible transiting exoplanets—was developed to answer this very question. Perhaps, not surprisingly, the answer has turned out to be that indeed a dedicated group of citizen scientists (over 100,000 at last count) can discover transiting exoplanet candidates that Kepler's best algorithms missed on its first pass. At the time of writing, four planetary transiting exoplanetary candidates have been discovered by Planet Hunter collaborators (Lintott *et al.* 2012). It should be acknowledged that these objects are just "candidates" at this present time, which means they have yet to be confirmed as bona fide exoplanets with masses less than the deuterium-burning limit (<13 Jupiter masses). The RV method is one of the most common ways for astronomers to confirm candidates as planets; the candidates discovered to date with Planet Hunters, however, are unsuitable for such follow-up with a signal too small to be realistically detected with our current best RV precision. There thus remains the possibility that these candidates are false positives (one of the most common false positives for transiting exoplanets is an eclipsing binary star blended or diluted by a tertiary or background star along the line of sight). Analytical research, however, has demonstrated that only a slim percentage of Kepler candidates (<5–10%) can be expected to be false positives (Morton and Johnson 2011). For the amateur astronomers volunteering with the

Planet Hunter citizen project, I'm going to guess that having the opportunity to discover a candidate that has a 90 to 95% chance of being an exoplanet, just by sitting down at one's computer, has a pretty sweet ring to it. For those amateurs interested in searching for and possibly detecting an exoplanet, data on new Kepler targets and more data on existing targets are released every few months.

3. How amateurs can assist in the characterization of transiting exoplanets

For the talented and ambitious amateur, observing night after night of potentially flat light curves, and scrutinizing subtle dips that may or may not be due to clouds, seeing variations, and so on (see section 2.1), may not sound particularly appealing. What may sound considerably more attractive is to observe the transits of known transiting exoplanets. Known transiting exoplanets have transit depths up to a few percent of the stellar flux from stars as bright as V~6, with the majority of candidates with V~10 or fainter; thus detecting these transits will still only be accessible to experienced amateurs with modest or larger aperture telescopes with a sensitive camera. While it may be an intriguing challenge in its own right for an amateur to robustly detect the ~1% transit dips of most transiting exoplanets, amateurs may be even more intrigued that professional astronomers frequently use the light curves shared by amateurs to learn a great deal about exoplanets' orbits (section 3.1) and in the future, possibly even their atmospheres (section 3.2).

3.1. Characterization of the orbits of exoplanets

Observing a great number of transits of an exoplanet can be very helpful to professionals to characterize the orbit, and as a result the properties, of a transiting exoplanet. Transit-timing (Holman and Murray 2005; Agol *et al.* 2005) is one such obvious example where astronomers look for small differences in the timing of transits from a strictly periodic orbit that might be the telltale signs of other smaller planets in that system that are gravitationally tugging the known planet back and forth. Other small asymmetries in the light curves that may become apparent after frequent observations include transit-duration or inclination variations that may result from precession, or may be the tell-tale signs of exomoons or starspots. What usually happens in the cases that amateur observations prove to be useful is that after a professional astronomer analyzes their own data, they observe an intriguing hint of one of these aforementioned effects; confirming these effects often requires comparison to a robust archive of transit observations—an archive that is often provided by amateur observers. One such search for transit—more aptly eclipse—timing variations that benefited from access to a robust archive of amateur observations was from my own research.

In Croll *et al.* (2011) I used the mid-transit times from twenty light curves obtained by amateur astronomers to rule out that the hot Jupiter WASP-12b was precessing at a detectable rate. The best-fit RV solution of WASP-12b indicated that, despite its very short orbital period (P ~26 hours), its orbit was mildly eccentric (*e* ~0.05)—that is, its orbit was not perfectly circular, but slightly elliptical in shape. Intriguingly, one of the secondary eclipse times (that is when the planet passes behind its star along our line-of-sight, and we experience a drop in flux due to the loss in light of the planet) for this planet was considerably offset from what one would expect for a circular orbit (Lopez-Morales *et al.* 2010), while another was not (Figure 2 top panel; Campo *et al.* 2011). If this discrepancy was not due to a systematic error or something more interesting, the best explanation for the offset of the times of secondary eclipse of this planet was that its orbit was precessing at a very rapid rate due to the stellar gravitational forces acting on the tidal bulge of the planet. The period of this precession is dependent on what is known as the tidal planetary Love number, k_2, of the orbit, which simply indicates how centrally condensed the planet is—that is, how massive the core of the planet is compared to its outer gaseous layers. For a planet like Jupiter, which has a ~10 Earth-mass core, k_2~0.5, while at the opposite extreme, a uniform density sphere will have a $k_2 = 3/2$ (Ragozzine and Wolf 2009). For the precession rate to be as rapid as these offset eclipse times indicated, the planet would, unexpectedly, have to have a very massive core. The best way to rule out this precession signal was to detect the secondary eclipse of this planet once again, and to determine whether the times were again offset from those of a circular orbit, or whether they fell exactly half an orbit after the transits. The problem was that professional astronomers had only observed a few more transits of this planet, and had not been routinely monitoring the transit, as was necessary to determine if the eclipses fell exactly half an orbit after the transits. Luckily, amateur observers had taken up the slack. By comparing my own observations of the secondary eclipse times of this planet with those published by both professional astronomers and a number of amateur astronomers shared on what is known as the Exoplanet Transit database (ETD; The Exoplanet Transit Database—http://var2.astro.cz/ETD/), I was able to show that the secondary eclipse times fell when we expected them, exactly half an orbit after the transits (Figure 2, bottom panel). This meant that the planet was not precessing at a detectable rate. The professionals and amateurs who shared their observations on the ETD likely had no idea at the time that their observations would eventually be used to elucidate whether we could answer how massive the core is of a gas giant planet ~1,400 light years (Chan *et al.* 2011) away from Earth.

3.2. Characterization of the atmospheres of exoplanets

Transiting exoplanets have been a significant boon to professional astronomers as it has allowed us to probe the atmospheric characteristics of these worlds many light-years from our own. One of the techniques for investigating the atmospheres of these alien planets is known as Transmission Spectroscopy, where one looks for minute transit-depth differences in and out of predicted absorption features from molecules in the atmospheres of these planets. These transit-depth differences result from the fact that the opacity of the planet's atmosphere is greater at the wavelengths of the absorption feature, meaning that the planet actually appears larger, resulting in the planet blocking out a greater fraction of the stellar light and thus having a deeper transit depth. Although the first detection of the atmosphere of an exoplanet used a type of instrument, size of telescope, and observing location not readily accessible to amateurs (Charbonneau *et al.* (2002) used the space-based, 2.4-m aperture Hubble Space Telescope and a spectrograph to disperse light over a narrower spectral range to detect sodium in the atmosphere of HD 209458), more recent detections may fall within the realm that may be accessible to particularly ambitious and technically astute amateurs. The planet HD 189733b orbits a bright host star (V ~6) and appears to display a transit depth that decreases monotonically with wavelength (Sing 2011), likely due to scattering from a haze/cloud layer in the upper atmosphere of that alien world. Although the differences between the transit depth of this planet in B-band (a wavelength of λ ~0.44 µm) and in z-band (l~0.91 µm) is too small (only ~0.05% of the stellar signal) to be currently accessible to amateurs, it is certainly possible that new planets (especially ones with large-scale heights and deep transits) may display larger transit-depth differences across the optical wavelength range. For this reason, avid amateurs and semi-professionals should consider observing transits over a range of wavelengths and publishing these light curves on the ETD. Given the host of complicating factors (starspots, limb-darkening, telluric atmospheric effects, and so on) that may masquerade as a possible signal, amateur observations alone likely won't be sufficient to confirm such a signal. However, an existing trove of precise amateur observations of the transit depths of exoplanets across a wide wavelength range may be just the thing a professional astronomer needs to believe the tentative signal in their own data, and to request higher precision follow-up observations. If helping to answer what gases are in the atmosphere of an alien world, or whether a planet has prominent clouds and/or hazes is of interest, then professional astronomers would certainly appreciate amateurs uploading as many high quality light curves of transits at various wavelengths/filters as possible to the ETD.

4. Concluding thoughts

The field of transiting exoplanets is a relatively new one. From this field's early days, though, the synergy between amateurs and professionals has been particularly potent. Hopefully this review has elucidated the myriad ways that passionate amateurs, whether they own an advanced telescope that is the envy of all their friends at the star party, or they simply have a modest computer and an internet connection, can ensure that this synergy continues in this field for years to come.

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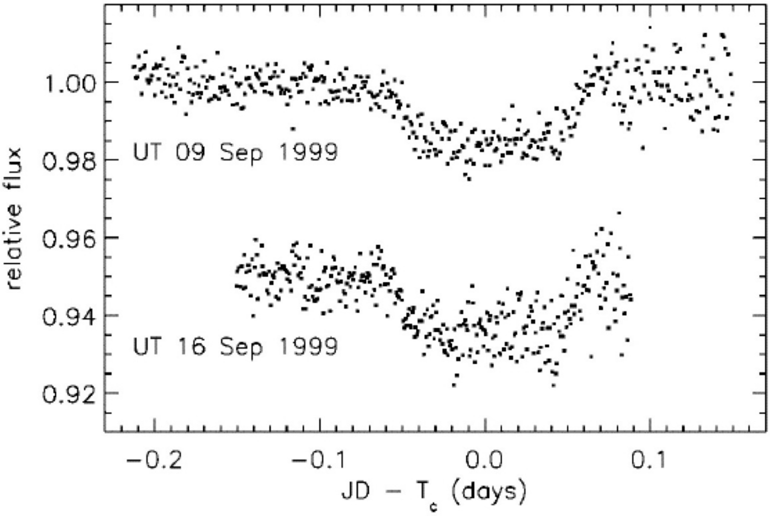

Figure 1. The dip in the light curve at JD – T_c = 0 day, signifies the first detection of the loss of light as a transiting exoplanet passes in front of its star. These observations were obtained with a 10-centimeter telescope set up in a parking lot. Figure obtained from Charbonneau *et al.* (2002).

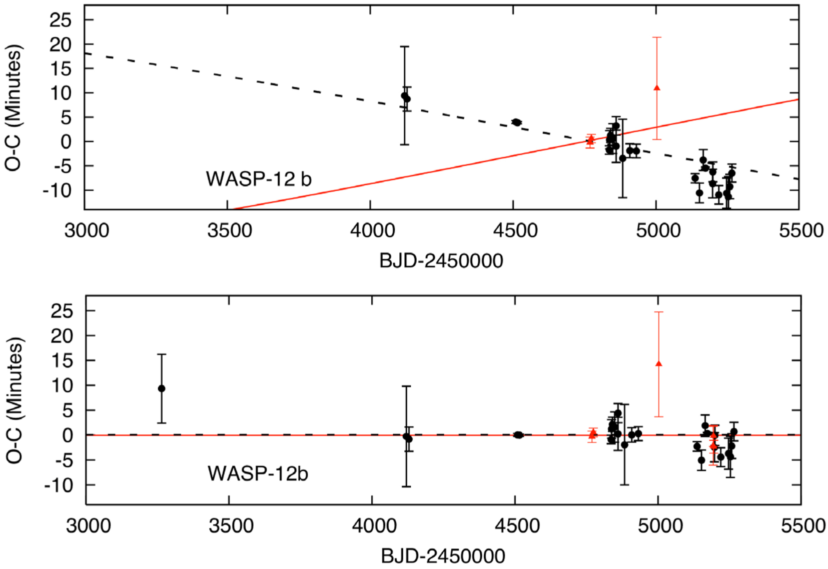

Figure 2. Transit (black points) and eclipse (red points) times of the hot Jupiter WASP-12b. The best-fit precessing model is shown with the dotted black line that indicates the expected transit times, while the solid red line indicates the expected eclipse times. The top panel indicates that a rapidly precessing model was favored before the addition of the Croll *et al.* (2011) eclipse times (bottom panel; red points); by comparing the Croll *et al.* (2011) eclipse times to the transit times of amateurs, it was shown that the planet was not precessing at a rate rapid enough to be currently detectable. Figure adapted from Croll *et al.* (2011).

Eclipsing Binaries in the 21st Century—Opportunities for Amateur Astronomers

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Abstract Eclipsing binaries play major roles in modern astrophysical research. These stars provide fundamental data on the masses, radii, ages, atmospheres, and interiors of stars as well as serving as test beds for stellar structure and evolution models. The study of eclipsing binaries also returns vital information about the formation and evolution of close binaries themselves. Studying the changes in their periods from the observations of eclipse timings provides insights into evolution of close binaries, mass exchange and loss, apsidal motion for eccentric systems, as well as the discovery of the low mass (unseen) third bodies. Moreover eclipsing binaries in clusters and other galaxies can provide accurate distances to the star clusters and galaxies in which they reside. More recently observations of eclipsing exoplanet-star systems (that is, transiting exoplanets) when coupled with spectroscopy are yielding fundamental information about the frequency and the physical properties of planets orbiting other stars. For the reasons discussed above, observations of eclipsing binary systems have been popular for AAVSO observers and many papers have been published (see Williams *et al.* 2012, this volume). A recent example is the highly successful AAVSO's Citizen Sky Project focused on the enigmatic long-period eclipsing binary ε Aur. Building on the success of the AAVSO during the last century, this paper explores the present and future prospects for research in eclipsing binaries. We focus on what can be done by AAVSO members and other amateur astronomers in the study of eclipsing binaries. Several examples of observing strategies and interesting (and scientifically valuable) projects are discussed as well as future prospects. As discussed, there are many opportunities for AAVSO members to contribute to the study of eclipsing binary stars and an increasing variety of objects to observe.

1. Introduction to eclipsing binaries

We can date the beginning of the study of eclipsing binaries (EBs) with the discovery of Algol (β Per) as an eclipsing binary by young "amateur" astronomer John Goodricke in 1783. The importance of eclipsing binaries stems from the fact that photometry and spectroscopy of eclipsing binaries and the analysis of their light and radial velocity curves returns essential information (which often cannot be found by any other means) about the physical characteristics of the stars—such as mass, radius, temperature, and luminosity (see Andersen 1991; Guinan and Engel 2006). Without eclipses most of these parameters could not be determined. These essential quantities are fundamental to the understanding of all stars, as well as to the star clusters and galaxies in which they reside, and to the basic physical laws that govern their behavior. Although the majority of stars in the solar neighborhood are members of binary or multiple star systems, only a tiny fraction (< 0.5%) of these have their orbital planes aligned closely enough to our line of sight that eclipses occur. To date about 15,000 eclipsing binaries have been discovered out of the possible ~100 million or more eclipsing binaries that are expected to be present in our Galaxy. Interestingly, most of these eclipsing binaries were discovered serendipitously in the Large and Small Magellanic Clouds and in the Galactic Bulge from photometric micro-lensing programs such as EROS, MACHO, and OGLE (see Guinan *et al.* 2004).

Nearly every type of star is represented as a member of an eclipsing binary system. These include main-sequence (as well as pre main-sequence) stars, subgiants, giants, and supergiants, with the entire range of spectral types and masses represented. Brown dwarfs, subdwarfs, white dwarfs, neutron stars, and black holes are also found as members of eclipsing binaries. And since 1999 with the discovery of HD 209458 as a short period eclipsing exoplanet system (Charbonneau *et al.* 2000), an increasing number of eclipsing planet-star systems (referred to as transiting exoplanet systems) have been discovered. Many of these systems have multiple planets. At the time of writing (May 2012) there are 2,321 exoplanet candidates, and 690 confirmed exoplanets—totaling about 3,012 possible exoplanets listed on the Kepler Mission web page. For a summary, see http://planetquest.jpl.nasa.gov. The vast majority of these exoplanets were discovered over the last three years from planetary transits in ultra-high precision photometry from the Kepler Mission (see Borucki *et al.* 2011) as well as many exoplanets found from the CoRoT Mission (see http://smsc.cnes.fr/COROT/).

2. Eclipsing binaries as astrophysical laboratories

The information provided by the study of eclipsing binaries quite often transcends the data obtained about stellar masses, radii, and luminosities (important as these quantities are to stellar physics and evolution). Certain types of eclipsing systems have properties that make them well-suited as astrophysical laboratories for the study of many diverse and important problems in modern physics and astronomy. A representative list of the major classes of binaries and the corresponding properties that make them astrophysically interesting is given in Table 1. Eclipsing binaries provide vital information on stellar atmospheres (limb darkening, gravity darkening, and atmospheric eclipse studies), stellar interiors and structure (through apsidal motion studies of eccentric eclipsing binaries), stellar activity and magnetic dynamos (X-ray, *UV*, and radio eclipse mapping of stellar coronae and chromospheres), and plasma physics (binaries with accretion disks). Moreover, there are a small number of systems that are well-suited for testing general relativity through apsidal motion studies. Others can be used for independent determinations of cosmic fractional helium abundances (Y), and some eclipsing binaries can be used to check the importance of convective overshooting in the nuclear cores of stars. For more details see "The Brave New World of Binary Studies" (Guinan and Engle 2006).

3. The study of eclipsing binaries by amateur astronomers—past and future

With the availability of reasonably priced, high quantum-efficiency (>70%) charge-coupled devices (CCDs), it is now possible for amateur astronomers to produce high quality photometry and light curves of relatively faint (~10–18th magnitude) eclipsing binaries with small to moderate aperture (<0.5 m) telescopes. Moreover inexpensive (or free) software is available to reduce and analyze the CCD observations. With modest equipment and a good CCD photometer, the studies of many different kinds of interesting eclipsing binaries are within the reach of many amateur astronomers. These include astrophysically attractive eclipsing binaries (see Table 1) as well as those that are members of open clusters and globular clusters, and even those in some nearby galaxies have become possible (also see section 4 of this paper). Moreover, with CCDs, useful spectroscopy of many brighter eclipsing systems is now being acquired by an increasing number of amateur astronomers. This revolution in technology has led to some changes in the approach to the study of eclipsing binaries by amateur astronomers.

In 1965, an Eclipsing Binary Committee (EBC) was established within the AAVSO. There is an excellent summary paper about the accomplishments of the EBC by Williams *et al.* (2012, this volume) and the wealth of work done by the members of this group. From mostly visual observations, AAVSO observers determined and published ~17,000 eclipse timings, determined periods, and secured light curves of mostly neglected or newly discovered eclipsing systems. They also improved ephemerides and updated periods for many systems. However, in the amateur CCD photometry era (starting in the late 1990s), visual observations of eclipsing binaries have become less important. Because of this, in 2005 the EBC was reconstituted as the Eclipsing Binary Section of the AAVSO and now focuses on mostly CCD photometry. Eclipse timings determined from PEP or CCD measures are the order of ~10 to 100 times more accurate than can be realized from visual timings. Of course, as stated by Williams *et al.* (2012): "When visual eclipse timings were the only data available, they were invaluable." The unique value of visual timings of eclipsing binaries is well illustrated in Figure 1 (from Kreiner *et al.* 2005), which shows the (O–C)-plot of eclipse timings of β Lyr going back to the time of Goodricke. The parabolic nature of the (O–C) values indicates that β Lyr's orbital period is increasing by (a huge) ~19 sec/yr. due to rapid mass exchange and loss.

However, even if visual observations of eclipsing binaries have become less valuable scientifically, watching a star fade by ~1 magnitude or more in a few hours (as in the case of Algol and many other similar systems) remains a thrill!

4. Some examples of observing and research programs of possible interest to amateur astronomers

In the following sections, we have selected several themes from this imposing list of binary studies for expanded development. The choices illustrate some new and exciting things we can learn about eclipsing binaries and that can be done by amateur astronomers.

- *The Pro-Am Cooperation and Collaboration:* Continue to partner with professional astronomers to carry out coordinated photometry and spectroscopy of astrophysically interesting eclipsing binary systems and selected transiting exoplanet systems that are being done (or planned) with space missions such as Kepler, Hubble Space Telescope (HST), Chandra X-ray Observatory, and XMM-Newton X-ray missions and others. Standardized *BVR* observations of X-ray binaries, chromospherically active binaries, and exoplanet systems are vital in correctly interpreting these stars. As in the case of CVs (some of which are eclipsing binaries), AAVSO members have played important roles in the past and will continue to do so. The cooperation between amateur and professional astronomers in the study of CVs is discussed by Szkody and Gaensicke (2012) in this volume. Participation in observing campaigns and Citizen Sky Programs on selected targets such as the recently completed program on the long-period eclipsing binary ε Aur is fun, engaging, and builds a sense of community as well as provides important contributions to Astronomy.

- *Photometry of bright Eclipsing Binaries undergoing rapid evolution:* For those who have photoelectric (PEP) or photodiode photometers, securing modern light curves of many eclipsing systems (brighter than ~5th mag.) is scientifically valuable. With sensitive CCD photometers photometry of bright (often neglected) eclipsing binaries is not practical or even feasible. Many of the brightest prototypical classical eclipsing binaries—such as Algol, β Lyr, U Cep, R Ara, VV Cep, μ Sgr, and many others are worth observing with photoelectric/diode photometers with standard *BVR* filters since in several cases their light curves and orbital periods change with time.

- *Eclipsing Binaries with Changing Eclipse Depths (orbital plane precession):* Photometry of eclipsing binaries that are undergoing rapid changes in their eclipse shapes and depths over time could be another interesting program. Most notable among these are several eclipsing binaries that have apparently stopped eclipsing, such as SS Lac (Torres 2001), QX Cas (Bonaro *et al.* 2009), and SV Gem (Guilbault *et al.* 2001). For QX Cas, Figure 2 shows the changes in the eclipse depths of QX Cas over the last fifty years and Figure 3 shows the derived model of the system depicted at secondary eclipse for these epochs. A recent list of such eclipsing binaries (or former eclipsing binaries) is given by Mayer (2005) and more recently by Zasche and Paschke (2012). Eclipsing binaries that have apparently stopped eclipsing include QX Cas, SV Cen, SV Gem, AY Mus, and SS Lac, while those whose eclipse depths are changing include IU Aur, V685 Cen, AH Cep,V699 Cyg, HS Hya, RW Per, V907 Sco, and possibly even Algol. The cause of these light curve variations, including the cessation of eclipses, is best explained from the precession of their orbital planes (that is, change of the inclination of their orbits) arising from the gravitational effects of a third star. The recent study of HS Hya by Zasche and Paschke (2012) indicates that its eclipses are becoming very shallow and that this would be an excellent star to observe as soon as possible. Also it would be worthwhile to secure photometry of the above systems to search for changes in their light curves (that is, eclipse depths). For example, the depth of the primary eclipse of Algol has not been checked for several years and this could also be a good project.

- *Coordinated* BVR *photometry of Eclipsing Binaries discovered by the Kepler Mission:* An interesting and important program would be to carry out coordinated CCD observations of interesting (and unusual) eclipsing binaries discovered recently by the Kepler Mission (see Prša *et al.* 2011; Slawson *et al.* 2011). Kepler returns exquisite ultra-high precision photometry and beautiful light curves but the photometry is essentially unfiltered, covering a very broad wavelength range. Standardized *BVR* photometry (even though much less precise than returned by Kepler) of selected ~10–14th magnitude Kepler eclipsing binaries would be very useful to help to better define the physical properties of the stars—especially the stars' temperatures. Systems with deep eclipses, or eccentric orbits, or with pulsating components, as well as those with changing light curves from the Kepler Mission sample of nearly 2,200 stars are the most compelling to observe. Carrying out photometry during the eclipses with multiband photometry is particularly valuable. It should be noted that the ultra-high precision photometry from Kepler on these stars (and ~150,000 others) is available for study from NASA's Mikulski Archive for Space Telescopes (MAST) website at http://archive.stsci.edu. The instructions for downloading, plotting, and analyzing these exquisite data are also available at the MAST site or can be found at the Kepler Mission website. This is worth taking a look at on cloudy nights. Programs for analyzing light curves of eclipsing binaries are discussed later in the paper.

- *Supporting* BVR *photometry (and Spectroscopy) for the BRITE-Constellation Mission:* An interesting program suitable for amateurs would be to carry out standardized photoelectric (PEP) or photodiode *BVR* photometry of bright eclipsing binaries that will be monitored by the BRITE-Constellation Mission starting this year. The BRITE-Constellation Mission is a planned network of up to six Nano-satellites designed to carry out filtered time-series photometry of the brightest stars in the sky (down to ~4th mag.). Each will fly a small-aperture telescope (3 cm) with a CCD camera to perform high-precision filtered (one filter designated for each instrument) photometry of the brightest stars in the sky (< 4th mag.) continuously for up to several years. These Nano-satellites are 20-cm cubes and each "orbiting camera" has a field of view of ~24 degrees. The first two of these satellites are expected to be launched during 2012. The BRITE Mission research team would be interested in collaborations with amateurs to carry out coordinated photometry (or better yet spectroscopy) of BRITE targets when these stars are being observed by the mission. This could be an interesting project—see BRITE (http://www.brite-constellation.at/).

5. Data mining: "observing" without a telescope—exploiting archival eclipsing binaries

As discussed previously (in the case of the Kepler Mission), there are large photometric data sets on variable stars, including eclipsing binaries, that are available over the internet. These archival data can be used directly or to supplement photometry for the study of eclipsing binaries. For example, photometry from early micro-lensing programs such as EROS, MACHO, and OGLE are available over the internet. These programs operated during the 1990s and serendipitously discovered thousands of relatively faint (fainter than 14th magnitude) eclipsing binaries in the Large and Small Magellanic Clouds, and also in the direction of the center of our Galaxy in the Galactic Bulge region. Data from these programs are available over the internet but much of this photometry has been exploited and published. However, some astronomical nuggets could turn up with deeper data mining.

The All Sky Automated Survey (ASAS) is a Polish project started in 1997 as a follow-up to the successful OGLE program. But unlike the previous survey programs, the ASAS program is devoted to the study of variable stars. It is a wide field ($4 \times 4°$ per pointing) photometric monitoring program to observe ~18 million stars south of declination +28° and brighter than ~14th magnitude. This highly successful variable star discovery and monitoring program uncovered over 50,000 variable stars including many eclipsing binaries (~80% of which are new variables). The photometry from ASAS is available over the internet (see: http://www.astrouw.edu.pl/asas/). Recently ASAS-North started operations so that photometry from that program may also soon be available.

In the near future, hundreds of thousands (possibly millions) of additional eclipsing system are expected to be discovered by Pan-STARRS, the Large Synoptic Survey Telescopes (LSST), and from space with the ESA Gaia Mission. Gaia has a billion-pixel CCD array that will measure positions and fluxes (magnitudes) for over one billion stars and galaxies (see http://gaia.esa.int/ for more information). Gaia is planned to be launched during 2013. Also, there are several transit planet search missions being carried out with networks of small telescopes. In addition to discovering exoplanet transit systems, they are also returning photometry for eclipsing binary stars. A partial list of some of these planet-search programs include: HATNet, MEarth, SuperWASP, and several others. And last but not least is AAVSOnet—a network of robotic photometric telescopes being developed by Arne Henden for use by AAVSO members and others to carry out photometry of variable stars (see http://www.aavso.org/aavsonet). AAVSOnet can be used free-of-charge by AAVSO members to carry out photometry of specific (~9–15th mag.) eclipsing binary systems (among other targets).

To help cope with the expected deluge of data (petabytes) in the near future from these programs, we are developing a Neural Network (NN) Artificial Intelligence (AI) based program to help to automatically analyze the light curves of tens of thousands of eclipsing binaries (see Prša *et al.* 2008; Guinan *et al.* 2009). More information can be found at the PHOEBE or EBAI websites.

6. Examples of useful programs and software for work on eclipsing binaries

Several examples of programs and software available for the study of eclipsing binaries are given below. These programs and websites are useful for modeling the light curves of eclipsing binaries and also to visualize most types of eclipsing binaries. Several additional programs (and software) are available over the internet.

PHOEBE (PHysics Of Eclipsing Binaries) is an excellent free downloadable astronomical software that permits the modeling of eclipsing binaries (EBs) based on real photometric and spectroscopic (radial velocity) data. It is based on the Wilson-Devinney code (Linux or Unix based). The software is highly recommended. The PHOEBE homepage is located at: http://phoebe.fiz.uni-lj.si. The contact person for PHOEBE is Dr. Andrej Prša.

BINARY MAKER 3 is commercial software (cost ~100 USD) that accurately calculates light and radial velocity curves for almost any type of binary, simultaneously displaying the theoretical and observed curves as well as a 3-D model of the orbiting stars. Professional-quality PostScript output can be created of all the major displays. The program comes complete with an extensive User Manual on a CD as well as a very complete Help System which not only explains how to use the program but also gives details on how to analyze eclipsing binary light curves. Individual displays can be customized and saved to meet the user's needs. Star spot modeling, eccentric orbits, and asynchronously rotating stars can also be accurately modeled (www.binarymaker.com).

STARLIGHT PRO produces animations of eclipsing binary stars and generates synthetic light curves. The effects of limb darkening, temperature, inclination, stellar size, mass ratio, and star shape are included. There is a free download for Windows (see http://www.midnightkite.com/index.aspx?URL=Binary for more information) .

NIGHTFALL eclipsing binary star program is online software that can be used to produce animated views of eclipsing binary stars, calculate synthetic light curves and radial velocity curves, and eventually determine the best-fit model for a given set of observational data of an eclipsing binary star system (Linux or Unix based: www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html).

ECLIPSING BINARY SIMULATOR (EBS) is a Window-based astronomy application to visualize the orbit and synthetic light curve of binary star systems. EBS was mainly developed for educational purposes and visualization of different types of eclipsing binary systems. This is an easy application to use to pass time on cloudy nights (see: http://astro.unl.edu/naap/ebs/anima).

7. Conclusions and future projections

Since the discovery of the first eclipsing binary system nearly 230 years ago by John Goodricke, these fascinating stars (and stars with transiting planets) have played important roles in the development of Astronomy. The availability of sensitive CCDs, photometric reduction and analysis programs, and reasonably priced telescopes has created a revolution, making it possible for motivated amateur astronomers to make significant contributions to this field. Moreover, CCDs, when coupled with commercially available spectrographs, also now make it possible to conduct useful spectroscopy of the brighter stars even with small telescopes.

Also past, present, and future wide-field photometry programs are providing (or will soon provide) the ever-expanding datasets on eclipsing binary stars in the Milky Way Galaxy and beyond. It is expected that over one million eclipsing binaries will be discovered within the next decade by these programs. It is hoped that important contributions will continue to be made by amateur astronomers in the exciting field of eclipsing binaries. It should be noted that many amateur astronomers today have more powerful equipment and telescopes (some completely robotic) than most professional astronomers had access to as recently as a few decades ago. So go for it and enjoy the ride! (and the eclipses!).

8. Acknowledgements

The authors acknowledge the hard work and efforts made over the last century (and up to the present) of the avid AAVSO, and other, amateur observers of eclipsing binary systems. Many have spent cold nights securing light curves or eclipse timings to improve orbital periods and study changes in periods. The authors wish to acknowledge support of grants from NASA and NSF for this study. We also thank the editors of this special AAVSO centennial volume for the work put in producing a fine compilation of papers. Also we wish to thank them for their patience and understanding for the late submission of this paper.

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Table 1. Binary systems as astrophysical laboratories.

Type of system	*Properties*
Detached eclipsing systems: both components located within their Roche lobes; form the backbone for the Mass-Luminosity Law.	Masses, radii, luminosities, and densities of stars; checks on stellar evolution; fundamental properties and precise distances.
Eclisping binaries with pulsating components (such as δ Sct, β Cep, γ Dor variables, and Cepheids). Examples: δ Cap, RZ Cas, R CMa....	Permits the measurement of radii, masses, densities, age, and evolution of the pulsating components. Calibration of age-mass for astereoseismology studies.
Eclipsing binaries with eccentric orbits: apsidal motion studies—internal structure of stars / tests of General Relativity in a few cases. Also "Heart Beat" Stars—induced pulsations near orbital periastron observed from Kepler data. A possible bright "Heart-beat" binary is μ Sgr.	Apsidal motion—stellar structure and interiors; gravitationally induced pulsations; several systems provide tests of general relativity. "Heart beat" binaries can provide probes of the internal structure of stars.
Chromospherically active binaries: RS CVn, BY Dra, and related systems.	Magnetic activity; star spots, chromospheric and coronal emissions; "solar-stellar connection."
Semi-detached systems: Algol-type binaries; W Ser and β Lyr—mass exchanging / losing systems.	Stellar and binary star evolution; mass exchange and loss; accretion processes; enrichment of ISM from mass loss.
Contact Binaries: a) Cool: W UMa-type systems (W UMa, VW Cep….); b) W-type / A-type systems (AW UMa).	Stellar activity and magnetism; binary star evolution; angular momentum loss; binary star coalescence from studies of long-term changes in orbital periods.
Hot contact systems: AO Cas-type systems; Wolf-Rayet (WR) binaries (e.g. V444 Cyg).	Binary star evolution and dynamics; interacting winds; mass loss (chemical enrichment of ISM).

Table 1 continued on following pages

Table 1. Binary systems as astrophysical laboratories, cont.

Type of system	*Properties*
Near Contact Systems (NCBs): V1010 Oph-type and FO Vir-type systems.	Stellar evolution; mass transfer and loss; magnetic activity in systems with cool components; marginal contact systems. Light curves change with time.
ζ Aur and VV Cep Systems: Long period interacting supergiants systems and ε Aur; supergiant + large disk (see recent AAVSO Citizen Sky Project).	Properties of evolved supergiant stars: masses, radii and atmospheric structure (from atmospheric eclipses) of evolved stars; mass loss rates; accretion processes.
Cataclysmic variables (CV) and nova-like (NL) binaries: (see Szkody and Gaensicke 2012, this volume).	Masses of white dwarf stars; accretion/accretion disks; accretion and plasma physics; angular momentum loss from magnetic braking and relativistic effects.
X-ray binaries with neutron star and black hole components: Low mass X-ray binaries (LMXBs) with neutron stars and high mass X-ray binaries (HMXBs) with mostly black hole components and related systems.	Properties of neutron stars; accretion; physics of hot plasmas and magnetic fields; black holes (e.g. Cyg X-1, CAL 87, V404 Cyg, Cir X-1).
Planet-star systems (transiting exoplanets); HD 209458 / hot Jupiter transiting exoplanets; over 690 verified systems from radial velocity and transits studies.	Properties of exoplanets (mass, radii, and densities); frequency of exoplanets; discovery of Earth-size planets from transits from Kepler and CoRoT Missions (3,100+ verified and exoplanet candidates).
Symbiotic Binaries: (M III + wd); long period binaries (examples of eclipsing symbiotic variable include CH Cyg, AR Pav, and V1413 Aql).	Wind accretion and mass loss rates from red giants; plasma physics. Some with high mass white dwarfs could be SN Ia progenitors.

Table 1 continued on next page

Table 1. Binary systems as astrophysical laboratories, cont.

Type of system	*Properties*
Eclipsing binaries displaying rapid changes in their light curves: 1. Evolutionary changes/mass loss/mass exchange (e.g. W Ser, β Lyr, R Ara…). 2. Changes in eclipse depths from variations in their orbital inclinations as viewed from Earth (examples: SS Lac, SV Gem, and QX Cas, have stopped eclipsing. 3. Varying star spot coverage and star spot cycles; RS CVn and related stars.	1. Test beds for stellar and binary star evolution. Studies of mass exchange and mass loss. 2. Dynamical test beds for effects of tertiary companions on the orbits of the close eclipsing binary. The third body causes the orbit to precess. 3. Study star spot properties and motions including differential rotation and also possible star spot cycles. Use eclipses to map star's surface.
Post common envelope binaries: main-sequence star + white dwarf systems: V471 Tau; Binary Nuclei of Planetary Nebulae; Pre-CV systems and double degenerate short period systems.	Common envelope evolution; mass loss / chemical enrichment of ISM / subdwarfs / white dwarf. Double-degenerate (D-D) systems are important to study but are faint and need high speed photometry. The more massive D-D systems are candidates for Type-Ia Supernovae.

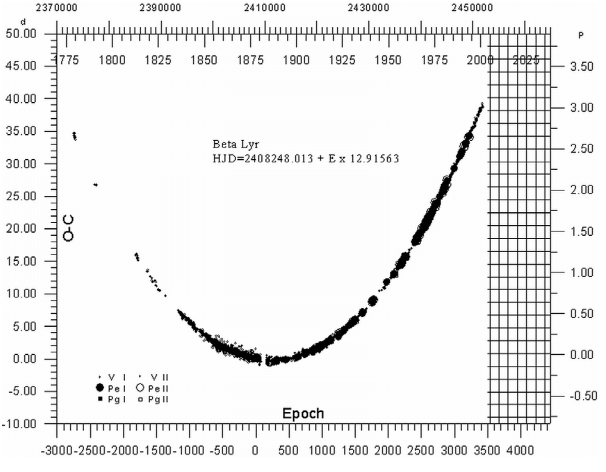

Figure 1. The O–C plot for β Lyr eclipse timings, including AAVSO data, from Kreiner *et al.* (2005). The orbital period is found to be increasing by ~19 sec/year due to rapid mass exchange and loss. The amount of mass being transferred between the two stars (or lost) is ~ 2 × 10^{-5} solar masses per year, or the equivalent of the Sun's mass every ~50,000 years.

