Long Term Photometric and Spectroscopic Monitoring of Semiregular Variable Stars

Robert R. Cadmus, Jr.
Department of Physics, Grinnell College, Grinnell, IA 50112; cadmus@grinnell.edu

Received September 12, 2014; revised December 8, 2014; accepted December 9, 2014

Abstract The understanding of semiregular variable stars presents a number of challenges that can be addressed by consistent long term photometric and spectroscopic monitoring. The observing program at Grinnell College has generated a large body of such data that has been used to investigate modes of pulsation, the role of dust, the possible role of chaos, and other issues. This paper summarizes these efforts and encourages other observers to help maintain the continuity of these data sets.

1. Introduction

The semiregular variable stars are pulsating red giants. Although a great deal of observational and theoretical effort has been expended in understanding these stars, and substantial progress has been made, a number of significant questions remain. There is clearly a great deal left to do and a great deal left to learn. It is likely that observations over extended periods of time will play an important role in our attempt to better understand these perplexing stars; the observing program at Grinnell College was designed to contribute to that effort.

The purpose of this paper is not to address all the scientific issues that are involved in this research program or to present final conclusions, but rather to make others aware of the work that we have been doing and the data that we have acquired, and to solicit the contribution of additional photometry from others in the future.

2. Background

The semiregular variable stars in this program are red giants that lie on the asymptotic giant branch (AGB) of the Hertzsprung-Russell diagram. They have extended atmospheres in which a variety of physical processes result in variations of luminosity and spectrum typically on timescales of hundreds of days, although much slower variations sometimes occur. The semiregular variables are similar to the Mira variables and have traditionally been distinguished from them on the basis of smaller visual light amplitudes and less consistent light curve shapes, but the exact nature of the relationship is still a matter for investigation. The study of these stars has been complicated both by the complexity of the light curves and by the array of physical processes that are probably at work. Much of the research on semiregular variables has focused on several related questions. (1) What is the nature and physical cause of the light variations? (2) What is the significance of the multiple sequences that are observed in the period-luminosity relations for long period variables? (3) What is the origin of the "long secondary periods"?

As the name suggests, the light variations of the semiregular variables are somewhat, but not entirely, regular. In fact, the light curves can be very messy. The dominant variation is periodic and additional periodicities are sometimes conspicuous. The application of Fourier analysis and other techniques in numerous studies (see, for example, Mattei *et al.* 1997; Kiss *et al.* 1999; Percy *et al.* 2003; Percy and Tan 2013) has shown that many of these stars are truly multiperiodic and the presence of periodicity suggests that systematic physical processes are at work. The exact nature of those processes is still a matter of some debate, but the prevailing interpretation of the primary light variations in semiregular variables is that these stars are radially pulsating, as is believed to be the case for some other classes of variable stars. Radial velocity measurements (Cummings *et al.* 1999; Lebzelter *et al.* 2000) strongly suggest that this is the case, as do the observations of variations in radius (Perrin *et al.* 1999) and theoretical models (Xiong and Deng 2007; Ireland *et al.* 2011). Furthermore, the spectra of these stars sometimes include hydrogen emission lines that appear to be the result of pulsation-induced shocks (Wood 1974; Willson 1976). After an extended debate (Wood 1995; Percy and Polano 1998; Willson and Marengo 2012) a consensus emerged that the dominant mode of pulsation is the fundamental for the Miras and an overtone for the semiregulars. Early work at Grinnell contributed to this conclusion (Cadmus *et al.* 1991). More recent observational and theoretical work has refined this picture but the complexity of the light variations and other characteristics of these stars leave a number of questions unresloved. For example, the association of modes with the Mira and semiregular classifications seems not to be absolute (Soszyński *et al.* 2013a), there are variations in the amplitudes of the light curves (Kiss *et al.* 2000; Percy and Abachi 2013), the origin of the long secondary periods is still unclear (Wood *et al.* 2004), and the degree to which the shorter-period variations are associated with overtone pulsation is still an interesting question.

