Studying Variable Stars Discovered Through Exoplanet-Transit Surveys: A "Research Opportunity Program" Project

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Abstract We discuss the study and classification of variable stars discovered as a by-product of searches for exoplanet transits—slight dimmings of stars by planets in orbit around them. We describe two specific projects carried out by undergraduate students in the University of Toronto's Research Opportunity Program. We discuss the nature of this program, in which second-year (sophomore) students can complete a research project for course credit.

1. Introduction

Extra-solar planets (exoplanets) are planets around stars other than the sun. As of September 2007, 212 exoplanets had been discovered since the first one was found in 1995 (see the website http://exoplanets.org). Almost all have been discovered through their gravitational effect on their star. The star moves in a small orbit with the same period as the planet. The star's orbital motion is detected by the precision radial velocity technique, developed by Campbell, Walker, and Yang (1988) among others.

Many of the exoplanets so far discovered orbit close to their star, and this increases the probability that a distant observer will observe a transit of the exoplanet across the face of the star, which decreases the brightness of the star—typically by one percent or less. Exoplanet transits have been used to study the properties of the planets; from them, the mass can be determined unambiguously, along with the radius and therefore the mean density. Several groups are also conducting exoplanet transit surveys as a way to discover additional exoplanets. Two such projects are EXPLORE and STARE.

2. EXPLORE

The EXPLORE (EXtra-solar PLanet Occultation REsearch) project is a transit search project carried out using wide-field CCD imaging cameras on 4-m class telescopes, and 8–10-m class telescopes for precision radial velocity verification of the photometric candidates (Mallén-Ornelas *et al.* 2003; EXPLORE 2007). Data were obtained in four filters: I_c, R_c, V, and B. The nightly datasets were typically 0.3–0.4 day long. The stars are typically 20th magnitude. An important feature of this project is the high photometric precision (up to 2 millimag) and high rate of time sampling (every few minutes), implemented with an efficient pipeline enabling rapid follow-up of promising candidates. See von Braun *et al.* (2005) for some recent results.

3. STARE

Unlike the EXPLORE project, the STARE project (*ST*ellar *A*strophysics & *R*esearch on *E*xoplanets) uses a relatively small telescope—a 10-cm Schmidt telescope. The telescope typically images an area of sky six degrees on a side (STARE 2007). Most of the target stars are of magnitude 10–12, and are measured in three photometric bands: *B*, *V*, and *R*. In 2001, STARE moved from a location in Boulder, Colorado, to a new home on the island of Tenerife. The STARE project subsequently joined with two other projects—using even smaller telescopes—to form the TrES (Trans-Atlantic Exoplanet Survey) network, which subsequently discovered its first exoplanet in 2004. See Rabus *et al.* (2007) for some recent results.

4. By-products of exoplanet transit surveys

Because the probability of discovering an exoplanet transit is so small, these surveys must image tens of thousands of stars every few minutes over many days or weeks. A significant fraction of the imaged stars are variable for reasons other than an exoplanet transit, and most of these variable stars are new discoveries. They potentially provide astronomers with large homogeneous surveys of variable stars, as well as with the possibility of discovering individual variable stars that are unique and/or important, and worthy of further study. The present project deals with the study and classification of these variable stars.

The specific objective of the two studies described in this paper was to see whether the classification of the newly discovered variable stars could be improved by using self-correlation (Percy and Mohammed 2004, and references therein) as an adjunct to Fourier analysis. We have found self-correlation to be useful in distinguishing between possible periods in the Fourier spectrum when several alias periods are present. The correct period, and the corresponding phase curve, along with color information, can then be used to classify the variable. This can be done in theory, at least: in practice, it is not always possible to classify the variable unambiguously; students learn that scientific research is not always cut-and-dried!

An equally important objective was to provide the students with a meaningful structured research experience that introduced them to research skills, and to research data that required them to use their skills to produce new research results.

