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STUDIES OF MIRA STARS AND THEIR SMALL-AMPLITUDE RELATIVES

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Abstract

Some aspects of the nature and evolution of Mira stars and their small-amplitude relatives are briefly described. As stars ascend the asymptotic giant branch, it appears that they begin to pulsate when their effective temperature drops below 3800 K. The amplitude tends to increase with decreasing temperature. The stars show appreciable periodicity, perhaps beginning to pulsate in a high radial overtone, then in lower overtones as they approach the Mira stage. Mode-switching is occasionally observed in the small-amplitude variables. There is appreciable irregularity in the latter stars, including long-term variability of unknown cause. Our understanding of these stars will certainly increase as a result of new Hipparcos parallaxes and other advances. The observation and analysis of these and other variables provides fruitful projects for students.

1. Mira stars in perspective

Mira stars are late M-type giant stars, pulsating with periods of 80 to 1000 days, and visual amplitudes greater than 2.5 magnitudes. There are also early to mid M-type giant stars, pulsating with shorter periods and smaller amplitudes; they are generally classified as semiregular (SR) or irregular (L) type variables, or as "small amplitude red variables" (SARV's: Eggen 1973a, for instance).

SARV's are much more numerous than Miras. In the *Bright Star Catalog* (BSC) (Hoffleit and Jaschek 1982), there are 28 Miras which reach the limit of the catalog (about 6.5 visual magnitude) at maximum. There would be even fewer whose time-averaged magnitude exceeded this limit. On the other hand, there are hundreds of early- to mid-M giants in the BSC which are known, suspected, or likely to be variable. They are the most numerous variables among the bright stars.

Mira stars are asymptotic giant branch (AGB) stars, with carbon cores, surrounded by helium-rich layers, in turn surrounded by hydrogen-rich envelopes. AGB stars are so called because of their position in the Hertzsprung-Russell graph of luminosity versus temperature; they are stars which are producing energy by thermonuclear fusion of helium around the carbon core, and of hydrogen around the helium-rich layers. In a scale model of a Mira in which the Sun was represented by a beach ball 1 meter in diameter, the core (which contains most of the mass of the star) would be represented by a grape, and the envelope would fill a baseball or football stadium.

Mira stars are the coolest and most luminous AGB stars. In this phase of evolution, two significant processes occur: (i) in the interior, helium shell "flashes"—caused by instabilities in the thermonuclear reactions in the thin shell of helium—occur every few thousand years or so, causing cyclic changes in the temperature, luminosity, and pulsation period of the star (Vassiliadis and Wood 1993); (ii) in the outer layers, mass loss occurs, as a result of the low escape velocity and radiation field of the star; this mass loss is enhanced by the pulsation of the star (Bowen and Willson 1991). At the peak of the mass loss phase, the star can lose a significant fraction of its mass within a million years.

2. Testing the evolutionary models

The periods of Mira stars are affected by at least three processes, listed here in order of increasing effect: (i) the slow AGB and post-AGB evolution, due to nuclear burning and mass loss; (ii) flash cycles lasting a few thousand years; (iii) random cycle-to-cycle period fluctuations of a few percent (Eddington and Plakidis 1929). Process (iii) dominates the (O-C) diagram, but it may be possible to detect processes (i) and (ii) by appropriate averaging of the rates of period change, over many stars. Percy and Au (1997) have done this by using the times of maximum brightness of 391 bright Mira stars (Kowalsky *et al.* 1986) and the average periods from 1911 to 1985, to construct (O-C) diagrams. These plot the difference between the observed and expected times of maximum brightness, assuming the period to be constant. If the period is changing at a constant rate, the (O-C) diagram will be a parabola. Parabolas were therefore fitted to the diagrams to determine the rate of period change (d/d). The stars were binned according to spectral group (M, S or CNR) and period, and the average rate of period change was determined in each bin. The average for all stars was +0.0000161 d/d. This was compared with the average rate of period change in the evolutionary models of Vassilaidis and Wood (1993) for different masses. The average rate for a 1.0 solar-mass model was + 0.0000282 d/d, in good agreement with the observations. The average rates for more massive models, were greater. It was not possible to make more detailed comparisons between theory and observation, because the observed period changes are clearly dominated by the random effects.