Theorists have made a noble effort to include many of the complex physical processes that are simultaneously in play in a radial pulsation model, but a complete description is not yet in hand. In addition, the presence of several processes in addition to those directly related to radial pulsation has been suggested and debated, often in the context of the vexing long secondary periods discussed below. These include non-radial pulsation (Stello *et al.* 2014), convection (Stothers 2010), rotation (Wood *et al.* 2004, which also discusses other effects), binarity (Nicholls *et al.* 2009), planets (Berlioz-Arthaud 2003), and chaos (Buchler *et al.* 2004). There is clearly much work to be done on these stars by both observers and theorists.

The existence of a period-luminosity (P-L) relation for long period variables was established long ago (Gerasimovič 1928) but the availability of large surveys such as OGLE and MACHO in the 1990s revolutionized this area of research by generating vast archives of light curves. These observations of stars in the Large Magellanic Cloud have been especially valuable because those stars are all at approximately the same distance so their relative luminosities can be determined with good accuracy. These new data led to the discovery of multiple P-L relations, called sequences, for various groups of stars, including the semiregulars (Wood *et al.* 1999). The Hipparcos mission, which generated greatly improved parallaxes for many stars, led to improvements in the P-L relations for galactic stars and showed that the same sort of sequences are present in that population (Soszyński *et al.* 2013b). A significant challenge has been to identify with certainty what distinguishes the stars that make up each of the handful of sequences. There is evidence that some of the sequences correspond to stars pulsating in different modes and others correspond to other phenomena (Wood 2000; Soszyński *et al.* 2007), but the distinctions are not always as sharp as one might wish. For example, the semiregulars appear to populate two of the sequences (Soszyński *et al.* 2013a).

One of the sequences in the P-L diagram is associated with the long secondary periods—light variations on a time scale that is roughly ten times longer than the likely pulsational periods (Wood *et al.* 1999). These variations in some semiregulars have been known for a long time (Payne-Gaposchkin 1954) and have been the subject of much research in recent years. A number of explanations for this phenomenon have been offered (Nicholls *et al.* 2009; Wood *et al.* 2004) but none has gained widespread acceptance.

While much progress has been made, understanding these aspects of the nature of the semiregular variables has been challenging, leaving significant questions only partially answered and offering ample opportunities for further research.

3. Observations

Grinnell College's Grant O. Gale Observatory began operation in 1983 and provided the opportunity to create a new astronomical research program. With the advice and encouragement of Lee Anne Willson of Iowa State University and Janet Mattei of the AAVSO we began a project to help resolve the question of the modes of pulsation of the Mira and semiregular stars. The AAVSO database showed that some semiregular variables experienced quiescent episodes during which the amplitude of the brightness variations dropped into the noise in the AAVSO visual observations. The scientific question was whether these events might be cases of mode switching, in which the quiescent episodes are characterized by low-amplitude variations with periods different from those of the normal oscillations. If so, precise observations of those low-amplitude variations might lead to mode identifications through comparison of observational period ratios with those predicted by theoretical models. Some of our results support this idea, but over the years the picture has become more complex.

The 39 stars in our program (a few of which have been observed over less than the full duration of the project) are listed in Table 1. Nine of the stars are carbon stars (EU And, S Aur, U Cam, WZ Cas, RS Cyg, TT Cyg, V778 Cyg, RY Dra, and UX Dra). Because the quiescent episodes do not occur predictably, more than a few stars had to be monitored to have a chance of catching a reasonable number of quiescent episodes in a realistic length of time.

Table 1. Program and Comparison Stars.