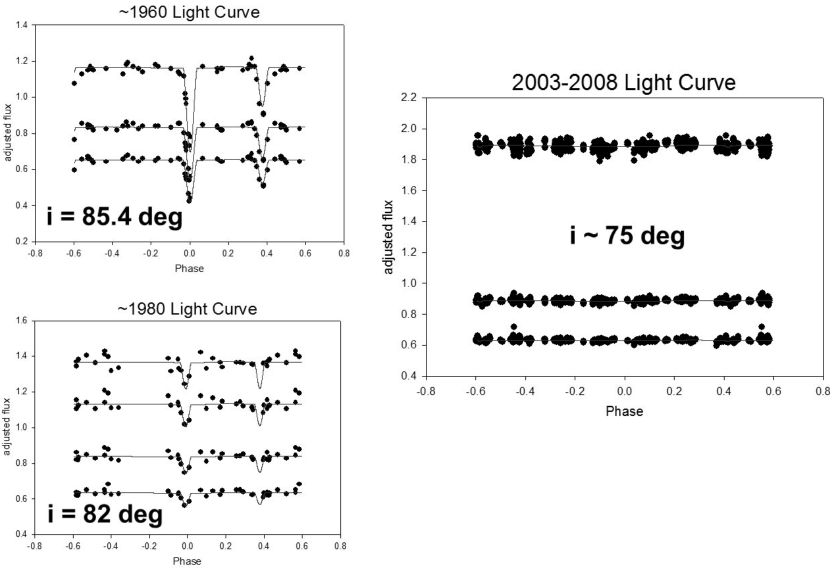

Figure 2. QX Cas light curves and PHOEBE model fits, showing changes in the orbital inclination. The epoch ~1960 UBV photometry is from Sandage and Tammann (1969) and the epoch ~1980 UBVR photometry is from Moffett and Barnes (1983); the 2003–2008 photometry was secured with the Four College Automatic Photoelectric Telescope by the authors. The photoelectric UBV and UBVR light curves of QX Cas (V ~ 10.5 mag; P = 6.007 days; e = 0.21) are shown for three observing epochs. Analyses of the light curves were carried out using the PHOEBE program and the best model fits are plotted among the data. No eclipses are evident from photometry secured after 2003 (even during the mid-1990s photometry of QX Cas from Arne Henden shows no evidence of eclipses). The resulting orbital inclinations are shown in the plots. The light curve analysis shows that QX Cas consists of B1.5 V and B3 IV stars with masses of $M_1 \sim 5.5\ M_\odot$ and $M_2 = 6.5\ M_\odot$, respectively and fractional radii (R/a) = 0.11 and 0.16. QX Cas is a member of the young open cluster NGC 7790 at an estimated distance of 3.3 kpc. Solutions adopted from Bonaro *et al.* 2009.

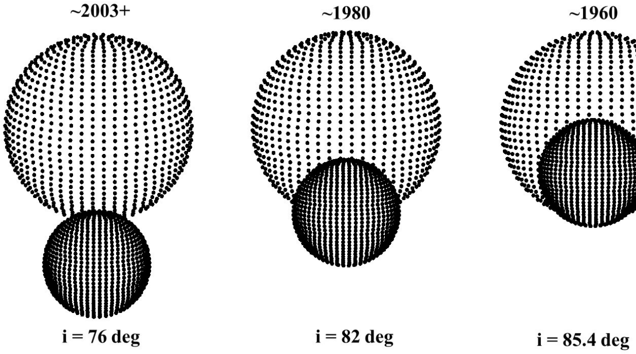

Figure 3. The models of the eclipsing binary QX Cas are shown at secondary eclipse. The relative sizes of the stars and orbital inclinations are derived from the analysis of the available photoelectric light curves using PHOEBE. As shown, the orbital inclination decreases from i ~85.4° during ~1960 to i ~76° from 2003 onward (from the analysis of the Villanova photometry).

RR Lyrae Stars: Cosmic Lighthouses With a Twist

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Abstract Since their discovery over a century ago, RR Lyrae stars have proven to be valuable objects for the entire field of astrophysics. They are used as standard candles and witnesses of galactic evolution. Though the pulsations that cause their light variations are dominated by relatively “simple” radial modes, some aspects of RR Lyrae pulsation remain enigmatic. Besides the visual, photographic, and photometric observations of these stars that span several decades, spectroscopic data provide an in-depth view on the pulsations. In the past decade, particularly since the launch of the satellite missions with asteroseismology as part of their program (for example, MOST, CoRoT, and Kepler), several findings have helped us better understand the structure and pulsations of RR Lyrae stars. Nevertheless, ground-based observations and long-term monitoring of RR Lyrae stars, as done by the AAVSO members, remain of utmost importance.

1. A century of RR Lyrae studies

The story of the discovery of the RR Lyrae stars starts at the end of the 19th century with the globular cluster studies initiated by Harvard astronomer Solon I. Bailey, rendering many variable stars. Those variables that were seen in large numbers, with short periods of under a day and photographic amplitudes of about one magnitude, were called cluster variables. Soon thereafter, similar variables were found in the field. Initially, the “cluster variables” were put in the same basket as the Cepheids because of the similarities in their light curves. When it was recognized that there are notable differences between the two types of stars (period, location, population type, kinematical properties), RR Lyrae itself, the brightest field star of this type discovered by Williamina Fleming in 1899, became the eponym of the class.

Both Cepheids and RR Lyraes were first thought to be variable due to a binary nature. The foundations for stellar pulsation theory that explains the light variations in RR Lyrae stars were laid by Eddington (1926).

2. What are they and why do we care about them?

RR Lyrae stars are pulsating low-mass stars that have evolved away from the main sequence and are burning Helium in their core. In the Hertzsprung-Russell diagram (HRD) they are located on the horizontal branch and its intersection with the so-called instability strip (see Figure 1). In this strip, crossing the HR diagram nearly vertically, pulsations are driven by the kappa (κ) mechanism. Kappa stands for the opacity of a stellar layer, its capacity to block incoming radiation. In most of the inside of stars, the opacity of stellar gas decreases as its temperature increases. However, there are some regions where this tendency gets weak, or even reversed. For example, in the hydrogen and helium partial ionization zones, connected to specific temperatures, the opacity increases as the temperature increases, that is, with compression. These zones, especially the helium partial ionization zones, are considered to be the regions for pulsation excitation in classical Cepheids and RR Lyrae stars. At compression, ionized material increases the opacity and the layer is pushed upwards by radiation pressure. When the layer moves up and reaches lower temperatures, recombination happens, the opacity decreases, the layer falls back, and the cycle is repeated. In order to be efficient drivers of pulsation, these partial ionization zones should be located at a critical depth in the star. For this, a suitable combination of stellar properties is needed, which is why the κ mechanism driven pulsations are confined to specific regions in the HRD, such as the instability strip.

RR Lyrae stars have typical periods of ~0.2 to ~1 day, amplitudes in the optical of 0.3 up to 2 magnitudes, and spectral types of A2 to F6. Most of them pulsate in the radial fundamental mode (called Bailey type RRab stars), the radial first overtone (Bailey type RRc stars), and, in some cases, in both modes simultaneously (RRd stars), see Figure 2. Type RRab stars have the larger light curve amplitudes (around 1 magnitude) and longer periods (~0.35–1 day); type RRc stars generally have more sinusoidal light curves with lower amplitudes (around 0.5 magnitude) and shorter periods (~0.2–0.45 day), though the period ranges overlap. The RRd stars pulsate in both radial modes simultaneously and hence have more complex light curves.

Since the large scale surveys and the satellite missions, higher-order radial overtone modes have been detected in RR Lyrae stars (Olech and Moskalik 2009; Benkő *et al.* 2010).

As the RR Lyrae stars are indeed occupying a small range in *V* magnitude on the horizontal branch (see Smith 1995), they qualify as excellent distance indicators. When we know their luminosity or absolute magnitude, this can be of great help in estimating the distances (and hence the ages) of globular clusters, and to galactic and extragalactic (local group) locations. Moreover, as an old stellar population and found in large numbers, the RR Lyrae stars can be used as witnesses of chemical and dynamical galactic evolution.

They also serve as test objects for low-mass stellar evolution and radial pulsation theory.

A frequency spectrum of an RR Lyrae star will typically show the main pulsation frequency (corresponding to the radial fundamental mode or the first overtone) as well as its harmonics (double, triple, quadruple frequency, and so on). Especially for the RRab stars, pulsating with higher amplitudes reflected in their non-sinusoidal light curves, the harmonics will be very prominent.

3. So we know what they are all about?

Despite their numerous applications in various fields of astrophysics, several aspects of RR Lyrae pulsation remain not fully understood.

One not completely resolved issue concerns the *Oosterhoff dichotomy* (Oosterhoff 1939). RR Lyrae-rich globular clusters can be divided into two groups on the basis of the properties of their RR Lyrae stars. Oosterhoff type I clusters, such as M3 and M5, contain many more RRab stars than RRc stars. The mean periods of both types of pulsators are 0.55 day for RRab stars and 0.32 day for RRc stars, respectively. Oosterhoff type II clusters, such as ω Cen, M15, and M53 have more nearly equal numbers of RRab and RRc stars and longer mean periods of 0.64 day and 0.37 day, respectively. There is a correlation with metallicity: Oosterhoff type II are more metal-poor than their Oosterhoff type I counterparts.

The most popular theoretical explanation for this phenomenon relies on a so-called "hysteresis mechanism" (van Albada and Baker 1973). There is an "either-or" region in the middle of the RR Lyrae instability strip where the pulsation mode is determined by the star's previous evolutionary path. RR Lyrae stars in Oosterhoff type II clusters are evolved from a position on the blue horizontal branch, whereas those in Oosterhoff type I globulars contain a mix of evolved and unevolved stars.

The existence of the Oosterhoff gap at $< P_{ab} > = 0.60$ day, among the halo clusters, and its absence among the galaxy's satellite systems, indicates that the halo could not have been built through the merger of systems exactly like the early counterparts of the Milky Way's current satellite galaxies (Catelan 2006).

I will now focus on one of the most stubborn and long-standing mysteries in stellar pulsation theory, the so-called *Blazhko effect*, since it is a phenomenon that observers of RR Lyrae stars are likely to encounter.

In 1907, Sergei Nicolaevich Blazhko reported on the periodic variations in the timing of maximum light for the star RW Dra (Blazhko 1907). Soon after that, it was realized that other, similar stars showed modulations of their light curve shape over time scales of weeks or even months. In 1916 Harlow Shapley reported on the changes in the spectrum, period, and light curve of the prototype RR Lyr itself. The Blazhko effect, as this periodic amplitude and phase modulation is called nowadays, turned out to be rather common in

RR Lyrae stars. Previously reported galactic occurrence rates were 20–30% for Galactic RRab stars and a few percent for RRc stars (Szeidl 1988), and somewhat lower in the LMC: 12% RRab and 4% RRc (Alcock *et al.* 2000, 2003). The most recent surveys, however, both from the ground (Jurcsik *et al.* 2009b) and from space (Szabó *et al.* 2009; Benkő *et al.* 2010), seem to indicate that close to 50% of the fundamental mode RR Lyrae pulsators show the Blazhko effect (Figure 3).

In the frequency spectra of Blazhko stars we will see multiplets with equidistant spacing (equal to the Blazhko frequency) around the main frequency and its harmonics (some schematic examples are shown in Figure 4). These reflect the amplitude and phase modulation happening in the star (see also Benkő *et al.* 2011).

After several decades of dedicated studies of Blazhko stars, a variety of behavior is observed in these stars: changing Blazhko cycles, additional longer cycles, multiple modulation periods, complex multiplet structures in the frequency spectra, additional frequencies corresponding to higher overtone modes.

3.1. Multicolor data and spectroscopy

Early studies of RR Lyrae variables, including Blazhko variables, were based on photographic and photometric data of the stars, often focusing around maximum light for the purpose of O–C (“observed minus calculated,” comparing expected with observed times of maximum light). From complete light curves of the stars we can get much more information on their pulsation properties.

For a real in-depth study of RR Lyrae stars, however, multicolor and spectroscopic data are the way forward.

Approaches to derive atmospheric parameters of RR Lyrae stars through multicolor photometry and/or spectroscopy, such as applied by De Boer and Maintz (2010), Sódor *et al.* (2009), Kolenberg *et al.* (2010a), and For *et al.* (2011), allow us to connect the complex atmospheric variations with the pulsation patterns, and even their modulations.

Sódor *et al.* (2009) devised an inverse photometric Baade-Wesselink method for determining physical parameters of RRab variables exclusively from multicolor light curves. Its application to the Blazhko star MW Lyr (Jurcsik *et al.* 2009a) shows how the mean global parameters, such as the radius, luminosity, and surface effective temperature of a modulated star vary over the Blazhko cycle. As a consequence, the instantaneous period varies over the Blazhko cycle. This modulation of the stellar parameters throughout the modulation is a very important result for the further development of Blazhko models.

RR Lyrae stars have rather tumultuous atmospheres due to high pulsation velocities in the outer layers of the star. This gives rise to shock waves in particular pulsation phases, reflected in spectral line broadening and doubling

(Gillet and Crowe 1988). Moreover, there is a gradient in velocity between different layers in the star, the so-called Van Hoof effect (Mathias *et al.* 1995).

In addition, new and exciting findings such as the occurrence of Helium emission (Preston 2009) and neutral line disappearance (Chadid *et al.* 2008) would be very interesting to study as a function of the Blazhko phase. These methods, and their extensions, in combination with high-precision and/or long-term photometric data, allow us to perform (literally) in-depth studies of the Blazhko phenomenon. As pointed out by Kovács (2009), accurate time-series spectral line analysis is needed to reveal any possible non-radial components.

3.2. Models for modulation

More than a century after the discovery of the Blazhko effect, we still are at a loss for a definitive explanation. But we are narrowing down the possibilities.

Until recently, the nonradial resonance model (Van Hoolst *et al.* 1998; Dziembowski and Mizerski 2004, and references therein) and the magnetic model (Shibahashi and Takata 1995; Shibahashi 2000, and references therein) were most commonly quoted. They both rely on the excitation of nonradial pulsation mode components in the modulated star, and state a connection between the modulation period and the rotation period. They provide predictions for the appearance of the Fourier spectra of modulated stars. The magnetic model for the Blazhko effect received some blows when spectropolarimetric observations indicated that a strong kiloGauss-order dipole field, a premise in the model (Shibahashi 2000), is not present in the prototype RR Lyr (Chadid *et al.* 2004) nor in a sample of seventeen selected modulated and non-modulated RR Lyrae stars (Kolenberg and Bagnulo 2009).

As neither of both models could explain the variety of observed behavior in Blazhko stars, an alternative idea was (re-)proposed by Stothers (2006, 2010). In this scenario, the amplitude and phase (period) modulation is caused by the cyclical weakening and strengthening of the convective turbulence in the star. The variations in convective turbulence can be caused by a transient magnetic field in the star. The presence of such a field, however, would be very hard to demonstrate. What makes the Stothers (2006) idea attractive is that it does not require the presence of nonradial modes, nor a clockwork regularity in the Blazhko cycles. Also, the variations of the mean parameters of the star, as mentioned above, are a consequence of the modulation of turbulent convection in this model. The Stothers model was recently challenged by the findings by Molnár and Kolláth (2010) and Smolec *et al.* (2011) that the modulation of the convective strength should be unphysically large to cause the observed modulation.

The latest development in the models for the Blazhko effect were triggered by uninterrupted, high-precision observations of Blazhko stars, as described in the next section.

4. Progress: expected and serendipitous

Several space telescopes have asteroseismology (or the study of pulsating stars) as an important part (or prime by-product) of their mission and have performed high-precision observations of RR Lyrae stars: the Canadian suitcase-sized MOST telescope (Gruberbauer *et al.* 2007), the French-led ESA space mission CoRoT (Chadid *et al.* 2010), and NASA's Kepler mission (Kolenberg *et al.* 2010b). These space missions deliver high-precision data and are not disturbed by daily and weather gaps, typical for Earth-based observations.

The new data on Blazhko stars reveal complex multiplet structures in the Fourier spectra and additional frequency peaks of which some can be explained in terms of radial overtones, and others not (Chadid *et al.* 2010, Benkő *et al.* 2010). The Kepler data allow us to find the smallest detectable amplitude and phase modulation values. However, still about half of the RR Lyrae stars do turn out to be unmodulated (see, for example, Nemec *et al.* 2011).

By a fortunate coincidence, the star RR Lyr itself, the prototype of the class and a Blazhko variable studied for over a century, is located in the Kepler field. Though initially thought to be too bright to be observed successfully with Kepler, the flux of the star can be recovered thanks to a custom aperture especially devised for the star (Kolenberg *et al.* 2011). In RR Lyr we detected a new phenomenon, reflected in alternatingly high and low maxima (Kolenberg *et al.* 2010b). This effect can be rather large, regularly 0.05 magnitude in RR Lyr. In the frequency spectrum, these variations with the double period result in the appearance of so-called half-integer frequencies. This phenomenon, called period doubling, was reported in models of Cepheids, stars that undergo radial pulsations just like RR Lyrae stars (Moskalik and Buchler 1990). It had, however, never been observed before in observational data of Cepheids or RR Lyrae stars. Szabó *et al.* (2010) find that a 9:2 resonance between the fundamental radial mode and the 9th overtone might be responsible for period doubling. The fact that period doubling was also found in a few other Blazhko stars, and not in non-modulated stars, revealed a possible connection between period doubling and modulation (Figure 5).

Period doubling does not occur at all phases in the Blazhko cycle. It can be very obvious in some phases, and invisible in others. And just like sometimes there is no strict repetition from one Blazhko cycle to the next, period doubling does not repeat in the same Blazhko phases for consecutive cycles.

Why was period doubling not detected earlier in ground-based data, particularly for a star as well-studied as RR Lyr? Besides the fact that period doubling does not always occur, the main reason is undoubtedly that RR Lyrae stars have periods of around half a day, and, when observing from one site on Earth, consecutive pulsation maxima are usually missed.

The observation of period doubling sparked new modelling efforts (Szabó *et al.* 2010; Kolláth *et al.* 2011), and recently a new model for the Blazhko effect was proposed by Buchler and Kolláth (2011). Using the amplitude equation formalism to study the nonlinear, resonant interaction between the two modes, they showed that the (9:2) radial resonance can not only cause period doubling, but it may also lead to amplitude modulation. Moreover, in a broad range of parameters the modulations can be irregular, just like recent observations show.

Therefore, we are now left with a new hierarchy for the models for explaining the Blazhko effect (Figure 6).

5. Pro-Am observations and RR Lyrae stars

Their large pulsation amplitudes, their pulsation periods, and their characteristic light curve shapes make the RR Lyrae stars easily distinguishable from other variables and gratifying targets for amateur observations.

Several groups worldwide have carried out observations of RR Lyrae stars. GEOS (Groupe Européen d'Observations Stellaires) is a European group of variable star observers with nearly eighty active members (of which ten are professionals). The GEOS RR Lyrae database (http://dbrr.ast.obs-mip.fr/) is intended to help observations and studies on RR Lyrae stars. It contains the times of light maximum of RR Lyrae stars obtained either visually, with electronic devices, or photographically. The data are collected in the literature (dating back to the end of the 19th century) or are submitted by the observers themselves (since 2004 also through automated observations). This database is a useful resource for the study of period changes in RR Lyraes, as well as the Blazhko effect.

The AAVSO has an impressive database of observations dating back more than a century. This database is a treasure chest for variable star research (including RR Lyrae stars) and part of these observations remain unpublished to date. Observations of RR Lyrae stars are gathered in the framework of the AAVSO's Short Period Pulsation Section. From time to time there are organized efforts focusing on legacy stars that have a Blazhko effect (see, for example, the AAVSO's "Variable Star of the Season Archive," http://www.aavso.org./vsots_archive).

Although the satellite missions deliver data with unprecedented precision on RR Lyrae stars, long-term monitoring of RR Lyrae stars is most valuable. Only such data can reveal phenomena happening on time scales of years, decades, or even longer, such as period changes due to stellar evolution, long-term changes in the Blazhko effect, and additional cycles with periods of years or longer. Sometimes sudden changes and transient phenomena can be observed in stars that have been followed for decades. Satellite missions and dedicated campaigns are limited in time. Moreover, the number of RR Lyrae stars observed with the satellite missions is limited, and generally the brighter stars, those that also can be followed more easily through spectroscopy, are not observed by the space missions. Nowadays, amateur observers play a very important role in contributing to the data that allow these discoveries. For these endeavors to be satisfying and optimally useful, interaction between professionals and amateurs is important, clarifying what kind of observations (of which targets) are needed.

6. Acknowledgements

I thank the "professional amateurs" with whom I have had the pleasure to interact and collaborate over the past years, for their enthusiasm and interest in variable stars and their valuable contributions to this field of research. I gratefully acknowledge the financial support of my Marie Curie project (Project PIOF-GA-2009-255267 - "SAS-RRL").

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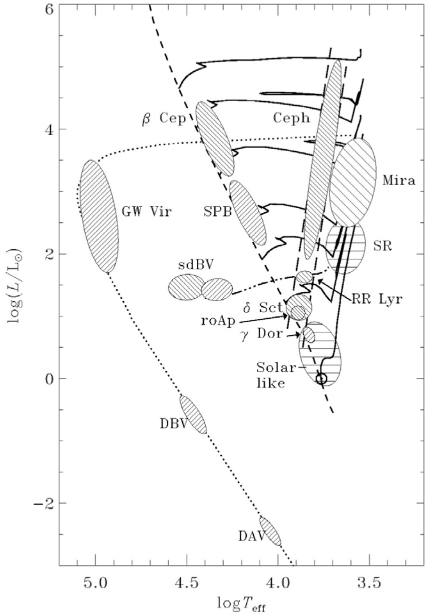

Figure 1. Stellar pulsations across the Hertzsprung-Russell diagram. Dashed line: zero-age main sequence; continuous lines: selected evolutionary tracks; triple-dot-dashed line: horizontal branch; dotted line: white dwarf cooling curve. The RR Lyrae stars are located on the horizontal branch in the instability strip. The hatching in the zones of pulsating stars represents the type of mode and the excitation mechanism: up-left for opacity-driven acoustic modes, up-right for opacity-driven internal gravity modes, and horizontal for stochastically excited modes. (From Christensen-Dalsgaard *et al.* 2004)

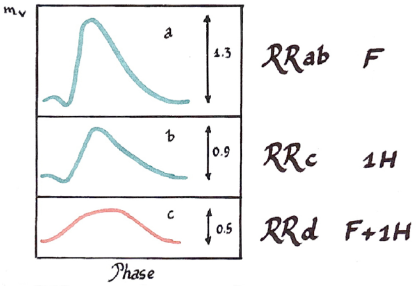

Figure 2. RR Lyrae Bailey subtypes. F: radial fundamental mode; 1H: radial first overtone.

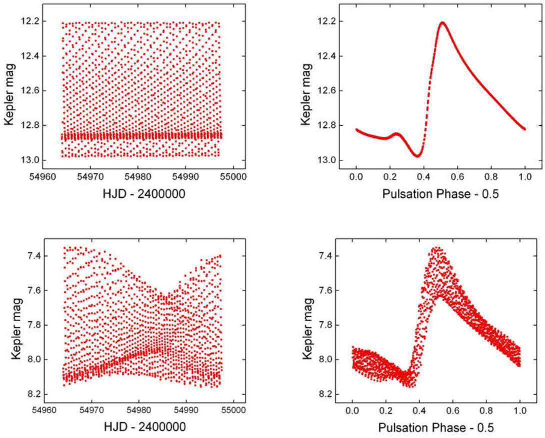

Figure 3. Kepler observations of a non-mdulated RR Lyrae star (top pair) and a Blazhko star (bottom pair). Left: 30-minute cadence data; right: folded light curve.

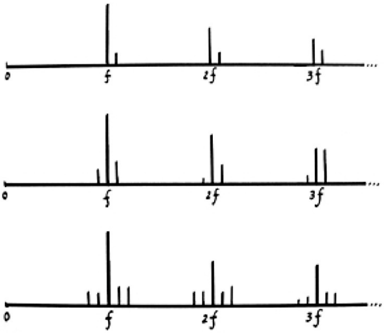

Figure 4. Typical frequency spectra for a Blazhko-modulated RR Lyrae star, showing multiplets. They can get even more complex than the schematic representations given here.

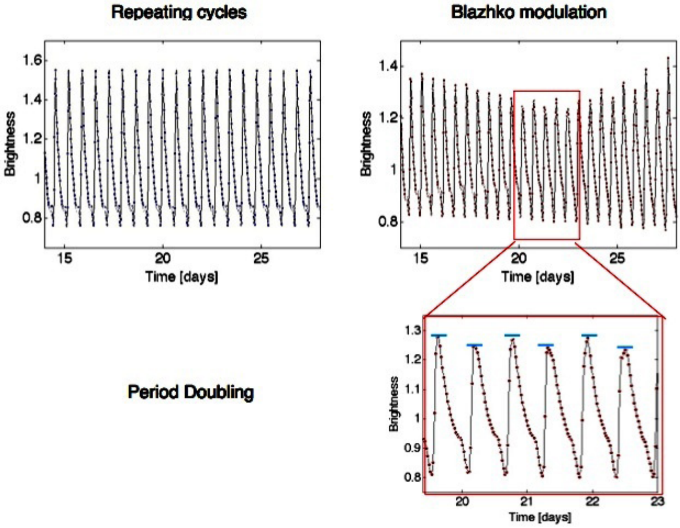

Figure 5. Period doubling manifesting in alternatingly higher and lower maxima, as seen in a star with Blazhko modulation (RR Lyr itself, top right panel). Period doubling is not seen in non-modulated stars (top left panel).

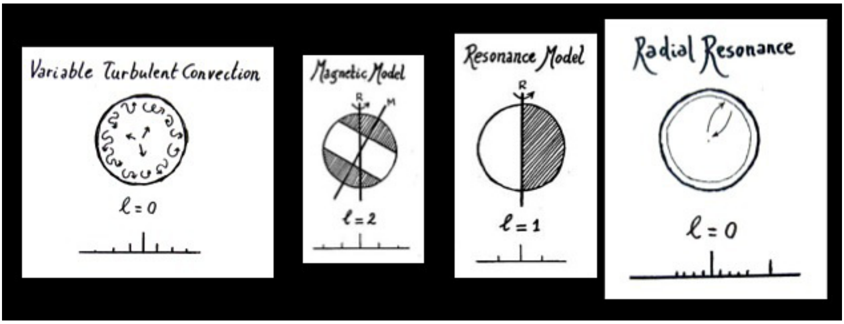

Figure 6. Models for the Blazhko effect: the present hierarchy.

Type 2 Cepheids in the Milky Way Galaxy and the Magellanic Clouds

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Abstract Type 2 Cepheids are radially pulsating variable stars that have been recognized as a distinct class for sixty years. As the lower-mass and hence lower-luminosity counterparts of the classical Cepheids, Type 2 Cepheids have attracted less observational and theoretical attention in the intervening decades. Fortunately, the recent availability of long, high-quality photometric time-series has renewed interest in these variables. The results from the OGLE-III surveys of the Large and Small Magellanic Clouds have been particularly exciting, especially with respect to the identification of "peculiar W Virginis" stars which appear to be components of binary systems. It has also become apparent that the sample of Milky Way field Type 2 Cepheids in catalogues is highly contaminated with other classes of variable stars. In this review, I describe important developments in the study of Type 2 Cepheids and suggest research opportunities—many of which do not require the acquisition on new data.

1. Introduction

In September 1952 the universe as we understood it became much larger. Ever since the first Type 2 Cepheids were discovered in globular clusters, it had been assumed that they shared the same luminosity at a given period as (classical) Cepheids in the disk of the Milky Way. In reality, there was a 1.5 magnitude difference between the two. The surprising announcement of this realization by Baade at the Rome IAU was quickly buttressed by followup remarks by Thackeray who had arrived at the same conclusion using observations of Large Magellanic Cloud variables. (See Baade (1956) for the complete firsthand account of how these events unfolded.) Reviews of Type 2 Cepheids and related stars have been published by Wallerstein and Cox (1984), Harris (1985b), and, most recently, by Wallerstein (2002). There have been a number of developments since the last work including the release of variable star catalogs from long-term, wide-area photometric surveys such as OGLE-III. In what follows, I will concentrate on work reported since Wallerstein (2002). I delve a little further back to review binary Type 2 Cepheids due to the recent realization that binarity is an importance influence on the production of certain Type 2 Cepheids.

2. Nomenclature

For the purposes of this review, Type 2 Cepheids are defined as those stars which are normally classified as BL Her variables (with periods between 1 and 4 days, also abbreviated CWB), W Vir stars (with periods greater than 4 days but most frequently greater than 8 days and less than 20 days, abbreviated CWA), and RV Tau stars (periods between maxima greater than 20 days). Somewhat confusingly, the RV Tau stars are subdivided into RVA and RVB types where RVB indicates an additional very long-period (500+ days) modulation of the light curve. Studies of Type 2 Cepheids in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC)—discussed later in this review—have revealed a smooth progression of properties between W Vir and RV Tau stars and so the adoption of a discriminating period is not physically motivated. While the alternating minima of different depths of RV Tau stars seemed a distinctive classification characteristic of the time, it has since been seen in the prototype W Vir itself (Templeton and Henden 2007) and in BL Her stars (Smolec *et al.* 2012). Its usefulness as a discriminating factor between classifications may be diminished, but the fact that the phenomenon is more widespread is a positive finding in terms of testing theory against observation. In any case, Buchler and Moskalik (1990) claim that the period-doubling behavior for the more luminous Type 2 Cepheids (W Vir/RV Tau) is the result of a 5:2 period resonance between the fundamental and the second overtone radial modes.

Historically, Type 2 Cepheids have often been referred to as "Population II Cepheids" but our understanding of their range of metallicities and their kinematics has evolved to the point where continuing to make use of such a title would mislead the reader.

While RR Lyr variables are closely related, space constraints prevent the discussion of their very considerable literature. The anomalous Cepheids (intermediate in mass and luminosity between Type 2 and classical Cepheids) are often discussed in Type 2 Cepheid papers but also will not be reviewed here.

3. Evolutionary context

The early detection of Type 2 Cepheids in globular clusters provided an immediate degree of evolutionary context for these stars although our physical understanding of stellar structure and evolution emerged much later. However, the brightest Type 2 Cepheids in globular clusters are still much fainter than the brightest stars of the field population and consequently the determination of abundance patterns at high spectral resolution relies dominantly on field stars.

Our current understanding of the evolution of Type 2 Cepheids (and their subtypes) was outlined by Gingold (1985) and references therein. It is assumed that these variables have masses similar to 0.6 $M_\odot$ when they begin to evolve away from the horizontal branch.

Maas *et al.* (2007) studied 19 Type 2 Cepheids and found a number of abundance patterns. BL Her stars were found to have an overabundance of Na by up to a factor of 5 while the W Vir stars show no such anomaly. This careful and pivotal study also contains an excellent discussion of the evolutionary options available to core helium-burning blue horizontal branch stars heading towards the instability strip from the hot side. The Na anomaly suggests that BL Her stars do not normally end up becoming W Vir or RV Tau stars later in their evolution. Assuming single-star evolution, they suggest that the BL Her stars result from a phase of high-temperature CNO processing which both leave them with enhanced Na and "deposits" them at the red end of the blue horizontal branch, resulting in a single pass through the instability strip. W Vir stars are thought not to have experienced such high-temperature CNO processing and start their journey off the horizontal branch nearer the blue end of the blue horizontal branch. W Vir stars then may pass through the instability strip on their way to the asymptotic giant branch (AGB) but have an additional excursion back and forth across the instability strip at higher luminosity due to helium shell flashes and/or internal structure readjustments on the AGB.

The traditional interpretation of the "no man's land" in period, between about 4 and 10 days, where Type 2 Cepheids are rarely found therefore maps back to the horizontal branch and the way in which evolutionary tracks diverge from each other as the stars evolve to cooler temperatures and higher luminosities.

4. Type 2 Cepheids in binary systems

In the Milky Way field, there are presently five Type 2 Cepheids known to be members of binary systems.

AU Peg is a 2.4-day BL Her star with a rapidly changing period. Precision radial velocites obtained by Harris *et al.* (1979) led them to conclude that AU Peg was a component of a spectroscopic binary with a period of order 50 days. Harris *et al.* (1984) obtained additional photometry and spectrscopy and concluded that AU Peg was in a 53.32-day orbit, that it had an [*Fe/H*] = +0.1 and that it must be very close to filling its Roche lobe. AU Peg appeared to be redward of the instability strip and thus binarity was implicated as a possible source of excitation of pulsation as well as a driver of the rapid period change. Vinkó *et al.* (1993) published additional photometry and found the period change to be non-linear. Furthermore, they disputed the tidal excitation interpretion in the earlier work, suggesting instead that AU Peg was simply near the red edge of the Instabilty Strip. Vinkó *et al.* (1998) obtained R = 11,000 optical spectroscopy of a number of Type 2 Cepheids and found that AU Peg was unique among them in revealing a P Cygni profile in its Hα line—indicating outflow. More recently the entire Type 2 Cepheid interpretation of AU Peg has been challenged by Jurkovic *et al.* (2007), who instead conclude that AU Peg is a double-mode pulsator (fundamental/first overtone) and a classical Cepheid despite its high galactic latitude and the enormous distance from the disk that such an interpretation would require. An interesting alternative explanation is that AU Peg is the first example of a double-mode Type 2 Cepheid.

Harris and Welch (1989) obtained new radial velocities and determined orbital characteristics for the single-lined spectroscopic binaries IX Cas and TX Del. They also pointed out that both stars had near-solar metallicities. The periods of IX Cas and TX Del, 9.2 and 6.2 days, respectively, are in a period range where few Type 2 Cepheids are known. Balog and Vinkó (1995) argue that the radius of TX Del is too large to be a Type 2 Cepheid and instead should be considered a classical Cepheid, despite the 1.2 kpc height above the disk that would require.

ST Pup is a 18.47-day W Vir star which was found by Gonzalez and Wallerstein (1996) to be in a spectroscopic binary with orbital period 410.4 days. Although it has a $[Fe/H] = -1.47$, it has a depletion pattern very similar to the longer-period stars in the sample of Maas *et al.* (2007) with the exception of an unexpectedly high Ca abundance.

Antipin *et al.* (2007) found the first galactic Type 2 Cepheid in an eclipsing binary: TYC 1031 01262 1. At present, there is no estimate of the Cepheid's metallicity, and no radial velocity observations suitable for determining other orbital characteristics are known to have been obtained.

Of the five systems discovered to date, it is noteworthy that three of the four that have had their composition estimated have near-solar or above-solar metallicities and have short orbital periods and distances. The most straightforward interpretation of this correlation is that there has been mass transfer from a more evolved companion prior to the current instability strip pass.

5. Type 2 Cepheids in Milky Way globular clusters

Clement *et al.* (2001) produced a catalog of all variable stars known in Milky Way globular clusters. Fifty-eight Type 2 Cepheids were identified at the time once two anomalous Cepheids are removed from their count. They note that all clusters containing Type 2 Cepheids have $[Fe/H] < -1.0$ and all except one have $[Fe/H] < -1.25$.

A recent census of Type 2 Cepheids in Milky Way globular clusters south of Declination −30° was provided by Matsunaga *et al.* (2006). Their new discoveries combined with previous work result in forty-six variables in twenty-six southern globular clusters. Their ten new discoveries bring the total number of Type 2 Cepheids in globular clusters to sixty-eight.

6. Type 2 Cepheids in the Milky Way field

The sample of Type 2 Cepheids associated with Milky Way globular clusters is likely to be complete or near-complete, since such stars are among the very brightest cluster members and, along with the horizontal branch RR Lyrae pulsators, have large photometric amplitudes.

The identification of a clean sample of true Type 2 Cepheids among Milky Way field stars has been much more problematic. The list of Harris (1985a) contained 152 field Type 2 Cepheids but was compiled prior to the microlensing, wide-field, and all-sky surveys. The surveys have been a two-edged sword in terms of improving our sample. They have both increased the number of Type 2 Cepheids known and dramatically improved the duration over which high-quality photometry exists but they have also introduced a significant number of false positive Type 2 Cepheid classifications.

A search of the Variable Star Index (Watson 2006) on May 6, 2012, revealed the numbers of Type 2 Cepheid classifications shown in Table 1. The first two variable types (CEP and CEP:) almost certainly contain "underclassified" classical Cepheids as well as Type 2 Cepheids. It is also this pair of classes which likely has the largest contamination of non-pulsating variables—stars that have rotation or orbital periods similar to Cepheids of both kinds.

While the LMC and SMC samples are likely near-complete, the mix of selection biases for the discovery of Type 2 Cepheids in the Milky Way field does not yet lend itself easily to numerical comparisons of subtypes between our galaxy and those in our companion galaxies.

Ed Schmidt's group at the University of Nebraska has been one of the most active in the study of field Type 2 Cepheids, with a number of careful photometric studies (Schmidt 2002; Schmidt *et al.* 2005a; Schmidt *et al.* 2005b; Schmidt *et al.* 2007; Schmidt *et al.* 2009) and spectroscopic studies (Schmidt *et al.* 2003b; Schmidt *et al.* 2003a; Schmidt *et al.* 2011). Schmidt *et al.* (2011) is an important synthesis of early work with numerous significant findings. It reports a uniform set of low-resolution spectra of 288 stars from Schmidt *et al.* (2007) and Schmidt *et al.* (2009)—the first large-scale attempt to produce spectral confirmation of classifications made with light curves. Although the authors expected to find about 560 new Type 2 Cepheids based on the estimates of Wallerstein (2002), they found only nineteen (elsewhere in the paper, the number twenty-three is stated.) This class of variable is easily mistaken for others based on light curves alone. Schmidt *et al.* (2011) also found that Type 2 Cepheids frequently had small (0.1 to 0.4 mag) amplitudes, contrary to conventional wisdom. This amplitude finding has been confirmed by OGLE-III for the LMC and SMC samples (discussed below). Of the "Cepheid Strip Candidates," as the new Type 2 Cepheid candidates are called, most have $-1.0 < [Fe/H] < 0.0$, suggesting an evolutionary path distinct from their counterparts in globular clusters. Although the numbers are small (and therefore the statistics are uncertain), the period distribution of the "Cepheid Strip Candidates" is quite flat in the traditionally underpopulated 4- to 10-day period range. This finding, too, is consistent with the OGLE-III surveys of the LMC and SMC and suggests that there is not such an evolutionary avoidance for this period range—the gap is at least partly due to photometric amplitude selection biases in discovery. The earlier correlation noted between Type 2 Cepheids in binaries and those with near-solar metallicities suggests that a significant fraction of the field population may be binary.