5. Research opportunity program

Undergraduate research should be an increasing priority for research universities in North America (Boyer Commission 1988), and many universities, including our own, are following this recommendation. It not only gives students a wide range of research skills, and other academic skills, but it also gives students a sense of "engagement" with both their subject of study and with their instructors. It is already an important part of the curriculum in many four-year undergraduate colleges in the U.S., and that is one reason why these colleges are very successful in preparing students for graduate and professional schools, as well as for the workplace. Regrettably, we have very few such colleges in Canada. In the sciences, undergraduate research is supported in the U.S. by the Research Experiences for Undergraduates (REU) program of the National Science Foundation.

At the University of Toronto, undergraduate research is carried out through several programs which are typical of programs elsewhere—a fourth-year project or "senior thesis" course, summer research assistantships (many funded through the Natural Sciences and Engineering Research Council—our equivalent of NSF), and the work-study program which provides career-related government-funded positions to eligible students during the academic year. There is also the University of Toronto Mentorship Program, that enables outstanding senior high school students to work on research projects at the university. These high school students are comparable, in ability, with undergraduates, and the Mentorship Program is excellent preparation for further research experiences when the students reach university.

In the present paper, we describe research that was carried out within the Research Opportunity Program (ROP), which is different from the programs mentioned above. This program provides an opportunity for students in their second year of study (sophomores) to earn a full course credit (one-fifth of a full load) by participating in a faculty member's research project. Students apply, and are interviewed in the spring of the previous year. Because there are relatively few ROP positions available, the ROP is competitive and prestigious.

My goal is for the student to carry out an original, self-contained project that can be presented at a conference and/or published in a journal (here it is!). Most students have not taken an astronomy course in their first year, so I provide a structured experience, with weekly meetings, that leads the students to the deliverables on which they are evaluated:

- Reading about stars, stellar evolution, and variable stars (the AAVSO website is exceptionally useful for this); understanding the algorithms and software that they will use; understanding the datasets that they will use, and how they "interact" with the software; testing the software with standard datasets, etc.

- Progress report submitted in January; since most students have never written such a report, I read and comment on a first draft; the second draft is evaluated.
- First results, generally obtained in December-January.
- A non-technical poster for the Faculty-wide "Research Fair" in February (Figure 1).
- Completion of the project, leading to a project report; again, I read and comment on a first draft; the second draft is evaluated.
- An interview about the report, to test the depth of the student's understanding of all aspects of the project.
- A journal recording their progress and reflections on their experience.

For me, the Research Fair is a highlight of the year. It not only showcases the students' work, but it also brings me and my students into contact with professors and students from across the Faculty of Arts and Science. We see the full range of research strategies and techniques in the humanities and social sciences, as well as in the physical, mathematical, and life sciences. We see the creativity of professors who have found a wealth of ways to engage undergraduates in their scholarship and research.

6. The EXPLORE project: Rahul Chandra

Rahul Chandra examined in detail seventeen short-period variable stars that had been analyzed, using Fourier and phase dispersion minimization techniques, by Clement *et al.* (2006) and Nguyen *et al.* (2006). These members of the EXPLORE collaboration identified about 80,000 stars in a Galactic plane field, analyzed the observations of about 5,500 of these on a total of 1,950 frames, and discovered twenty-three new variable stars. The seventeen stars analyzed were listed as "additional variable stars"; no classification was suggested.

Chandra used the additional technique of self-correlation to complement the other two techniques. The following example, also shown in the accompanying figures, illustrates the nature of the project:

Star 1515-1 has a Fourier peak at 0.39965... cycle/day (a period of about 2.5 days), and two others that are almost as high (Figure 2); the self-correlation diagram (Figure 3) shows that this 0.4 cycle/day peak is clearly the correct one because there are minima at multiples of this value. There is no evidence for alternating deep and shallow minima such as would be found in an ellipsoidal variable, for instance. These would be apparent from the self-correlation diagram. Clement *et al.* (2006) and Nguyen *et al.* (2006) obtained a period of 2.519446 days, and an amplitude of 0.078 in I_c, and the amplitude that we derive is consistent with this value. The (V–I_c) color is 2.10, which corresponds to a late K or early M star but, given that this is a 20th-magnitude star that could be reddened, it could be almost any kind of periodic variable.