3. The road to Mira-hood

Red giants begin to pulsate well before they reach the Mira stage. As they ascend the AGB in the HR diagram (and presumably as they ascend the giant branch as well), they begin to pulsate when they reach a temperature of about 3800 K, corresponding to a spectral type of M1 III. This was first determined by Stebbins and Huffer (1930), who tested the variability of about 200 M giants and about 200 B-K giants. They found that giants earlier than M0 showed a constant scatter in magnitude, which was equal to the expected observational error (namely, about 0.012 magnitude). The scatter began to increase at M0 and M1, and especially at M2 and later. This was confirmed by the surveys by Percy and Fleming (1991) and Percy and Shepherd (1992), and by the AAVSO photoelectric program's "Project SARV" (Percy *et al.* 1994). By spectral type M2, virtually all M giants are variable, though the amplitude can be quite small.

4. Do K giants pulsate?

These surveys all indicate that K giants do not pulsate, though a few may vary as a result of starspots and rotation. Yet there are over 200 suspected K giant variables in the BSC. Percy (1993) carried out a survey of about 50 of these, using an automatic photometric telescope (APT), and found that virtually all of them were constant. (Percy used an APT because, suspecting that most of the stars would prove to be non-variable, he did not think that this would be a very inspiring project for a student observer, or for the AAVSO photoelectric program!)

Nevertheless, a recent study by Edmonds and Gilliland (1996), using the Hubble Space Telescope (HST), suggests that K giants in the globular cluster 47 Tuc may be variable with amplitudes of 5 to 15 millimagnitudes. Such amplitudes would not have

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been detected by other surveys. The time scales of the variability are not well determined, because of the difficulty of long-term monitoring with HST, but they appear to be 1 to 4 days. The authors suggest that the variability is due to low-order radial or non-radial pulsation. These stars appear to lie at the lower end of the AGB (rather than near the bright end, as Miras and other SARV's do), so they may represent a new class of variable stars, perhaps analogous to Arcturus, whose pulsation has been studied by spectroscopic techniques.

5. The periods of SARV's

SARV's have generally been thought to be semiregular at best. The first detailed study of a SARV was by Percy, Landis, and Milton (1989). They found from six seasons of photoelectric observations of EU Del (M6 III) that this star showed a well-defined period of 62.74 days, which had been stable for at least two decades. A subsequent analysis of 10 years of photoelectric observations of 30 SARV's in the AAVSO program showed that most of them had a well-defined period of 20 to 200 days. The presence of such a wide range of periods, in stars with similar spectral types, suggests that they may be pulsating in different modes.

Many SARV's are also variable on time scales of hundreds of days, an order of magnitude longer than the primary periods. The cause of these variations is not known.

The earliest M type variables, with the smallest amplitudes, are of special interest. Eggen (1973b) has proposed the name "Sigma Lib variables" for the most extreme examples. They would have periods of 20 days or less, and amplitudes less than 0.1 mag. Percy and Au (1994) carried out an APT study of several possible Sigma Lib variables, with probable periods given in parentheses: HR 5150 (M2 III; 6 d); HR 5154 (M2 III; 17 d); HR 5215 (M2 III; 15? d); HR 5266 (M3.5 III; 18? d); HR 5300 (M1.5 III; 19 d). These stars are being re-observed, to confirm these interesting short periods.

6. The pulsation modes of Miras

We shall argue that the SARV's are pulsating in higher modes than the Mira stars, so we should first discuss the controversial question of the pulsation mode of the Miras.

Miras are known to be radially pulsating, on the basis of their synchronous photometric and spectroscopic variations. In the outer layers of the star, the pulsation actually takes the form of an outward-moving shock wave. SARV's are also radially pulsating, on the basis of their observed radial velocity variations (e.g., Cummings *et al.* 1995), though the longer-term variations may be due to some other process.