Another major study was that of Soszyński *et al.* (2011) who reported on the classical and Type 2 Cepheids of the OGLE-III microlensing survey fields in the galactic bulge. Of the 335 Type 2 Cepheids, there were 156 BL Her, 128 W Vir, and 51 RV Tau stars. This is the most uniformly observed and selected sample of galactic Type 2 Cepheids. Observations analyzed for this paper were acquired between 1997 and 2009.

7. Type 2 Cepheids in the Magellanic Clouds

Prior to the microlensing surveys of the 1990s few Type 2 Cepheids were recognized in the LMC and SMC.

The very first claim of a Type 2 Cepheid in either of the Magellanic Clouds was made by Tifft (1963) where 1.4300-day period was suggested for a star (6-31) in the field of the SMC which was possibly associated with the globular cluster NGC 121. Such a star would now be classified as a BL Her. Curiously, the star (now also cataloged as 2MASS J00262813-7136591) has not had further photometric follow-up. Payne-Gaposchkin and Gaposchkin (1966) reported only three "W Vir" stars in the SMC: HV 12901, HV 1828, and HV 206. The last of these had a period of 103.8 days which would fall into the period range of RV Tau stars by a more modern usage.

The first LMC Type 2 Cepheids, HV 5690 and HV 2351, were reported by Hodge and Wright (1969). Both were characterized by changing periods. Subsequently, Payne-Gaposchkin (1971) listed a total of seventeen "Population II Cepheids," including the two already discovered. The periods for the seventeen stars ranged from 11.439 to 50.87 days and ten of the stars have notes regarding observed period change. In the photographic surveys of the era, the shorter-period BL Her stars were below the detection threshold.

Welch (1987) obtained single-epoch, near-infrared (JHK) photometry of nine LMC and two SMC Type 2 Cepheids. Three of these with periods between 35.9 and 47.8 days showed K(2.2μm) excesses, indicating the presence of warm circumstellar dust.

The higher-quality, deeper CCD photometry acquired during the microlensing surveys dramatically improved our understanding of the Type 2 Cepheid populations of the LMC and SMC. The MACHO Project published its findings of Type 2 Cepheids (W Vir and RV Tau stars) in Alcock *et al.* (1998) which established the pattern of increased light curve variability with period and showed that there was no clear demarcation between the two classes. The existence of a common period-luminosity relation for the stars was also revealed.

The OGLE-III catalogs of LMC (Soszyński *et al.* 2008) and SMC (Soszyński *et al.* 2010) Type 2 Cepheids are the seminal observational works for these variables.

- In the LMC, 197 Type 2 Cepheids were found (64 BL Her, 96 W Vir, and 37 RV Tau—where the W Vir/RV Tau dividing period was taken to be 20 days).

- In the SMC, 43 Type 2 Cepheids were found (17 BL Her, 17 W Vir, and 9 RV Tau).

- "Exemplar" light curves for the LMC and SMC Type 2 Cepheids have been produced, providing definitive light curve shape classification. It is of interest to note that that light curve amplitude is the smallest in the period range 4–8 days where few Type 2 Cepheids were found in photographic surveys. The dearth of stars in that period range is thought to be due to evolutionary considerations, but amplitude-related discover selection biases may also have played a role.

- In both the LMC and SMC, a set of "Peculiar W Virginis" (hereafter, PCWA) stars were identified with distinctive light curve shapes (more symmetric) and bluer than their normal W Vir counterparts at the same period. The observed fraction of PCWA stars in eclipsing binaries or with ellipsoidal variation (4 of 16 in the LMC and 4 out of 7 in the SMC) is high enough to suggest that all such stars are in binary systems. A clear implication of this finding is that the production of PWCA stars is the result of binary interaction.

- In the LMC sample three of the seven Type 2 Cepheids in eclipsing systems have pulsation periods between 4 and 6 days where the frequency of Type 2 Cepheids is typically very low. Binary interaction may play an important role in populating this period range. If so, study of the few Type 2 Cepheids with similar periods in the Milky Way field may clarify whether such stars are always in binaries.

- The PCWA stars in the SMC all show multiperiodicity. Presumably the addition periods are the result of the Cepheid being non-spherical due to tidal effects.

While the Type 2 Cepheids in the LMC and SMC are too faint for detailed abundance work, they suggest additional avenues of exploration in the Milky Way field and bulge.

8. Opportunities

There is a surprising amount of discovery space available in the study of

Type 2 Cepheids. Here are some immediate suggestions for new observations and/or analysis:

- The great majority of photometry which exists for Type 2 Cepheids in globular clusters is photographic and imprecise. Since these stars are among the brightest in their clusters, they can be easily detected and measured with modern imagers in standard bandpasses. Profile-fitting photometry is needed in such crowded fields, but there are plenty of stars available to get the point spread function right.

- Suspected or uncertain Type 2 Cepheids in catalogs can be further assessed by examining the additional information now available in proper motion surveys, near-infrared colors, and cross-references with X-ray source catalogs. The rotation periods of spotted stars such as BY Dra and RS CVn variables frequently result in their misclassification as Type 2 Cepheids.

- There are few precise (± 2 km s^{-1}) radial velocities of field Type 2 Cepheids—a factor which limits our ability to understand both the frequency of binarity and the dynamical population from which they have been produced.

- No variable star catalog from a long-term photometric survey of the northen sky has yet been released. There are sure to be additional, relatively bright Type 2 Cepheids identified by such a survey and a program of routine photometry of newly-discovered stars will inevitably pay dividends.

- A re-classification of field W Vir stars into "normal" and "peculiar" is warranted as a result of the OGLE-III surveys of the LMC and SMC. It would be most interesting to investigate how metallicity and rates and directions of period change are correlated with these two classes of objects.

- The Type 2 Cepheids discovered in photometric surveys already have time-series available for period change analysis with hundreds to thousands of epochs. Patterns of non-pulsation modulation are waiting to be discovered and defined. The ellipsoidal modulation due to a tidally-distorted pulsator in orbit around a close companion can easily be teased out of available data - a purely photometric indication of binarity.

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Table 1. Counts of Type 2 Cepheid types in VSX.

Variability type	*N*	*Variability type*	*N*	*Variability type*	*N*
CEP	491	CWA:	19	RVA	72
CEP:	141	CWB	237	RVA:	3
CW	11	CWB:	24	RVB	26
CW:	2	RV	81	RVB:	1
CWA	240	RV:	35		

Classical Cepheids After 228 Years of Study

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Abstract A review is presented of much of our current observational knowledge of classical Cepheids. Outlined are the basic observational parameters of Galactic Cepheids derived over the past 228 years, with emphasis on current trends and ongoing problems. Although the calibration of the Cepheid period-luminosity (PL) relation has normally made use of variables in the Magellanic Clouds, presently that can be accomplished using only Galactic Cepheids. It is also possible to calibrate the PL relation without recourse to observations, given that their fundamental properties are well enough understood.

1. Introduction

Cepheids are yellow supergiant stars that can reveal to astronomers exactly how distant they are through regular measurement of their brightness variations in a few photometric bands. Much more is known about them today than fifty or one hundred years ago, yet, for every morsel of new information that is learned, further questions arise that make investigation of such stars a constantly challenging pursuit.

Cepheids are named for the bright example of the class, δ Cephei, whose regular variability over the course of 5.37 days was noticed by John Goodricke in October 1784, a month after his friend Edward Piggott noted light variations in η Aquilae, another bright Cepheid with a pulsation period of 8.36 days. The valuable characteristic of Cepheids as distance indicators was discovered more than a century later when Henrietta Leavitt noticed in 1908 that the mean brightness of Cepheids in the Small Magellanic Cloud correlated closely with the period of variability for the stars: the well-known Cepheid period-luminosity (PL) relation (Leavitt 1908; Leavitt and Pickering 1912). The relationship was calibrated using Galactic variables (Hertzsprung 1913), and Harlow Shapley was one of the first to make use of the feature for practical purposes in a study of the Sun's location within the Galaxy relative to globular clusters (Shapley 1918a, b), with distances to the latter inferred with respect to the short period "Cepheids" populating some of them. The distinction between classical Cepheids like δ Cep and η Aql and Type II Cepheids (BL Herculis objects, W Virginis variables, and RV Tauri stars) and RR Lyrae variables was not made until many years later. See Fernie (1969) for a detailed review.

The initial calibration of Cepheid luminosities and the application of the PL relation to the measurement of distances to nearby galaxies came soon thereafter. In fact, it is probably true that much of what we understand about cosmology and the nature of the universe is tied to knowledge of the Hubble constant H_0, as derived from observations of Cepheids in relatively nearby galaxies (Freedman *et al.* 2001).

Cepheids are also a topic of interest for stellar interior modellers. The simple linear, non-rotating, adiabatic models of a few decades ago are currently being replaced by much more sophisticated calculations involving differential rotation, more physically realistic mixing, and proper consideration of changing element abundances on interior opacity sources. In the future, fully three-dimensional models may eventually become the norm, consuming extraordinary amounts of computer calculation time per model. The time may eventually arrive when it will take a complete suite of models to match individual Cepheids, which appear to differ from one to another in very distinct ways, particularly in atmospheric contamination by CNO elements (Turner and Berdnikov 2004).

2. Properties of classical Cepheids

Cepheids display very repeatable light curves, most being asymmetric with a rapid rise to maximum light followed by a slower decline, with light minimum occurring 0.6–0.7 cycle after light maximum. The radial velocity variations are almost a mirror image of the light variations in the variables, indicating that Cepheids are brightest roughly when their photospheres are most rapidly expanding, and faintest roughly when they are contracting the fastest. There is a small phase shift between the two relations, radial velocity minimum occurring a few percent of the cycle length after light maximum. Short period Cepheids (periods $P < 10d$) tend to be of spectral types F5-F8 at light maximum, and G or K at light minimum, with correspondingly cooler spectral types for longer period variables (Kraft 1963).

Cepheids also display a feature known as the Hertzsprung progression (Figure 1), a secondary bump in their light curves that appears near light minimum (~0.5 cycle after maximum) in Cepheids with periods of about 5 days, but gradually closer and closer to light maximum in Cepheids of longer period, being coincident with light maximum at pulsation periods of ~10 days, giving them the appearance of having a double maximum or a broad maximum. For Cepheids of longer period the bump appears on the rising light portion of the light curve, progressing towards light minimum and disappearing at periods of ~20 days.

The origin of the bump has been a matter of debate for decades, and has been attributed to either a light echo of the surface pulsation from the stellar core or surface excitation of the second overtone mode, for which the period is extremely close to one-half of the fundamental mode period (the periods of adjacent pulsation modes become shorter by a factor of ~0.7 as one goes to higher order modes, so the period of the second overtone mode relative to the fundamental mode is 0.7 × 0.7 ≈ ½). A subset of short-period Cepheids displays light curves that are almost perfectly symmetric (Figure 2), matching sine waves so closely (see the sine wave light curve in the lower part of the figure) that they were referred to as s-Cepheids. The nature of such objects is controversial. Efremov (1968) argued that their symmetric light curves were the signature of Cepheids in the first crossing of the instability strip, although that may be a simple consequence of the small amplitudes for some stars. The two s-Cepheids SZ Tau and V1726 Cyg, whose light curves are plotted in Figure 2, are members of the clusters NGC 1647 (Turner 1992) and Platais 1 (Turner *et al.* 2006b), respectively, and appear to pulsate in the first overtone and fundamental mode, respectively, in high order strip crossings. Other s-Cepheids that are likely members of open clusters seem equally split between fundamental mode and overtone pulsation.

Thirty years ago Simon and Lee (1981) introduced Fourier diagnostics to the study of Cepheid light curves. It had been recognized previously that light curves could be matched to Fourier series quite well, the only question being how many terms to include when there were gaps in the light curve coverage. Simon took the matter further by noting that certain combinations of low-order Fourier series terms, sine term amplitudes and phase offsets, such as R_{21}, the ratio of amplitudes for the second order to first order terms, and ϕ_{21}, the normalized difference in phase offsets between the second and first order terms, correlated smoothly with pulsation period, except for a discontinuity at P = 10d where the secondary bump passes through light maximum (see, for example, the behavior of R_{21} shown by Zabolotskikh *et al.* 2005). For short-period Cepheids there is a heavily-populated primary sequence, considered to coincide with fundamental mode pulsators, and a less-populated secondary sequence, considered to represent overtone pulsators, subsequently confirmed by Fourier decomposition of the light curves of double mode Cepheids (e.g., Antonello and Mantegazza 1984; Pardo and Poretti 1997). The technique was also extended to s-Cepheids by Antonello and Poretti (1986) in order to demonstrate that they are likely overtone pulsators, although the definition of "s-Cepheid" was broadened somewhat in the process and it is unclear what parameters like R_{21} and ϕ_{21} mean when the data are noisy and the second order term in the Fourier series may actually be zero.

Another characteristic of Cepheids is that all undergo changes in pulsation period as a result of stellar evolution. Cepheids represent post-hydrogen burning stages of stars with main sequence masses in excess of about 4 $M_{\odot}$, progenitors that had spectral types hotter than B5 in a former life. They are currently yellow supergiants in a variety of short-lived evolutionary stages between that of B dwarfs and their later existence as red supergiants. Most are evolving through the instability strip for the second or third time as core helium burning objects, some may be passing through it for the fourth or fifth time as shell helium burning stars, and a rare few seem likely to be in the first crossing, the stage of hydrogen shell burning that lasts an order of magnitude or more less time than other stages.

As yellow supergiants evolving through the instability strip in the Hertzsprung-Russell (H-R) diagram, Cepheids become unstable to pulsation because the regions of hydrogen (H) and helium (He, He^+) ionization lie deep enough to drive radial expansion and contraction through a piston-type mechanism. Evolution through the instability strip takes on the order of a half million years for some stars, so it is not a process normally detectable in the course of a human lifetime. But it does result in very small changes in average radius for the stars as they evolve, increases for stars evolving towards the cool side of the instability strip in the Hertzsprung-Russell (HR) diagram, and decreases for stars evolving towards the hot side. That produces small, cumulative changes in pulsation period that are readily detectable from O–C analyses of their light curves, as noted by Szabados (1983), Fernie (1984), Turner (1998), and Turner *et al.* (1999).

The study of Cepheid period changes through O–C analysis is an excellent way to test stellar evolutionary models (Turner *et al.* 2006a). But period changes can also arise from other effects: orbital motion about a companion, which produces cyclical variations in O–C data over the orbital period of the system, random changes in pulsation period, which for some Cepheids, for example, V1496 Aql (Berdnikov *et al.* 2004), can dominate evolutionary effects, and possibly mass loss (Neilson *et al.* 2012). The existence of such complications makes it imperative to establish Cepheid pulsation periods from existing photometric data as carefully as possible. Fourier techniques, for example, can sometimes generate erroneous results. By contrast, the Hertzsprung method takes full advantage of the repeatability of Cepheid light curves to best advantage, particularly when used in O–C analyses (Tsesevich 1971; Belserene 1988; Berdnikov 1992), and generates the most accurate results.

The light amplitudes for Cepheids vary in magnitude according to the filter used to observe them, being largest in the ultraviolet and smallest in the infrared. Maximum blue (ΔB) or visual (ΔV) light amplitude also increases progressively with pulsation period, with the exception of a small dip for $P \approx 10^d$ where the light curve bump is coincident with light maximum. The largest amplitude Cepheids are found just to the hot side of instability strip center, with variables of smaller amplitude towards the strip edges (Kraft 1963; Hofmeister 1967; Sandage and Tammann 1971; Payne-Gaposchkin 1974; Pel and Lub 1978; Turner 2001; Sandage *et al.* 2004). That characteristic was combined with rate of period change by Turner *et al.* (2006a) in order to produce a parameter capable of estimating the strip crossing mode for individual Cepheids (Turner *et al.* 2006b; Turner 2010).

For many years Polaris held the record as the smallest amplitude Cepheid, particularly in the decades around 1988, when its visual amplitude dropped to 0.025 magnitude (Turner 2009). But, at their current level near 0.055 magnitude, the pulsations of Polaris are an order of magnitude larger than those of HDE 344787, a recently discovered double-mode Cepheid that is rapidly becoming a challenge to observe as its light amplitude decreases towards its eventual demise as a variable star (Turner *et al.* 2010b). Both stars display the largest rates of period increase for Cepheids with pulsation periods of 4 to 5 days, a signature of variables crossing the instability strip for the first time. The discovery of X-ray emission from Polaris and a few other bright Cepheids (Engle *et al.* 2009) is an additional complication that challenges our understanding of the stars.

3. Calibration of the PL relation

The calibration of the Cepheid PL relation was for many years accomplished by deriving the slope of the relationship using Cepheids in the Magellanic Clouds, where interstellar extinction and differential reddening is small, and fixing the zero-point using Milky Way Cepheids of known distance. The last step was not without challenges. The large masses and short-lived evolutionary state of Cepheids make them relatively rare objects. None are closer than ~100 parsecs, which was traditionally the limit for trigonometric parallax determinations with older refracting telescopes. Nearby Cepheids (e.g. Polaris) are also relatively bright, presenting problems for parallax measurements from photographic plates.

The launch of the Hipparcos satellite two decades ago changed the situation, since its on-board telescope/detector combinations had the capability of measuring absolute parallaxes of high precision for stars brighter than about tenth magnitude, including a sample of more than 200 Cepheids. Most Cepheids measured by Hipparcos have very accurate parallaxes, but there is a subset of objects of lower quality and precision that comprises a relatively large proportion (~1/2) of the sample (Turner 2010). A smaller group of ten classical Cepheids have also had their parallaxes measured using the Hubble Space Telescope (HST) by more traditional methods (Benedict *et al.* 2002, 2007), with improved precision and an accuracy generally better than the Hipparcos results. The zero-point for the PL relation is now considered to be firmly established (see Turner 2010; Turner *et al.* 2010a).

An alternate route to the calibration is by means of Cepheids belonging to open clusters, since zero-age main-sequence (ZAMS) fits for open clusters can provide distance estimates for cluster members with a precision reaching ~2% in the best cases, the accuracy depending upon the ZAMS calibration tied to the nearby Hyades and Pleiades clusters and the effects of metallicity on the main-sequence luminosity zero-point. In the 1960s the sample of Galactic clusters containing short period Cepheids as bona fide members was only a half dozen or so, which made it difficult to fix the slope of the relation with much confidence, but the sample now numbers twenty-four of all periods (Turner 2010), with a potential to reach forty to fifty stars, allowing both the slope and zero-point to be established independent of Cepheids in the Magellanic Clouds.

Since Cepheids are so regular in their variability, their parameters can also be established by the Baade-Wesselink method, a technique proposed by Baade (1926) and developed for practical use by Wesselink (1946). The luminosity of a star is the product of its surface area and surface brightness. For a spherical object, a reasonable approximation for an evolved star like a Cepheid, the surface area is $4\pi R^2$, where R is the star's radius, and the surface brightness is the radiance, given by $\sigma T_{\mathrm{eff}}{}^4$, where σ is the Stefan-Boltzmann constant and T_{eff} is the star's effective temperature. The star's luminosity is therefore $L = 4\pi R^2 \sigma T_{\mathrm{eff}}{}^4$. During a Cepheid's pulsation cycle it reaches the same effective temperature or surface brightness at different phases, yet there can be a difference in brightness at those phases of Δm, in magnitudes. The ratio of the star's radii at such times, R_2/R_1, is equal to $10^{0.2\Delta m}$, while the differences in the star's radius, $R_2 - R_1$, can be found independently using measures of its radial velocity, which track the cyclical motion of the surface layers, thereby allowing the average radius to be established. In particular, the radial motion of the star's surface is given by $v_R = p\,(V_R - V_0)$, where V_R is the measured radial velocity, V_0 is the systemic velocity of the star along the line of sight, and p is a factor, typically close to 4/3, to correct the measured velocity for the fact that it represents the combined light originating from photospheric radiation coming from the entire nearside hemisphere of the Cepheid.

Over the course of a complete light cycle, the surface of a Cepheid moves through a distance $4\Delta R$, where ΔR is the amount by which the mean radius of the star increases or decreases during the interval. That value can be obtained through numerical integration of the radial velocity curve, namely $4\Delta R = p \int (V_R - V_0)\, dt$ in calculus notation, where the integral is over the entire cycle. If the semi-amplitude of the radial velocity curve is denoted by ΔV_R (in km s^{-1}) and it is approximated by a sine wave, it follows that $\Delta R \approx 2.63 \times 10^{-2}\, P\, \Delta V_R\, R_\odot$, where P is the pulsation period in days and the projection factor has been approximated as 4/3. For the bright Cepheid δ Cep, $P = 5.37$ days and the radial velocity varies between +3 and –36 km s^{-1} (i.e., $\Delta V_R = \pm 19.5$ km s^{-1}). The estimated radius variations are therefore about $\pm 2.8\, R_\odot$, close to the actual value of $\pm 2.3\, R_\odot$ about a mean radius of 43 $R_\odot$ (Turner 1988), the difference being accounted for by a slightly smaller adopted value of p and the non-sinusoidal nature of the light and velocity curves for δ Cep. The radius variations for δ Cep therefore amount to ±5%, typical of most Cepheids, where the range is from less than 1% to ~10% in extreme cases.

The method of isolating phases of identical surface brightness during a Cepheid's cycle is all-important. When the technique is applied correctly, a plot of radius ratios versus radius differences should generate a tight loop traced out counterclockwise for phase pairs running from light maximum to light minimum (Evans 1976; Turner 1988), and the slope should be close to the reciprocal of the minimum radius (Abt 1959). The use of a color index like *B–V* to isolate such phases, the situation for most early applications of the Baade-Wesselink method, generates results contrary to expectations (e.g., Turner 1988), primarily because the colors are affected by variable atmospheric line blanketing created by a combination of cyclical spectral line broadening arising geometrically from the general expansion and contraction of the stellar photosphere and a sudden, large increase in atmospheric microturbulence during the contraction phases (Benz and Mayor 1982; Turner *et al.* 1987). Most recent applications have used color indices less affected by such influences, such as *V–I* spanning visual to infrared wavelengths, or indices in the infrared itself, which are more closely linked to stellar surface brightness variations (e.g., Gieren *et al.* 1989). Narrow band spectrophotometric indices also work well (Turner 1988; Turner and Burke 2002). Current techniques mainly employ the former, typically using variants that employ sophisticated statistical methods to test the validity of the results.

An early estimate for the projection factor of $p = 1.412$ by Getting (1934) was later reduced to 1.31 from model atmosphere calculations (Parsons 1972; Karp 1975), then increased back to values near 1.4, with a period dependence, when Hindsley and Bell (1986) used more recent Kurucz model atmospheres. The values used in Baade-Wesselink analyses then varied from author to author over the next two decades, until more recent stellar atmosphere models were employed and Gray and Stephenson (2007) noted that a toy model for the pulsation of bright Cepheids implied values of p closer to 1.3 in some cases, depending upon the source of radial velocity measures. More recent work by Nardetto *et al.* (2009, and in press), Laney and Joner (2009), and Neilson and Lester (2011) continue to argue the case for different values near $4/3 \pm 0.1$, with a possible period dependence.

The method of measuring radial velocities is an extremely important consideration. Most lines visible in Cepheid spectra, the lines of neutral iron (Fe I) for example, are formed at higher layers of a Cepheid's atmosphere than the deeper regions generating the stellar continuum. Since pulsation results in a variable extension, or stretching, of the atmosphere rather than a simple up-down displacement, the lines used for radial velocity measurement should be higher ionization species like singly ionized iron (Fe II) to properly track the radial motion of the deeper layers where the light originates that is responsible for the brightness differences Δm. But many radial velocity observations in the literature were obtained using cross-correlation techniques, often dominated by low ionization species, which is why the value of p may continue to be debated.

The debate may be of only minor concern, however. Independent studies of the period-radius relation for Galactic Cepheids by Laney and Stobie (1995), Gieren *et al.* (1998), and Turner and Burke (2002) yield nearly identical values for the slope and zero-point of the relation, despite different methodologies, with the average Cepheid radius being almost exactly proportional to $P^{3/4}$ (Turner *et al.* 2010a). The radius of any Cepheid can therefore be estimated reliably from its pulsation period, provided that it corresponds to fundamental mode pulsation in the star. A polynomial linking a star's effective temperature to its reddening-free $B–V$ color index has been derived by Gray (1992), allowing one to derive a Cepheid's luminosity directly. The technique generates results that are a close match to Cepheid luminosities established from trigonometric and open cluster parallaxes (Turner and Burke 2002; Turner 2010; Turner *et al.* 2010a), where any such comparison also requires a knowledge of bolometric corrections for Cepheids in order to link absolute bolometric magnitudes M_{bol} (= $-2.5 \log L$) to intensity-averaged absolute visual magnitudes $<M_V>$, where the bolometric correction BC = $M_{\mathrm{bol}} - <M_V>$.

The importance of an accurate knowledge of the interstellar reddening affecting individual Cepheids now becomes clear. For the above technique to yield reliable results, it is essential to account properly for the reddening produced within our Milky Way Galaxy or, for extragalactic Cepheids, in other galaxies. For many years reddenings for Galactic Cepheids have been obtained from a variety of sources essentially linked to period-color relations, which do not account for the intrinsic temperature width of the instability strip and the distribution of individual Cepheids within it. Considerable use has been made, for example, of compilations by Fernie (1990a, b), which are of that type. More direct reddenings are available, for example those tied to reddening-free indices (e.g. Turner *et al.* 1987) or to space reddenings (Turner 2001; Benedict *et al.* 2002, 2007; Laney and Caldwell 2007; Turner *et al.* 2011), which entail use of reddenings derived for close neighbors of Cepheids to infer color excesses for the variables. Cepheids belonging to open clusters play an important role in the latter. Kovtyukh *et al.* (2008) have also used the relationship of Gray (1992) between stellar effective temperature and unreddened $B–V$ color with model stellar atmosphere fits to Cepheid spectra over their pulsation cycles to deduce their reddenings from their observed color variations, a novel inversion of the normal procedure.

The period-luminosity relation that results from using the above relationships with Galactic Cepheids of well-established reddening and Cepheids with HST or cluster parallaxes is shown in Figure 3. The derived relationship is described by $\log L/L_{\odot} = 2.409 + 1.168 \log P$. The scatter is intrinsic, and results from the temperature width of the instability strip. Cepheids of a given period can be small amplitude variables on the hot or red edges of the strip, or large amplitude variables just blueward of strip center.

Cepheids that are members of binary systems or open clusters can also be used to establish a Cepheid period-mass relation. Cepheids in open clusters have identical ages to cluster members, which can be established from model isochrone fits to the unreddened color-magnitude diagrams for the clusters (e.g., Turner *et al.* 2008). The inferred ages for cluster Cepheids can then be used with published models by Meynet *et al.* (1993) to establish masses for stars at the terminal stages of core hydrogen burning, designated as M_{RTO}, for stars at the red turnoff (RTO) for the clusters. Such masses should be close to, or perhaps slightly smaller than, the masses of the corresponding Cepheids. An analysis of that type was made by Turner (1996), subsequently updated by Turner *et al.* (2010a) to include more recent results for a few clusters (Turner *et al.* 2006b, 2008, 2009).

More recent results are now available for TW Nor in Lyngå 6 (Majaess *et al.* 2011) and SU Cas in Alessi 95 (Turner *et al.* 2012), and can be combined with masses derived for the binary Cepheids W Sgr (Evans *et al.* 2009), OGLE-LMC-CEP0227 (Pietrzyński *et al.* 2010), and V350 Sgr (Evans *et al.* 2011). The results, presented in Figure 4, confirm the consistency of binary masses and evolutionary masses for Cepheids, and suggest a simple relationship between the mass of a Cepheid and its pulsation period. Turner (1996) found that Cepheid masses scale as $P^{1/2}$, but the data of Figure 4 appear to vary as $P^{0.4}$. The implication is that the pulsation period varies as $M^{2\frac{1}{2}}$. The deviation of long-period Cepheids from a simple $P^{1/2}$ relationship could alternatively be evidence for the importance of mass loss for such stars (e.g., Marengo *et al.* 2010; Neilson *et al.* 2011).

The same data can be used to construct a period-age relation for Cepheids in open clusters, as displayed in Figure 5. The best-fitting linear relation to the data is given by $\log t = 8.48 - 0.724 \log P$. In this case, the slope of the relationship cannot be interpreted in terms of a simple power law, being tied as it is to the evolutionary models of Meynet *et al.* (1993).

4. The extragalactic setting

The use of the period-luminosity relation for extragalactic Cepheids usually involves a reddening-free formulation referred to as the Wesenheit function, after Madore (1976, 1982). An example for Johnson system *BV* magnitudes is $W_{BV} = \langle M_V \rangle - R_V\,(B-V)$, where R_V is the ratio of total-to-selective extinction for interstellar dust. For Cepheids a value of $R_V \cong 3.3$ seems valid, although there is no guarantee that it applies to dust in all directions of the Galaxy, or within other galaxies, for that matter. All reddening-free relations are at best an approximation; in the case of the Wesenheit function it reduces the intrinsic scatter in period-absolute magnitude relations, but overcorrects for intrinsic color spread of the instability strip. It works only if Cepheids in other galaxies are very similar in their intrinsic properties to Galactic Cepheids, and the dust extinction properties are more-or-less the same. Because of concerns about the latter, however, standard usage involves observations of Cepheids in the visible to near-infrared region, where the effects of interstellar extinction are reduced.

The extension of photometric imaging to increasingly fainter brightness limits is also generating reliable photometry for Type II Cepheids and RR Lyrae variables in nearby galaxies. Type II Cepheids include BL Her variables (P = 1–8 days), W Vir stars (P = 8–20 days), and, in recent years, the RV Tau variables, which exhibit period doubling, a phenomenon that has attracted considerable attention in the last year from its ubiquitous nature. Together with the RR Lyrae variables, Type II Cepheids appear to describe a unique PL relation of their own that can be used to establish galaxy distances reliably (e.g., Majaess *et al.* 2009; Majaess 2010). Likewise, radially pulsating δ Sct variables follow a PL relation similar to that for classical Cepheids (Fernie 1992), and both relations, when combined, provide a powerful tool for establishing accurate distances to nearby galaxies.

5. Cepheids and the AAVSO

Despite the existence of over 200,000 visual observations of Cepheids in the AAVSO International Database, the variables have not received the same degree of attention from AAVSO observers as Miras and cataclysmic binaries, possibly because they represent a smaller sample of stars of perceived regular behavior. Nevertheless, the bright variable δ Cep has been a popular target for beginning observers and interested amateurs, and AAVSO visual and CCD observations have been extremely useful for studies of Cepheid period changes (Berdnikov *et al.* 2003; Turner 1998; Turner *et al.* 2001, 2007). Brightness estimates for Cepheids published in the *Journal of the AAVSO* by students at the Maria Mitchell Observatory (e.g., Starmer 1989) have also been useful for such studies (see references in Turner 1998), and there have also been relevant articles on period-finding and O–C analyses (Belserene 1988, 1989) that are useful for the analysis of Cepheid period changes. Visual observations of δ Cep by AAVSO observers appear to be accurate, despite large scatter, although the finder chart for visual observers needs to be updated to make it applicable for non-dark-adapted observers (Turner 1999, 2011). Reference magnitudes on AAVSO charts for the nearby variable μ Cep are more closely tied to the Johnson system, for example.

The future of Cepheid observations by the AAVSO is unclear, given the large survey instruments that are beginning to appear. Yet AAVSO observations of bright Cepheids should continue to fill a niche where data are needed. The recently developed project by Variable Stars South observers for precision monitoring of bright southern Cepheids (Walker 2011) is an excellent example. As evident from the recent AAVSO observing campaign on Hubble's variable V1 in the Andromeda galaxy M31, a Cepheid with a period of ~30 days (*AAVSO Alert Notice 422*), Cepheids continue to make interesting objects for observation.

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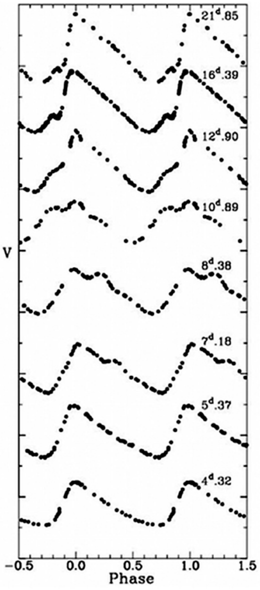

Figure 1. The Hertzsprung progression seen in the light curves of, from top to bottom, the Cepheids WZ Sgr, X Cyg, Z Sct, VX Per, S Sge, η Aql, δ Cep, and Y Lac. Visual magnitude steps are 1.0 magnitude between large divisions and the pulsation periods are indicated. The data are from Moffett and Barnes (1980, 1984), and have been offset in order to fit comfortably in the diagram.

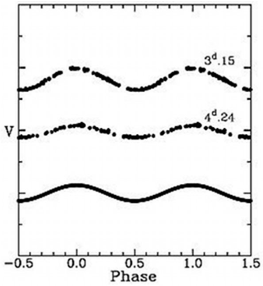

Figure 2. Light curves of, from top to bottom, the Cepheids SZ Tau, V1726 Cyg, and a simulated sine wave Cepheid with an amplitude of A_V = 0.25 magnitude. Terminology is the same as in Figure 1. The data are from Milone (1970) and Turner *et al.* (2001), offset to fit comfortably in the diagram.

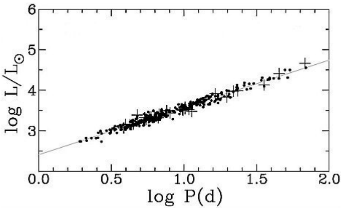

Figure 3. The period-luminosity relation for Galactic Cepheids of well-established reddening (points) and with HST or cluster parallaxes (plus signs).

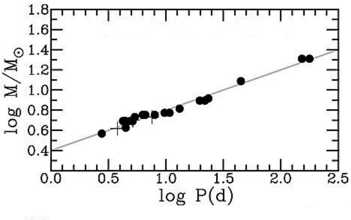

Figure 4. The Cepheid period-mass relation defined by members of open clusters (filled circles) and binaries (plus signs). The plotted relation is described by $M \sim P^{0.4}$.

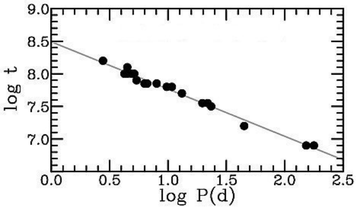

Figure 5. The Cepheid period-age relation defined by members of open clusters. The plotted relation is described by log t = 8.49 – 0.724 log P.

Miras

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Abstract Mira variables share essential characteristics: High visual amplitude, periods of hundreds of days, red colors (spectral types M, S, and C), and the presence of emission lines at some phases. They are fundamental mode pulsators, with progenitor masses ranging from <1 to several solar masses. In this review, we summarize what is known from modeling and observational studies, including recent measurements from optical and IR interferometry, and studies involving large samples of stars particularly in the Magellanic Clouds. While we have a good idea of how these stars fit into the big picture of stellar evolution, many important details remain to be settled by a combination of more ambitious models and new observational techniques. Carrying on observations of bright Mira variables will be essential for interpreting observations of large numbers of fainter sources as well as for assessing the completeness and accuracy of the models.

1. Miras—fundamentals, mostly old news

Oxygen-rich Mira variables are red giants with visual amplitudes of 2.5 to > 7.5 magnitudes and relatively stable light curves; this corresponds to visual brightness changes from ×10 to ×1000. Their bolometric magnitude variation is about 1 magnitude, meaning the luminosity is varying only by a factor of 2–3. The reason that the visual brightness changes so much more over the cycle is that there are strong variations in the opacity of the atmosphere from minimum to maximum light, largely the result of variable amounts of TiO and other molecules.

There are fewer carbon-rich Miras, although plenty of variable carbon stars that are very similar to Miras in their bolometric variability. The difference in the atmospheric chemistry when C/O is > 1 vs. < 1 is part of the reason for this difference; the other is probably the sensitivity of the stellar radius to C/O, meaning the stars migrate across the zones of pulsational instability as C/O increases.

The pulsation of the Mira variables is driven by the same kind of process that drives the pulsation of Cepheids, and is a result of changes in the opacity and the dependence of pressure on temperature and density when hydrogen and helium are ionizing or recombining. In the Cepheids, the pulsation is rooted in the He+ <–> He++ zone, and in the Miras, in the H <–> H+ and He <–> He+ zones. Early modeling that showed this was done by Wood (1974; also Fox and Wood 1982) and by Ostlie (Ostlie and Cox 1986; Cox and Ostlie 1993).

The mode of pulsation is usually derived by taking the observed period, mass, and radius and comparing this with the periods derived from models with the same M and R. Thus, for red giants with M and R appropriate for Mira variables Ostlie and Cox found:

Fundamental mode
$P = 0.012\text{d}\ R^{1.86}\ M^{-0.73}$ or $\log P = -1.92 - 0.73 \log M + 1.86 \log R$

First overtone
$P = 0.04\text{d}\ R^{1.5}\ M^{-0.5}$ or $\log P = -1.40 + 1.5 \log R - 0.5 \log M$

These are both radial modes—that is, all the motion is in and out—and differ in that for the fundamental mode, all parts of the star move out or in together while for the first overtone, part of the star moves out while another part moves in. Thus the overtone mode has a shorter effective wavelength and if we assume the pulsation is like a sound wave, with the same sound speed, shorter wavelength → shorter period.