7. The STARE project: Mario Napoleone

Napoleone's project was atypical, within my ROP experience, in the sense that he independently came up with the project during the preceding summer. Normally, I prepare a list of possible projects, and present this to the student, along with some recommendations.

Napoleone carried out Fourier, self-correlation, and phase-diagram analysis on 146 stars in the AUR0 list (STARE 2007), for which periods had been determined by Fourier analysis, and classifications had been suggested by the STARE team. Phase diagrams can be useful for identifying stars with alternating deep and shallow minima, such as ellipsoidal variables, and variables with non-sinusoidal light curves. Classification was confirmed on about seventy stars using all three techniques. Self-correlation proved inconclusive on about sixty stars, but the other two techniques supported their classification. Self-correlation gave marginal confirmation on ten stars, but the other two techniques supported their period and hence their classification. Two stars showed very confusing results using all three techniques. The following example, also shown in the accompanying figures, illustrates the nature of the project.

Star AUR0-3355 has a Fourier peak at 3.4 days, along with alias peaks (Figure 4); the 3.4-day peak is confirmed by self-correlation analysis; there are minima at integral multiples of this value (Figure 5). The peak-to-peak amplitude is 0.080 magnitude. The phase curve is approximately sinusoidal, and there is no evidence for alternating deep and shallow minima. The STARE classification of γ Doradus seems doubtful, given the long period of the star; γ Doradus stars normally have periods of 1 to 3 days. It may be a rotating variable.

8. Discussion and conclusions

For several stars in these two surveys, self-correlation analysis provided more secure identification of the period of the star. In most cases, it did not provide any significant additional information.

Both studies point out the value of having additional information about the newly-discovered variable stars, such as spectral type or color, to aid in classification, though, if the stars are faint and heavily reddened, it is sometimes difficult to determine their intrinsic properties. Such information is available for both these surveys, but the classification may still be ambiguous. If the classification must be done solely on the basis of period, however, self-correlation analysis provides a useful adjunct to Fourier and phase-diagram analysis, especially when there are alias peaks in the Fourier spectrum.

Both Chandra and Napoleone received enriching educational experiences. They learned a branch of astronomy in some detail. They were exposed to real datasets, and research-grade techniques of time-series analysis. They learned to make judgments about classification, often on the basis of less-than-ideal data. They received guidance and experience in various forms of scientific communication.

There are also large-scale surveys for other kinds of variable objects, such as gravitational microlenses, and optical counterparts of gamma-ray bursts that also yield large numbers of new variable stars. The considerations outlined in this paper apply to them also.

The kind of research that is done by undergraduate students can also be done by skilled amateur astronomers. These individuals normally contribute to astronomical research through the measurements that they make, but they can help to analyze and interpret the vast amount of archival photometric data that is available. A book, specifically targeted to undergraduate student researchers, and skilled amateur astronomers, is now available (Percy 2007).

Hard copies of Chandra's and Napoleone's project reports can be obtained from John Percy: john.percy@utoronto.ca.

