Do Yellow Semiregular (SRd) Variables Show Long Secondary Periods?

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Abstract Semiregular pulsating variable supergiants of spectral types F, G, and K (SRd variables in the *General Catalogue of Variable Stars*), and RV Tauri (RV) stars share many similarities in their physical properties, evolutionary status, and light curve properties. A significant fraction of RV variables (called RVb stars) show long secondary photometric periods, an order of magnitude longer than the primary (pulsation) period. We have searched for long secondary periods in eight well-studied SRd variables in the AAVSO visual observing program, using light curve analysis, and especially self-correlation analysis. We first tested the procedure on four RVa variables, and on four RVb variables, and derived new values for the long secondary periods in the latter. We find no compelling evidence for long secondary photometric periods in the RVa or SRd variables. Since the RVb phenomenon is believed to be due to binarity, it is not clear why SRd variables could not also be binary members which show long secondary periods.

1. Introduction

Yellow semiregular (SRd) variables are old, low-mass, pulsating yellow supergiants whose variability is semi-regular at best. RV Tauri (RV) variables are old, low-mass, pulsating yellow supergiants whose light curves are characterized by alternating deep and shallow minima. It has long been suspected that RV and SRd variables are related to each other, and to the Population II Cepheid (CW) variables, in their physical and evolutionary characteristics, their period-luminosity relations, and their light curves. Some CW variables show incipient RV behavior, or are slightly irregular. In most RV variables, the behavior is semiregular in the sense that it deviates from the "alternating deep and shallow minima" rule to a greater or lesser extent. The distinction between CW, RV, and SRd is often based on observation of a limited number of cycles; the classification might be different if a larger number of cycles had been observed and carefully studied. Percy and Mohammed (2004) have recently used self-correlation analysis to characterize the light curves of RV and SRd stars. They find that some RV stars show only a marginal tendency (if any) to alternate between deep and shallow minima, and that some SRd variables show a high degree of periodicity.

Both RV Tauri and SRd variables are sun-like stars near the end of their lifetimes.

They inhabit the same instability strip, and their physical properties are similar. They are both either undergoing "blue loops" from the asymptotic-giant branch (AGB) in the Hertzsprung-Russell Diagram (HRD) due to thermal instabilities or "flashes" in their hydrogen- and helium-burning shells or, in the case of the most luminous stars, in transition from the AGB to the white dwarf region (Gingold 1976).

Some RV variables also show long secondary periods, an order of magnitude longer than the short (pulsation) periods; those that do are classified as RVb; those that do not are classified as RVa. We therefore ask: do any SRd variables also show long secondary periods, as do the RVb variables? The RVb phenomenon is thought to be due to some sort of binary model (Percy 1993, Fokin 1994, Pollard *et al.* 1997, Van Winckel *et al.* 1999, Maas *et al.* 2002), and there is no reason why SRd variables should not occur within such binary systems if RV variables do.

Long secondary periods are also found in about one-third of pulsating red giants. The origin is unclear; Wood *et al.* (2004) have stated that these long secondary periods in pulsating red giants are "the only unexplained type of large-amplitude stellar variability known at this time."

In this paper we use self-correlation analysis to search for long secondary periods in a sample of SRd variables.

2. Self-correlation analysis

Self-correlation analysis (SCA) is a simple method of time-series analysis which measures the cycle-to-cycle behavior of the star, averaged over all the data. It is suitable for semiregular variables, and variables with seasonal gaps in the data. It is a useful adjunct to Fourier analysis, and light curve analysis. See the recent paper in this journal by Percy and Mohammed (2004) for a more complete description of the method.

The self-correlation diagram (SCD) plots the average magnitude difference (Δ magnitude) against the difference between the times of observation (Δ time). The key features of the self-correlation diagram are as follows: (i) there are minima at multiples of the period, if any; (ii) the minima will gradually disappear with increasing Δ time if the variability is not strictly periodic; (iii) the value of Δ magnitude, as Δ time approaches zero, is the average observational error; (iv) the difference between the height of maximum and minimum in the SCD is ~0.45 times the average peak-to-peak range of variability in the light curve. The latter relation is an empirical result, based on the analysis of real and simulated light curves (Percy *et al.* 2003).