For the Miras, there are two difficulties with this approach. One problem is that we don't have direct measurements of the masses of the stars, and the other is that the radius measurements can be ambiguous or misleading. These difficulties were the cause of a long debate over the correct mode assignment for the Mira variables. In recent years the radius measurements have been improved and disambiguated via interferometry, and we have some new constraints on the current masses—see section 3. However, the debate was mostly settled before these results came in, based on modeling of shock waves in the atmosphere and a better understanding of the dynamics of the stellar atmospheres and winds.

The gist of the dynamical argument for the pulsation mode is this: When material in the atmosphere goes through one of the pulsation-induced outward-propagating shocks, it is given a kick and begins to travel outward. This trajectory is close to ballistic, that is, like a ball tossed upward. The stellar gravity acts on the material, bringing it back to its original position, or close to it, in time for the next shock to hit—just as hitting a ping-pong ball with a paddle can keep it in the air indefinitely if you always hit it at the right moment at the same place. For a purely ballistic motion, the infall velocity when the next shock comes through is equal to the outward motion after the previous shock, so the change in velocity is from +v to –v or 2v. This is the shock velocity amplitude, and can be deduced observationally from the Doppler shifts in spectral lines. The observed shock amplitudes are sufficiently large that they dictate a large gravity, inconsistent with the radii that give the observed periods with reasonable guesses about the masses of these stars (Hill and Willson 1979 and Willson and Hill 1979).

There are other ways to get at least a clue about the mode of pulsation. Typically, for fundamental mode pulsation, the motions are large enough to produce an asymmetric light curve—this is seen in Cepheids, RR Lyrae stars, and Miras. Overtone pulsation, in contrast, tends to produce more symmetric or sinusoidal variation and also smaller amplitude variability—this is definitely true when M and R are fixed, and still likely if P is held constant while M and/or R are varied.

In section 3 we will discuss at somewhat greater length the results of interferometric studies deriving the stellar radii at various phases of the pulsation cycle and some of what this has taught us about these stars. In section 2 we briefly review recent evolutionary modeling of relevance for Miras; in section 4, light curves and their shapes and secular changes; in section 5, the relation of these stars to RV Tauri stars and to planetary nebulae (if any), and in section 6 we discuss the recent waves of observational data from surveys and what such data can tell us when carefully analyzed.

The mass of a Mira variable is less than or equal to the mass of the star when it was on the main sequence. If we had a reliable formula for the mass loss as a function of mass, radius, luminosity, and so on, then we could integrate over the evolution and get a current mass—but we do not have such a formula (Bowen and Willson 1991; Willson 2000, 2009). If we had very good constraints on their radii we could get estimates for the masses from their pulsation periods; however, as noted above, radii are uncertain.

We do have a handle on the progenitor masses based on the distribution of the Miras in the galaxy—in simplest terms, we assign Miras to an appropriate population (old, young) based on their galactic orbits and on their metallicity. In our galaxy there is a correlation of age (older = lower mass) and metallicity in the sense that the shortest-period Miras have the lowest masses and metallicities. This fits with the age-metallicity correlation in general for field stars, and suggests the progenitors of the 200- to 250-day Miras were main sequence stars with masses near 1 solar mass while the 400- to 600-day Miras come from stars with progenitor masses ≥ 2 solar masses.

The assignment of a progenitor mass to a particular star based on its period can be risky, however, as these stars experience period changes during the course of shell flash cycling (see section 2). A star that normally sits at 500 days will spend up to 10% of its time between 200 and 300 days, for example. So at least the shorter-P population is expected to be contaminated with some higher-progenitor-mass interlopers.

Some recent attempts to derive masses for particular Miras based on interferometric observations have yielded masses close to the expected progenitor masses—something that we expect from the period-luminosity relation but that is nice to have confirmed by a more direct measure. Thus, for example, Lacour *et al.* (2009) find a mass of about 2 solar masses for χ Cyg, consistent with its relatively long period and large amplitude.

2. Modeling Miras with an emphasis on recent progress

There are three categories of models that are relevant for the study of Miras. The first is evolutionary models—following a star as it progressively uses up its nuclear fuels. The second is pulsation modeling, including testing very small perturbations for whether they will grow or damp out, and nonlinear modeling that seeks to determine the full-amplitude behavior of the pulsating star. The third is modeling of the atmosphere and wind, for the dual purposes of reproducing observed light curves, colors, and spectra and of determining the mass loss rates and velocities of the outflow for stars with a range of properties.

Miras are stars at the tip of the asymptotic giant branch; this much was known by the time LAW began to work on these stars in the 1970s. From evolutionary models we know that a star that begins with about 1 solar mass—a typical Mira progenitor star—will convert H to He in its core on the main sequence, taking about 10 Gyr to achieve this very slow "burning" of H. Then, the now predominantly He core will collapse into a degenerate state about the size of Earth and the star will expand to become a red giant. As to why it makes this transition, and fairly quickly, see Renzini and Ritossa (1994) and Iben (1993) for some authoritative arguments; a classic review of the evolution of low to intermediate mass stars is Iben (1967).

The source of energy for the red giant is the conversion of H to He in a shell around its degenerate core; thus the core mass gradually increases as it collects the garbage of the H-burning process. When the core of degenerate He reaches about half a solar mass, conversion of He to C and O begins by the triple-alpha process, where a very temporary He+He pair in the form of unstable ^{8}Be is joined by a third He before it breaks up, and where the resulting C can add one more He to form O. Because the core is degenerate, it does not quickly readjust its structure when this new energy source turns on, and so, the process runs away—we call this the "Helium core flash." While one might expect this to explode the star, it does not, but after a brief disequilibrium the star settles into quiescent He burning as a horizontal branch star or clump giant, the extent to which it leaves the red giant track depending on the mass it has at this point.

When the He in the core has become C and O, the core again settles into a dense, degenerate state and the star once again evolves with increasing L up the "asymptotic giant branch" (AGB), so called because the track gradually converges to the earlier red giant track. Now, the conversion of H to He alternates with the conversion of He to C and O in a series of shell flashes or thermal pulses. (These pulses, which take perhaps 100,000 years to complete, are not to be confused with the pulsations that occur on a time scale of a few months or years.)

Some of the longer period Miras come from higher mass progenitors, 2 $M_{\odot}$ or more. Above about 2.8 solar masses the evolution is slightly different, with no He core flash. For a description of the evolution of these higher masses, see for example Iben (1975) or recent papers by Herwig (e.g. 2008) or Marigo *et al.* (2011, 2008). Grids of models are available online at various sites, including http://stev.oapd.inaf.it/cgi-bin/cmd (see Nasi *et al.* 2008), and an evolution code is available via the MESA project, http://mesa.sourceforge.net/, in two forms—a version for education and exploration and a version for serious research projects.

Red giants and AGB stars have degenerate cores surrounded by very deep convection zones reaching nearly all the way from the core to the surface, or from about 0.01 to 100 times the present solar radius $R_\odot$. Convection is very hard to model, and the behavior of the gas near the edges of the convection zone turns out to be critical for, for example, the contamination of the outer envelope and atmosphere with the products of the nuclear burning. One consequence of such contamination is a gradual increase in the ratio of carbon to oxygen, C/O. Carbon stars have $C/O > 1$ and S stars have $C/O \approx 1$ while most stars, including M-type Miras, have $C/O < 1$. As C/O changes, so does the internal opacity and thus the radius of the star for a given L and M (Marigo and Girardi 2007). Also, because C and O form a very stable molecule, CO, the chemistry of the surface layers, atmosphere, and wind changes dramatically as C/O passes 1, and the kinds of grains that form and assist in the mass loss process also change.

Evolutionary modeling in recent years has focused on the convection process, particularly on the effects of "convective overshoot" mixing material beyond the boundaries of what are otherwise the domains of convective instability. There have also been advances in modeling the variations that occur during He shell flashes. Very little has been done to study the pulsation in more detail—the linear analyses done in the late 1970s and 1980s give useful results, and models with full-up non-linear non-adiabatic pulsation in a fully convective envelope are just out of reach of existing codes and machines, although we expect advances in this area in the next decade.

3. Interferometry and other methods for probing the near-star environment

Interferometry is a means of seeing detail not possible with a single aperture or telescope. Long baseline interferometry, using two or more telescopes, provides the finest spatial resolution. Aperture masking and segment tilting interferometry, that involves dividing the mirror of a very large telescope into smaller sub-apertures (using a mask, for example), has also been used to study Miras (Haniff *et al.* 1992; Woodruff *et al.* 2008, 2009). Earlier papers also cite "speckle interferometry" which is not really interferometry at all but rather a method for getting around the effects of seeing by adding short exposure sub-images together (Labeyrie 1970; Bonneau and Labeyrie 1973).

To resolve the diameters of Miras requires milli-arcsec resolution even for the nearest stars (χ Cyg, R Leo, and Mira). Resolved diameters yield more than just a number; watching the variation of the diameter over the cycle allows for determination of ΔR/R which, with observed velocities, can yield R and thus distance as well as a constraint on pulsation models. Another constraint on models comes from the variation of the apparent angular diameter with the wavelength of the observations, telling us how the atmospheric opacity varies with wavelength and revealing molecule-rich or dust-rich layers in the atmosphere.

Starting from the measurement of o Ceti's diameter by Pease in 1931 using an optical Michelson interferometer, the main goal of these studies was to resolve the controversy on Miras' pulsation modes by measuring their radius. While early results (Tuthill *et al.*1994) measured overly large radii, suggesting that Mira variables should be first overtone pulsators, subsequent analysis (Menesson *et al.* 2002; Perrin *et al.* 2004) found that these diameters were actually biased by the presence of molecular layers (mainly CO and H_2O) a few stellar radii above the photosphere. This breakthrough was enabled by the introduction of a new generation of instruments at world's largest interferometers (VLTI in the southern hemisphere and PTI/CHARA in the north), capable of simultaneously measuring the angular diameter at several broad and narrow bands. These observations can be directly compared with time-dependent hydrodynamic simulations (see, for example, Hillen *et al.* 2012), providing precious observational constraints to stellar models and pulsation theory (Le-Bouquin *et al.* 2009; Martí-Vidal *et al.* 2011) and allowing the exploration of non-equilibrium chemistry in the stellar atmosphere (Paladini *et al.* 2009).

Interferometry with more than two elements also yields information about departures from spherical symmetry in the system. Ragland *et al.* (2006) combined the light from the three apertures of the IOTA interferometer to study the asymmetry of M- and C-type giants with different pulsation properties. Non-zero closure phase (a signature of departure from spherical symmetry) was found in 30% of the targets, or essentially all that were reliably resolved. This asymmetry did not depend on the chemistry of the atmosphere, but was much more common among Miras than other types of long period variables. These asymmetries were located in close proximity of the stellar surface (1.5–2 stellar radii) suggesting an origin either related to the presence of large convective cells in the stellar photosphere, discrete dust clouds formation, or the interaction with a companion. Recent results using aperture synthesis techniques borrowed from radio-interferometry have allowed the reconstruction of true images for a few late-type pulsating variables (for example, χ Cyg in Lacour *et al.* 2009, or RR Aql in Karovicova *et al.* 2011). These images have provided direct evidence for the presence of hot cells in the stellar atmosphere and, combined with radial velocity measurements, have allowed the mapping of speed, density, and position of diverse molecular species in pulsation-driven atmospheres.

Asymmetric dust shells have also been detected around several targets, using either the thermal-infrared long baseline interferometry, or speckle, aperture masking, or segment-tilting techniques on large-aperture telescopes. The recent detection of large, transparent grains as close as 1.5 stellar radii around a number of mass-losing cool giants (including the carbon Mira R Leo, Norris *et al.* 2012) shows the potential of these techniques for probing the dust formation processes that are key for understanding mass loss in Mira variables. While the current angular resolution is not sufficient to measure the motion of these dust layers during the pulsation cycle, the ultimate goal of these observations is to fully characterize the stratification, geometry, and kinematics of the extended Miras' atmosphere, in order to finally understand how mass loss processes are connected to the stellar pulsations, and the root causes for the asymmetries and inhomogeneity observed in their circumstellar environments (Wittkowski *et al.* 2012).

4. Light curves—shapes and secular changes

In addition to the dominant signature of pulsation, Mira variable light curves show an interesting variety of features. The ratio of rise time to cycle length, called *f* by Campbell (1955), varies over a range from about 0.5 down to 0.1 or 0.2 among some of the longest-period Miras. Some of the stars show bumps on their rising or falling branches, and these bumps may come and go over the course of a number of cycles—see, for example, the long-term light curve for χ Cyg. Some of the stars show long-term modulations of their periods or their amplitudes or their mean magnitudes, and these variations are not at all well understood. Some show steady decreases or increases in the periods, often with correlated amplitude changes. Some stars behave like regular Miras for some decades, then fairly abruptly switch to smaller amplitude and/or shorter period variation, causing them to be reclassified as SR stars; it is not clear whether, if we waited long enough, this would happen to a large or a small fraction of our Mira stars.

Templeton *et al.* (2005) looked at a century of AAVSO data for Miras and found that about 10% show significant long-term variability of their periods. The specific variations are, however, all over the map, from apparently sinusoidal (where we need another century to be sure) to apparently steady decrease or increase to abrupt changes from constant to steeply decreasing. While about 1% of the stars are expected to be in a rapidly varying phase of the shell flash cycle, and about 1% of the light-curves show period variations consistent with this explanation, the other 9% of Miras show period variations that are unexplained at present.

5. Relation of Miras to other classes of variables and to planetary nebulae (not)

SR variables differ from Miras in that they have smaller amplitudes, less stable light curves, or are not red giants. Classically, smaller amplitude ones are SRa, less stable ones are SRb, and supergiants are SRc. However, there is substantial evidence that these distinctions are not the best for separating physically different objects, as some SRa appear to be very much like Miras apart from their visual amplitudes; some Miras start behaving erratically and are reclassified as SRb; and the sequence of pulsating AGB stars extends perhaps as high as seven or eight solar masses, making the distinction with SRc also a bit unclear. Some excellent discussions of these classes of objects may be found in the papers by Hron and Kerschbaum (Kerschbaum and Hron 1996; Kerschbaum *et al.* 1996; Hron *et al.* 1997; Lebzelter *et al.* 1995).

The RV Tauri stars are thought to be a post-Mira, possibly pre-planetary-nebula phase of evolution. The light curves have some characteristics in common with some Miras, including double maxima and long term modulations. Not all Miras become RV Tauri stars, only those from the low-mass, low-luminosity, low-metallicity end of the Mira distribution. For a discussion of RV Tauri stars and their relation to Mira variables see Willson and Templeton (2009).

While it is often stated that the same stars that go through a Mira stage later become central stars of planetary nebulae on their way to becoming white dwarf stars, recent work suggests that only a fraction of Miras can become the central stars of PNe and quite possibly none of the classical Miras will do so; it now appears likely some form of binarity is required for all but perhaps the highest mass progenitors of PNe. This conclusion is reached after recognizing that there are only about 15% as many PNe produced per year as there are stars leaving the AGB per year, so at most 15% of the Miras can become the central stars of PNe. Also, the time scale for evolution across the HR diagram after the AGB is too slow for most of the stars, being perhaps long enough for just the higher masses; finally, the fact that most PNe are not spherically symmetric hints at more than a single-star origin for the PNe. See, for example, papers presented at IAU Symposium 283, Planetary Nebulae, an Eye to the Future (held in 2011, proceedings soon to appear).

6. Using photometric surveys to characterize the Mira and carbon star components of populations

One of the most powerful tools to study variable stars populations in our and other galaxies is represented by unbiased multi-epochs photometric surveys at optical and infrared wavelengths. If the distance to the stars is known (for example, for stars in the same galaxy or cluster), it is then possible to plot the absolute magnitude of the stars as a function of log period. Pulsators with different mode and amplitude tend to be distributed on separate sequences, corresponding to different period-luminosity relations. This approach has been famously pioneered by Peter Wood, using the MACHO database for Large Magellanic Cloud (LMC) variables. Miras appear to be distributed at the bright end of a linear sequence (the "C" sequence as defined in Wood 2000) populated by fundamental mode pulsators, with semiregular (SR) variables at the lower, fainter end of the sequence. Recent results from the OGLE-III survey (Soszyński *et al.* 2009, 2011) have confirmed these results and extended them to the Small Magellanic Cloud (SMC). This analysis is less successful for galactic Miras, due to the uncertainties in their distance stemming from the poor quality of their Hipparcos parallax. The Gaia mission, by collecting accurate parallaxes of Mira variables across the whole disk of our Galaxy, will be an invaluable resource towards the calibration of a precise period-luminosity relation, on par to what is currently available for Cepheids (Whitelock 2012). Given their higher intrinsic luminosity than other standard candles (Cepheids and RR Lyrae), Miras can be adopted as probes for galactic structure, and precise distance indicators for the farthest galaxies in the local group.

Optical and near-IR surveys offer only a limited capability in discriminating between M-type and carbon Miras. Thermal infrared photometry, on the other end, allows probing the wavelength range where dust features of mass-losing Miras are stronger, providing an excellent diagnostic for their extended atmosphere. Period-luminosity diagrams made for the LMC using Spitzer Space Telescope data show similar sequences as Wood (2000), but an increased level of separation between carbon- and oxygen-rich Miras (Riebel *et al.* 2010). Color-color and color-magnitude diagrams for both the LMC and the SMC in Spitzer bands (Blum 2006; Boyer 2011) provide an even better separation, and allow studying the statistics of carbon and M-type Miras at different metallicity. The main result of these surveys is the confirmation that a low metallicity environment favors the formation of carbon Miras, due to the smaller number of third dredge-up events that are required to push the C/O ratio above unity. These surveys have also highlighted a population of long period variables with very large infrared excess, usually referred to as "extreme AGB" stars. These objects, presumably associated with very large mass loss rates, in the LMC and SMC are generally characterized by a C-rich dust chemistry. While some of these sources lie at the top of the fundamental mode period luminosity sequence, most of them are overtone pulsators (Riebel *et al.* 2010). This result may, however, be the consequence of observational biases preventing the redder sources to be detected in optical and near-IR surveys like MACHO and OGLE-III.

7. Final comments

As Figure 1 shows, research on Miras has waxed and waned several times during the century of the AAVSO. Generally, new observing capabilities or much improved modeling codes lead to increased activity, followed by a decline in action until the next advance. Studies of individual stars and systems are fed by spectroscopy, interferometry, and detailed atmospheric modeling, while studies of the evolution of the stars and the consequences of mass loss associated with the Mira stage are being advanced by evolutionary modeling, infrared observations, and the statistical analysis of large populations of variable stars.

The AAVSO has played and continues to play a central role in the study of Miras. Most of the papers in Figure 1 are observational; theory papers are a minority. Indeed, in 1972 when LAW's first refereed paper appeared, apparently one eminent astronomer commented "There's a theorist working on Miras. He must be out of his mind!" Nearly every observational study of galactic Miras includes reference to phases or light curves based on data collected by AAVSO or its sister organizations around the world. While the massive studies of Magellanic cloud Miras based on the dark-matter-search byproducts and the huge IR surveys turning up many more of these highly evolved stars described in section 6 mostly do not directly refer to AAVSO data, interpreting the resulting period-luminosity plots and understanding how the Miras and their SR cousins are related will again depend on long-term observations and studies of bright, relatively nearby stars. Future large surveys, including the LSST (Large Synoptic Survey Telescope), will focus on very faint stars and have a duration of observations ranging from a few years to a couple of decades; AAVSO already has a century of data. For stars with periods around a year, a decade is a very short window of observation.

At the present time the observational technologies are expanding our ability to probe the circumstellar environment, to study large samples of stars in a systematic way, and to model the essential physical processes in the interiors, atmospheres, and winds. However, in all of these areas much remains to be done as we are still limited by the capabilities of our computers, detectors, and telescopes.

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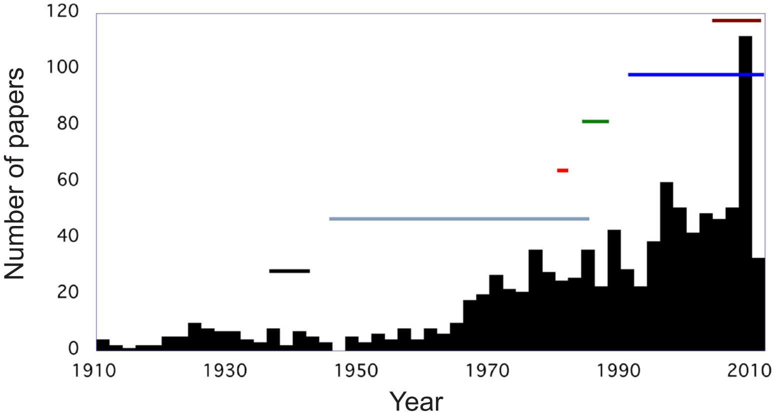

Figure 1. 1,000 refereed papers pulled up by ADS on a search for the words “Mira,” “Long period variable,” or “AGB star” in the title, from 1910 to 2010, plotted as a function of time. Some events that may have influenced the graph include (horizontal bars) WW II 1939–1945, the Palomar era 1949–1992, IRAS 1983, Hipparcos 1989–1993, the dark-matter searches MACHO, OGLE, and so on (starting 1993), and Spitzer (from 2003). IRAS and Spitzer, being infrared missions, definitely boosted interest in these stars. A big surge also came about three years after the beginning of the MACHO, OGLE, and similar projects.

Non-Mira Pulsating Red Giants and Supergiants

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Abstract We review the present understanding of (i) non-Mira pulsating red giants, that is, those with visual amplitudes less than 2.5 magnitudes, and (ii) pulsating red supergiants. We also identify some unsolved problems with these stars. We highlight the contributions by skilled amateur astronomers in the AAVSO and other organizations, using visual, photoelectric, and CCD photometry.

1. Definition

This paper reviews the development of our present understanding of pulsating red giants (PRGs) with V amplitudes less than 2.5. For convenience, we shall call them smaller-amplitude pulsating red giants or SAPRGs. Those with larger amplitudes are classified in the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1985) as Mira stars, and are reviewed by Willson (2012) elsewhere in this volume. The choice of Δmag = 2.5 as a cutoff is somewhat arbitrary. First of all, the amplitude is highly wavelength dependent; a Mira star can have a visual amplitude of almost ten magnitudes, and a bolometric amplitude of less than two magnitudes. This phenomenon is due to the behavior of molecular bands in the spectrum, such as TiO; it is therefore dependent on the chemical composition of the atmosphere. Furthermore: there are stars with amplitudes equal to 2.5, and stars whose amplitude varies from above to below 2.5.

Red stars of luminosity class II and I (bright giants, and supergiants) show variability properties similar to those of red giants. We shall discuss pulsating red supergiants in section 9.

Henry *et al.* (2000) carried out a photometric survey of 187 G and K giants, and concluded that giants cooler than K5 are all variable, due to radial pulsation.

Some warmer giants are also pulsating variables, but the pulsation is more similar to that of the sun than to the K5-M-type pulsators. Here we exclude the discussion of G-K giants, for which asteroseismology with the Kepler space telescope has completely revolutionarized the field (see, for example, Bedding *et al.* 2010, 2011).

There are a dozen excellent essays on Mira and semiregular/SAPRG variables in the "Variable Star of the Season" archives on the AAVSO website. There are also many relevant papers in the proceedings of the *Biggest, Baddest, Coolest Stars* workshop (Luttermoser *et al.* 2009).

2. Discovery and observation

Variable star observing was initially done visually. Variables with amplitudes of 2.5 are easy to detect and study visually, those with smaller amplitudes less so. Many bright red giants (and other stars) were initially suspected of variability—incorrectly.

Photographic monitoring programs, such as that at the Harvard College Observatory, led to the discovery and study of large numbers of Miras and semiregulars, leading to the determination of periods of hundreds and thousands of days. Many of these stars have been in the AAVSO visual observing program for a century. Only with such systematic, long-term monitoring is it possible to study the variability of these stars on all relevant time scales.

By 1930, photoelectric photometry of PRGs was well underway; Stebbins and Huffer (1930) published a photoelectric study of the variability of such stars, carried out at Washburn Observatory. During the 1970s, Olin Eggen (1977 and references therein) published several photoelectric studies of SAPRGs of various kinds, with a view to determining their kinematical, physical, and pulsational properties.

In the 1980s, long-term photoelectric photometry of SAPRGs was carried out both by the AAVSO PEP Program (Percy *et al.* 1996) and by robotic telescopes (for example, Percy *et al.* 2001). By the 1990s, massive CCD surveys of SAPRGs in galactic fields and in the Magellanic Clouds were being carried out; some of these are described in section 10. See Figure 1 for examples of PEP V light curves of a selection of SAPRGs.

3. Incidence

All M-type giants (and supergiants) are variable, as are mid- to late-K giants—but with very small amplitude. Pulsating red giants are the most numerous variables among the bright stars. Of the 9,096 stars in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982), 545 are M type or equivalent, and all these are giants or supergiants. There are an additional 2,233 K stars, almost all giants or supergiants. About ten percent of the stars in the catalogue are K5-M9 giants, almost all of them SAPRGs, so they are the most numerous variables among the bright stars (followed closely by pulsating B/Be stars).

In the *General Catalogue of Variable Stars* (on-line version, Samus *et al.* 2012), there are 7,587 Mira or Mira: stars, 6,063 SR stars, and 3,746 Lb or Lc or L: stars.

4. Classification

Pulsating red giants, other than Mira (M) stars, are classified in the GCVS (Kholopov *et al.* 1985) as semiregular (SR) or irregular (L); SR are subdivided into SRa and SRb (giants), where SRb have less obvious periodicity than SRa, and SRc (supergiants). There are also SRs variables which are SR variables with "short" periods (generally 30 days or less); about 100 stars are placed in this (arbitrary) class. L are divided into Lb (cool giants) and Lc (cool supergiants).

These types are defined thus: SR: "...giants or supergiants of intermediate and late spectral types showing noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities...." L: "Slow irregular variables. The light variations of these stars show no evidence of periodicity, or any periodicity present is very poorly defined, and appears only occasionally...." Clearly these definitions are qualitative at best, but they were reasonable in the early days of variable star astronomy, especially if they were based on dense, long-term visual or photographic light curves.

Eggen (1977 and references therein) obtained extensive photoelectric photometry of pulsating red giants, and classified them as large-amplitude (LARV), medium-amplitude (MARV), small-amplitude (SARV), and σ Lib stars with very small amplitude. Again: there is actually a continuous spectrum of amplitudes from 2.5 mags to very small; the subclasses are arbitrary.

It is also useful to classify red giants according to their atmospheric composition: M (normal oxygen-rich), C (carbon rich), or S (intermediate).

An important classification is by pulsation mode. This can be done if the star is pulsating in two or more modes, or if its luminosity and temperature are both known, as described below.

5. Physical properties

SAPRGs are solar-type stars which, towards the ends of their lives, are exhausting the hydrogen fuel in their cores, and expanding and cooling to become red giants. They occupy the red giant branch in the Hertzsprung-Russell Diagram. Subsequently, they ignite helium fusion in their cores; as they exhaust the helium, they again expand and cool to become "asymptotic red giants" because they occupy the asymptotic giant branch in the HRD. In the sun, energy is transported by convection in a "convection zone" in the outer layers. In a red giant, the convection zone extends deep in the star. Convection is a poorly-understood process in astrophysics, so theoretical models of PRGs are uncertain.

One consequence of the convection is that, in some red giants, material which has been processed by nuclear reactions is transported to the surface, and the spectrum of the star shows strong lines of carbon. The star is a carbon star, as compared with normal red giants whose composition is similar to that of the sun. Indeed, the spectra of red giants can be very complex because, at their low temperatures, molecules such as TiO are very abundant in their atmospheres.

The best-understood SAPRGs are those near enough to have accurate *Hipparcos* parallaxes. They also have negligible reddening, especially at near-infrared wavelengths. The excellent study by Tabur *et al.* (2010) shows the power of studying nearby SAPRGs.

6. Pulsation properties

The stars that we are reviewing have periods between a few days and a few hundred days. For stars with known physical properties (especially distance), these periods can be shown to be low-order radial pulsation periods (Percy and Parkes 1998; Percy and Bakos 2003). This can also be shown by stars with two or more pulsation modes (Kiss *et al.* 1999: larger-amplitude SAPRGs, Percy *et al.* 2003: smaller-amplitude SAPRGs), since period ratios can be determined observationally, and compared with theoretical pulsation models of the stars. The radial pulsation can be confirmed by spectroscopic radial velocity measurements (Cummings 1999).

Massive surveys of stars in the Magellanic Clouds, or of nearby stars with known physical properties (discussed below) show that the stars obey sequences of period-luminosity relations, corresponding to different low-order radial modes.

The amplitudes of these stars range downward from 2.5 magnitudes (by definition) to the limits of detectability; the majority of red giants have pulsation amplitudes of only a few hundredths of a magnitude.

Kiss *et al.* (1999) have carried out a comprehensive time-series analysis of AAVSO visual observations of a large sample of SR variables; most have one period; some have two periods; and a few have three periods. Their sample included five L-type variables: AA Cas, DM Cep, TZ Cyg, V930 Cyg, and CT Del. They found a period of 367 days for DM Cep (possibly an artifact), 247 days for V930 Cyg, and 138 and 79 days for TZ Cyg, and apparently no periods for the other two stars. Some of the stars in this study showed significant changes in amplitude (Kiss *et al.* 2000). Percy *et al.* (2003) also found significant changes in amplitude in their multi-mode pulsators, on time scales of 2,000–3,500 days.

Percy and his students are currently analyzing several dozen SRa/SRb stars not analyzed by Kiss *et al.* (1999), using visual observations in the AAVSO

International Database (AID). These stars exhibit a very wide range of behavior, from highly periodic, to irregular, to non-variable.

As for the irregular (L-type) variables, Percy and Terziev (2011) analyzed visual observations of 125 such stars in the AID. They found 20 to be periodic, 18 to be possibly periodic, but with small amplitude, 55 to be truly irregular, some with amplitudes less than 0.1, and 32 to be probably non-variable.

7. Long secondary periods

Astronomers have known for decades that large numbers of PRGs have long secondary periods (LSPs), an order of magnitude longer than the primary pulsation periods (Payne-Gaposchkin 1954; Houk 1963). When period-luminosity relations can be formed, it is clear that the LSPs are correlated with the primary periods, or both are correlated with some property of the star such as its radius. The nature and cause of the LSPs is not known. Peter Wood and his collaborators have investigated a multitude of possible causes; most recently, Nicholls *et al.* (2009) have examined both physical and geometrical mechanisms for producing such periods, and conclude “We are unable to find a suitable model for the LSPs....”

8. Importance of SAPRGs

Mira variability plays an important role in mass loss and evolution of stars with masses of approximately 1 to 8 solar masses, and therefore in the general recycling of matter in galaxies. SAPRGs do not undergo significant mass loss. However, because of their shorter periods and smaller amplitudes, SAPRGs are easier to analyze in detail, and their physical properties are easier to determine—especially for nearby stars. It may therefore be possible to use them to refine evolution and pulsation models of these stars. Since they obey period-luminosity relations, it may also be possible to use them for distance determination.

9. Pulsating red supergiants

All red supergiants are pulsating variables; Antares, Betelgeuse, and μ Cephei are well-known examples. These are of special interest to the public because of their brightness and color, and their “imminent” demise as supernovae. They are also of astrophysical interest because of their crucial role in stellar evolution and mass loss, and therefore in galactic ecology. Also: because these stars are very luminous, there have been many studies of possible period-luminosity relations in these stars (Stothers 1969; Pierce *et al.* 2000).

The most comprehensive study of light variations in pulsating red supergiants was published by Kiss *et al.* (2006), who analyzed AAVSO data for forty-eight supergiants, collected over the last century. They were able to measure two significant and distinctly different periods for more than a third of the studied stars (Figure 2). Theoretical models imply low-order radial pulsations for the shorter periods, while periods greater than 1,000 days form a period-luminosity relation that is similar to that of the long secondary periods of the asymptotic giant branch stars. Despite the well-defined periodicities, red supergiant variability is far from being predictable: there is strong evidence that oscillations are constantly affected by stochastic processes, adding a certain level of irregularity that is very similar to the pulsation characteristics seen in the sun.

Systematic, sustained spectroscopic observations have also provided useful insight into both the regular and the chaotic motions in red supergiants such as Betelgeuse (Gray 2008).

10. Massive surveys of pulsating red giants in selected starfields

Time-domain surveys have become one of the hottest topics in observational astronomy with the advent of the largely autonomous or fully remote-controlled telescopes with digital detectors. The flagship surveys included the MACHO, OGLE, and EROS projects, each observing millions of stars towards the Magellanic Clouds and the Galactic Bulge, hunting for unpredictable brightenings and fadings of background stars caused by the gravitational microlensing effect of a massive object passing in front of the stars. Of these, the OGLE (Optical Gravitational Lensing Experiment) project, so far with three distinct phases of operations and the fourth in progress, has been the most successful in making a full census of pulsating red giants in the Magellanic Clouds. The importance of these objects lies in the fact that all stars are located at a known distance and the luminosities are thus well known. Recently, Soszyński *et al.* (2009) and Soszyński *et al.* (2011) presented the most extensive catalogues for the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), with almost 92,000 long period variables in the LMC and 20,000 in the SMC, drawing an exquisite picture of red giant variability in whole galaxies. These samples are dominated by short-period (less than 100 days) and small-amplitude (less than 0.5 magnitude in the *I* band) semiregular variables, identified by Kiss and Bedding (2003) as stars still evolving on the first red giant branch, when their energy production is located in hydrogen-burning shells around the yet-to-be-ignited helium cores.

The most fruitful approach so far has been the study of period-luminosity (PL) relations in the Magellanic Clouds. The rich structure in the period-absolute magnitude plane has been studied by many authors, see Soszyński *et al.* (2007) and references therein. OGLE data analyzed by Soszyński *et al.* (2007) revealed fourteen different period-luminosity sequences, some of them consisting of three closely spaced ridges. The multitude of the PL relations comes partly from the presence of many different modes of pulsations, partly from the full sample being a mixture of red giants with different chemical composition and evolutionary state.

The latest and still ongoing survey producing M giant light curves never seen before is that of the Kepler space telescope, which has been observing several thousand red giants since mid-2009 in its fixed field of view in the constellations Cygnus and Lyra. The unprecedented light curves—in most cases well into the sub-millimagnitude range in precision—are becoming more and more useful for the semiregular variables as their time-span becomes longer by each day of operations. Kepler targets include such well-known bright variable stars as the semiregular variable AF Cyg and the symbiotic semiregular star CH Cyg, with promising results to come soon.

11. Surveys of nearby pulsating red giants with known physical properties

Tabur *et al.* (2010) presented the results of a unique five and a half-year photometric campaign that monitored 247 southern bright semiregular variables with useful Hipparcos parallaxes. Using the periods from the light curves and geometric distances, they constructed the period-luminosity sequences of the sample, revealing a negligible difference between the red giant PL-relations in the two Magellanic Clouds and in the Milky Way. A comparison of other pulsation properties, including period-amplitude and luminosity-amplitude relations, has shown that pulsation properties of stars on the first red giant branch are consistent and universal, indicating that their PL-sequences are suitable as high-precision distance indicators. Also, M-type giants with the shortest periods (less than 10 days) bridge the gap between G and K giant solar-like oscillations and M-giant pulsation, revealing a smooth continuity as we ascend the giant branch.

12. Current problems and directions in SAPRG research

- Studies of multiperiodicity, mode switching, amplitude and period variations in these stars. Can these be linked with evolution?
- What is the source of the semiregularity or irregularity?
- Specifically: what is the relative role of kappa-mechanism pulsation, and convection, and how does this vary with the physical properties of the star?
- What determines which mode(s) will be excited in a given star?
- What is the nature and cause of the long secondary periods?
- How can we use pulsating red giants as distance indicators and tracers of Galactic structure?

All the surveys mentioned above have nicely demonstrated that studying ensemble properties is a powerful new way of scientific research, one that has only become available in the recent years of enormous technical development. We can expect that answers to most of these questions will be found by further studies of large samples or extremely sophisticated analyses of individual stars.

13. The roles of amateur observations

The time-scale of M giant variability is so long that meaningful analyses require many years, often decades of observations. The longest, homogeneous surveys with modern instrumentation are barely longer than ten years in time-span. Consequently, the role the amateurs play will remain very important in the studies of long period variables. Even though the visual observations have very limited accuracy, their real strength comes from being homogeneous for many cycles of the pulsations. For example, for a semiregular star with a dominant pulsation period of 200 days (think of Z UMa and alikes), detecting the effects of convection on the oscillations requires several decades of data, something that is only possible with the coordinated work of amateur astronomers. On the other hand, an increasing number of amateurs are getting involved in photometric measurements, either with CCDs or DSLR cameras. These enable the observers to improve accuracy by one or two orders of magnitude compared to the visual data, hence detecting variability at much lower amplitudes (and usually with much shorter periods) than ever seemed to be possible for non-professionals.

In conclusion, pulsating red giants have always been prime targets for amateurs and they will remain so. While large surveys have been extremely successful in finding tens of thousands of (faint) pulsating red giants, the bright end is still problematic, with stars that saturate in almost every survey data. We think this field will keep being an important meeting point of amateurs and professionals, where the shared interest in these beautiful stars will bring us together in the forthcoming years.