9. Acknowledgements

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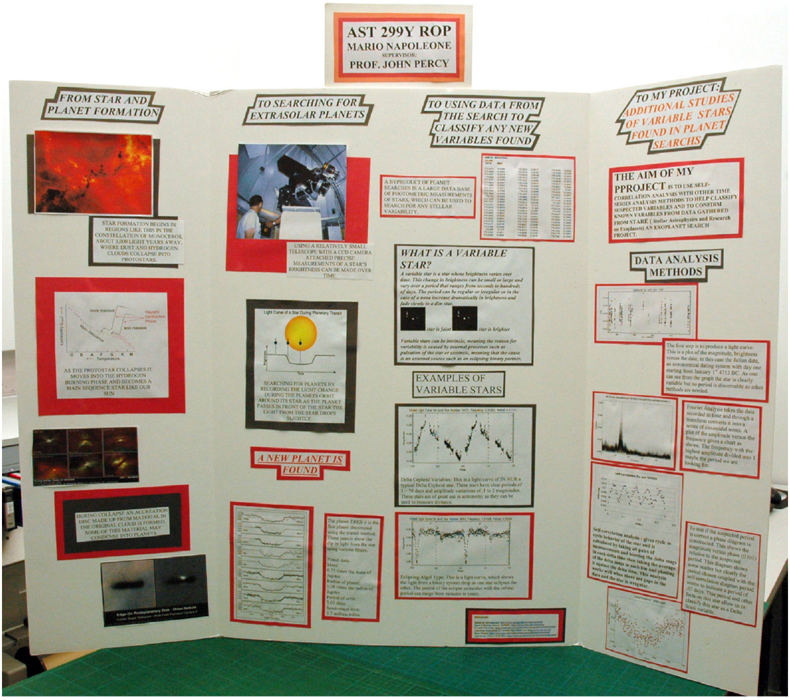

AST 299Y ROP
MARIO NAPOLEONE
SUPERVISOR:
PROF. JOHN PERCY

FROM STAR AND PLANET FORMATION

STAR FORMATION BEGINS IN REGIONS LIKE THIS IN THE CONSTELLATION OF MONOCEROS, ABOUT 3,000 LIGHT YEARS AWAY, WHERE DUST AND HYDROGEN CLOUDS COLLAPSE INTO PROTOSTARS.

AS THE PROTOSTAR COLLAPSES IT MOVES INTO THE HYDROGEN BURNING PHASE AND BECOMES A MAIN SEQUENCE STAR LIKE OUR SUN

DURING COLLAPSE AN ACCRETION DISC MADE UP FROM MATERIAL IN THE ORIGINAL CLOUD IS FORMED. SOME OF THIS MATERIAL MAY CONDENSE INTO PLANETS

TO SEARCHING FOR EXTRASOLAR PLANETS

USING A RELATIVELY SMALL TELESCOPE WITH A CCD CAMERA ATTACHED PRECISE MEASUREMENTS OF A STAR'S BRIGHTNESS CAN BE MADE OVER TIME.

SEARCHING FOR PLANETS BY RECORDING THE LIGHT CHANGE DURING THE PLANETS ORBIT AROUND ITS STAR AS THE PLANET PASSES IN FRONT OF THE STAR THE LIGHT FROM THE STAR DROPS SLIGHTLY.

A NEW PLANET IS FOUND

The planet *TRES-1* is the first planet discovered using the transit method. These panels show the dip in light from the star using various filters.

Planet data:
Mass:
0.75 times the mass of Jupiter.
Radius of planet:
1.08 times the radius of Jupiter.
Period of orbit:
3.03 days.
Semi-major axis:
3.7 million miles.

TO USING DATA FROM THE SEARCH TO CLASSIFY ANY NEW VARIABLES FOUND

A BYPRODUCT OF PLANET SEARCHES IS A LARGE DATA BASE OF PHOTOMETRIC MEASUREMENTS OF STARS, WHICH CAN BE USED TO SEARCH FOR ANY STELLAR VARIABILITY.

WHAT IS A VARIABLE STAR?

A variable star is a star whose brightness varies over time. This change in brightness can be small or large and vary over a period that ranges from seconds to hundreds of days. The period can be regular or irregular or in the case of a nova increase dramatically in brightness and fade slowly to a dim star.

star is faint *star is brighter*

Variable stars can be intrinsic, meaning the reason for variability is caused by internal processes such as pulsation of the star or extrinsic, meaning that the cause is an external source such as an eclipsing binary partner.

EXAMPLES OF VARIABLE STARS

Delta Cepheid Variables: This is a light curve of IN AUR a typical Delta Cepheid star. These stars have clear periods of 1 – 70 days and amplitude variations of .1 to 2 magnitudes. These stars are of great use in astronomy as they can be used to measure distance.

Eclipsing Algol Type: This is a light curve, which shows the light from a binary system drop as one star eclipses the other. The period of the eclipse coincides with the orbital period can range from minutes to years.