Program Star	*Comparison Star*	*Check Star*
RU And	TYC 2814-1513-1	TYC 2814-0038-1
RV And	SAO 037822	TYC 3289-2064-1
EU And	SAO 052967	SAO 053004
RS Aqr*	TYC 5201-0192-1	GSC 05201-01479
S Aql	SAO 105808	TYC 1618-1495-1
S Aur	TYC 2411-1188-1	TYC 2411-2135-1
U Boo	TYC 1481-0504-1	GSC 01481-00446
V Boo	SAO 064187	SAO 064166
RW Boo	SAO 064264	SAO 064243
RX Boo	SAO 083321	SAO 083337
U Cam	SAO 012900	SAO 012866
RS Cnc	SAO 061288	SAO 080745
V CVn	SAO 044591	SAO 044551
WZ Cas	SAO 021005	SAO 020984
W Cyg	SAO 050934	SAO 050936
RU Cyg	SAO 033682	TYC 3967-1406-1
RS Cyg	SAO 069635	TYC 3151-1755-1
TT Cyg	SAO 068626	SAO 068629
V778 Cyg	SAO 032689	SAO 032728
U Del	SAO 106396	SAO 106603
RY Dra	SAO 016018	SAO 015879
UX Dra	SAO 009296	SAO 009392
X Her	SAO 045895	SAO 045850
SX Her	SAO 084212	SAO 084221
RT Hya*	SAO 135967	SAO 135972
RS Lac	TYC 3211-0412-1	TYC 3211-0746-1
U LMi	SAO 061743	GSC 02508-00679
X Lib*	TYC 6196-0048-1	TYC 6197-0774-1
X Mon	SAO 133965	SAO 133930
RV Peg*	SAO 072329	GSC 02734-01339
S Per	SAO 023236	TYC 3698-0184-1
U Per	SAO 022853	TYC 3688-0234-1
RW Sgr*	TYC 6304-0290-1	TYC 6300-2225-1
W Tau	TYC 1265-0016-1	TYC 1265-1072-1
Z UMa	SAO 028201	SAO 028193
RZ UMa	SAO 014492	TYC 4132-0395-1
ST UMa	SAO 043786	SAO 043764
R UMi	SAO 008567	SAO 008520
SW Vir	SAO 139201	SAO 139218

* *Limited data.*

The photometric observations were made with the 0.61-m telescope at Grinnell College's Grant O. Gale Observatory using a photoelectric photometer incorporating an uncooled 1P21 photomultiplier. This instrument has been used throughout the project to maintain consistency. V- and B-band data were acquired differentially relative to the comparison and check stars in Table 1. No significant variations of the check stars relative to the comparison stars were observed, although in a few cases there may be hints of variability at a very low level that does not compromise the program star light curves. The data were reduced by subtracting the sky background, correcting for both first and second order atmospheric extinction, and transforming to the Johnson UBV system. An effort was made to avoid major gaps in the data by observing in twilight when necessary and applying a nonlinear correction for the temporal variation in sky brightness. To produce a cleaner data set for further analysis the reduced data were represented by a manually guided spline fit; this is the smooth curve in the light curve figures.

Low-resolution spectroscopic measurements have also been made of these same stars, including a long (1997–2013) series of observations of RS Cyg and more limited, but continuing (2000–present), spectroscopic monitoring of the other stars. These data were acquired with a conventional Cassegrain spectrograph and either a Reticon photodiode array detector for the RS Cyg series or a CCD camera for the continuing monitoring project. The spectrograph was configured in its lowest-resolution mode, in which resolution is sacrificed for the sake of increased spectral coverage: about 6,000 Å for the Reticon detector and about 3,000 Å for the CCD. In both cases the dispersion is about 6.5 Å/pixel and the resolution is about 10Å. The RS Cyg spectra were corrected for instrumental effects and atmospheric extinction, but no flux correction has been done so far. The reduction of the spectra from the monitoring project is in progress.

4. Results

Representative examples of the photometric data are shown in Figures 1 and 2. The stars in this program exhibit a wide variety of light curve shapes. For most of the stars the variation in B–V is small compared to the variation in V, but all the carbon stars show large variations in B–V that indicate that the blue end of the spectra of these stars varies by about twice as much as does the red end.