14. Acknowledgements

We thank the AAVSO observers for a century of measurements, and the AAVSO staff for making them available. JRP thanks his students for their hard work and inspiration, and the Natural Sciences and Engineering Research Council of Canada for support of his research. LLK has been supported by the "Lendület" Young Researchers' Program of the Hungarian Academy of Sciences and the Hungarian OTKA Grants K76816, MB08C 81013, and K83790.

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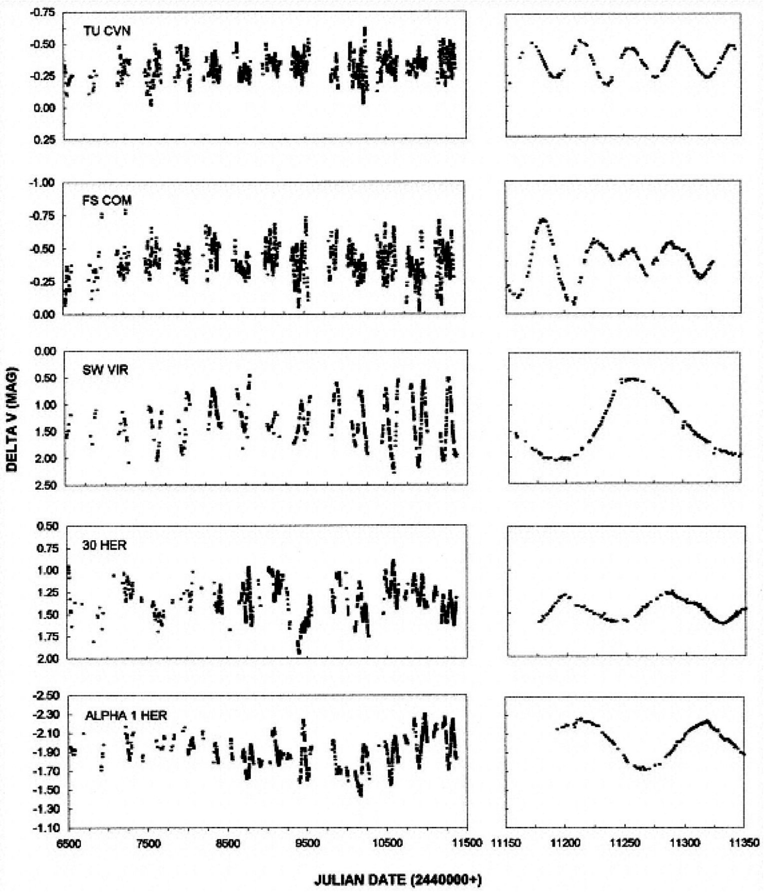

Figure 1. A selection of PEP V light curves of SAPRGs; left: 5,000 days, right: 200 days. TU CVn has a single short period; FS Com is multiperiodic; SW Vir has a longer period and larger amplitude; all of the stars show variability on both shorter and longer periods. From Percy *et al.* (2001).

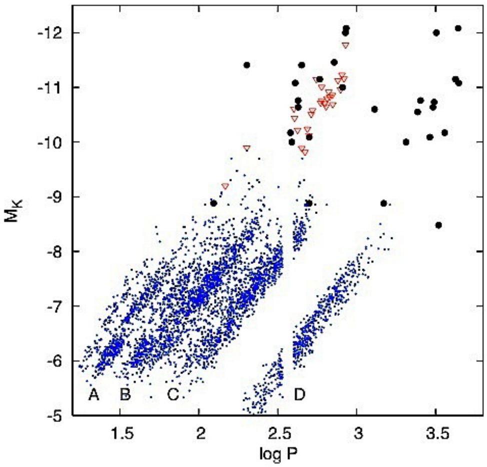

Figure 2. Period-luminosity (absolute K magnitude) relations for red supergiants in our galaxy (black circles) and the Large Magellanic Cloud (red triangles) and for red giants in the LMC (blue dots), the latter taken from the MACHO database. See Kiss *et al.* (2006) for further details. Note the separate PRG period-luminosity relations, corresponding to different pulsation modes; the supergiant sequences are extensions of these. Sequence D corresponds to long secondary periods.

What Are the R Coronae Borealis Stars?

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Abstract The R Coronae Borealis (RCB) stars are rare hydrogen-deficient, carbon-rich, supergiants, best known for their spectacular declines in brightness at irregular intervals. Efforts to discover more RCB stars have more than doubled the number known in the last few years and they appear to be members of an old, bulge population. Two evolutionary scenarios have been suggested for producing an RCB star, a double degenerate merger of two white dwarfs, or a final helium shell flash in a planetary nebula central star. The evidence pointing toward one or the other is somewhat contradictory, but the discovery that RCB stars have large amounts of ^{18}O has tilted the scales towards the merger scenario. If the RCB stars are the product of white dwarf mergers, this would be a very exciting result since RCB stars would then be low-mass analogs of type Ia supernovae. The predicted number of RCB stars in the Galaxy is consistent with the predicted number of He/CO WD mergers. But, so far, only about sixty-five of the predicted 5,000 RCB stars in the Galaxy have been discovered. The mystery has yet to be solved.

1. Introduction

R Coronae Borealis (R CrB) was one of the first variable stars identified and studied. It received the "R" which designates it as the first variable star discovered in the constellation Corona Borealis. Its brightness variations have been monitored since its discovery over 200 years ago (Pigott and Englefield 1797). Early spectra showed variations in the strengths of the Swan bands of C_2 (Espin 1890) and evidence of the absence of hydrogen was soon detected (Ludendorff 1906; Cannon and Pickering 1912), although not confirmed until later (Berman 1935; Bidelman 1953). In addition, the explanation behind the large declines in brightness, the production of thick clouds of carbon dust, was deduced very early on (Loreta 1935; O'Keefe 1939). But the stellar evolution that produced R CrB remains mysterious.

The R Coronae Borealis (RCB) stars are a small group of carbon-rich supergiants. About sixty-five RCB stars are known in the Galaxy and over twenty in the Magellanic Clouds. Their defining characteristics are hydrogen deficiency and unusual variability. RCB stars undergo massive declines of up to 8 magnitudes due to the formation of carbon dust at irregular intervals. The RCB stars can be roughly divided into a majority group which share similar abundances, and a small minority of stars, which show extreme abundance ratios, particularly Si/Fe and S/Fe (Asplund *et al.* 2000). There are also six hydrogen-deficient carbon (HdC) stars that are RCB stars spectroscopically, but do not show declines in brightness or IR excesses (Warner 1967; Goswami *et al.* 2010; Tisserand 2012).

Two scenarios have been proposed for the origin of an RCB star: the double degenerate (DD) and the final helium-shell flash (FF) models (Iben *et al.* 1996; Saio and Jeffery 2002). The former involves the merger of a CO- and a He-white dwarf (WD) (Webbink 1984). In the latter case, thought to occur in 20% of all AGB stars, a star evolving into a planetary nebula (PN) central star undergoes a helium flash and expands to supergiant size (Fujimoto 1977). Three stars (Sakurai's Object, V605 Aql, and FG Sge) have been observed to undergo FF outbursts that transformed them from hot evolved PN central stars into cool giants with spectroscopic properties similar to RCB stars (Clayton and De Marco 1997; Gonzalez *et al.* 1998; Asplund *et al.* 1998, 1999, 2000; Clayton *et al.* 2006).

Recent observations and population synthesis models imply that there are a significant number of close DD binaries in the Galaxy. A majority of binaries, close enough to interact sometime during their evolution, will end up as DD systems where both stars are WDs (Nelemans *et al.* 2005; Badenes and Maoz 2012). If the resulting DD system has a short enough period ($\lesssim$ 0.2 hr) it will enter a phase of mass-transfer and may merge in less than a Hubble time due to the loss of energy due to gravitational radiation. This may result in a SN Ia explosion if the total mass of the DD system is greater than the Chandrasekhar limit, or in RCB and HdC stars if the mass is lower than this limit (Webbink 1984; Yungelson *et al.* 1994).

Recently, the surprising discovery was made that RCB stars have ^{16}O/^{18}O ratios that are orders of magnitude lower than for any other known stars (Clayton *et al.* 2005, 2007; García-Hernández *et al.* 2010). Greatly enhanced ^{18}O is evident in every HdC and RCB that has been measured and is cool enough to have detectable CO bands. IR spectra of Sakurai's Object, obtained when it had strong CO overtone bands, showed no evidence for ^{18}O (Geballe *et al.* 2002). Therefore, Sakurai's Object and the other FF stars on the one hand, and most of the RCB and HdC stars on the other hand, are likely to be stars with different origins. No overproduction of ^{18}O is expected in the FF scenario but in a DD merger, partial helium burning may take place leading to enhanced ^{18}O (Clayton *et al.* 2007). This strongly suggests that the RCB stars are the results of mergers of close WD binary systems. These discoveries are important clues which will help to distinguish between the proposed DD and FF evolutionary pathways of HdC and RCB stars.

There have been three conferences devoted to hydrogen-deficient stars held in 1985, 1995, and 2007. The proceedings of these conferences contain many papers concerning the RCB stars and related objects (Hunger *et al.* 1986; Jeffery and Heber 1996; Werner and Rauch 2008). The last general review of the RCB stars appeared sixteen years ago (Clayton 1996). Since then, the number of RCB stars known has more than doubled and about 250 papers have been written. This review will concentrate on the advances in our knowledge of RCB stars that have been made since 1996.

2. How to identify an RCB star

2.1. The light curve

As seen in Figure 1, the RCB light curve is unique. No other type of star displays such wild, irregular, large amplitude variations (see, for example, Payne-Gaposchkin and Gaposchkin 1938; Clayton 1996).

- An RCB star will stay at uniform brightness at maximum for months or years. Then, there will be a sudden drop in brightness of more than three magnitudes taking a few days or weeks, followed by a recovery to maximum light, which is typically slower, taking months or years. Notice the latest decline of R CrB, itself, shown in Figure 1. After over 1,000 days at maximum, it plunged seven magnitudes in less than 100 days and has stayed in a deep decline for almost 2,000 days.

- The characteristic time between declines in RCB stars is typically about 1,000 days, but there is a wide range in activity among the RCB stars (Feast 1986; Jurcsik 1996).

- The stars also show regular or semiregular pulsations with a small amplitude ($\Delta V \lesssim 0.1$ magnitude) and periods of 40–100 days (see, for example, Lawson *et al.* 1990; Percy *et al.* 2004).

2.2. The spectrum

Figure 2 shows the maximum light spectra of the RCB stars, S Aps ($T_{eff} \sim 5000$ K) and RY Sgr ($T_{eff} \sim 7000$ K), and the carbon star, RV Sct.

- The RCB spectra are characterized by weak or absent hydrogen Balmer lines, and weak or absent CH λ4300 band. But, there is a wide range of hydrogen abundance in the RCB stars. For example, V854 Cen shows significant hydrogen in its spectrum (Kilkenny and Marang 1989; Lawson and Cottrell 1989). There is an anti-correlation between hydrogen and metallicity in the RCB stars (Asplund et al. 2000).

- The RCB star spectrum contains many lines of neutral atomic carbon. The cooler stars ($T_{eff} < 6000$ K) show strong absorption bands of C_2 and CN, as seen in S Aps, but in the warmer stars, such as RY Sgr, these bands are weak or absent. A warm RCB star can appear almost featureless in the visible, having no Balmer lines, helium lines, or molecular bands.

- In most, but not all, RCB stars, the abundance of ^{13}C is very small. This can be seen in the two wavelength sections shown in Figure 2. The isotopic Swan bands of C_2 are separated in wavelength, so the spectra can be inspected to see the relative strengths of $^{12}C^{12}C$ λ4737.0 and $^{12}C^{13}C$ λ4744.0 in the blue, and $^{12}C^{12}C$ λλ6059, 6122, 6191, and $^{12}C^{13}C$ λλ6100, 6168 in the red (Lloyd Evans *et al.* 1991; Kilkenny *et al.* 1992; Alcock *et al.* 2001).

- The strength of the CN λ6206 band compared to the $^{12}C^{12}C$ λ6191 band is relatively weak in the RCB stars compared to the carbon stars (Lloyd Evans *et al.* 1991; Morgan *et al.* 2003).

The description above applies to RCB spectra at or near maximum light. In deep declines, a rich narrow-line emission spectrum appears consisting of lines of neutral and singly ionized metals, and a few broad lines including Ca II H and K, and the Na I D lines (Payne-Gaposchkin 1963; Alexander *et al.* 1972; Feast 1975). The decline spectrum is described in detail in Clayton (1996). More recent papers detailing the decline spectra of RCB stars include Rao and Lambert (1997), Rao *et al.* (1999), Clayton *et al.* (1999a), Skuljan and Cottrell (1999), Lawson *et al.* (1999), Rao and Lambert (2000), Clayton and Ayres (2001), Kipper (2001), Skuljan and Cottrell (2002a, 2002b), Rao *et al.* (2004), Kipper and Klochkova (2006b), and Rao *et al.* (2006). A small subclass of RCB stars is much hotter with effective temperatures of about 20,000 K. See De Marco *et al.* (2002, and references therein) for a description of their spectra.

2.3. Infrared emission

- Every RCB star has an IR excess, from the K-band to far-IR wavelengths due to warm circumstellar dust ($T_{eff} \sim 400$–1000 K) (Feast *et al.* 1997). Most Galactic RCB stars have been detected by 2MASS, IRAS, AKARI, and WISE (see, for example, Walker 1985; Tisserand 2012). Recently, two RCB stars, R CrB and HV 2671, were detected out to 500 μm by the Herschel Space Observatory (Clayton *et al.* 2011a, 2011b).

- The mid-IR spectra of RCB stars are mostly featureless since there are usually no silicate, SiC, or polycyclic aromatic hydrocarbon (PAH) features present (Lambert *et al.* 2001; Kraemer *et al.* 2005; García-Hernández *et al.* 2011a). However, V854 Cen and DY Cen do show emission features attributed to PAHs and C_{60} (Lambert *et al.* 2001; García-Hernández *et al.* 2011b).

3. The population of RCB stars

Clayton (1996) listed thirty-four Galactic and three LMC RCB stars. Since then, the number of confirmed RCB stars has almost doubled in the Galaxy, and greatly increased to over twenty in the Magellanic Clouds. Tables 1 and 2 list all the RCB and HdC stars known in the Galaxy and the Magellanic Clouds which have been confirmed by spectral classification, light curve behavior, and IR excesses. V2331 Sgr is a strong new candidate from its light curve and IR excess, but does not have a spectrum (Tisserand *et al.* 2012). EROS2-LMC-RCB-6, and OGLE-GC-RCB-2 are also good candidates that do not have spectra (Tisserand *et al.* 2009, 2011; Tisserand 2012). V391 Sct was originally classified as a dwarf nova that brightened from V = 17 to 13 magnitudes. But Brian Skiff (2010) suggested that this star might be an RCB star based on brightness variations seen on a few plates. This is supported by the ASAS-RCB-3 light curve which, while it does not show any declines, reveals that the star is normally V = 13, not V = 17. Its spectrum shows it to be a warm RCB star, very similar to RY Sgr and it has an IR excess (Tisserand *et al.* 2012). A strong spectroscopic candidate, KDM 6546, has no light curve (Morgan *et al.* 2003). It was previously classified as a CH star (Hartwick and Cowley 1988). Three stars included in the RCB list of Clayton (1996), GM Ser, V1773 Oph, and V1405 Cyg, had not been spectroscopically confirmed (Kilkenny 1997). GM Ser is not an RCB star (Tisserand *et al.* 2012). The other two stars are still unconfirmed and so are not included in Table 1. Another star, MACHO 118.18666.100, previously identified as an RCB star (Zaniewski *et al.* 2005), has been shown to be misidentified (Tisserand *et al.* 2008).

There are also four hot (15,000–20,000 K) RCB stars known. One, HV 2671, was recently discovered in the LMC (Alcock *et al.* 1996). The three Galactic stars are, V348 Sgr, MV Sgr, and DY Cen. These stars are all hydrogen-deficient, carbon-rich stars, and have RCB-type light curves (Clayton 1996; De Marco *et al.* 2002; Clayton *et al.* 2011b). DY Cen and MV Sgr have the typical RCB-star large helium abundances, but V348 Sgr and HV 2671 are in general agreement with a born-again post-AGB evolution, and are similar to Wolf-Rayet central stars of PNe with carbon and helium being close to equal in abundance (De Marco *et al.* 2002). So DY Cen and MV Sgr seem to be related to the cooler RCB stars, but V348 Sgr and HV 2671 may be [WC] central stars. The six known HdC stars are also listed in Table 1. One of these stars, HD 175893, may be an RCB star since it has an IR excess (Tisserand 2012). However, no declines have been observed for this star.

There is a small group of stars, of which DY Per is the prototype, that resemble the RCB stars (Alksnis 1994). These stars have very deep declines at irregular intervals, but the rate of fading is very slow and the shape of the declines is much more symmetrical than the typical RCB decline (Alcock *et al.* 2001). DY Per is significantly cooler ($T_{\mathrm{eff}} \sim 3500$ K) than the coolest RCB stars (Keenan and Barnbaum 1997).

Both of the evolutionary theories, the DD and the FF scenarios, suggest that the RCB stars are an old population (Clayton 1996). The distribution on the sky and radial velocities of the RCB stars tend toward those of the bulge population (Drilling 1986; Cottrell and Lawson 1998; Zaniewski *et al.* 2005). Tisserand *et al.* (2008) determined that the RCB stars follow a disk-like distribution inside the Bulge with a scale-height <250 pc. The distribution of the RCB stars on the sky, including the new expanded sample from Table 1, is plotted in Figure 3. There is no direct measurement of the distance to any Galactic RCB star (Alcock *et al.* 1996). But, now that significant numbers of RCB stars have been identified in the LMC, whose distance is well known, the absolute brightness of the RCB stars has been determined to range from $M_V = -3$ for stars with $T_{\rm eff} \sim 5000$ K to -5 for stars with $T_{\rm eff} \sim 7000$ K (Feast 1979; Alcock *et al.* 2001). HV 2671, the hot RCB star in the LMC, has $M_V \sim -3$ (Alcock *et al.* 2001; Tisserand *et al.* 2009).

Webbink (1984) suggested that the DD scenario would result in a population of about 1,000 Galactic RCB stars. Iben *et al.* (1996) put the Galactic RCB population resulting from the same scenario at about 300 stars, and calculated that the FF scenario would imply anywhere from 30 to 2,000 RCB stars at any given time. All of the evidence thus far suggests that there are many more than the ~65 known RCB stars in the Galaxy (see, for example, Zaniewski *et al.* 2005). The number of RCB stars expected in the Galaxy can be extrapolated from the LMC RCB population, using the method described by Alcock *et al.* (2001), and including all the new LMC stars. This implies a population of RCB stars in the Galaxy of almost 5,700. RCB stars are thought to be ~0.8–0.9 $M_\odot$ from pulsation modeling (Saio 2008), and this mass agrees well with the predicted mass of the merger products of a CO- and a He-WD (Han 1998). On the other hand, FF stars, since they are single WDs, should typically have masses of 0.55–0.6 $M_\odot$ (Bergeron *et al.* 2007).

The merger rate of He+CO DDs is predicted to be $\sim 0.018\ {\rm yr}^{-1}$ in the Galaxy (Han 1998). As of 1988, only one such DD system was actually known to exist (Saffer *et al.* 1988). The SPY project and other surveys have studied many WDs for evidence of binarity and the number of known DD systems is now ~100 (see, for example, Nelemans *et al.* 2005; Kilic *et al.* 2010, 2011; Parsons *et al.* 2011; Brown *et al.* 2011; Badenes and Maoz 2012). To see how well this number matches the predicted number of RCB stars in the Galaxy, we need to estimate how long an RCB star formed from a DD merger will live. This lifetime can be calculated as, $t = \Delta M \times X \times Q/L$, where L is the luminosity of RCB stars, ΔM is the accreted mass of He, X is the mass fraction of He in the accreted material, and Q is the energy generated when one gram of He is burned to ^{12}C. Assuming that $Q \sim 7 \times 10^{18}$ erg, $\Delta M = 0.1 M_\odot$, $X = 0.3$, and $L = 10{,}000\, L_\odot$, $t \sim 3 \times 10^5$ yr. Using the estimate of Han (1998) for the production of RCB stars from DD mergers, then the predicted population of RCB stars in the Galaxy at any given time would be ~5,400 which agrees well with the number extrapolated from the LMC above.

4. Evolutionary history

Table 3 summarizes the observational data that must be addressed by evolutionary models of RCB stars (Asplund *et al.* 2000, Jeffery *et al.* 2011). They are discussed below with respect to the FF and DD models. Two entries, the high abundance of silicon and sulphur, and the anti-correlation of hydrogen with iron, cannot be well explained by either scenario. The condensation of certain elements into dust has been suggested for the Si/S problem, although it is unclear that this would work (Asplund *et al.* 2000). The H/Fe anti-correlation is unexplained but Sakurai's Object follows the same trend.

4.1. Do RCB stars evolve from final flash stars?

The light curve behavior and spectroscopic appearance of V605 Aql in 1921 and more recently of Sakurai's Object are reminiscent of the RCB class. There are, however, several reasons why FF stars are unlikely to be the evolutionary precursors of the majority of RCB stars. The FF objects have deeper light declines (> 10 magnitudes) than do RCB stars (~ 8 magnitudes). This may be due to the fact that RCB stars have more dust lying near the star which scatters light around the intervening dust cloud. This may account for the flat-bottom appearance of deep RCB declines. See Figure 1. The abundances of FF objects, shortly after the outburst, do appear similar to those of RCB stars, except for some interesting differences. First there are significant amounts of ^{13}C present in Sakurai's Object, but not in most RCB stars. In the two years after it appeared, Sakurai's Object had $^{12}C/^{13}C \sim 4$ (Pollard *et al.* 1994; Asplund *et al.* 1999; Pavlenko *et al.* 2004). In general, RCB stars have $^{12}C/^{13}C \geq 100$. However, a few RCB stars do have detectable ^{13}C including both majority and minority stars. V CrA, V854 Cen, VZ Sgr, and UX Ant have measured $^{12}C/^{13}C < 25$ (Rao and Lambert 2008; Hema *et al.* 2012). Second, there is no sign of ^{18}O in the IR CO bands of Sakurai's Object (Eyres *et al.* 1998). Finally, several Galactic and LMC RCB stars, including R CrB, itself, show significant Lithium in their atmospheres (Rao and Lambert 1996; Asplund *et al.* 2000; Kipper and Klochkova 2006a). Renzini (1990) suggested that in a FF the ingestion of the H-rich envelope leads to Li-production through the Cameron-Fowler mechanism (Cameron and Fowler 1971). The abundance of Li in the atmosphere of the FF star, Sakurai's object, was actually observed to increase with time (Asplund *et al.* 1999).

In general, Sakurai's abundances resemble V854 Cen and the other minority-class RCB stars with 98% He and 1% C (Asplund *et al.* 1998). Although only low resolution spectra are available for V605 Aql from 1921, it likely had similar abundances (Clayton and De Marco 1997). New spectra obtained of V605 Aql in 2000 indicate that it has evolved from $T_{eff} \sim 5000$ K in 1921 to ~ 95,000 K today (Clayton *et al.* 2006). The new spectra also show that V605 Aql now has stellar abundances similar to those seen in [WC] central stars of PNe with ~55% He, and ~40% C. In the present state of evolution of V605 Aql, we may be seeing the not too distant future of Sakurai's Object. There are indications that Sakurai's Object is evolving along a similar path (Kerber *et al.* 2002; Hajduk *et al.* 2005). Some doubt has recently been thrown on the FF nature of V605 Aql on the grounds of high neon abundances found in its ejecta (Wesson *et al.* 2008; Lau *et al.* 2011).

For a very short time, perhaps as short as two years, both V605 Aql and Sakurai's Object were almost indistinguishable from the RCB stars. Unfortunately, this extremely short RCB phase of the FF stars means that they cannot account for even the small number of RCB stars known in the Galaxy.

4.2. Do RCB stars evolve from white dwarf mergers?

RCB and HdC stars have $^{16}O/^{18}O$ ratios close to and in some cases less than unity, values that are orders of magnitude lower than measured in any other stars (the Solar value is 500) (Clayton *et al.* 2005, 2007; García-Hernández *et al.* 2010). The three HdC stars, that have been measured, have $^{16}O/^{18}O < 1$, lower values than any of the RCB stars. These discoveries are important clues in determining the evolutionary pathways of HdC and RCB stars, whether the DD or the FF. No overproduction of ^{18}O is expected in the FF scenario. New hydrodynamic simulations indicate that WD mergers may very well be the progenitors of O^{18}-rich RCB and HdC stars (Longland *et al.* 2011; Staff *et al.* 2012).

Webink (1984) proposed that an RCB star evolves from the merger of a He-WD and a CO-WD which has passed through a common envelope phase. He suggested that as the binary begins to coalesce because of the loss of angular momentum by gravitational wave radiation, the (lower mass) He-WD is disrupted. A fraction of the helium is accreted onto the CO-WD and starts to burn, while the remainder forms an extended envelope around the CO-WD. This structure, a star with a helium-burning shell surrounded by a ~100 $R_\odot$ hydrogen-deficient envelope, closely resembles an RCB star (Clayton 1996; Clayton *et al.* 2007). The merging times (~10^9 yr) might not be as long as previously thought, which makes the DD scenario an appealing alternative to the FF scenario for the formation of RCB stars (Iben *et al.* 1996, 1997). In addition, Sai"EHo and Jeffery (2002) suggested that a WD-WD merger could also account for the elemental abundances seen in RCB stars. Pandey *et al.* (2006) have suggested a similar origin for the EHe stars.

The isotope, ^{18}O, can be overproduced in an environment of partial He-burning in which the temperature and the duration of nucleosynthesis are such that the $^{14}N(\alpha,\gamma)\,^{18}F(\beta^+)\,^{18}O$ reaction chain can produce ^{18}O, if the ^{18}O is not further processed by $^{18}O(\alpha,\gamma)\,^{22}Ne$ (Warner 1967; Lambert 1986; Clayton *et al.* 2007). The surface compositions of HdC and RCB stars are extremely He-rich (mass fraction 0.98), indicating that the surface material has been processed through H-burning. After H-burning via the CNO cycle, ^{14}N is by far the most abundant of the CNO elements, because ^{14}N has the smallest nuclear p-capture cross-section of any stable CNO isotope involved. However, the majority of RCB stars have log *C/N* = 0.3 and log *N/O* = 0.4 by number, equivalent to mass ratios of *C/N* = 1.7 and *N/O* = 2.2 (Asplund *et al.* 2000). The N/O ratio represents the average for the majority RCB stars although the individual stars show a large scatter. Thus C is the most abundant and O the least abundant CNO element. These abundances are consistent if the material at the surfaces of HdC and RCB stars experienced a small amount of He-burning, as, for example, at the onset of a He-burning event that is quickly terminated. This partial He-burning would not significantly deplete He, but could be sufficient for some of the ^{14}N to be processed into ^{18}O. At the onset of He-burning, ^{13}C is the first α-capture reaction to be activated because of the large cross-section of $^{13}\mathrm{C}(\alpha, \mathrm{n})\,^{16}\mathrm{O}$. Thus, a large ^{12}C/^{13}C ratio and enhanced s-process elements are both consistent with partial He-burning.

As mentioned above, some RCB stars show enhanced Li abundances, as does the FF star Sakurai's Object (Lambert 1986; Asplund *et al.* 1998). As shown by Herwig and Langer (2001), Li enhancements are consistent with the FF scenario. However, the production of ^{18}O requires temperatures large enough to at least marginally activate the $^{14}\mathrm{N}(\alpha, \gamma)$ reaction. The α capture on Li is eight orders of magnitude more effective than on ^{14}N. For that reason, the simultaneous enrichment of Li and ^{18}O is not expected in the WD merger scenario. This is an important argument against the FF evolution scenario as a progenitor of RCB and HdC stars with excess of ^{18}O. The abundance of ^{18}O cannot be directly measured in R CrB because it is too hot to have CO, but it is overabundant in ^{19}F, which does imply a high ^{18}O abundance (Pandey *et al.* 2008). Since ^{18}O strongly supports the DD merger/accretion scenario, the obvious solution is that there could be (at least) two evolutionary channels leading to RCB, HdC and EHe stars, perhaps with the DD being the dominant mechanism. Unfortunately the division between majority- and minority-class RCB stars does not lend itself naturally to this explanation, since Li has only been detected in the majority group (Asplund *et al.* 2000).

4.3. Mass-Loss and dust formation

It has long been accepted that the characteristic RCB declines in brightness are caused by the formation of optically thick clouds of carbon dust (Loreta 1935; O'Keefe 1939; Clayton 1996). But the formation mechanism is not well understood. Empirical analysis of the spectroscopic and light curve evolution during declines implies that the dust forms close to the stellar atmosphere and then is accelerated to hundreds of km s^{-1} by radiation pressure (Clayton *et al.* 1992; Whitney *et al.* 1993). There is strong evidence for variable, high-velocity winds in RCB stars associated with dust formation (Clayton *et al.* 2003, 2012). The HdC stars, which produce no dust, also have no evidence for winds (Geballe *et al.* 2009). Other observational evidence indicates that there is also gas moving much more slowly away from the star (see, for example, García-Hernández *et al.* 2011a and references therein).

The observed timescales for RCB dust formation fit in well with those calculated by carbon chemistry models which show that the dust forms near the surface of the RCB star due to density and temperature perturbations caused by stellar pulsations (Feast 1986; Woitke *et al.* 1996). There is a strong correlation between the onset of dust formation and the pulsation phase in several RCB stars (Crause *et al.* 2007). All RCB stars show regular or semiregular pulsation periods in the 40- to 100-day range (Lawson *et al.* 1990). The dust forming around an RCB star does not form in a complete shell, but rather in small "puffs" (Clayton 1996). Only when a puff forms along the line of sight to the star will there be a decline in brightness. Studies of UV extinction and IR re-emission of stellar radiation indicate that the covering factor of the clouds around RCB stars during declines is $f<0.5$ (Feast *et al.* 1997; Clayton *et al.* 1999b; Hecht *et al.* 1984, 1998). The typical dust mass of a puff is $\sim 10^{-8}\,M_{\odot}$ (Feast 1986; Clayton *et al.* 1992).

In the recent deep decline of R CrB, shown in Figure 1, the puff dust mass is $\sim 10^{-8}\,M_{\odot}$, assuming the dust forms at $2\,R_*$ ($R_* = 85\,R_{\odot}$), and that a puff subtends a fractional solid angle of 0.05 (Clayton *et al.* 2011a). Since the dust would accelerate and dissipate quickly due to radiation pressure, dust must be formed continually by R CrB to maintain itself in a deep decline for four years or more. If a puff forms during each pulsation period (~40 days), R CrB would be producing $\sim 10^{-7}\,M_{\odot}$ of dust per year. Assuming a gas-to-dust ratio of 100 (Whittet 2003), the total mass loss rate is $10^{-5}\,M_{\odot}\,yr^{-1}$.

Little is known about the lifetime of an RCB star. We have a lower limit from the fact that R CrB itself has been an RCB star for 200 yr (Pigott and Englefield 1797). The large diffuse dust shell around R CrB, seen in the far-IR, could possibly be a fossil PN shell (Clayton *et al.* 2011a). Assuming an expansion velocity of a PN shell (~20 km s^{-1}), then the shell would take 10^5 yr to form. If the mass-loss was more like the high-velocity winds seen in RCB stars today (~200 km s^{-1}), then the shell would be about an order of magnitude younger (Clayton *et al.* 2003). If R CrB is the result of a FF rather than a DD, then the size and timescales would be consistent with the nebulosity, now seen in far-IR emission, being a fossil PN shell. The nebulosity, including cometary knots, seen around R CrB and UW Cen looks very much like a PN shell (Clayton *et al.* 1999b, 2011a). The mass of the shell is estimated to be $\sim 2\,M_{\odot}$, which is consistent with it being a PN (Clayton *et al.* 2011a). Adaptive optics and interferometry have been used to study dust very close to RCB stars (de Laverny and Mékarnia 2004; Bright *et al.* 2011, and references therein).

Any gas lost during a DD event would have far less mass. If the shell is an old PN shell then this would suggest that R CrB is the product of an FF event rather than a DD merger. R CrB is one of the stars with lithium on its surface, also a possible indicator of an FF. About 10% of single stars will undergo a final-flash event (Iben *et al.* 1996). About this percentage of RCB stars (R CrB, RY Sgr, V CrA, and UW Cen) show evidence of resolved fossil dust shells (Walker 1994).

Understanding the RCB and HdC stars is a key test for any theory that aims to explain hydrogen deficiency in post-AGB stars. Solving the mystery of how the RCB stars evolve is an exciting possibility, but it will also be a watershed event in the study of stellar evolution that could lead to a better understanding of other types of stellar merger events such as type Ia supernovae.

The observations in the AAVSO database have been invaluable to my research on RCB stars throughout my career. For R CrB alone, there are a staggering 238,136 brightness estimates in the AAVSO International Database, stretching back to 1843. The usefulness of the AAVSO data is only increasing with the addition of digital data which allow the low-amplitude RCB star pulsations to be studied in detail. The AAVSO International Database is a model for the many other photometric databases coming on line. The need for longterm monitoring combined with reliable photometry is essential for the identification and characterization of the many transient objects that are being discovered.

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Table 1. Spectroscopically confirmed Milky Way RCB stars.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
XX Cam	04	08	38.75	+53	21	39.5	8.7	1		x	x	—
SU Tau	05	49	03.73	+19	04	22.0	9.5	1		✓	✓	—
UX Ant	10	57	09.06	–37	23	55.0	12.2	1		x	x	^{13}C
UW Cen	12	43	17.18	–54	31	40.7	9.6	1	x	✓	✓	—
Y Mus	13	05	48.19	–65	30	46.7	10.5	1	x		x	—
DY Cen	13	25	34.08	–54	14	43.1	12.0	1				hot RCB
V854 Cen	14	34	49.41	–39	33	19.2	7.0	1	x	x	x	Minority, ^{13}C
Z UMi	15	02	01.33	+83	03	48.6	11.0	1	x		✓	Minority
S Aps	15	09	24.53	–72	03	45.1	9.6	1	✓			—
ASAS-RCB-1	15	44	25.08	–50	45	01.2	11.9	2				V409 Nor
R CrB	15	48	34.41	+28	09	24.3	5.8	1		✓	✓	—
ASAS-RCB-9	16	22	28.83	–48	35	55.8	11.3	2, 3				IO Nor
RT Nor	16	24	18.68	–59	20	38.6	11.3	1			x	—
RZ Nor	16	32	41.66	–53	15	33.2	11.1	1			✓	
ASAS-RCB-2	16	41	24.75	–51	47	43.4	12.0	2				—
ASAS-RCB-3	16	54	43.60	–49	25	45.0	11.8	2, 3				—
ASAS-RCB-12	17	01	01.41	–50	15	34.8	11.8	2				—
ASAS-RCB-4	17	05	41.25	–26	50	03.4	13.3	2, 3				GV Oph
V517 Oph	17	15	19.74	–29	05	37.6	12.6	1				—
ASAS-RCB-10	17	17	10.21	–20	43	15.7	11.5	2				—
EROS2-CG-RCB-12	17	19	58.50	–30	04	21.3	14.1	4				—

Table continued on following pages

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}*O*	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
V2552 Oph	17	23	14.55	–22	52	06.3	10.8	5, 6		✓	x	—
EROS2-CG-RCB-7	17	29	37.09	–30	39	36.7	14.1	4				—
EROS2-CG-RCB-6	17	30	23.83	–30	08	28.3	12.8	4				V1135 Sco
V532 Oph	17	32	42.61	–21	51	40.8	11.7	7				—
OGLE–GC–RCB–1	17	35	18.12	–26	53	49.2	14.6	8				—
EROS2-CG-RCB-8	17	39	20.72	–27	57	22.4	13.0	4				—
EROS2-CG-RCB-10	17	45	31.41	–23	32	24.4	12.5	4				—
EROS2-CG-RCB-5	17	46	00.32	–33	47	56.6	13.5	4				—
EROS2-CG-RCB-4	17	46	16.20	–32	57	40.9	12.5	4				—
EROS2-CG-RCB-9	17	48	30.87	–24	22	56.5	15.2	4				—
EROS2-CG-RCB-11	17	48	41.53	–23	00	26.5	12.3	4				—
ASAS-RCB-7	17	49	15.70	–39	13	16.0	12.7	2				V653 Sco
EROS2-CG-RCB-1	17	52	19.96	–29	03	30.8	12.4	4				—
ASAS-RCB-5	17	52	25.30	–34	11	28.0	12.3	2				—
EROS2-CG-RCB-2	17	52	48.70	–28	45	18.9	14.5	4				—
MACHO 401.48170.2237	17	57	59.02	–28	18	13.1	14.5	9				—
EROS2-CG-RCB-3	17	58	28.27	–30	51	16.4	11.1	4				—
EROS2-CG-RCB-13	18	01	58.22	–27	36	48.3	11.4	4				—
V1783 Sgr	18	04	49.74	–32	43	13.4	12.5	2				—
WX CrA	18	08	50.48	–37	19	43.2	11.0	1	✓			—
ASAS-RCB-11	18	12	03.30	–28	08	33.0	12.0	2				—

Table continued on following pages

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
V739 Sgr	18	13	10.54	–30	16	14.7	14.0	1				—
EROS2-CG-RCB-14	18	13	14.86	–27	49	40.9	12.5	4				—
V3795 Sgr	18	13	23.58	–25	46	40.8	11.5	1		✓		Minority
VZ Sgr	18	15	08.58	–29	42	29.4	11.8	1		✓	x	Minority, ^{13}C
IRAS 18135–2419	18	16	39.20	–24	18	33.4	12.8	2, 10				—
RS Tel	18	18	51.22	–46	32	53.4	9.3	1			x	—
MACHO 308.38099.66	18	19	27.36	–21	24	08.2	16.3	9				—
MACHO 135.27132.51	18	19	33.87	–28	35	57.8	14.3	9				—
GU Sgr	18	24	15.58	–24	15	26.5	11.3	1		✓?	x	—
V581 CrA	18	24	43.46	–45	24	43.8	10.0	2				—
V391 Sct	18	28	06.57	–15	54	44.7	13.3	2				—
MACHO 301.45783.9	18	32	18.60	–13	10	48.9	17.3	9				—
NSV 11154	18	37	51.26	+47	23	23.5	12.0	11				—
V348 Sgr	18	40	19.93	–22	54	29.3	10.6	1				hot RCB
MV Sgr	18	44	31.97	–20	57	12.8	12.0	1				hot RCB
FH Sct	18	45	14.84	–09	25	36.1	13.4	1		✓?	x	—
V CrA	18	47	32.30	–38	09	32.3	9.4	1		✓?	x	^{13}C
ASAS-RCB-8	19	06	39.87	–16	23	59.2	10.9	2				—
SV Sge	19	08	11.76	+17	37	41.2	11.5	1	✓			—
V1157 Sgr	19	10	11.83	–20	29	42.1	12.5	1				—
RY Sgr	19	16	32.76	–33	31	20.4	6.5	1		✓	x	—

Table continued on next page

Table 1. Spectroscopically confirmed Milky Way RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	*^{18}O*	*F*	*Li*	*Notes*[2]
	h	*m*	*s*	°	′	″						
ES Aql	19	32	21.61	–00	11	31.0	11.6	12	✓			—
V482 Cyg	19	59	42.57	+33	59	27.9	12.1	1		✓?	x	—
ASAS-RCB-6	20	30	04.96	–62	07	59.2	13.1	2, 3				AN 141.1932
U Aqr	22	03	19.70	–16	37	35.2	10.5	1	✓		✓?	—
UV Cas	23	02	14.62	+59	36	36.6	11.8	1		✓	x	—
HdC Stars												
HE 1015–2050	10	17	34.232	–21	05	13.87	16.0	13				—
HD 137613	15	27	48.316	–25	10	10.15	7.5	14	✓			—
HD 148839	16	35	45.788	–67	07	36.69	8.3	14	x		✓	—
HD 173409	18	46	26.627	–31	20	32.07	9.5	14	x			—
HD 175893	18	58	47.29	–29	30	18.08	9.4	14	✓			IR Excess
HD 182040	19	23	10.08	–10	42	11.54	7.0	14	✓			—

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[1] *Spectroscopic references: 1) Clayton (1996, and references therein), 2) Tisserand et al. (2012, in preparation), 3) Miller et al. (2012), 4) Tisserand et al. (2008), 5) Hesselbach et al. (2003), 6) Rao and Lambert (2003), 7) Clayton et al. (2009), 8) Tisserand et al. (2011), 9) Zaniewski et al. (2005), 10) Greaves (2007), 11) Kijbunchoo et al. (2011), 12) Clayton et al. (2002), 13) Goswami et al. (2010), 14) Warner (1967), .*

[2] *Note: RZ Nor has a faint blue star nearby. This may explain why the RZ Nor declines are not very deep and it appears bluer during declines.*

Table 2. Spectroscopically confirmed LMC and SMC RCB stars.