3. Methodology and data

We first analyzed a small sample of RVa and RVb stars (Table 1) to test the method. We then analyzed a sample of eight well-observed SRd variables, including two long-period examples. All data were downloaded from the AAVSO website, from the AAVSO International Database. We generally chose, as the bin size for SCA, the primary pulsation period of the star, in order to eliminate this factor from the SCD. The scatter in each bin will therefore be large, but will be primarily due to the pulsation of the star. Since the long secondary periods are normally an order of magnitude larger than the primary pulsation period, they should be revealed by SCA.

It is possible that, because of the nature of the visual data, there may be small, spurious long-term variations in the stars, because of changes in the reference stars used, and in their assumed magnitudes. But such changes will be very long-term, and non-periodic.

4. Results

The results are summarized in Table 1, and representative examples are shown in Figures 1–8. The Table gives the known short (pulsation) period, the long secondary period determined by SCA, and the average peak-to-peak range of the light curve, Δ mag determined through self-correlation analysis. The pulsation periods are taken from the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1985) as accessed through SIMBAD, except for Z Aur, for which the GCVS does not give a period. See Templeton (2004) for a discussion of the period of this star.

The four RVb variables—IW Car, DF Cyg, SU Gem, and AI Sco—behave as expected; there are minima, in the SCDs, at multiples of the known long secondary periods. The periods derived from the SCDs are: for IW Car, 1,470 days; for DF Cyg, 775 days; for SU Gem, 680 days; and for AI Sco, 985 days. The values given in the fourth edition of the GCVS are ~1,500, 780.2, 680, and 966.6 days, respectively. Our values were determined by using all available minima in the SCDs of long data sets, using a methodology which is well suited for this purpose, so they are significant contributions to our understanding of these stars. SCA does not provide a formal standard error for these periods but, from the quality of the SCDs, the number of minima in the SCD, and from the agreement between the periods found from the different minima, the errors are ±1% for IW Car and DF Cyg, and ±2% for SU Gem and AI Sco.

The RVa variables are not expected to show long secondary periods. However, the AC Her SCD seems to show minima at multiples of 390 days, but with an amplitude which is less than 0.01 magnitude. The binary period of this star is 1,196 days, so the 390-day period is neither the binary period, nor half the binary period. If the period was related to orbital motion, then we would expect to find one of those two relations. It is possible that this effect is spurious, and due to an interaction between the short period, the bin size (which is chosen to be the same as the period), and the seasonal gaps in the data. If the effect was real, then we would expect the minima to occur at multiples of 390 days, whereas the first occurs at 500 days or slightly longer. The V Vul SCD shows an irregular pattern with an amplitude of less than 0.01 magnitude.

Of the SRd variables, none shows evidence of periodic or quasi-periodic minima on time scales about 10 times the short-term pulsational period. Z Aur, DE Her, and SX Her (Figures 6, 7, and 8) show very small variations on time scales much greater than this. But there are not periodic minima, as there would be if there was a true long secondary period. These variations may also be spurious, and due to subtle, long-term changes in the way in which the observations were made (see Section 3). The SCD of DE Her also shows a complex pattern of alternating high and low points on a time scale of about twice the period, which we believe is an interaction between the pulsation period (165 days), the bin size (which is chosen to be the same as the period), and the seasonal gaps in the data.

5. Discussion and Conclusions

Self-correlation analysis of known RVb variables shows that this technique is an effective way of studying long secondary periods, even with visual measurements whose accuracy is limited (typical accuracy 0.2 magnitude, as compared with photoelectric measurements whose accuracy is typically 0.01 magnitude). In this way, we have determined new values of the long secondary periods in 4 RVb stars. Visual measurements have the advantage of being numerous, and continuous over long periods of time, thanks to observers in the AAVSO and its sister organizations.

We have found possible evidence of very small (<0.01 magnitude) long-term variations in the RVa star AC Her, with a time scale of 390 days. Given the nature of the data, however, this result is tentative and borderline, and requires independent confirmation.

We analyzed several well-observed SRd variables, and found no compelling evidence for long secondary periods in the SCD. We did a cursory examination of the light curves of several other less well-studied SRd variables, using the on-line AAVSO Light Curve Generator (http://www.aavso.org), and did not find evidence of long secondary periods in these. Thus, none of the SRd variables show evidence of long secondary periods like those of RVb stars. Why might this be?