A number of the stars did undergo quiescent episodes, revealing small oscillations that were not apparent in the AAVSO data. An example is shown in Figure 2. As an aside, data sets like this are subject to a constraint that is similar to the quantum mechanical Uncertainty Principle (which is itself just a manifestation of wave behavior). For a given set of data the magnitude resolution can often be improved by binning in time, but at the expense of temporal resolution; the product of magnitude uncertainty and time uncertainty can be imagined to be equal to a constant, even if that is not the precise mathematical relationship. For instrumentally acquired data that constant is much smaller than for visual data, which is why we have enough magnitude resolution to be able to see the relatively rapid time variation in a low amplitude signal during the quiescent episodes. Nevertheless, the extensive data accumulated by visual observers were critical in the conception of the project described here and continue to be vital to many other research projects.

In some cases the frequency during the quiescent episode is about the same as that when the amplitude is large, but in most cases it is higher. It was data like these, and specifically the "quiescent" to "normal" frequency ratio, that led to our earlier conclusion that the semiregular variables were likely to be overtone pulsators (Cadmus *et al.* 1991). As we have observed a greater number of quiescent episodes in a variety of stars we have found that these frequency ratios tend to be near integers.

An obvious thing to do with light curves like these is to subject them to Fourier analysis in order to determine what frequencies are present and with what strengths, although this exercise is fraught with peril, especially with complex light curves like these. We have nevertheless done that in two different ways. First, we did a straightforward Fourier analysis of each complete light curve. The values of the ratios of the frequencies of the peaks above the dominant peak to that of the dominant peak itself clump near integer values, a harmonic relationship that is characteristic of the Fourier spectra of periodic waveforms and similar to the distribution of the quiescent episode frequency ratios described above. This shows that the frequencies that appear during the quiescent episodes are among those that characterize the light curve in general, but they manage to exist independently, not simply as a component of a shape. We have used the information on the multiple frequencies present in the light curves to construct a plot of the period-luminosity relationships for the various components, resulting in a set of sequences much like that obtained for LMC data (Wood 2000).

Our second approach was a time-dependent Fourier analysis, in which segments of the light curve are analyzed separately and those results are combined to make a frequency vs. time "map." (Similar kinds of maps based on wavelet analysis can be generated using the WWZ function in the AAVSO's VSTAR package.) This approach clearly shows how a large-amplitude component can temporarily fade, leaving behind a

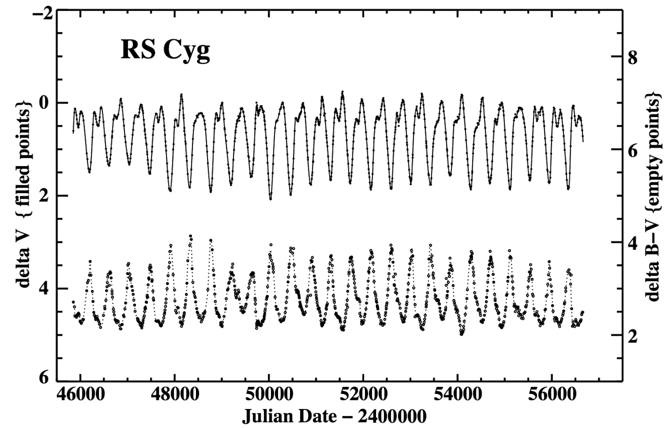

Figure 1. The V light curve (above) and B–V color curve (below) for RS Cyg. This is a carbon star that shows the characteristic large variations in B–V.

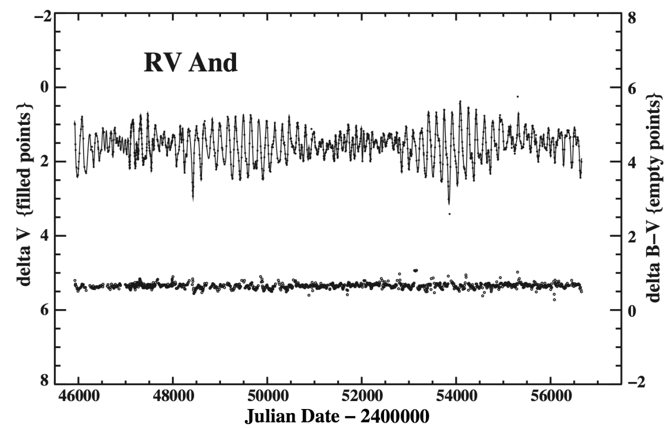

Figure 2. The V light curve (above) and B–V color curve (below) for RV And. This star exhibits quiescent episodes. The small variation in B–V is characteristic of the non-carbon stars.

lower-amplitude, higher-frequency component and giving the impression of a mode switch. The temporal variation of the strengths of the frequency components is often quite complex.