Name	R.A. (2000)			Dec. (2000)			Max	Spec. Ref.[1]	^{18}O	F	Li	Notes
	h	m	s	°	′	″						
LMC Stars												
EROS2-LMC-RCB-3	04	59	35.78	–68	24	44.68	14.3	1				—
HV 12524	05	01	00.36	–69	03	43.2	14.5	2				MACHO 18.3325.148
KDM 2373	05	10	28.50	–69	47	04.3	13.8	1, 3				MACHO 5.4887.14, EROS2-LMC-RCB-2
HV 5637	05	11	31.37	–67	55	50.6	15.8	4				MACHO 20.5036.12
EROS2-LMC-RCB-1	05	14	40.17	–69	58	40.1	15.2	1				MACHO 5.5489.623
HV 2379	05	14	46.20	–67	55	47.4	14.9	2				MACHO 16.5641.22
MACHO 79.5743.15	05	15	51.79	–69	10	08.6	15.2	2				—
MACHO 6.6575.13	05	20	48.21	–70	12	12.5	15.3	2				—
HV 942	05	21	48.00	–70	09	57.4	15.0	2				MACHO 6.6696.60
MACHO 80.6956.207	05	22	57.37	–68	58	18.9	16.0	2				—
W Men	05	26	24.52	–71	11	11.8	13.8	4			✓	MACHO 21.7407.7
MACHO 80.7559.28	05	26	33.91	–69	07	33.4	15.8	2				—
MACHO 81.8394.1358	05	32	13.36	–69	55	57.8	16.3	5				—
HV 2671	05	33	48.94	–70	13	23.4	16.1	5				MACHO 11.8632.2507, Hot RCB
EROS2-LMC-RCB-4	05	39	36.97	–71	55	46.4	15.1	1				MACHO 27.9574.93
KDM 5651	05	41	23.49	–70	58	01.8	14.4	3				MACHO 15.9830.5
HV 12842	05	45	02.88	–64	24	22.7	13.7	4			✓	—

Table continued on next page

Table 2. Spectroscopically confirmed LMC and SMC RCB stars, cont.

Name	*R.A. (2000)*			*Dec. (2000)*			*Max*	*Spec. Ref.*[1]	^{18}O	*F*	*Li*	*Notes*
	h	*m*	*s*	°	′	″						
MACHO 12.10803.56	05	46	47.74	–70	38	13.5	15.1	2				—
KDM 7101	06	04	05.53	–72	51	23.1	14.2	1, 3				EROS2-LMC-RCB-5
SMC Stars												
RAW 21	00	37	47.40	–73	39	02.0	15.6	1, 3, 6				EROS2-SMC-RCB-1
RAW 476	00	48	22.87	–73	41	04.7	15.5	1, 6				EROS2-SMC-RCB-2
EROS2-SMC-RCB-3	00	57	18.12	–72	42	35.3	16.0	1, 6				MACHO 207.16426.1662

[1] *Spectroscopic references: 1) Tisserand et al. (2009), 2) Alcock et al. (2001), 3) Morgan et al. (2003), 4) Clayton (1996, and references therein), 5) Alcock et al. (1996), 6) Tisserand et al. (2004).*

Table 3. DD vs FF[1]

Property	*DD*	*FF*
Extreme H deficiency but some H present	yes?	yes
H abundance anti-correlated with Fe	?	?
Li abundance high in 5 stars (all majority)	no	yes
C/He ~ 1%	yes	no
$^{12}C/^{13}C > 500$	yes	no
High N, O	yes	yes
High Na, Al	yes?	yes
High Si, S	?	?
Enrichment of s-process elements	yes?	yes
Abundance uniformity/non-uniformity for majority/minority	no?/yes	yes/no?
Similar to Sakurai's object	no	yes
Nebulosity present in a few stars	yes?	yes
RCB Lifetime	yes	no
Lack of binarity	yes	no?
^{18}O and ^{19}F greatly enhanced in (all?) stars	yes	no
M_V = –3 to –5 mag	yes	yes
Mass = 0.8–0.9 $M_\odot$	yes	no?

[1] *Adapted and updated from Table 7 of Asplund et al. (2000).*

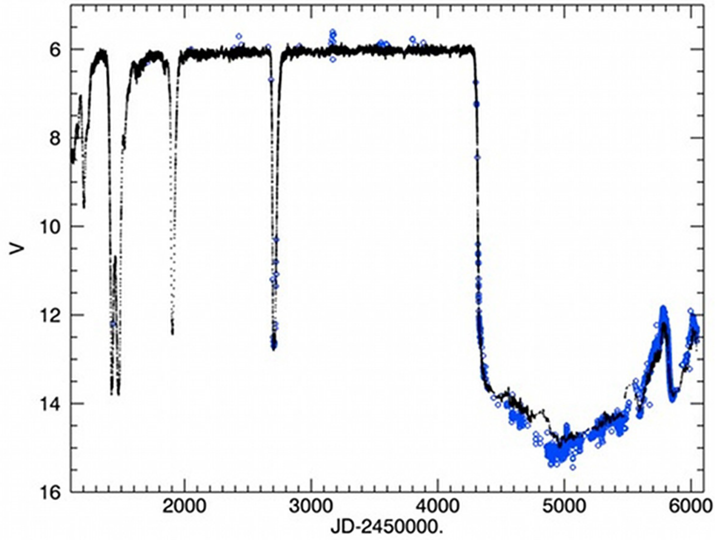

Figure 1. Light curve of R CrB from 1998 to 2012 using AAVSO data. Visual magnitudes are plotted as black dots. Johnson V data are plotted as open circles.

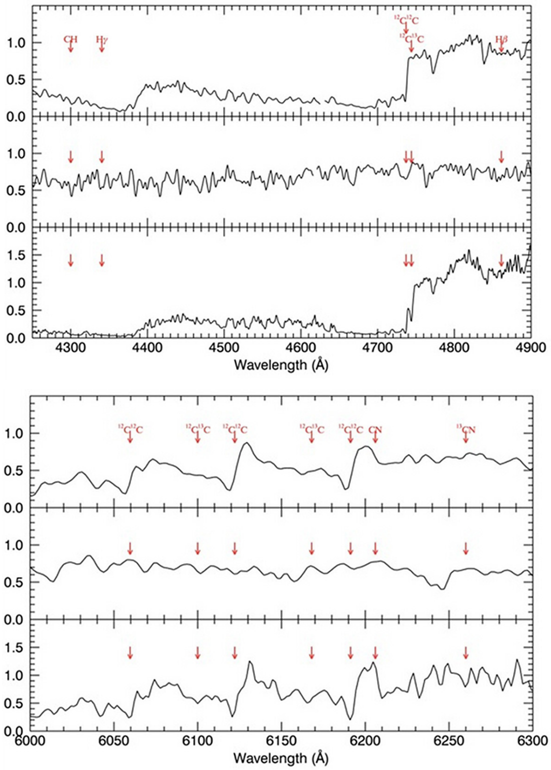

Figure 2. Blue (upper figure) and red (lower figure) sections of the spectra of a cool RCB star, S Aps (top plots), and a warm RCB star, RY Sgr (middle plots), as well as the carbon star, RV Sct (bottom plots), showing some of the spectroscopic features that define RCB stars.

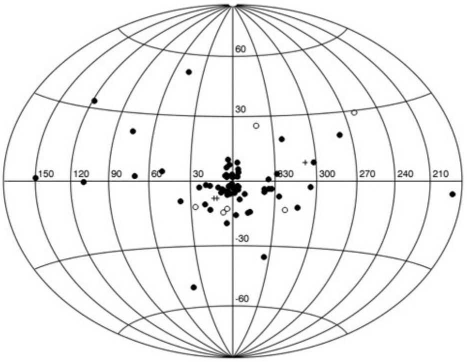

Figure 3. Distribution of RCB stars on the sky in the Galaxy showing that they are consistent with an old, bulge popularion. Cool RCB stars (filled circles), hot RCB stars (crosses), HdC stars (open circles).

Cataclysmic Variables

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Abstract This paper presents a concise summary of our current knowledge of cataclysmic variables, including definitions of types and the observational basis for classification, what we have been able to piece together about evolution, and discoveries from recent surveys. We provide a list of unanswered problems and questions and references for seeking additional information. The importance of AAVSO observations in the past and for the future is highlighted.

1. What we know about CVs

The basic definition of a cataclysmic variable (CV) is a mass-transferring close binary containing a white dwarf primary and a secondary that is usually a late-type main sequence star (although a few cases with giant or brown-dwarf secondaries exist). A good starting point for understanding the general properties of CVs is the book by Warner (1995) or by Hellier (2001). Various catalogs of CVs have been compiled over the years by Downes *et al.* (1997; on-line version frozen in 2006 at http://archive.stsci.edu/prepds/cvcat/), Ritter and Kolb (2003; current on-line version at http://www.MPA-Garching.MPG.DE/RKcat/), Drake *et al.* (2009; online at http://nesssi.cacr.caltech.edu/catalina/AllCV.html) and Szkody *et al.* (2011; online catalog at http://www.astro.washington.edu/users/szkody/cvs).

CVs are thought to form from wider binaries composed of two main sequence stars when the more massive star becomes a giant and forms a common envelope around the system. As the two stars orbit within this common envelope, their separation decreases and the orbital period shrinks from days to hours. Once the common envelope dissipates, the resulting white dwarf-main sequence binary system evolves without mass transfer, continually losing momentum through a braking wind from the secondary and decreasing its orbital period until the secondary fills its Roche lobe and begins to transfer mass to the white dwarf. At this point, it becomes a bona-fide CV. As the period continues to shrink to 3 hours, the secondary star structure changes, becoming completely convective, and at a period near 2 hours, gravity waves become the source of momentum loss (resulting in low mass transfer rates) until a period minimum near 80 minutes is reached. After this point, the structure of the secondary again changes (becoming degenerate) and the orbital period increases.

A cataclysmic variable is usually identified by its variability on timescales of minutes (from flickering) to hours (from orbital variations) to weeks-years (from mass accretion variations), by its peculiar spectrum showing broad, usually doubled, Balmer emission lines, or by the detection of X-ray emission, which is generated by the material that accretes onto the white dwarf. The observational appearance of a CV depends primarily on two parameters: the amount of mass transfer, and the magnetic field strength of the white dwarf.

In a non-magnetic CV, where the white dwarf has no detectable field (typically much less than 1MG), the mass flow from the companion star builds up an accretion disk around the white dwarf. In these accretion disks, the material slowly spirals inwards towards the white dwarf. The rate at which the mass migrates through the disk depends on the viscosity of the material, as it is this "stickiness" that allows the exchange of angular momentum. There are two regimes in which accretion disks can be found, one of low viscosity, where the mass flow through the disk is slow, and one of high viscosity, where the mass flow is correspondingly much faster. In which of these states a CV is found depends on the rate at which the companion star supplies fresh material to the outer edge of the disk. For high mass transfer rates, the disk is in a stable state of high viscosity, hot, and the dominant source of light. These systems typically have orbital periods longer than 3 hours and are called nova-likes. They have no large-amplitude outbursts, and their spectra are often lacking the emission lines that are typical of most CVs, that is, they are rather inconspicuous. Thus, some of the brightest known CVs were found only very recently, and rather serendipitously, such as LSIV-08°3 with V=11.5 (Stark *et al.* 2008).

For low mass transfer systems, the material in the accretion disk has a low viscosity and is cool. The rate at which material flows through the disk is actually lower than that provided by the companion star. Thus, the disk gradually grows in mass and heats up, until its temperature becomes sufficiently high to switch into the hot, high-viscosity state, where the accumulated mass is rapidly flushed onto the white dwarf. Systems that undergo these quasi-regular outbursts are called dwarf novae, and are the most common sub-class of CVs. The underlying physical mechanism of the accretion disk instability is important in a wide range of other astronomical objects; for example, it is thought that the protostellar accretion disks in T Tauri stars and the disks around supermassive black holes in the centers of galaxies also undergo outburst cycles.

Because of their short timescales, CVs are the best "laboratory" to study accretion disk physics. A particularly interesting sub-class among the non-magnetic CVs is the Z Cam type of system: here, the accretion rate is close to the borderline between hot, stable, and cool, unstable disks, and these systems can switch back and forth between being a dwarf nova and a novalike.

Mike Simonsen (2011) has initiated a dedicated project to obtain high-quality light curves for a large number of Z Cam stars. For orbital periods between 3 and 4 hours, a peculiar class of CVs exist called SW Sex stars (Thorstensen *et al.* 1991). These systems show single Balmer emission lines as well as a prominent HeII 4686 emission line, show transient absorption at some phases, and are often discovered as eclipsing systems. A list of SW Sex objects is provided by Hoard *et al.* (2003; an online updated list is at http://www.dwhoard.com/home/biglist). A few of these SW Sex stars show low circular polarization, indicating a relatively high magnetic field for the white dwarf (for example, Rodriguez-Gil *et al.* 2001). Some novalikes, including the SW Sex stars, occasionally fade by several magnitudes, for weeks to years. During these low states, the mass transfer from the secondary star is interrupted, and the accretion disk becomes very faint, or vanishes altogether. Consequently, the white dwarf and the secondary star can be observed directly. It appears that the white dwarfs in these systems are extremely hot, which suggests that the high accretion rates observed during the high states probably prevail for thousands of years.

A completely different picture is found among the magnetic CVs. If the white dwarf has a very high magnetic field (> 10 MG), the mass transfer stream impacts directly onto the white dwarf magnetic poles without forming a disk (King and Lasota 1993). In these systems (called Polars), the field locks the secondary and the white dwarf spin to the orbit so all variations are on the orbital timescale. The high field is identified from the presence of strong circular polarization or from Zeeman splitting. At very low accretion rates, broad cyclotron humps are prominent in the spectrum. Polars, just like the novalikes mentioned above, can cycle aperiodically between low and high states. This suggests that variations in the mass transfer rate from the companion star are inherent to all CVs, but that in dwarf novae, these variations are smoothed out by the accretion disk. For white dwarf fields of about 1–10 MG, an outer accretion disk forms but the inner disk is disrupted by the field so the material rains onto the white dwarf in broad accretion curtains. In these Intermediate Polars (IPs), the white dwarf spin is usually evident as a strong pulse visible in optical or X-ray at about one-tenth of the orbital period, even though the last years have seen the discovery of IPs with both much smaller and larger spin-to-orbital period ratios.

As CVs accrete from their companion stars, a layer of hydrogen-rich material builds up on the white dwarf, which will eventually ignite in a violent thermonuclear reaction, called a classical nova. All CVs should undergo many classical nova eruptions, with typical recurrence times of thousands of years. However, for high mass white dwarfs, this recurrence time can be as short as a few decades. A spectacular example is T Pyx, which showed regular nova eruptions every ~20 years until 1966, but then went unexpectedly quiet—until 2011, when it surprised astronomers who had already started to develop theories why it would not erupt any time soon. These recurrent novae may eventually explode as type Ia supernovae, if the white dwarf reaches the Chandrasekhar limit.

The realm of satellite observations in the last few decades enabled ultraviolet, X-ray, and IR observations of CVs that vastly contributed to our knowledge of the components within these binaries. In disk CVs, the accretion disk was shown to be a dominant source of UV light, especially during an outburst. The delay between the start of the outburst in optical vs UV light led to increased understanding of the way the outburst proceeds through the disk. In the systems where the white dwarf could be seen as well as the disk, studies throughout the outburst interval showed how the white dwarf was heated by the outburst and subsequently cooled over months to years. Determination of the temperatures of the white dwarfs at quiescence revealed the difference in heating efficiency between magnetic accretion onto a pole vs disk accretion onto a boundary layer, as the white dwarfs in Polars had lower temperatures than disk CVs (Sion 1991; Araujo-Betancor *et al.* 2005). X-ray observations also showed differences between disk and magnetic CVs. The IPs revealed the hardest, most absorbed X-ray spectra, leading to models of accretion curtains, while the Polars typically showed both soft and hard X-rays (the hard from the accretion column and the soft from the heating of the white dwarf surface by the x-rays from the column). Spitzer observations of disk CVs produced surprising results on dust rings within and around several CVs (Brinkworth *et al.* 2007; Hoard *et al.* 2009). Ground-based near-IR spectroscopy also revealed some surprises. When the secondary stars could be observed, the majority of those in disk CVs showed a depletion of CO and metals compared to normal main-sequence stars, whereas the secondaries in Polars do not show this effect (Howell *et al.* 2010). In some short period systems, no evidence of a secondary is seen, implying a very low mass, brown-dwarf type object (Patterson 2011).

In the last decade, the Hamburg Quasar Survey (HQS) and the Sloan Digital Sky Survey (SDSS) produced many new CV candidates. Followup photometry and spectroscopy confirmed several new IPs and SW Sex stars from the brighter objects found by HQS (Rodriguez-Gil *et al.* 2007), and more than 200 CVs from the SDSS which could reach to fainter magnitudes (Szkody *et al.* 2011). Determination of the orbital periods of over 100 of the CVs from the SDSS revealed a period distribution that was much closer to that predicted by population models, with the majority of objects having periods less than 2 hours (Gaensicke *et al.* 2009). However, the minimum period where most of the CVs appear occurs at a slightly larger value (80 minutes) than the 70 minutes predicted by population models (Kolb and Baraffe 1999). These results confirm the basic picture of angular momentum losses via magnetic braking at periods longer than 3 hours and via gravitational radiation at periods under 2 hours, but will require some tweaking of these parameters along with the structure of the stars to obtain a perfect match (Knigge *et al.* 2011). Many new eclipsing CVs are found among the SDSS systems, in which accurate masses and radii can be measured (Littlefair *et al.* 2006). These studies led to the puzzling fact that the white dwarfs in CVs are on average much more massive compared to both single white dwarfs and those in pre-CVs (Zorotovic *et al.* 2011). The only two answers to this discrepancy are that either the white dwarfs in CVs grow in mass, or that the current-day CV population descends from progenitors that are different from the pre-CVs we have found so far.

Other results from SDSS included the discoveries that there are significant populations of Polars with mass transfer rates three orders of magnitude lower than typical Polars (Low Accretion Rate Polars or LARPs; Schwope *et al.* 2002; Schmidt *et al.* 2005), and there are many CVs containing accreting, pulsating white dwarfs (Szkody *et al.* 2010).The LARPS provide a means to study wind loss from a low mass star, as the low accretion rates preclude the existence of an accretion shock above the white dwarf surface and the visible cyclotron radiation likely stems from the concentration of the wind from the secondary by the interaction of the fields of the two stars. This magnetic interaction has been explored by Kafka *et al.* (2010) for a variety of systems, demonstrating that magnetic prominences occur in many systems other than solar-type stars.

The pulsating white dwarfs have also led to probes of the instability region of white dwarfs. Asteroseismology of white dwarfs has shown their importance for the determination of stellar parameters of mass, age, spin, core composition, magnetic field strength, and distance (Winget and Kepler 2008), The white dwarf pulsators in CVs have the added advantage of undergoing accretion, which heats the white dwarf and changes the composition and rotation, allowing the study of how these parameters affect the instability strip. In addition, the presence of outbursts allows the unique advantage of observing a white dwarf move out of the instability strip (when its heated by the outburst) and then moving back in (as it cools to its quiescent temperature), changes which take millions of years for single white dwarf but only a few years for CVs.

2, Open questions

While the general evolutionary picture and the characteristics of the types of CVs are known at some level, there are major unsolved questions which remain. These include:

1) What is the actual number density and distribution of CVs in the Galaxy? As future surveys push to fainter limits and sample the disk as well as the halo, we can finally determine the real population of CVs in the Milky Way.

2) What happens to CVs once they reach the period minimum? Theory predicts that they evolve back to longer periods, and that ~70% of all CVs should have evolved to that state. Yet, among more than a thousand CVs, at best a handful of those “period bouncers” are known. Does this imply that these highly evolved CVs look very different from the CVs we know now, and we have so far simply not been able to identify them? Or are the models fundamentally flawed?

3) What are the detailed physics occurring in the common envelope? So far, many of the theoretical models of cataclysmic variable evolution rely on rather crude parametrization of the complex processes in the common envelope, but with the large samples found by Sloan, it will become possible to provide some observational constraints for these parameters.

4) What is the correct physics to describe viscosity in accretion disks? Magnetic turbulence is generally accepted to be the most important effect, yet, no model of this magneto-rotational instability can so far reproduce the observed characteristics of dwarf nova outbursts. Will we finally be able to determine the spectral energy distribution (SED) of a low mass accretion rate disk?

5) What is the correct angular momentum prescription below the gap (besides gravitational radiation) that can account for the observed period minimum spike and the exact period distribution? Is it related to some residual magnetic braking?

6) What causes the period gap? The classic idea is that magnetic braking becomes inefficient, however, recent studies of single M-dwarfs suggest that the reality may be more complex.

7) How do Polars form and why are no magnetic white dwarfs in wide binaries observed? Are LARPS the progenitors of polars? Is there a difference in the emergence of systems containing magnetic white dwarfs versus non-magnetic?

8) What causes Polars, as well as the novalike disk systems with orbital periods between 3 and 4 hours, to cease mass transfer and enter low states? Are the associated mass transfer variations of the companion stars a general phenomenon among all CVs?

9) Can the white dwarfs in CVs grow in mass? Current classical nova models seem to categorically rule out this possibility, yet, observations show that the average mass in CVs is much higher than among pre-CVs.

10) What are the secondaries like in period-bouncers?

11) Do CVs contain exoplanets? Long-term studies of the ephemeris of eclipsing CVs reveal variations of the mid-eclipse times, which can be explained by a third, unseen body tugging on the CV binary. However, many other effects can result in the observed variations, and a much longer baseline of eclipse time monitoring will be necessary to unambiguously confirm or refute the presence of circumbinary planets.

3. The importance of the AAVSO for CVs

Since the very early days of CV research, the AAVSO has played a vital part in obtaining the data on which discoveries and resulting breakthroughs in understanding are based. The long term light curves of the dwarf novae SS Cyg and U Gem, spanning more than a century, provided the impetus for the modeling of dwarf novae outbursts (Cannizzo and Mattei 1998). Observations of the onset of outbursts that triggered UV and satellite observations revealed a delay between the optical and UV light that led to further understanding of the outburst scenario (Cannizzo 2001). The simultaneous monitoring of SS Cyg by the AAVSO observers and the EUVE and RXTE satellites revealed a strong anti-correlation between the soft and hard X-rays during an outburst, providing new insight into the processes at the boundary between the white dwarf and the accretion disk (Wheatley *et al.* 2003). After Polars were found, the long term records of the AAVSO showed the various high and low states of accretion and helped reveal that Polars spend most of their time in low states. Combined with multi-epoch X-ray observations, Hessman *et al.* (2000) used twenty years' worth of AAVSO observations to accurately measure the accretion rate in AM Her, the prototypical polar, and to estimate the fraction of the companion that is covered by star spots. Most recently, HST observations on CVs have required a ground based optical measurement within twenty-four hours of the scheduled HST time to confirm the objects at quiescence. Due to vagaries of weather at any one site, this requirement has led to a vital need for AAVSO monitoring prior to and during observation. The AAVSO CV Section page handled by Mike Simonsen provides campaigns and highlights requests to promote the best interaction between observers and scientists. The Z CamPaign is one productive example of an ongoing campaign that is unique to AAVSO. No single individual or professional could accomplish the concentrated observations that recently produced new scientific results on the number of Z Cam systems and some unique members (Simonsen 2011). The installation of AAVSOnet, providing robotic telescope access at a variety of sites, has been used in these campaigns and other programs, enabling productive observations at both hemispheres and at good weather sites. The archive provided by all of these observations is used by scientists around the world.

The future is moving toward large surveys and large satellites. If funding is realized, PanSTARRS and LSST will provide constant monitoring of the southern and northern skies by the next decade. These surveys will change the landscape for some AAVSO programs, eliminating the need for monitoring of some stars, but enhancing the need in many other areas. The proposed surveys saturate at fairly bright limits of 16–18 magnitudes. This means that there will continue to be a need to continue the long term archive of brighter CVs that is the fodder for theorists. While the surveys will sample some timescales, the coverage is not ideal for CVs with orbital periods of hours, not days, and outbursts that can rise within one night. The survey filters are mostly concentrated toward the red, while CVs have more activity levels in the blue than the red. The survey telescopes are pre-programmed to move around the sky for a certain pattern so observations that are simultaneous with satellites will still be in demand. Another major mission to be launched next year is GAIA, which will observe the entire sky for at least five years, measuring distances to about a billion stars. Given its location above the Earth's atmosphere, GAIAs scanning pattern is not affected by bad weather, and the mission's first data to become available will be alerts of variable objects identified during the repeated observations. Ground-based confirmation and time-series follow-up will be a key area where AAVSO observers can play a very important role. The surveys will expose a huge number of variables at all magnitudes. The bright end will be a bonanza for AAVSO to scavenge and determine types of objects and behavior at times when the survey is not looking. The era of new opportunities in the field of CVs is just beginning.

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Symbiotic Stars

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Abstract Symbiotic stars are interacting binary systems composed of a white dwarf (WD) accreting at high rate from a cool giant companion, which frequently fills its Roche lobe. The WD usually is extremely hot and luminous, and able to ionize a sizeable fraction of the cool giant wind, because it is believed the WD undergoes stable hydrogen nuclear burning on its surface of the material accreted from the companion. This leads to consider symbiotic stars as good candidates for the yet-to-be-identified progenitors of type Ia supernovae. Symbiotic stars display the simultaneous presence of many different types of variability, induced by the cool giant, the accreting WD, the circumstellar dust and ionized gas, with time scales ranging from seconds to decades. The long orbital periods (typically a couple of years) and complex outburst patterns, lasting from a few years to a century, make observations from professionals almost impossible to carry out, and open great opportunities to amateur astronomers to contribute fundamental data to science.

1. Introduction

Observing symbiotic stars (hereafter SySts) is real fun and a great opportunity for the amateur astronomer (hereafter AA) to contribute fundamental, better to say “unique” data. In fact, the long orbital periods and outburst phases (measured in years) make observations by professionals almost impossible to carry out, especially for those that have to access, on highly competitive grounds, to telescopes at large observatories. SySts show variability over a wide range of time scales: seconds/minutes (accretion flickering), minutes/hours (rotation of the white dwarf), days/months (rotation, pulsations of the cool giant, recombination in the ionized circumstellar gas, shock fronts, bipolar jets), months/years (orbital periods, eclipses, reflection effects, ellipsoidal distortions, Mira pulsations), months/centuries (outbursts). Some of these types of variability are best seen and display larger amplitude in the red, others at blue wavelengths, as we will see later on in detail.

To enhance their value, to provide firmer grounds for physical modeling, and to allow astronomers to safely combine data collected by various AAs (sometimes different *generations* of AA), the photometric observations should be carried out in standard photometric bands, well-calibrated into accurate local photometric sequences by application of suitable color equations. Henden and Munari (2000, 2001, 2006) have calibrated photometric sequences around eighty-one well-known SySts and are working to extend them to all other catalogued SySts. By adopting these photometric sequences, the AAs can bring their observations closer to (and easier to integrate with) data collected by professionals who frequently use the same photometric sequences for their observations or when reconstructing past photometric histories from measurement of old photographic plates preserved in plate stacks around the world (like those at Harvard, Sonneberg, Pulkovo, and Asiago).

Even though this review focuses on photometry, it's a pleasure to note how spectroscopy is now becoming wide-spread among AA. Useful low resolution spectra of about twenty known SySt in quiescence are within the grasp of AAs using 0.5m telescopes, and a similar number of additional SySts can be reached during their outburst phases. The Hα is so bright that high resolution profiles of this emission line can be obtained for numerous SySts even with 0.5m telescopes. The profile and intensity of Hα is deeply modulated by the orbital motion, and it strongly responds also to the ionization of the circumstellar gas, eclipses, outbursts, winds, bipolar jets, and so on: monitoring the Hα of SySts is really fun! As a guideline, low resolution spectra should cover from 4000 to 7000Å at 2–5 Å/pixel, while high resolution observations of Hα should cover an interval of 100–200Å at 0.1–0.35 Å/pixel.

2. A typical symbiotic star

Let's begin with outlining what type of binary system a typical SySt is, and to this aim Figure 1 presents the optical spectrum of Z Andromedae, a prototype of this class of objects (see also Skopal 2011). A SySt is composed of: (1) a late type giant (LTG), most frequently of M2-M5III spectral types, not pulsating (in only ~20% of the cases it pulsates like a long period Mira), with its strong TiO absorption molecular bands modulating the spectrum at red wavelengths. The LTG dominates spectra and photometry at R_C-, I_C-band wavelengths.; and (2) an extremely hot (≥80,000 K) and luminous (of the order of a thousand solar luminosities) white dwarf (WD). It orbits the LTG and accretes from it, both via wind capture or Roche lobe overlow. The WD is so hot that its emission is concentrated in the far ultraviolet and X-rays, and it becomes directly observable at *U*, *B*, and *V* bands usually only during outbursts when its outer layers expand and cool.

The large temperature and luminosity of the WD (much larger than accountable by release of potential energy of accreting material, or by plain thermal irradiance along the cooling track) are explained by assuming that the WD undergoes stable hydrogen nuclear burning on its surface of the material accreted from the LTG (Munari and Buson 1994; Sokoloski 2003). The presence of many Super-Soft X-ray Sources (SSSx) among SySts is a direct confirmation of this scenario (many other SySts are not detected as

SSSx simply because there is so much circumstellar material around them that the X-rays are all locally absorbed). To keep the nuclear burning stable, the WD has to accrete at a high rate (a rate much larger than in the other types of interacting binaries, like the cataclysimc variables). This rate is fine tuned by the mass of the WD: below the critical value, the nuclear burning switches off; above it the material accreted in excess expands under the effect of the huge radiation pressure, and the overall structure would thus resemble a red giant star (in such a case our binary system would appear as if composed of two red giants in mutual orbit, no emission line would be seen, and the object would not be classified as a SySt).

The stable nuclear burning at the surface of the WD has one very important implication for SySts. Contrary to novae, where the nuclear burning is a highly explosive process that ejects into space essentially all the accreted material, the non-explosive burning occurring in SySts (both during quiescence and outbursts) allows the WD to retain the accreted matter, and stably grow in mass. If the companion LTG has enough material to transer, the WD can grow in mass until the Chandrasekhar limit of 1.4 $M_\odot$ is reached, at which point the WD could explode as a type Ia supernova (Munari and Renzini 1992). The exact nature of the precursors of SN Ia is still a matter of debate, but there is wide consensus that SySts are promising candidates.

There are two additional very important components in a typical SySt: circumstellar gas and dust. A SySt is embedded in a great amount of circumstellar gas (hereafter CG), created mostly by the wind blowing off the LTG, and which is ionized by hard radiation from the WD. The ionized fraction of the CG extends up to 100 astronomical units from the central binary, and it gives rise to two spectacular phenomena (compare the spectrum of the prototype SySt Z And in Figure 1): (i) very bright emission lines (in particular Hα) adorning the spectrum at all wavelengths and tracing conditions of high ionization (Allen 1984 classification criterion dictates the presence of emission lines from HeII or higher ionization species like [Fe VII] or [NeV]), and (ii) a bright blue continuum that, over *U* and *B* bands, is much brighter than the LTG, frequently pushing the *U–B* colors of SySts to largely negative values. If the number of energetic photons emitted by the WD goes up, also the amount and the brightness of the ionized circumstellar gas increases, and the reverse holds true. Thus the CG acts like a calorimeter, reverberating for us at optical wavelengths what the embedded WD does in far ultraviolet and X rays. Photo-ionization modeling of the observed flux of emission lines (corrected for reddening) can accurately fix the luminosity and temperature of the WD without the need for observations by orbiting satellites in the far ultraviolet and X-rays.

Circumstellar dust is almost always present when the LTG is a Mira variable. The dust is concentrated around the LTG and can be so thick as to cause spectacular extinction: in He 1-36 Allen (1983) estimates that the circumstellar dust dims the LTG by 20 magnitudes in the *V* band while the external ionized gas is left unaffected. Sometimes the SySts harbouring a Mira variable undergo periods of what seems to be protracted dust extinction. It is believed that this is caused by the dust being concentrated in a shadow cone produced by the LTG itself, where the dust is shielded from the disruptive ionizing radiation of the WD. Periodically, along the orbital motion, the SySt is seen through such dust cone and an attenuation results.

SySts belong mostly to the Old Bulge/Thick Disk stellar population of the Galaxy and as such they appear concentrated toward the plane of the Galaxy and in particular its central regions. We know about 300 SySts, and the total population in the Galaxy is estimated to range from 30,000 (Kenyon *et al.* 1993) to 300,000 (Munari and Renzini 1992). Symbiotic stars have been discovered also in external galaxies, including the Magellanic Clouds, M31, M33, IC 10, NGC6822, and the Draco dwarf galaxy. Most of the known SySts have been discovered as emission-line objects during objective prism surveys of the Milky Way, and many were originally classified as compact planetary nebulae (PNe); the true nature of some transition objects is still hotly debated (for example, V471 Per = VV-8). Additional SySts lie probably still unrecognized among poorly studied PNe. There is a natural and smooth overlap between PNe with binary nuclei and SySts, the main difference being: in PNe the ionized gas has been ejected by the progenitor of the current WD nucleus, while in SySts the gas is blown off the LTG companion and that ejected by the WD progenitor has already long gone.