The actual pulsation mode can be investigated in several ways. If two or more modes are present in the star, either simultaneously or at different times, then the ratio of the periods of the modes can be compared with the periods determined from theoretical models. This is a standard procedure for Cepheids and their relatives. Barthès and Tuchman (1994) have presented some evidence for multiperiodicity in two Miras. Their results suggest that the primary period is the first overtone. The evidence, however, is not strong. Percy and Bagby (1996) have analyzed the varying magnitudes of maximum brightness of several dozen bright Miras, and found some evidence for multiperiodicity, with the first overtone being the most likely primary mode. The data, however, were not well suited to the analysis, so the evidence is also not strong. Comparison of pulsation velocities predicted by non-linear pulsation models with those observed in actual stars suggests that the pulsation is in the fundamental mode, but this result is not definitive.

The most promising approach is to determine the physical properties of the stars more accurately, and calculate the pulsation constant Q. This can be compared with the results of theoretical calculations such as those of Ostlie and Cox (1986). The pulsation constant is defined as the period in days, times the square root of the mean density of the star, in units of the sun's mean density. (Because Q is approximately constant for any type of pulsating star, it follows that the period is inversely proportional to the square root of the mean density of the star.)

Equivalently, an observed period-luminosity relation can be compared with one based on the theoretical periods. Thanks to interferometry (Haniff *et al.* 1995; van Belle *et al.* 1996), more accurate angular diameters and effective temperatures can be determined. The masses of the Mira stars are not directly known, but most Miras belong to an old population of stars with masses 1.0 to 1.5 times the mass of the sun. The work of Haniff *et al.* (1995) suggests that the Miras are pulsating in the first overtone (Feast 1996); the work of van Belle *et al.* (1996) suggests that at least some of the Miras may be pulsating in the fundamental mode.

In the Large Magellanic Cloud, Sebo and Wood (see Wood 1995), and subsequently the MACHO gravitational microlensing survey (Welch 1996), observed that in the period-luminosity relation, the small- and large-amplitude red variables occupy a series of parallel sequences which can be interpreted in terms of stars pulsating in different radial overtones.

7. The pulsation modes of the SARV's

There are no known examples of SARV's which pulsate in two or more modes simultaneously, but there are several examples of SARV's which have switched modes (Cadmus *et al.* 1991; Percy and Desjardins 1996; and especially Szatmary *et al.* 1995). The latter authors list 10 possible mode switchers. The period ratios range from 1.54 to 2.03; the median is 1.81. They interpret the modes as adjacent radial modes, and conclude that the modes are the fundamental and the first overtone, because only these adjacent modes have a ratio as high as 2.0. Percy and Desjardins (1996) calculated Q values for the modes in W Boo, and found that they matched the second and fourth overtones (or possibly the first and third), i.e., they were not adjacent modes. This would be consistent with the theoretical result: in general, pulsation models of AGB stars show that, as the star evolves to higher luminosities (and lower temperatures), lower-order radial modes become unstable (Wood 1995). Improved temperatures for SARV's as well as Miras are already available from stellar interferometry (Dyck *et al.* 1996); improved luminosities, and therefore improved Q values, will soon come from Hipparcos parallaxes.

8. Educational considerations

The observation and analysis of variable stars is an excellent way for students to develop and integrate a wide range of skills in math, science, and computer studies (Mattei *et al.* 1995). The AAVSO has developed an exciting new education project, "Hands-On Astrophysics: Variable Stars in the Math/Science Lab," to take advantage of this situation. Students have already participated actively in my own research on Miras and SARV's through the University of Toronto Mentorship Program, which enables outstanding senior high school students to work on research projects at the university, through the Summer Career Placement Program of the government of Canada, the Ontario Work-Study Program, the NSERC Summer Undergraduate Research Award program and, this year, the University of Toronto's Research Opportunities Program for second-year students.

Red variables have an interesting combination of regularity and irregularity which makes them interesting and challenging for period analysis. Because of their extreme properties, they are interesting to interpret theoretically. Our data come from many sources, including the AAVSO, APT's, and our 0.4-m reflector on campus. Other sources of data are appearing: the variable star measurements from the Optical Gravitational Lensing Experiment (OGLE) are available on the Internet, and photometry from two experiments aboard the Hipparcos satellite, monitoring up to a million stars over four years, will soon be publicly available on CD-ROM at modest cost. Sophisticated but user-friendly software for data management and analysis will be available as part of the AAVSO's "Hands-On Astrophysics" educational project (Mattei *et al.* 1995). Thus there will be increasing opportunities for students to participate in the excitement of doing real science with real data.

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