According to the binary model for the RVb phenomenon, the variable star and a companion orbit within a circumbinary dust torus. During part of the orbit, the variable star goes behind the near side of the dust torus, and its brightness decreases. The evidence for the binary model is to some extent circumstantial, and is based on observations of the circumstellar dust and gas (Van Winckel *et al.* 1999, Maas *et al.* 2002). It includes the infrared excess which is found in RV Tauri stars, and the depletion of refractory elements in the spectra of their photospheres; the refractory elements are assumed to be tied up in the dust grains. Direct observations of binary motion in RV and SRd variables are challenging because of the long periods expected, and the complications due to the pulsational velocity variation. Pollard *et al.* (1997) carried out a long-term spectroscopic survey of several RV variables, and found “evidence of long-term radial velocity variations... in a number of the RVb stars”; Maas *et al.* (2002) studied RU Cen and SX Cen. For SX Cen and also for U Mon, the binary period is the same as the long secondary period in the light curve.

However, there are RVa stars such as RU Cen, and AC Her (the brightest member of the RVa sub-group) which are binaries, but do not show the RVb phenomenon. Van Winckel *et al.* (1999) and Maas *et al.* (2002) conclude that the photometric class of RV Tauri stars does not represent a physical difference, but merely a geometrical projection effect. There may be a circumbinary dust torus, but the pulsating star is not periodically obscured by it. This may also be true for the SRd variables. That would raise the question of why semiregularity of the light curve should be correlated with a geometrical projection effect. Keep in mind also that the distinction between SRd variables and RV variables is not sharp (Percy and Mohammed 2004). It is also possible that SRd variables do not have thick circumstellar dust toruses. Lloyd Evans (1985) found that the dust shells around RVa variables were thinner than those around RVb variables, and the same may be true of those around SRd variables.

Unfortunately studies of SRd variables are even fewer than studies of RV variables. There is still much to be learned about the nature and evolution of both of these groups.

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Table 1. Period and range of long-term variability of RV and SRd Variables

Name	*Type*	*Pshort (d)*	*Plong (d)*	*Δ mag*
IW Car	RVb	67.5	1470	0.45
DF Cyg	RVb	49.808	775	2.70
SU Gem	RVb	50.0	680	1.80
AI Sco	RVb	71.0	985	1.60
UZ Oph	RVa	87.44	—	<0.10
V Vul	RVa	75.7	—	<0.04
TX Per	RVa	78.0	—	<0.10
AC Her	RVa	75.01	—	<0.02
AG Aur	SRd	96.0	—	<0.10
Z Aur	SRd	110/137	—	<0.04
TZ Cep	SRd	83.0	—	<0.10
DE Her	SRd	165.2	—	<0.10
SX Her	SRd	102.9	—	<0.02
UU Her	SRd	80.1	—	<0.04
RS Lac	SRd	237.26	—	<0.2:
BM Sco	SRd	815.0	—	<0.2

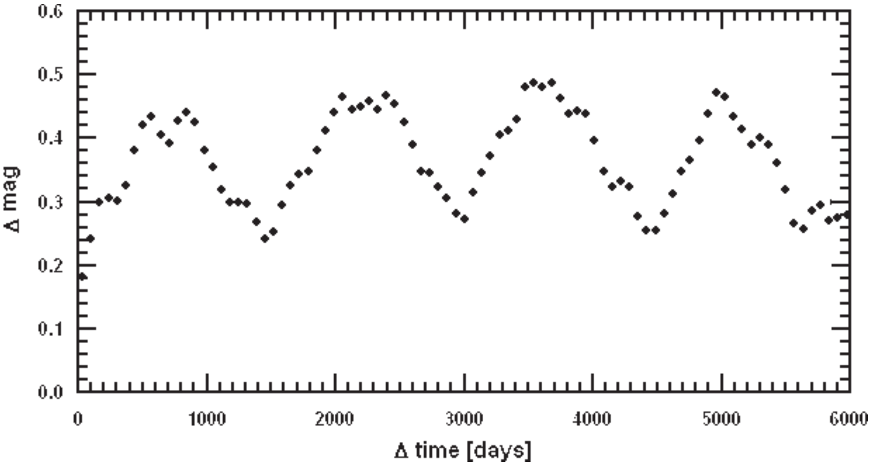

Figure 1. The self-correlation diagram for IW Car, an RVb star. There are minima at multiples of 1,470 days—the long secondary period. In this and the subsequent Figures, the value of Δ mag at Δ t = 0 reflects the observational error, and the scatter due to the primary (pulsation) period.