3. Various types of variability seen in symbiotic stars

In describing the major types of variability displayed by SySts we will refer to observations carried out in the Johnson *UBV*-Cousins R_C I_C bands. Similar considerations hold true for the corresponding bands of the Sloan u' g' r' i' z' system. The main types of variability seen in SySts are:

- *ellipsoidal*, when the cool giant fills its Roche lobe. Due to orbital motion, the area of the Roche lobe projected onto the sky varies continuously, with two maxima (when the binary system is seen at quadrature) and two minima (when the cool giant passes at superior or inferior conjunctions) per orbital cycle. Popular examples of SySts showing ellipsoidal distortion of their light-curve are T CrB (orbital period 227 days, amplitude $\Delta m = 0.3$ magnitude) and BD–21.3873 (orbital period 285 days, amplitude $\Delta m = 0.2$ magnitude). The ellipsoidally modulated I_C-band light curve of LT Del is illustrated in Figure 2;

- *heating-reflection effect*, caused by the hard radiation field of the hot and luminous WD (radiating mainly in the X-ray and far ultraviolet domains) that illuminates and heats up the facing side of the LTG (which thus reprocesses to the optical domain the energy received in the X-ray and far ultraviolet from the WD). The heated side of the LTG is therefore brighter and hotter (bluer) than the opposite side (which is not illuminated by the WD radiation field). During an orbital period, the heated side comes and goes from view, causing a sinusoid-like light-curve characterized by a single sharp minimum and a broader, single maximum (compare the *B*-band light-curve of LT Del in Figure 2). The effect is strongly wavelength-dependent, being maximum in the *U* band and declining in amplitude toward the I_C band where it is usually undetectable. It is also stronger in systems seen equator-on, and vanishes for those seen pole-on. The amplitude may be fairly large, as in LT Del where its accounts for $\Delta B = 0.7$ (compare Figure 2) and $\Delta U = 1.6$, $\Delta V = 0.2$ (Arkhipova and Noskova 1988). The heating-reflection effect is the principal tool to derive orbital periods of SySts (Mikolajewska 2003);

- *pulsation*, like that of a Mira variable (about 20% of the known SySts harbor a Mira). Popular examples are R Aqr (pulsation period of 386 days, minima as faint as $V = 12$, maxima as bright as $V = 5$ magnitudes) or UV Aur (pulsation period of 395 days, minima as faint as $V = 11$, maxima as bright as $V = 7.5$ magnitude);

- *rotational*, of both the LTG and the WD. The rotation period of the LTG is of the same order as of the orbital one, thus measured in years. The rotation period of the WD is instead measured in hours, and its photometric amplitude is always pretty small;

- *eclipses of the WD* (and/or the ionized gas around it) by the LTG. Sometimes the eclipses escape detection by optical photometry during quiescence because the WD is small in radius and radiates mostly in the X-rays and far ultraviolet. During the outbursts the white dwarf emission shifts to longer wavelengths and becomes conspicuous in the optical, thus allowing the eclipses to be detected if the orbital inclination is sufficiently large. Classical examples of SySts for which the eclipses passed undetected in quiescence and instead became outstanding features of the outburst light-curve are FG Ser and V1413 Aql. Because the eclipsing body is cool and the eclipsed one is hot, the visibility of eclipses increases toward shorter wavelengths (for example for FG Ser in outburst it was $\Delta V = 1.4$, $\Delta B = 1.9$, and $\Delta U = 2.3$ magnitudes);

- *re-processing* by the CG of the energy radiated by the WD. The amount of ionized CG (and therefore its luminosity) is directly related to the amount of energy radiated by the WD and its *quality*, that is, the fraction of radiated photons which are energetic enough to ionize hydrogen and thus make it shine. A change in the WD radiation output would reflect in a different amount of ionized CG, and therefore in a variation of its brightness, especially in *U* and *B* bands;

- *outbursts*. There are three basic types of outburst displayed by SySts: (1) Type A—the one most frequently seen in SySts, presents amplitudes of $\Delta B = 2–5$ magnitudes (invariably declining toward red wavelengths) and durations of a few years, usually with many different maxima and minima during a single outburst episode. After such a train of multiple maxima, the SySt returns to flat quiescence conditions where it stays for a period of time usually much longer than spent in outburst. Light curves typical of such type of outburst are shown in Figure 3. Their cause is probably an increase in the mass transfer from the LTG to the WD. While the nuclear burning at the surface of the WD continues, the extra transferred material causes the WD to react by expanding its outer envelope. This expansion occurs at roughly constant luminosity and therefore causes a drop in the surface temperature (following the black body law $L = 4\pi R^2 \sigma T^4$), from ≥80,000 K to ~12,000–7,000 K. The peak of the WD radiation field shifts from the X-rays to the optical, where the SySt appears much brighter, in "outburst." The much cooler radiation field from the WD is thus lacking energetic photons, and the high ionization emission lines quickly disappear from SySts undergoing this type of outburst; (2) Type B—outbursts lasting for about a century, like the example of BF Cyg shown in Figure 4 or other well known cases, like V1016 Cyg, HM Sge, and AG Peg. All of them are characterized by a rapid rise to maximum (a couple of years at most), and then a slow, century-long decline with superimposed a lot of other smaller amplitude activity; (3) Type C—we could call them "a nova within a symbiotic binary." Outstanding examples are RS Oph, T CrB, and V407 Cyg, all being celebrated recurrent novae, characterized by very rapid evolutions (from a few weeks to a few months). The WDs of these systems are quite massive, close to the Chandrasekhar limit, and undergo eruptions like those of normal novae every few decades. The light curve of the 2010 such eruption of V407 Cyg is shown in Figure 5, and the spectacular evolution of Hα is presented in Figure 6 (which is within the observational possibilities of 0.7-m AA telescopes equipped with high resolution spectrographs). In quiescence, the slowly expanding LTG wind is ionized only in the immediate vicinity of the WD (sharp and weak Hα). When the WD undergoes a true nova eruption, the initial intense flash of hard radiation ionizes a vast fraction of the LTG wind still slowly expanding (sharp component in the March 15, 2010, Hα profile). The suddenly ionized LTG wind soon starts to recombine to neutral conditions, which it completes in less than a week, while the fast nova ejecta began to expand around the WD (broad component in the March 15, 2010, Hα profile). As the fast nova ejecta attempt to continue their expansion within the pre-existing dense and slow wind blown off the LTG, they are progressively slowed down (resulting in the narrowing of the Hα profile for April 7, 2010, spectrum in Figure 6). After some months, the nova ejecta have been almost entirely stopped by the pre-existing slow wind. The low electronic density characterizing the cavity the nova ejecta have swept within the LTG wind allows feeble emission from forbidden lines to appear (see the [NII] emission lines at 6548 and 6584 Å flanking Hα in the profile for September 22, 2010, in Figure 6).

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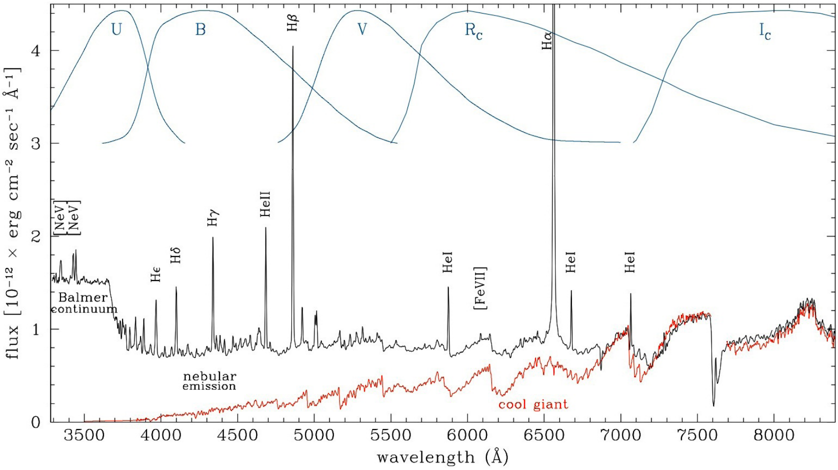

Figure 1. Optical spectrum of Z And in quiescence (Dec. 22, 2011, Asiago 1.22m telescope), with major emission lines identified. The contribution by the cool giant is highlighted, and the transmission profiles of Johnson UBV and Cousins R_C I_C bands are overplotted. The Hα line is truncated to enhance visibility of the rest.

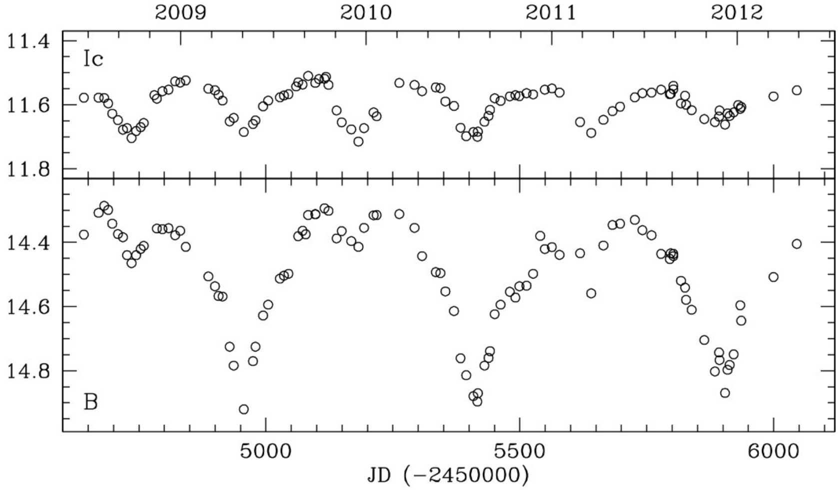

Figure 2. Recent light curve of the symbiotic star LT Del in quiescence (ANS Collaboration observations). The B-band lightcurve at the bottom is dominated by the heating-reflection effect, with one deep minimum per orbital period (when cool giant passes at inferior conjunction). The I_C-band light curve at the top is modulated by the ellipsoidal distortion of the cool giant filling its Roche lobe (two equal maxima and two equal minima per orbital period).

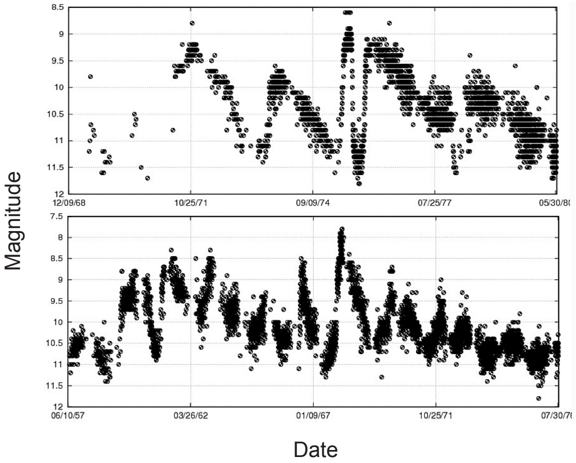

Figure 3. AAVSO light curves for the 1970–1978 outburst of CI Cyg (top) and 1957–1973 outburst of Z And (bottom). They are classical examples of type A outbursts of SySts, characterized by a train of multiple maxima before the system returns to quiescence and where it will remain for a period of time usually much longer than spent in outburst.

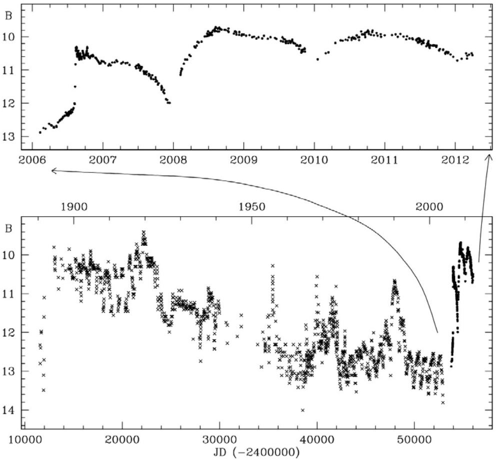

Figure 4. The historical B-band light curve of the symbiotic star BF Cyg. The object entered a major outburst around 1894, and took the whole of the 20th century to decline back to quiescence conditions, while displaying a lot of superimposed activity (including eclipses of the outbursting WD by the cool giant). In 2006, BF Cyg entered a new major outburst; whether it will last long as the previous one is a matter of speculation (crosses from Leibowitz and Formiggini 2006; dots from ANS Collaboration observations).

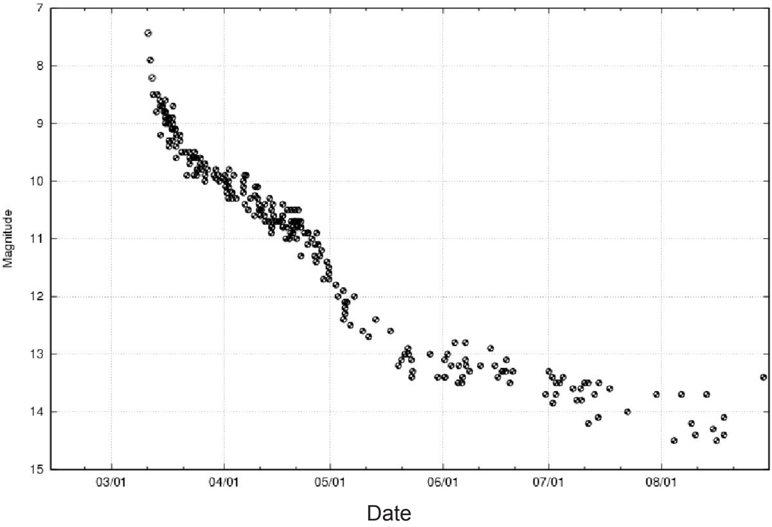

Figure 5. AAVSO light curve of the outburst of V407 Cyg during the spring-summer of 2010.

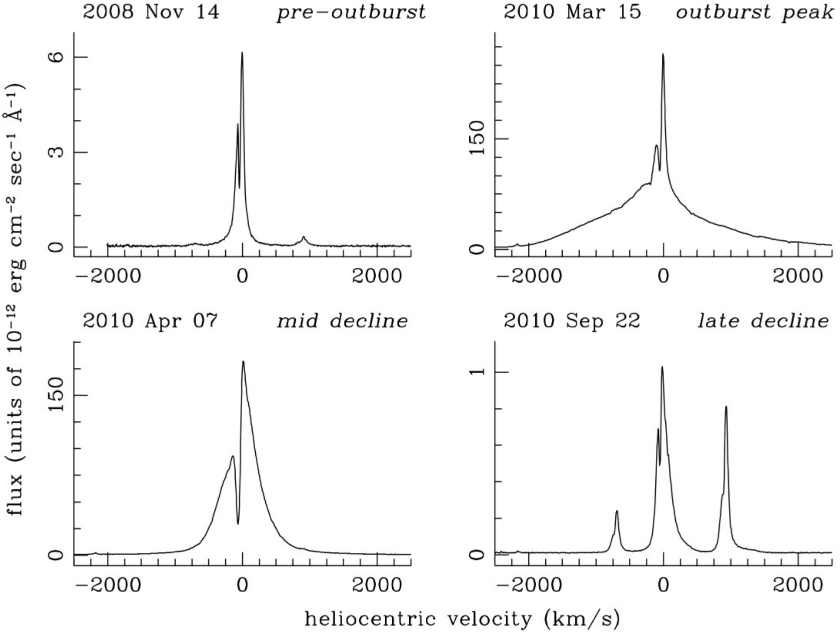

Figure 6. Evolution of the Hα emission line profile of V407 Cyg during the 2010 outburst. Note the ordinate scale which is different in each panel (adapted from Munari *et al.* 2011).

Classical and Recurrent Novae

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Abstract The physical nature and principal observational properties of novae are reviewed. Suggested improvments to optical photometry and discovery strategies are discussed. Nova eruptions occur in close binary systems, in which a white dwarf (WD) steadily accretes material on its surface from a lower mass cool companion. The accreted envelope is in electron degenerate conditions and grows steadily in mass with time, until a critical amount is accreted (which is inversely related to the WD mass). At that point, a fast evolving thermo-nuclear runaway starts burning hydrogen, in a short flash lasting about a hundred seconds, which is terminated by the violent ejection into the surrounding space (at a speed in excess of the escape velocity) of the whole accreted envelope (or a sizeable fraction of it). The nova is discovered only when, several hours or a few days later, the expansion and cooling of the fireball ejecta make them emit profusely at optical wavelengths; the later decline in brightness is regulated by interplay between dilution of the ejecta into surrounding space, gas and dust opacities, and temperature/luminosity of the central WD when the ejecta eventually become optically thin. The time interval between consecutive outbursts from the same nova is usually (far) longer than recorded history, but for a small number of objects (named recurrent novae) it is short enough that more than one outburst has been observed for them.

1. Introduction

For centuries, the term *nova* simply meant the unexpected appearance of a *new star* in the sky, fixed with respect to the other stars (to distinguish it from planets and comets), that after some time usually vanished from view. Now we know that quite different types of object can emerge from obscurity, sometimes briefly, as the result of completely different physical processes, like supernovae of various types, pre-main-sequence young objects of the FU Ori variety, very evolved objects undergoing late thermal pulses as displayed by V4334 Sgr (Sakurai's Object), cataclysmic variables in outburst, enigmatic events like V838 Mon (widely celebrated for its light-echo), and obviously the classical novae.

From an observational point of view, a *classical nova* (hereafter *nova* for short) is a stellar outburst characterized by a rapid rise toward maximum brightness (a matter of hours or days), a large amplitude in the optical ($8 \leq \Delta\,\mathrm{mag} \leq 16$), mass ejected at high velocity (from a few hundreds to a few thousands km sec^{-1}, as indicated by the very wide emission lines and/or largely blue-shifted absorption components in P Cyg profiles), post-maximum optical spectra evolving toward increasing excitation and ionization, and nebular conditions usually prevailing during advanced decline (that is, forbidden emission lines dominating the spectra). For the vast majority of novae, only one outburst has been observed in historical times. However, a few novae (like the celebrated U Sco, RS Oph, or T CrB) have undergone more than one outburst. They are called *recurrent novae*. It is believed that, should the monitoring time extend for hundreds or thousands of years, all novae would be seen to erupt again (and again). About 500 galactic novae are known. Duerbeck (1987) presented an accurately researched catalog and atlas of essentially all novae that erupted before 1986, which also included finding charts especially useful for old objects, long returned to quiescence conditions. Accurate coordinates, basic information, and finding charts for more recent novae were provided by Downes and Shara (1993) and Downes *et al.* (1997, 2001, 2005).

2. A model nova

Cataclysmic variables (CVs) and novae are believed to be the same binary systems, in which a low mass cool companion transfers material via Roche lobe overflow to a more massive white dwarf (WD). The orbital periods are a few hours long, and the orbital separations are on the order of the Sun's radius. During the hundreds or thousands of years spent away from nova outbursts, the material lost by the companion goes to form an accretion disk before terminating its journey by piling up on the surface of the WD (if the WD is strongly magnetized, the formation of an accretion disk is prevented and the material flows onto the WD via the magnetic poles). The accretion disk is prone to instabilities that cause regular, low amplitude bright phases termed CV-type outbursts (unfortunately, they are also called *dwarf* nova outbursts, a confusing terminology and another example of the irresistible attraction of astronomers for inapt terminology when better alternatives would be at hand). SS Cyg is a famous CV, whose accretion disk every two months goes through a CV-type outburst that brightens the system from $V=12$ to $V=8$. This cycle has continued uninterrupted since when SS Cyg was discovered in the late nineteenth century; (a wonderful AAVSO historical light curve covering about 110 years of observations and every outburst since discovery has been presented by Cannizzo and Mattei 1998).

The envelope accreted on the surface of the WD is in *electron degenerate* conditions, an unusual state of matter characterized by the fact that the pressure is not related to the temperature. In normal experience, you heat up something and it reacts by expanding: to lift a balloon, you raise the temperature of the air it contains and the resulting increase in pressure swells the balloon, which begins to ascend following Archimedes's principle (the density of the hot air in the balloon is lower than that of the cooler outside air). We write this by saying that its *equation of state* is $P \propto \rho T$, that is, the pressure is proportional to density times temperature. For electron degenerate material the equation of state modifies to $P \propto \rho^{\alpha}$, that is, there is no more dependence on temperature. Let's turn back to our nova in the making. With passing time, the envelope of material accreted on the surface of the WD steadly grows in mass until a critical value is reached (which is inversely related to the WD mass). When this occurs, the hydrogen present in the envelope starts to be burned via the CNO cycle, whose energy production rate (ε_N) is extremely sensitive to temperature: $\varepsilon_N \propto T^{18}$. The energy released by the nuclear burning heats up the envelope which however cannot react by expanding (its pressure is independent of temperature), and in turn the rise in temperature increases the nuclear energy production rate, that is, a circular argument. The temperature in the envelope rises exponentially out of control; (the envelope is experiencing a *thermo-nuclear runaway* or TNR). In a matter of few tens of seconds, it reaches the *Fermi temperature* (of the order of 350 million Kelvin) at which point the electron degeneracy is suddenly removed and the equation of state instantaneously reverts to that of ordinary gas ($P \propto \rho T$): the envelope can now react to its extremely high temperature by expanding. The expansion is so violent that the envelope is actually ejected into the surrounding space at a speed exceeding the escape velocity, and it will never return. The resulting drop in temperature first slows down and then effectively stops the TNR. A few minutes were enough to ignite the TNR, let it develop, and stop it. At this stage the nova has not been discovered yet: it will become visible only hours/days later when the fireball of the expanding ejecta has grown in size enough and its surface temperature as declined to about 10,000 K to shift the peak of radiated energy from the initial γ- and X-rays to the optical range.

When SS Cyg undergoes such a TNR and the consequent resulting nova outburst (maybe tomorrow, maybe a thousand years from now), it will rise in brightness so much that it will probably become, for days/weeks, the brightest star of the whole sky, rivalling or surpassing Vega and Sirius. But do not worry: a few months later SS Cyg will be back to quiescence and in a few decades more, it will resume its CV-type, ~60-day cycle outbursts, for the fun of future enthusiastic observers!

3. Some statistics on novae

3.1. Where they appear

Novae do not appear randomly on the sky, but they concentrate along the Milky Way and in particular in its central regions. There are eighty-eight constellations on the sky, but no nova has ever been observed in over twenty-two of them, most notably Hydra, Ursa Major, Pegasus, and Draco that together cover an area of 4,800 square degrees, or about 12% of the whole sky (the statistics in this review are based exclusively on official International Astronomical Union (IAU) data, in particular *IAU Circulars* and *CBET*s). A list of the constellations arranged according to the number of novae they produced is given in Table 1. Sagittarius, with its 114 novae, leads the group.

Sagittarius is however favored by being a large constellation (867 square degrees). To assess the productivity of the various constellations, it is better to refer to the number of novae which appeared there, per unit area, essentially dividing the data in Table 1 by the constellation area. The results are given in Table 2, expressed as the number of novae appearing in the given constellation over an area of 100 square degrees. The small Scutum (covering just 109 square degrees on the sky; only Circinus, Sagitta, Equuleus, and Crux being smaller) now stands out as where the concentration of novae is the highest (therefore, Scutum would be a good target to image if your are considering starting to look for novae yourself !).

3.2. How bright they are

The distribution of novae in terms of magnitude at maximum and of outburst amplitude (that is, the difference in magnitude between quiescence and outburst maximum) is presented in Figure 1 (panels a and d). The data are rather heterogeneous (coming from old blue-sensitive photographic plates, visual estimates, unfiltered CCDs, properly calibrated BVRI observations, and so on; when the information is available, they refer to the actual maximum brightness, but sometimes only the brightness at the time of discovery is known).

The distibution of magnitude at maximum looks like a Gaussian distribution peaking around magnitude = 8.7. Such a distribution suggests that most of the novae peaking to magnitude 8 or brighter have indeed been discovered. Conversely, the majority of those reaching only magnitude 11 or 12 pass unnoticed. However, the number of Galactic novae does not increase indefinitely toward fainter magnitudes (contrary to the case of supernovae, where fainter magnitudes means larger volumes of space and greater numbers of host galaxies): the size of our Galaxy is limited and the novae are intrinsically very bright objects. Let's take for example Figure 2, which summarizes the distribution in magnitude of the ninety-five novae discovered in the Andromeda galaxy (M31) over the five-year interval 2007–2011 (an average of ~20 novae per year): the distribution peaks between 17.0 and 17.5 in R_C, corresponding to a peak $M(R_c) = -7.3$ magnitude in the absolute magnitude distribution. The discovery of real faint novae in the central bulge region of M31 is no doubt adversely biased; nonetheless the peak of the distribution in Figure 2 seems well established observationally. A $M(R_c) = -7.3$ magnitude Galactic nova would appear to us shining at

$$R_c = M(R_c) + 5 \log d - 5 + A_R = -12.3 + 5 \log d + A_R \qquad (1)$$

where d is the distance expressed in parcsecs and A_R is the amount of interstellar extinction in the R_C band (which relates to E_{B-V} reddening as $A_R = 2.6 \times E_{B-V}$). At a distance of 3 kpc and an extinction $A_R = 1.6$ magnitude, our $M(R_c) = -7.3$ nova would shine at a comfortably $R_c = 6.7$ magnitude. Even pushing it to the center or our Galaxy ($d = 8.5$ kpc, $A_R \approx 5$ mag.), it would still score $R_c \approx 12.3$, well within the observing capability of amateur telescopes (provided their focal length is long enough to discern the nova among the myriads of similarly bright stars crowding the views of telescopes aimed at the center of the Galaxy).

The average magnitude of discovered novae has not significantly changed over the last eighty years, since photographic emulsions substituted for the eye as detector in patrol searches (Figure 1c). What has been continously improving is instead the frequency of nova discoveries, as illustrated in Figure 1b. From about 2.5 novae per year on average at the beginning of the twentieth century, it rose to about 4 during 1980–1990. The surge to about 8 novae per year over the last 5 to 10 years is undoubtedly connected to the widespreading use of sensitive CCDs as detectors and electronic blinking of images. Figure 1b suggests we are currently on a steep rise, and the number of novae discovered per year should appreciably increase during the next 5 to 10 years.

3.3. Who discovers them

Table 3 lists the most prolific nova discoverers, nearly all of them amateur astronomers, a group of highly motivated and dedicated people led by William Liller, who works from Viña del Mar, in Chile. He has for a long time recorded sky images with a 35-mm camera, an 85-mm lens, Kodak Technical Pan 2415 film, and an orange filter, and then made use of a homemade, 25-power stereo viewer. One eye looks at the new sky photograph, while the other at an archival image. If a candidate nova appears in one image but not the other, that prompts further investigation and confirming observations. Such an eye inspection is equivalent to blinking on a computer monitor electronic images taken with CCDs. Their dropping costs, the ever-increasing area of their detectors, and the real-time inspection of their images allowed by electronic blinking (either via automated software or eye inspection on a computer monitor), are making DSLR cameras the primary tool for current nova hunters. The discovery of novae will presumably remain, for a long time, a business reserved for amateurs: professional telescopes are too inefficient to cover large areas of the sky at bright limiting magnitudes night after night.

4. The light curve

A schematic light curve for a nova is shown and described in Figure 3. With the increasing number and quality of photometric observations, the great diversity among the observed light curves is increasingly evident, to the point that speaking of a *typical* light curve for novae is losing its meaning. Many examples of light curves of novae have been presented, among others, by Payne-Gaposchkin (1957), Kiyota *et al.* (2004), and Strope *et al.* (2010), the latter offering also a new morphological classification scheme.

After the initial rapid rise (a matter of just a few hours in very fast novae like U Sco), the nova goes through a maximum optical brightness phase that can be anything from an immediate rebound toward decline, to a smooth and well-behaved round phase, or a series of erratic ups-and-downs on top of a flat plateau, or a second and equally well-behaved maximum, and so on. A non-exhaustive compilation of observed behaviors at maximum brightness is shown in Figure 4. Then, past maximum phase, the decline toward quiescence sets in, and it is usually characterized by two phases: a faster one, when the ejecta are still optically thick (the central source cannot be seen from outside) and that lasts until the nova has declined by 3–4 magnitudes from maximum, and then a slower one, when the ejecta become optically thin (the whole body of them becomes directly exposed to the hard ionizing radiation emanating from the central star, and the latter is visible from outside the ejecta).

The time when the transition from optically thick to optically thin conditions occur in the ejecta also marks in some novae the onset of transient events perturbating an otherwise smooth decline, either dust formation or (semi-periodic) oscillations. Dust grains can form in the ejecta, and the resulting dust obscuration can dim by several magnitudes the brightness of the nova. After a maximum is reached, the obscuration by dust progressively reduces and, after a while, the nova resumes the decline path it would have followed in the absence of dust formation. The dilution of the dust grains caused by the ongoing expansion of the ejecta is the main reason for the end of the obscuration phase. The radiation absorbed in the optical heats up the dust grains which re-emit it at longer wavelengths, and the nova appears several magnitudes brighter at infrared wavelengths (thus, during the dust phase, the infrared light curve is a mirror image of the optical light curve). With the transition from optically thick to optically thin conditions in the ejecta, oscillations of various types may be seen in several novae. They can be either of the type making the nova look temporarily fainter (like for instance V2467 Cyg / N Cyg 2007) or brighter (as in V2468 Cyg / N Cyg 2008 No. 1). These oscillations can either appear irregular in both phase and amplitude, or follow a regular, sinusoidal-like pattern. One of the novae showing the most spectacular set of oscillations was GK Per (N Per 1901). They started when the nova was 3.5 magnitude down from maximum brightness, and lasted several months; at least 20 oscillation cycles were counted, with peak-to-valley amplitudes ranging from 1.0 to 1.5 magnitudes. A generally agreed physical explanation for the oscillations does not yet exist, though various models have been suggested.

5. The spectrum

The spectra of novae, right at maximum brightness, are dominated by an underlying hot continuum with only relatively weak emission lines, sometimes only Hα being visible in emission. All absorption lines show large negative radial velocities, indicating that they are forming in a rapidly expanding medium. As soon as the nova begins to decline, the emission lines rapidly get progressively stronger than the continuum. This is the combined effect of the underlying continuum declining in intensity while, for some time, the emission lines increase in their absolute flux. After the transition from optically thick to optically thin ejecta has been completed, the underlying continuum essentially vanishes, and nearly all the flux recorded from the nova comes from emission lines only.

The spectrum of a nova around maximum and early decline can be either of the *FeII* or the *He/N* type, and an example of them is shown in Figure 5 (note that the ordinate scales are in logarithm of the flux to enhance visibility of the weak features). A FeII-type nova displays, in addition to hydrogen Balmer emission lines, many permitted emission lines from FeII, especially from multiplets 27, 28, 37, 38, 42, 48, 49, 73, 74. Conversely, a He/N-type nova, in addition to Balmer lines, will display emission lines from helium and nitrogen but not from FeII.

The early classification of a nova spectrum is important because it will set the stage for what to expect next in its evolution. In comparison with FeII-type, He/N novae usually decline faster, show larger expansion velocities (that is, broader emission lines), and eject a lower amount of mass. While FeII novae appear to belong to an older stellar population, heavily concentrated toward the bulge of the Galaxy, He/N novae show a lower concentration toward the center of the Galaxy and are instead more concentrated along the disk of the Galaxy, suggesting a younger parental stellar population and more massive WDs. All FeII novae display a nebular spectrum during their advanced decline, while a few He/N novae sometimes do not. An example of a nebular spectrum is shown in Figure 6 (note how the flux of the continuum in between the emission lines is almost null). Conversely, only He/N may display coronal emission lines (lines of extremely high ionization such as [FeX] 6375, [FeXI] 3987, 7892, [FeXIV] 5303, [NiXIII] 5114, [NiXV] 6702, [ArX] 5532, [ArXI] 6915, all seen during the 2006 outburst of RS Oph).

Amateur spectroscopic observations can provide both a confirmation and a classification (FeII or He/N types) of candidate novae, and then follow their early post-maximum evolution. A 60-cm telescope equipped with a spectrograph working at dispersions from 2 to 4 Ångstroms/pixel can do that for novae brighter than $V = 11$. The exceptional intensity of the Hα emission line in nearly all novae allows one to follow the evolution of its profile (frequently multi-peaked and with P Cyg absorption components varying with time) for a long time into the decline. A spectrograph working at 1 Ångstrom/pixel on a 60-cm telescope can easily observe and resolve the Hα profile for novae down to $V = 12$ magnitude.

6. Hints about observing novae

Amateur astronomers are already providing fundamental photometric data on novae. However, significant improvements, easy to implement, are still possible, and some of them are suggested in this concluding section.

6.1. Discovery

Most amateurs carry out their patrols for novae and discover them on unfiltered CCD images. It would be advisable to carry out the search with well-known photometric filters instead. The on-line AAVSO Photometric All-Sky Survey (APASS) provides suitable Jonhson *BV* and Sloan $g'r'i'$ comparison stars down to 16th magnitude anywhere on the sky. Cousins' R_c, I_c magnitudes can be easily obtained from the following relations calibrated on APASS data:

$$\begin{aligned} R_c &= r' - 0.095 \times (g' - i') - 0.141 \\ I_c &= i' - 0.055 \times (g' - i') - 0.364 \\ (R{-}I)_C &= 0.894 \times (r' - i') + 0.212 \end{aligned} \tag{2}$$

for APASS fields south of the equator, while for APASS fields north of the equator they are:

$$\begin{aligned} R_c &= r' - 0.065 \times (g' - i') - 0.174 \\ I_c &= i' - 0.044 \times (g' - i') - 0.365 \\ (R{-}I)_C &= 0.918 \times (r' - i') + 0.198 \end{aligned} \tag{3}$$

There is very little to lose if the observations are carried out, for example, in the standard R_c Cousins or Sloan r' bands: the sensitivity of most CCDs peaks there; they include the emission of the strong Hα line; and the background sky brightness is lower there than at bluer wavelengths. The discovery images will be the only ones covering that part of the light curve, that is, the critical phases preceding or around optical maximum, but if they were not obtained in a proper photometric system it will be very difficult to extract solid physical information from them. Frequently, the un-filtered photometry is unavoidably ignored in subsequent analysis and modeling.

6.2. Maximum brightness

It happens too frequently that a nova is rapidly forgotten after the initial discovery. While the discovery is surely personally rewarding and an important contribution to the field, accurate photometric monitoring (especially in the *B* and *V* bands) of the nova while it is passing through maximum brightness, is vital to fix fundamental quantities like the exact time of maximum, its brightness and its color. From the *B–V* color the reddening and extinction will easily follow. The *B* and *V* magnitudes exactly 15 days past maximum constrain the distance to the nova. Knowing the exact *B* and *V* magnitudes at maximum brightness will allow one to define the fundamental quantities t_2 and t_3 in both bands (that is, the time required for the nova to decline by 2 and 3 magnitudes, respectively). From t_2 and t_3 the distance to the nova can be derived, and many other parameters (like the mass of the ejecta, the mass of the WD, or when the optically thin phase will begin) can be constrained. In most cases, by the time professionals can access a telescope and turn it to a recently discovered nova, it will be already past maximum, and a fundamental piece of information would be lost if not provided by amateurs.

In addition, the time of maximum brightness is a period of unexpected behavior by many novae. Some examples are illustrated in Figure 4. So far, very few novae have been accurately and multi-band monitored through their maxima. Consequently, this phase is still so poorly documented that many theoretical models do not treat it in a way able to account for the observed peculiarities. Providing accurate multi-band monitoring of maximum brightness for a greater number of novae could allow one to search for correlations between behavior at maximum and other parameters of the nova light curve or spectral properties. This in turn would both motivate and constrain theoretical efforts attempting to model peculiar maxima.

6.3. Novae in the center of the Galaxy

Compared to the novae normally discovered by amateurs, those erupting close to the center of the Galaxy will appear fainter (because of the greater distance and larger intervening extinction) and will be harder to spot against their higher stellar density backgrounds. The extremely high stellar densities at the core of the Galaxy suggests that many novae that erupt there go undiscovered every year.

The reason they escape detection lies probably in the use of DSLR cameras for nova patrol. While entirely appropriate to search for novae elsewhere on the sky, their limiting magnitude is too bright and their focal length too short to be able to detect most of the novae erupting in the central regions of our Galaxy.

To discover them, a longer local length and a larger lens than in DSLR cameras seems appropriate. The area to patrol is limited (of the order of 12 × 12 degrees) and a longer focal length could cover it with a limited number of overlapping images, providing a sufficient spatial resolution to isolate a $V = 12$ magnitude nova from the dense surrounding stellar background. The dividends paid by such a program focused just on novae at the heart of our Galaxy could be high.

6.4. The interesting case of V2672 Oph (Nova Oph 2009)

Nova Oph 2009 (V2672 Oph) reached maximum brightness at $V = 11.35$ on 2009 August 16.5 UT. With observed $t_2(V) = 2.3$- and $t_3(V) = 4.2$-day decline times, it is one of the *fastest* known novae, being rivalled only by V1500 Cyg (Nova Cyg 1975) and V838 Her (Nova Her 1991) among classical novae, and U Sco among the recurrent ones. The line of sight to the nova passes within a few degrees of the Galactic Center, crosses the whole bulge, and ends at a galacto-centric distance larger than that of the Sun. This is probably a record distance and position among known Galactic novae. It is not incidental that, to discover it, K. Itagaki used an *f*/3 21-cm reflector, providing light gathering power and spatial resolution far in excess than a DSLR camera. On the basis of its many remarkable similarities to U Sco, it is highly probable that this nova is a recurrent one, possibly with a recurrence time as short as that of U Sco (Munari *et al.* 2011), and it should be inserted among the areas to be monitored regularly in the future.

The central region of the Galaxy has been imaged (on films and with CCDs) countless times, especially by amateurs looking for impressive pictures. It is quite possible that other outbursts of V2672 Oph lie unnoticed on such archival images, especially those imaging at red wavelengths. A devoted search is highly encouraged and I would be pleased to be informed (at the e-mail address given above) about the results. A list of negative results (reporting about date, UT, band, focal length, limiting magnitude of the image) would also be relevant to put constraints on the recurrence time scale. Figure 7 identifies the nova on a R_C image obtained close to maximum brightness, and provides magnitudes for reference stars.

6.5. Photometric monitoring

If observers provide only a few photometric points each, to cover the entire light curve of a nova it is necessary to combine data from many different observers. The dispersion of points in such a combined light curve is however so large (up to 1 magnitude) that all details are smeared out. The main reason is that during decline the flux from a nova is mainly concentrated in a few emission lines. Two nearly identical filters can produce drastically different data, if one includes in the transmission profile a strong emission line and the other not. This is what usually happen with the *V* filter, whose steep rising blue transmission edge coincides with the [OIII] 4959, 5007 doublet, usually the strongest emission line during the nebular phase. Figure 6 illustrates the situation.