TO MY PROJECT: ADDITIONAL STUDIES OF VARIABLE STARS FOUND IN PLANET SEARCHS

THE AIM OF MY PPROJECT IS TO USE SELF-CORRELATION ANALYSIS WITH OTHER TIME SERIES ANALYSIS METHODS TO HELP CLASSIFY SUSPECTED VARIABLES AND TO CONFIRM KNOWN VARAIBLES FROM DATA GATHERED FROM STARE (Stellar Astrophysics and Research on Exoplanets) AN EXOPLANET SEARCH PROJECT.

DATA ANALYSIS METHODS

The first step is to produce a light curve. This is a plot of the magnitude, brightness versus the date, in this case the Julian date, an astronomical dating system with day one starting from January 1st 4713 BC. As one can see from the graph the star is clearly variable but no period is discernable so other methods are needed.

Fourier Analysis takes the data recorded in time and through a transform converts it into a series of sinusoidal terms. A plot of the amplitude versus the frequency gives a chart as shown. The frequency with the highest amplitude divided into 1 maybe the period we are looking for.

Self-correlation analysis : gives cycle to cycle behavior of the star and is calculated by taking all pairs of measurements and binning the delta mags in each delta time then taking the average of the delta mags in each bin and plotting it against the delta time. This analysis works well when there are gaps in the data and the star is irregular.

To test if the suspected period is correct a phase diagram is constructed. This shows the magnitude versus phase (0 to1) relative to the suspected period. This diagram shows some scatter but clearly the period chosen coupled with the self-correlation diagram period seems to indicate a period of .07 days. This period and other facts on this star allow us to classify this star as a Delta Scuti variable.

Figure 1. The ROP Research Fair. Students from across the Faculty of Arts and Science present poster papers about their research projects.

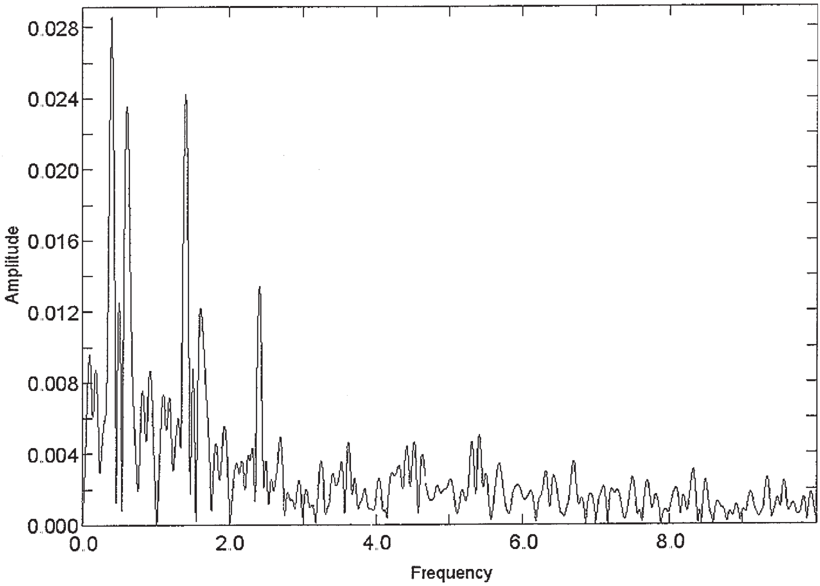

Figure 2. The Fourier spectrum of EXPLORE star 1515-1, showing a real peak (0.39965... cycle/day) peak and two alias peaks.