Although much of the work in this field has been focused on the relationship between the frequency composition of light curves and the pulsational modes of the stars, there has also been interest in the possible role of chaotic processes in determining the shapes of some light curves. Grinnell photometric data have been compared with theory to show that chaotic processes may be involved (Buchler *et al.* 2004). There is probably more to be done in this area.

Spectroscopic monitoring of all the stars in this program is an ongoing project, but we have made an especially intensive effort to obtain a large set of spectra for RS Cygni; an example is shown in Figure 3. The light curve of this star has distinctive dips in most of its maxima (see Figure 1) and spectra might reveal their cause. The spectra were arranged to make a plot of intensity vs. wavelength and phase but no obvious correlation between line strengths and the photometric dip was immediately apparent. This may indicate that dust is responsible and work is continuing on this puzzle.

Long term, high resolution spectroscopic monitoring of these stars would be valuable, especially to provide better information on atmospheric motions. We are currently developing a fiber-fed radial velocity spectrometer to be used for that purpose.

5. Discussion and future directions

The results described here are preliminary and much remains to be done, both observationally and theoretically. The ability to observe the detailed behavior of stars during quiescent episodes appears to be a useful way to constrain the interpretation of Fourier spectra and other results. In addition, there is certainly science to be extracted from the data for the stars that have not yet experienced quiescent episodes. The RS Cyg spectra have revealed an interesting aspect of the behavior of this star but the final interpretation is not yet in hand.

When this project began thirty years ago we were in a position to make observations that were beyond the reach of most AAVSO observers, but that situation has changed dramatically. Now many of those observers, as well as automated photometric observing programs (Percy *et al.* 2001, for example), are able to do the sort of photometric work that we have been doing and it makes sense for Grinnell to focus more on spectroscopic monitoring that is needed but less easily done. However, continuation of the sort of photometry that we have been doing is very desirable for two reasons. First, the longer a high quality light curve becomes, the more useful it is because it may provide context for newly observed phenomena and provide better tests of chaos models. Second, the spectroscopic work that we are doing will be more useful if there are good light curves to accompany it. We would welcome the participation of AAVSO observers in this effort.

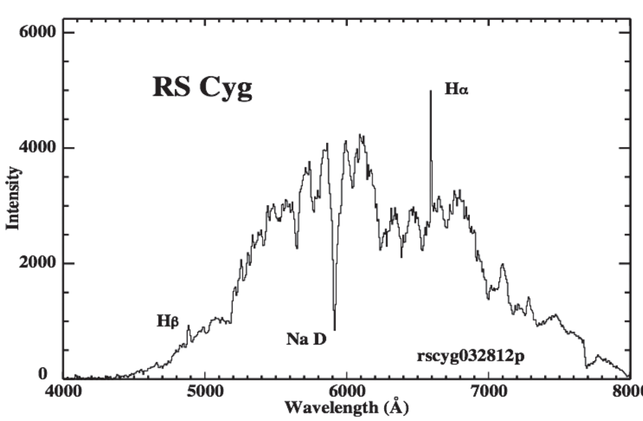

Figure 3. The spectrum of RS Cyg. Note the strong Na absorption line and the Balmer emission lines. The overall shape of the spectrum is instrumental; no flux correction has been applied.

6. Acknowledgements

It is a pleasure to thank Lee Anne Willson and many Grinnell College undergraduate students for their assistance in these projects. In addition, the insight of Janet Mattei was essential. Financial support was provided by the National Science Foundation, Research Corporation, the American Astronomical Society, Sigma Xi, and Grinnell College. The comments provided by a referee were helpful and appreciated.

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