It is advisable that once an observer begins to observe a nova (the earlier in its evolution the better), they should try to keep focused on it for the longest possible period of time. Their photometric equipment will remain the same through the observing campaign, and the collected data will be self-consistent: all the finer details of the light curve will be visible because it will not be necessary to combine with other external data.

To avoid the strongest emission lines and collect an important measurement of the true continuum underlying them, Stromgren *b* and *y* filters could be used in addition to standard Johnson *B* and *V* throughout the whole light curve. It is true that being narrower they will collect less light and the exposure times will consequently be longer, but this will be counter-balanced by the increasing physical value of the measurements. The following relations

$$\begin{aligned} y &= V - 0.062 \times (B\text{–}V) + 0.027 \\ b &= B - 0.469 \times (B\text{–}V) + 0.060 \\ (b\text{–}y) &= 0.593 \times (B\text{–}V) + 0.033 \end{aligned} \tag{4}$$

provide an useful mean to estimate Stromgren b and y magnitudes of comparison stars from their APASS B and V values.

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Table 1. Number of novae that appeared in the listed constellations, updated to 2012. The constellations that never displayed a nova (such as Ursa Major) are not listed.

Sgr	114	Vul	10	Mus	5	Leo	3	Lup	2	Tau	1	Crv	1
Oph	45	Car	10	Vel	4	CrA	3	Lib	2	Pyx	1	CrB	1
Sco	43	Ser	8	TrA	4	Boo	3	Eri	2	Psc	1	Com	1
Aql	33	Nor	8	Sge	4	Aur	3	Cru	2	Pic	1	CMa	1
Cyg	22	Her	8	Mon	4	Ari	3	Ara	2	Lyr	1	Cha	1
Sct	18	Cir	7	Lac	4	And	3	Vir	1	LMi	1	Cet	1
Cen	14	Per	6	Cas	4	Tri	2	UMi	1	For	1	Cep	1
Pup	11	Gem	6	Ori	3	Pav	2	Tel	1	Del	1	Aqr	1

Table 2. Ranking of the constellations in Table 1 in terms of nova productivity per unit area on the sky (here expressed as the number of novae that appeared over an area of 100 square degrees).

Sct	16.50	Mus	3.61	Gem	1.17	CrB	0.56	Tel	0.40	Cep	0.17
Sgr	13.14	Cru	2.92	Per	0.98	Crv	0.54	UMi	0.39	Tau	0.13
Sco	8.66	Cyg	2.74	Ara	0.84	Pav	0.53	Lib	0.37	Psc	0.11
Cir	7.50	CrA	2.35	Mon	0.83	Del	0.53	Lyr	0.35	Aqr	0.10
Aql	5.06	Car	2.02	Vel	0.80	Ori	0.50	Boo	0.33	Vir	0.08
Sge	5.00	Lac	1.99	Cha	0.76	Aur	0.46	Leo	0.32	Cet	0.08
Nor	4.84	Pup	1.63	Ari	0.68	Pyx	0.45	Com	0.26		
Oph	4.75	Tri	1.52	Cas	0.67	LMi	0.43	CMa	0.26		
Vul	3.73	Cen	1.32	Her	0.65	And	0.42	For	0.25		
TrA	3.64	Ser	1.26	Lup	0.60	Pic	0.41	Eri	0.18		

Table 3. List of the most prolific nova discoverers and the number of novae credited to them (from official International Astronomical Union discovery documentation).

40	W. Liller	9	M. Mayall	7	Y. Nakamura
14	K. Nishiyama	9	P. Camilleri	6	M. Wolf
14	H. Nishimura	8	G. Pojmański	6	D. MacConnell
14	F. Kabashima	8	L. Plaut	6	Y. Kuwano
14	H. Honda	8	A. Cannon	6	C. Hoffmeister
12	G. Haro	7	M. Yamamoto	6	K. Haseda
11	I. Woods	7	J. Seach	6	C. Burwell
11	W. Fleming	7	Y. Sakurai		

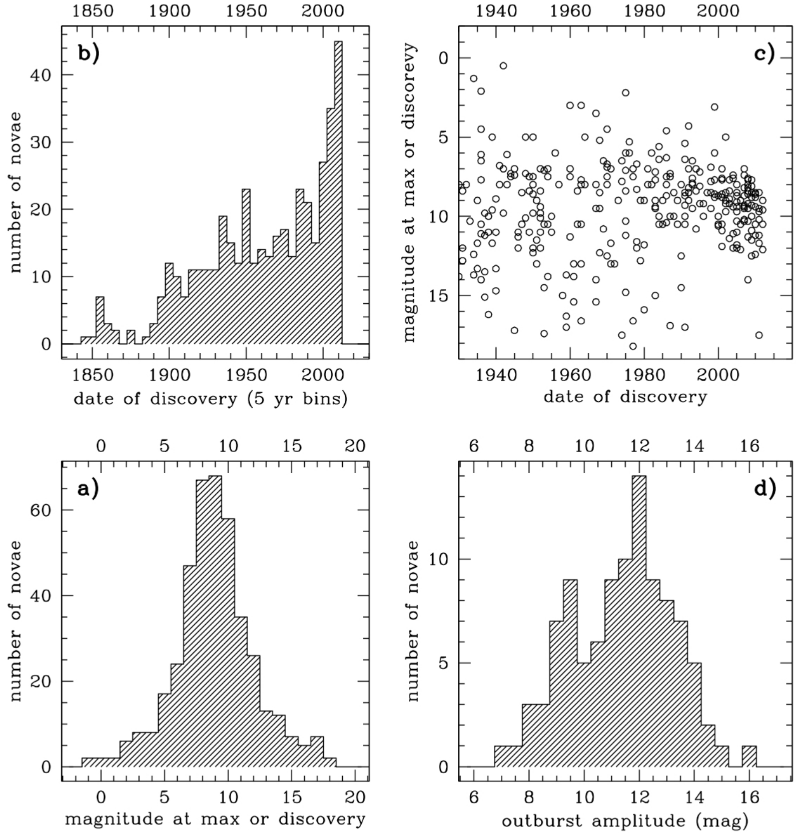

Figure 1. Statistics about Galactic novae updated to 2012: a. distribution in magnitude at maximum (or, when not available, at the time of discovery); b. number of novae discovered, counted in five-year-wide bins; c. brightness of discovered novae as function of time; d. distribution of the amplitude of nova outburst (this panel adapted from Figure 2.3 of Warner 2008).

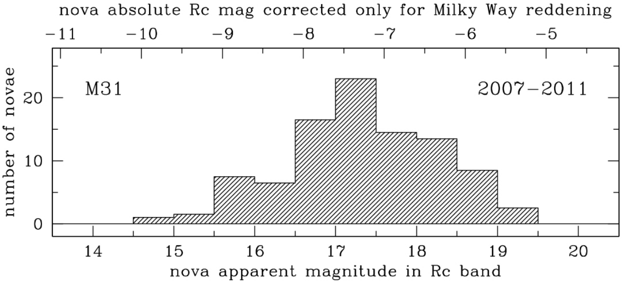

Figure 2. Distribution in R_C magnitude of the 95 novae discovered in M31 over the five-year period between 2007 and 2011.

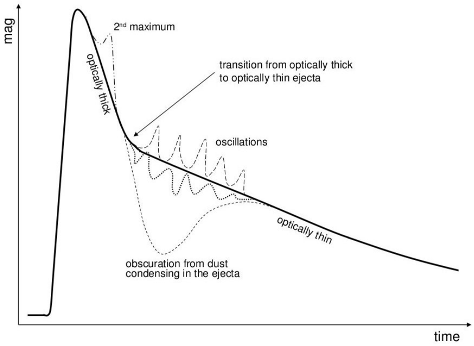

Figure 3. Schematic representation of the optical light curve of a nova. The thicker solid line provides the reference background behavior, the thinner and dashed/dotted lines represent alternative behaviors displayed by some novae.

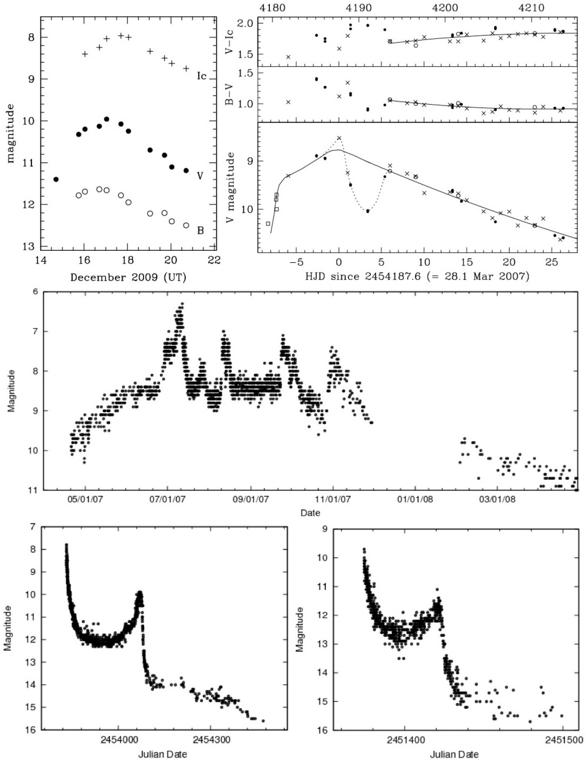

Figure 4. Some examples of the many different behaviors shown by novae around maximum brightness: the textbook smoothness exhibited by V1722 Aql/N Aql 2009 (upper left; Munari *et al*. 2010); the single pulsation-like cycle displayed by V2615 Oph/N Oph 2007 (upper right; Munari *et al.* 2008); the chaotic train of several maxima presented, over a flat plateau, by V5558 Sgr/N Sgr 2007 (center; AAVSO); the second maximum shown by V2362 Cyg/N Cyg 2006 (bottom left; AAVSO); and V1493 Aql/N Aql 1999 No.1 (bottom right; AAVSO).

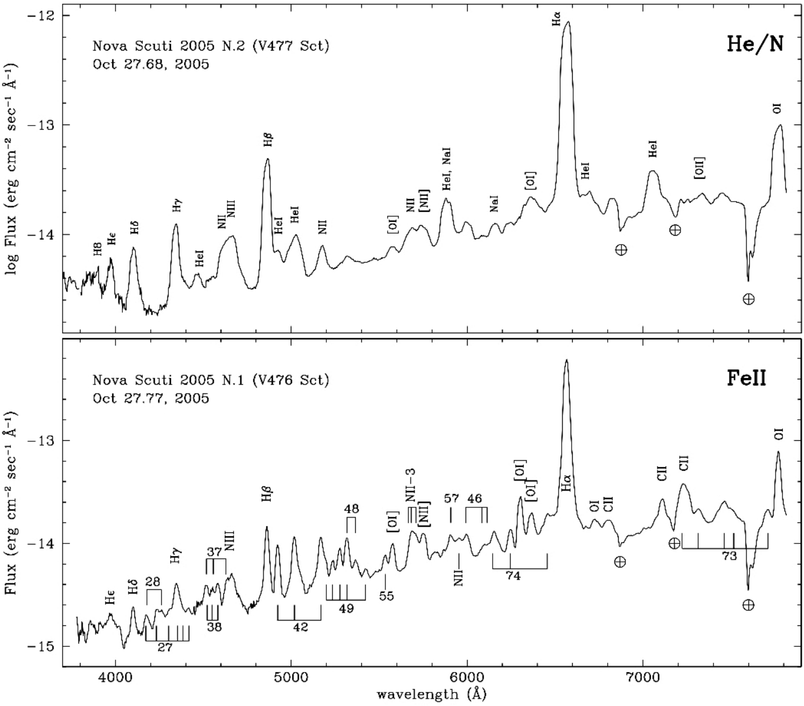

Figure 5. Examples of spectra of FeII and He/N types of novae (around maximum and along the optically thick part of the decline light-curve; Munari *et al.* 2006a, 2006b). To enhance visibility of the weak features, the absolute fluxes on the ordinate scale are plotted in logarithmic units. Major emission lines are identified. Comb-like markings identify FeII lines and the associated number the respective multiplet. Strong telluric absorption bands at 6850, 7160, and 7580 are also marked. Note the larger width of the lines in V477 Sct, tracing a large ejection velocity than in V476 Sct.

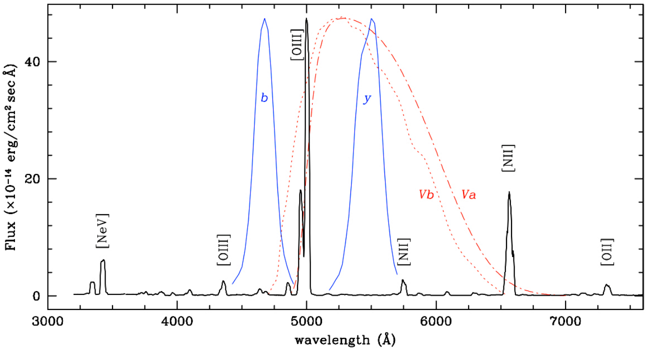

Figure 6. The nebular spectrum of Nova Cir 1995, as observed in 1996. The major forbidden emission lines are identified ([OIII] 4363, 4959, 5007 Å, [NII] 5755, 6458, 6584 Å, [NeV] 3346, 3426 Å, [OII] 7325). The transmission profiles of two commercially available *V*-band filters (labelled *Va* and *Vb*) are overplotted to show their difference in trasmitting the [OIII] 4959, 5007 Å and the [NII] 6458, 6584 + Hα 6563 Å blends (from Munari and Moretti 2012). The transmission profiles of Stromgren *b* and *y* filters are also overplotted. By avoiding the strongest emission lines, they provide a direct measurement of the true continuum emission of the nova.

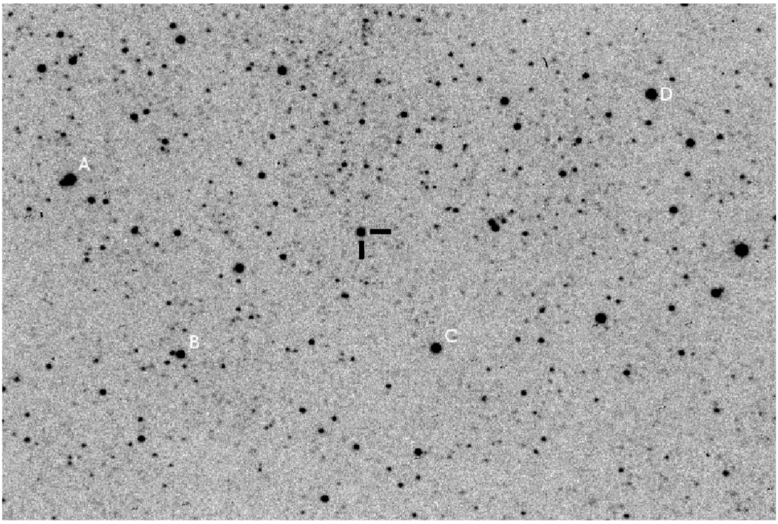

Figure 7. Finding chart for V2672 Oph/N Oph 2009 (J2000: R.A. $17^h\,38^m\,19.72^s$, Dec. –26° 44' 13.7") when it was shining at $R_C = 11.64$ a couple of days past maximum. The *V*, *B–V*, $V–R_C$, $V–I_C$ values for the four comparison stars are: 11.250, +2.032, +0.990, +1.991 for A; 12.039, +0.689, +0.300, +0.746 for B; 11.620, +1.518, +0.763, +1.560 for C; and 11.290, +1.814, +0.916, +1.797 for D. 18 × 13 arcmin image courtesy S. Dallaporta (Meade 10-inch + SBIG-ST8).

A Century of Supernovae

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Abstract The concept of "supernova," a class of exploding stars more than 100 times the luminosity of an ordinary nova, was introduced almost eighty years ago. Over that time the physics of supernovae has matured into a rich field of study with the identification of several types of explosions and models to explain many of the observations. While there has not been a supernova visible in our Galaxy in over 300 years, only twenty-five years ago a naked-eye supernova, SN 1987A, was intensively studied in a companion galaxy to the Milky Way. Type Ia supernovae have proven to be a reliable way to estimate cosmological distances and these standardizable "candles" have greatly improved the estimate of the local expansion rate of the universe. Pushed to great distances these supernovae have demonstrated that the universe is accelerating, a discovery recognized with the 2011 Nobel Prize in physics.

1. Introduction

The founding of the AAVSO predates the concept of "supernova" by twenty years. New stars, or novae, had been seen through the centuries and introduced to western science by Tycho's and Kepler's observations, but the differentiation between the luminosities of ordinary novae and supernovae required the development of a extragalactic distance scale in the late 1920s and early 1930s (Baade and Zwicky 1934). Hubble had recognized a class of particularly luminous events he referred to as "exceptional novae" (Hubble 1929), but for a new age of "supermarkets" and comic books featuring "Superman," it was Baade and Zwicky's "super-nova" that caught the imagination of the public (Koenig 2005).

Supernovae are stellar explosions that completely disrupt their progenitor star while classical novae result from the thermonuclear fusion on the surface of a compact stellar remnant such as a white dwarf. Novae leave their binary star system intact to nova again another day, decades or millennia down the road. Supernovae yield high velocity gas, luminous energy, and sometimes a neutron star or a black hole. The creation of a neutron star was one of Zwicky's early explanations for the power of these explosions (Baade and Zwicky 1934) although the neutron had been discovered less than two years earlier.

Supernovae were clearly more energetic than novae, based on the new extragalactic distance scale of the 1930s. The absolute magnitude (the apparent magnitude of a star if it were placed 10 parsecs (32.6 light-years) from the Earth) of supernovae range from –16 to –19 while the brightest novae reached –10 magnitude. Searches for intermediate luminosity events have been recently made possible with new, wide-field instrumentation (Kasliwal 2011). Gamma-ray astrophysics and wide-field optical searches have also identified classes of explosions more luminous than supernovae—“hypernovae” (Iwamoto *et al.* 2000; Garnavich *et al.* 2010). Hypernovae have absolute magnitudes of –20 to –21 but their explosion mechanisms are uncertain and their origins appear diverse.

Supernovae and their cousins are important to the ecology of galaxies and the universe. These stellar explosions inject energy into the interstellar gas that triggers star formation. The heavy elements synthesized in supernovae have polluted the pristine hydrogen and helium from the Big Bang, allowing the formation of planets (and people). Supernovae have also become valuable tools for the study of cosmology and have led to the discovery of the accelerating universe and “dark energy” (Reiss *et al.* 1998; Perlmutter *et al.* 1999).

2. Searching for supernovae

In the late 1930s Baade and Zwicky teamed up with Johnson and Minkowski to begin the world’s first systematic search for supernovae (Baade and Zwicky 1938) using a Schmidt telescope on Palomar Mountain. They soon discovered one of the three brightest supernovae of the last century, SN 1937C (supernovae are named by the year of their discovery followed by a letter matching the order of discovery within that year), which reached an apparent magnitude of 8. By the start of the Second World War they had found fifty supernovae and made critical spectroscopic observations that led to the standard classification scheme for supernovae that is still used today. If a supernova has no hydrogen in its spectrum, it is called a “Type I,” while if hydrogen is present it is a “Type II.” Future supernova discoveries would lead to division of these broad classes into sub-types and the physics of the explosions are not well described by this binary scheme, but taxonomy comes before understanding.

Some form of supernova search using photographic plates continued at Palomar for the next forty years. Other observatories began to contribute as well, leading to an average of about fifteen supernova discoveries per year by the start of the 1980s. It is also possible (but difficult) to discover supernovae visually. Robert O. Evans has discovered over forty supernovae mostly through directly visual observation with a small telescope. But a transformation in the way supernovae are discovered and studied arrived with the availability of Charged-Coupled Device (CCD) detectors in the late 1980s. CCDs are nearly ten times more sensitive than photographic plates or the eye, meaning that a 12-inch telescope plus a CCD goes as deep as a 1-meter scope using photography.

CCDs opened up a much larger volume of space for the amateur astronomer to search for supernovae. Arbour, Aoki, Armstrong, Boles, Puckett, Schwartz, and others made important contributions to supernova studies by discovering hundreds of events over the past twenty years.

Professional astronomers also put the new technology to use. Electronic detectors plus computer image manipulation led to automated searches that minimize human interaction (Li *et al.* 2000). The increasing size of CCD chips and the ability to mosaic detectors in a single instrument revolutionized supernova searching. Instead of shooting an image of a single galaxy with the hope that a supernova will appear, hundreds or even thousands of galaxies could be imaged simultaneously with a single exposure. This led to mass production of supernova discoveries at intermediate and high redshift (Frieman *et al.* 2008; Schmidt *et al.* 1998).

3. The core-collapse supernovae

Zwicky's speculation that supernovae result from the formation of a neutron star was right on, at least for a significant fraction of supernovae. Stars that begin their lives with masses more than about eight times the mass of the Sun eventually run out of energy production in their cores. Once this happens they are unable to resist gravity and the core collapses into a neutron star or black hole. The gravitational energy is turned into kinetic as the outer envelope is ejected at high velocity. In fact, the process we call a core-collapse supernova is more complicated. It probably requires neutrino deposition, asymmetric shocks, and additional exotic physics to launch the envelope into space.

The model of supernova production, gravitational energy released in core collapse, did not fully explain the variety of spectra seen in the 1930s through the 1960s. The broad features in the spectra caused by the high velocity of the ejected gas made it difficult to identify the lines. The presence of hydrogen was clear in Type II events but the identification of other elements in Type II and those found in Type I supernovae remained controversial (Branch 1990).

In fact, nature was playing a trick on astronomers. Type I supernovae actually came from two completely different progenitors and energy sources. It was not until the early 1980s that the peculiar spectra seen in a number of Type I supernovae led to the division of that class into subtypes Ia and Ib. Wheeler and Levreault (1985) asserted that the origin of the Type Ib supernovae was similar to Type II despite significant differences in their spectra. Soon, another subclass, Type Ic, was added that, like Type II and Type Ib, was from massive star core-collapse. We now know that Type Ia supernovae are not generated by the collapse of the center of a massive star, but are caused by the nuclear fusion of a compact, low mass star.

The spectral classification scheme was well established by the early 1990s. Hydrogen-rich spectra are from Type II events just as Zwicky had set out. Type Ib supernovae are core-collapse events rich in helium and Type Ic explosions are core-collapse supernovae with little hydrogen or helium. Type Ib and

Ic progenitors have lost their hydrogen and/or helium through a wind or by transferring it to a companion star.

The success of the scheme was short-lived, as a supernova was discovered in the nearby galaxy M81 at the end of March 1993 that did not stick to a single category. SN 1993J showed hydrogen in its early spectrum (Garnavich and Ann 1994) but later displayed strong lines of helium. Apparently SN 1993J had only a thin layer of hydrogen atop a helium atmosphere so that as the supernova aged and we viewed deeper layers, the classification shifted from II to Ib. Other, less bright supernovae have since shown this transformation and this intermediate class has been called "Type-IIb."

4. The supernova of the century: SN 1987A

There has not been a supernova discovered in our Galaxy for over 300 years, but in 1987 we got the next best thing. The first supernova of 1987 was found in the nearest galaxy to the Milky Way, the Large Magellanic Cloud (LMC) at a distance of only 150,000 light-years. This sounds like a huge distance, but SN 1987A became the first naked-eye supernova since Kepler's in 1604 and reached 2nd magnitude (see Figure 1). It explosion was so bright major observatories with their large telescopes had difficulty observing it near maximum light. Its proximity and location in a well-studied galaxy meant that the progenitor of a supernova could finally be identified from archival studies.

SN 1987A was a Type II event and was clearly caused by the core collapse of a massive star. The prevailing theory for core-collapse supernovae was that they happened during the red supergiant phase of stellar evolution when the outer layers are puffed out and reach cool temperatures at the surface. But careful astrometry of archival plates showed that the star at the position of the explosion was a blue, more compact star (Lasker 1987). Confusion dominated the early days of this historic event, but eventually it was confirmed that the first supernova progenitor identified was not what had been expected. Further stellar modeling showed that the low heavy element content in the LMC means that evolving massive stars spend some of their time as blue compact supergiants and can explode during that phase.

SN 1987A had more surprises in store. Several months after discovery the ultraviolet spectrum of the supernova began to change. Emission lines from highly ionized atoms grew in strength over a year and then began to fade. When the Hubble Space Telescope finally reached orbit and its bad optics were fixed, images of SN 1987A revealed one of the most spectacular sights in the sky: a triple ring system tilted to our line-of-sight and centered on the supernova debris. The gas in the rings had been released during the red supergiant phase of the star and left drifting slowly away from the star as it shrank to a blue supergiant. This circumstellar gas was then ionized and set glowing by the X-rays and ultraviolet light from the explosion (Figure 2).

SN 1987A has been intensively studied by HST for nearly a decade. From the observations it is clear that SN 1987A is beginning to make a comeback. The fast-moving supernova ejecta is beginning to sweep up the inner circumstellar ring and the collision is creating hard radiation as well as heating the gas. The entire remnant is getting brighter (Larsson *et al.* 2011). How bright the rejuvenated supernova will become is hard to predict, but it is possible that SN 1987A will again be visible in small telescopes in the southern hemisphere.

5. The GRB/supernova connection

Gamma-ray bursts (GRB) are short bursts of high energy photons that appear to come from all directions on the sky. They were first detected by Defense Department satellites in the 1960s, but were a national security secret so they were known to very few people. Throughout the 1990s, NASA's Compton Gamma-ray Observatory discovered thousands of GRB, but with little improvement in understanding their origin. From this study it became clear that there were two classes of GRB, short bursts that last less than 2 seconds and long bursts than can last a couple of minutes. The range of models published to explain the GRB phenomenon was vast. Some theorists speculated that GRB came from within our Solar System, others from the halo of the Milky Way, and still others that believed GRB were at cosmological distances.

But there was no way to estimate the distance and, therefore the energetics, of GRB from gamma-rays alone. Gamma-rays are difficult to focus, so the positional errors on any burst covered large tracts of sky. In 1997 the small Italian satellite BeppoSAX began detecting GRB. It was designed to also look for X-rays from the bursts which could be localized to a small patch of sky. This led to the discovery of optical afterglows from GRB and a revolution in GRB science (Groot *et al.* 1997). Optical afterglows were clearly connected with very distant galaxies, meaning the bursts were at cosmological distances and extremely energetic events.

The optical afterglows from GRB fade very quickly, on timescales of hours to days. The light curves of long GRB often show breaks in the rate of fading and these are signs of beaming of the energy output (Stanek *et al.* 1999). That the burst comes out as a narrow beam greatly reduces the energy budget of GRB and places them near the total energy derived from core-collapse supernovae.

Late-time bumps in the optical light curves of GRB afterglows and the association between GRB and young stars produced speculation that the long GRB phenomenon has its origin in supernova explosions. This was finally proven by the nearby GRB 030329, which reached 13th magnitude and was widely studied. Days after the burst spectroscopy revealed a Type Ic supernova getting brighter while the GRB afterglow light faded (Stanek *et al.* 2003). Since then several more Type Ic supernovae have been directly associated with long GRB. The prevailing model is that very massive star cores collapse directly to black holes and that accretion into the black hole can power an “engine” for seconds or minutes. Narrow jets shoot out from the star, producing gamma-rays and later X-rays, optical, and radio emission. If the jets are pointed in our direction we get to see a GRB.

Short GRB are even more difficult to study than long bursts and less is known about their origin.

6. Thermonuclear supernovae

Type Ia supernovae (SNIa) derive their energy from thermonuclear fusion. A low mass star like the Sun will eventually evolve into a white dwarf star. This is a remnant core after the outer layers of hydrogen and helium have been ejected. The white dwarf is rich in the elements synthesized in the late stages of its stellar life: carbon and oxygen. It is also very small and extremely dense. A white dwarf has the mass of the Sun but the diameter is close to that of the Earth. These white dwarf stars sound exotic, but they are the most common way stars end their lives.

Normal stars resist collapse by fusing elements in their cores and the resulting energy creates a pressure that pushes against gravity. Failure to generate energy is what makes massive star cores collapse. What prevents white dwarf stars from losing to gravity? Quantum mechanics. The density of white dwarfs is so high that electrons nearly occupy the same position, so in the quantum world they must have different momentum. In fact, electrons must have very high momenta to avoid occupying the same quantum states and the pressure created by these “degenerate” electrons supports the white dwarf from collapse. A young Chandrasekhar (1931) predicted that electrons could only support stars with masses less than about 1.4 $M_{\odot}$, so we expect no white dwarfs more massive than this.

An isolated white dwarf will stay unchanged for as long as atoms last. But a white dwarf in a binary star system has a chance of becoming an energy producer once again. That is, if some of the matter of the companion can be transferred to the white dwarf, then the mass of a white dwarf could be pushed toward Chandrasekhar’s limit. Exactly how mass is transferred remains uncertain. A normal star may leak mass on to the white dwarf through the gravitationally neutral point between the two. Or, the white dwarf can capture mass from the wind of a stellar giant. It may even be that a companion white dwarf merges with the heavier white dwarf and that sets the fusion reaction starting. Whichever way mass is transferred, as the white dwarf approaches 140% of the mass of the Sun, carbon is predicted to begin to fuse near its center. Once fusion begins the energy generated is enough to continue the burning and a runaway fusion explosion occurs.

Despite the small mass of a white dwarf, SNIa tend to generally be more energetic than core-collapse events. Some of the brightest supernovae of the past century, such as SN 1937C, SN 1972E, and SN 2011fe, have been Type Ia thermonuclear supernovae. The reason SNIa are bright is that they synthesize a sizable amount of radioactive nickel during the carbon fusion. The mass of nickel produced ranges from 0.1 to 0.9 $M_\odot$ and this is the main source of luminosity and light curve shape diversity in SNIa.

The radioactive nickel decays to radioactive cobalt (week time scale) that then decays to stable iron (three month time scale), emitting energetic gamma-rays and positrons that are thermalized in the thick ejecta and drive the optical light curve. Arnett (1982) showed that maximum light occurs when the radioactive energy deposition equals energy loss through light emission. This "Arnett rule" allows us to directly estimate the nickel yield in supernovae just by measuring the peak luminosity.

The light curves and spectra of SNIa tend to be very uniform. Theory says they explode near the Chandrasekhar limit, so they come from a fairly narrow range of mass and conditions. This is not to say that all SNIa are identical. Some of the most interesting supernova research in the past 20 years has been attempts to understand the extreme SNIa events. Still, the majority of SNIa are very predictable, almost boring in their consistency.

7. The distance scale and the accelerating universe

Progress in astrophysics over the last century has only been possible by the ever-improving methods of distance estimation. Accurate distances are critical for the physical modeling of new phenomena and the development of cosmological models. Variable stars such as Cepheid and RR Lyrae pulsators have played critical roles in mapping the size of the Milky Way and the distances to nearby galaxies. The current expansion rate of the universe, the Hubble parameter, has been tightly constrained by the distance indicators pioneered over many decades. But supernovae, in particular Type Ia supernovae, appear to be the best distance indictors of the century.

While SNIa are very uniform, their peak luminosities vary by more than a factor of two, making them poor "standard candles." But Phillips (1993) calibrated a relation between the peak luminosity and the decline rate of the SNIa light curve. The absolute magnitude of a SNIa could be determined by observing the optical light curve near maximum light. The technique was expanded by Riess *et al.* (1996) to use the color of the supernovae as an estimate of the amount of dust scattering light coming from the explosion. Using the color and light curve information, SNIa distances were accurate to 7%, an unheard-of precision for astronomical distances.

With this new and powerful tool, cosmologists set off to sharpen estimates of the local expansion rate of the universe. This still required using Cepheid variables to calibrate the zeropoint of the SNIa distance scale using the handful of galaxies where both stars could be studied (Jha *et al.* 1999). Hubble (1929) estimated the Hubble parameter was 500 km/s/Mpc early in the century, but with the help of SNIa, we now know H_o = 72 km/s/Mpc with an precision of 5%.

SNIa are bright at maximum light and can be seen to very large distances. Their refinement as standardizable candles in the 1990s set two groups off on a quest for the next big cosmological parameter: the matter density of the universe. The "Supernova Cosmology Project" and the "High-Z Supernova Search" began discovering SNIa five to seven billion light-years away with the goal of measuring the expansion rate in the past (see Figure 3). The idea was that matter in the universe slows the universal expansion over time due to gravity, so by measuring the change in the expansion rate one can infer the mass density (Garnavich *et al.* 1998).

To their surprise, both research groups discovered that the expansion rate of the universe has not been slowing down, but has been speeding up. That is, the universal expansion is accelerating (Reiss *et al.* 1998; Perlmutter *et al.* 1999)! This was shocking news since it requires something other than matter to be a major player in the mass/energy budget of the universe. The unknown energy that drives the accelerating universe has been dubbed "dark energy" and remains one of the biggest mysteries to be solved in the next century of the AAVSO.

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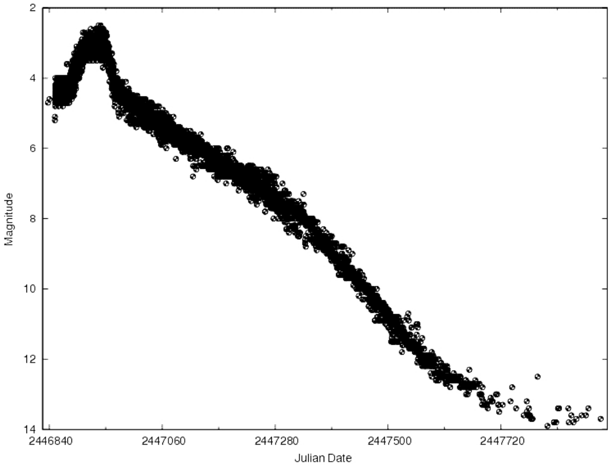

Figure 1. The AAVSO light curve of SN 1987A. The light curve begins a faster decline 400 days after peak brightness because dust begins to form in the inner ejecta.

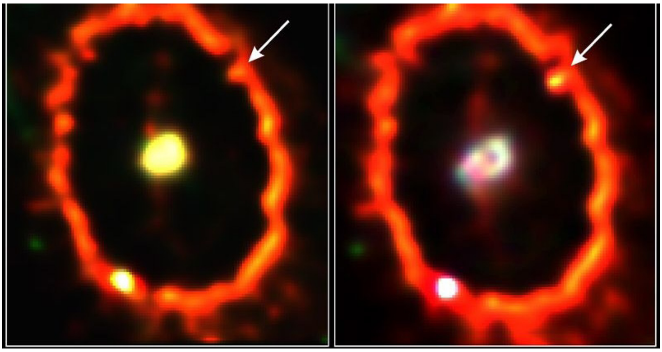

Figure 2. HST images of SN 1987A and the inner ring in 1994 (left) and 1997 (right). The arrow points to the first "hotspot" on the ring where the fast-moving supernova ejecta is running into the slower circumstellar gas. The ring is now filled with these hotspots as the ejecta begins to sweep up the circumstellar gas.

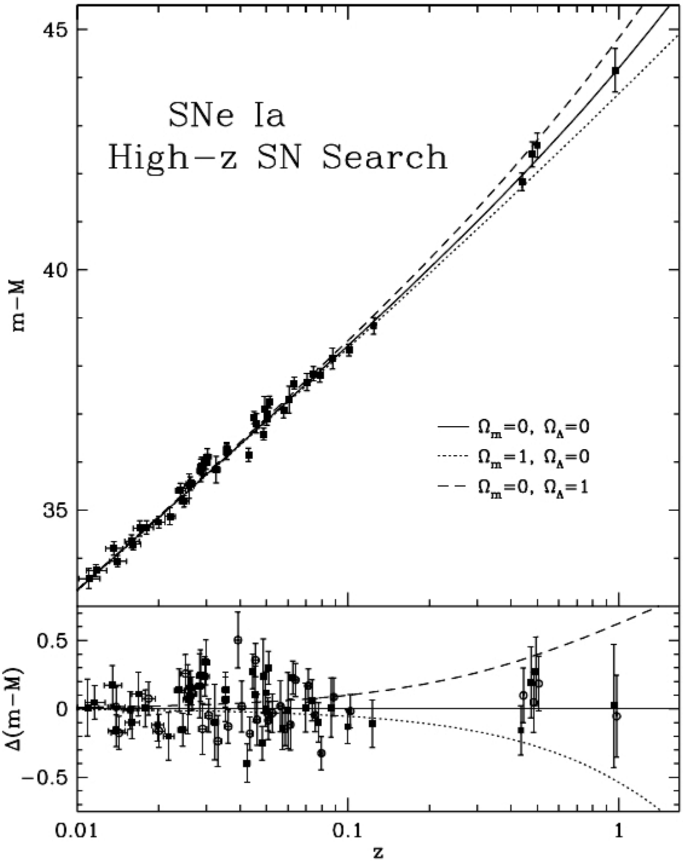

Figure 3. The Hubble diagram (distance versus velocity) for nearby supernovae and four high-redshift supernovae discovered by the High-Z Supernova Search Team (Garnavich *et al.* 1998). The lower panel displays the distance residuals about a universe with no matter (Ω_m) and no dark energy (represented by a vacuum energy Ω_Λ). The squares and circles indicate the supernova distances calculated by two different techniques. The high-redshift supernovae in the diagram tend to fall on the empty universe model meaning that the matter density in the universe is low. A few months after publication of these results more supernovae were added to the analysis that demonstrated the expansion is accelerating and a dark energy is required.

NOTES