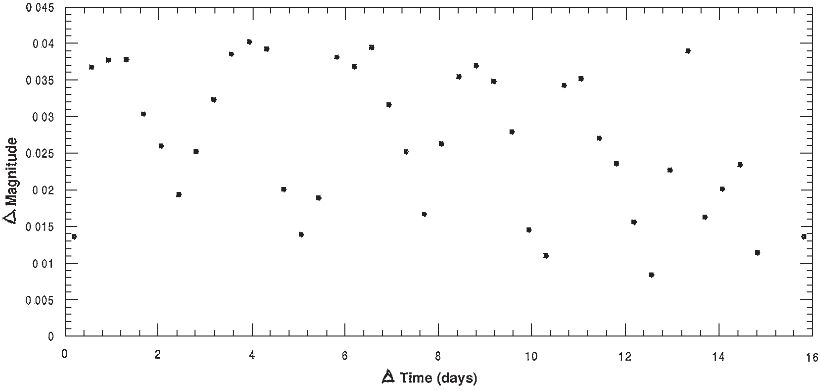

Figure 3. The self-correlation diagram of EXPLORE star 1515-1, showing minima at multiples of 2.50... days.

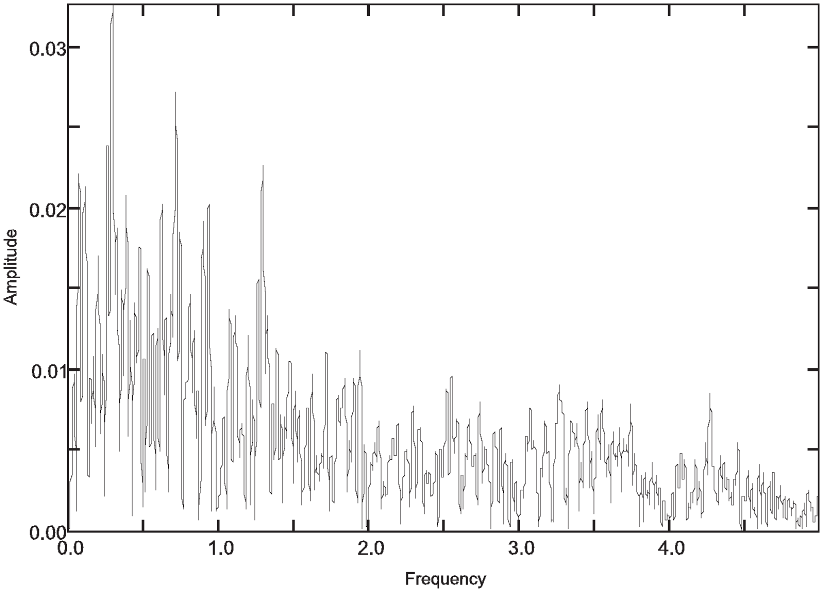

Figure 4. The Fourier spectrum of STARE star AUR0-3355, showing a real peak (0.29... cycle/day) and several alias peaks.

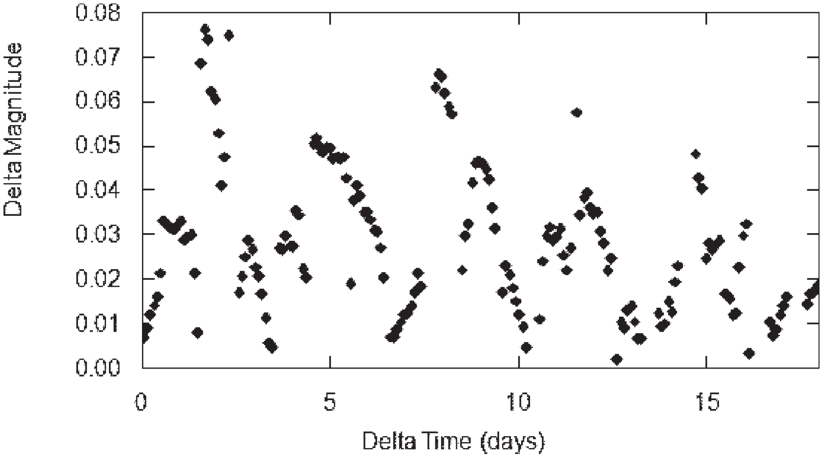

Figure 5. The self-correlation diagram of STARE star AUR0-3355, showing minima at multiples of 3.4... days. The diagram becomes somewhat scattered at values of Delta t for which there are very few Delta magnitudes.