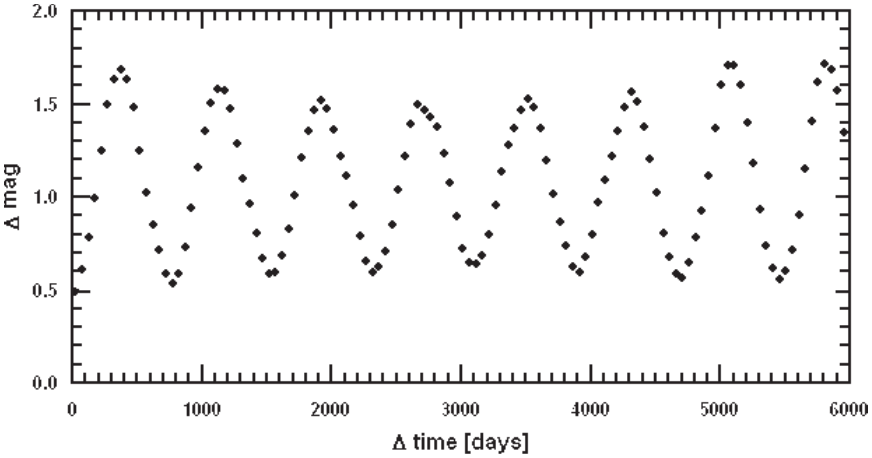

Figure 2. The self-correlation diagram for DF Cyg, an RVb star. There are minima at multiples of 775 days—the long secondary period.

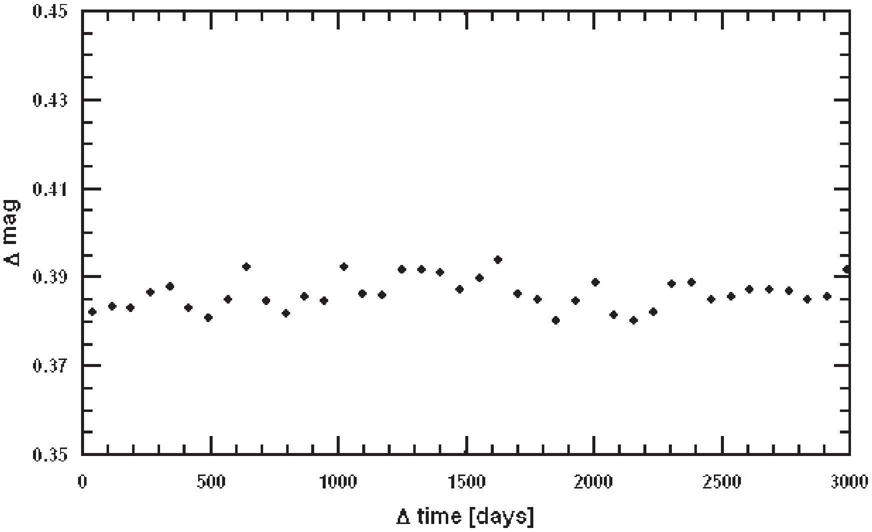

Figure 3. The self-correlation diagram for V Vul, an RVa star. There are no periodic or quasi-periodic minima greater than a few millimagnitudes on time scales of up to 3,000 days.

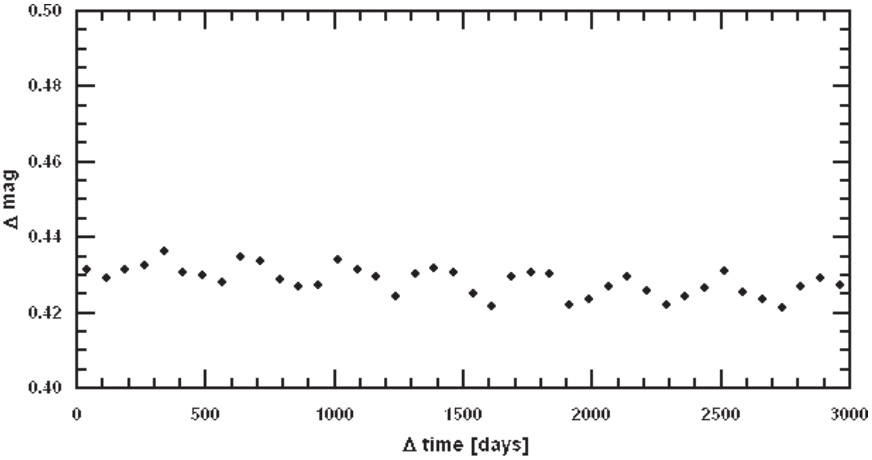

Figure 4. The self-correlation diagram for AC Her, an RVa star. There are possible minima at multiples of 390 days, but the amplitude is less than 0.01, and the minima may be spurious.

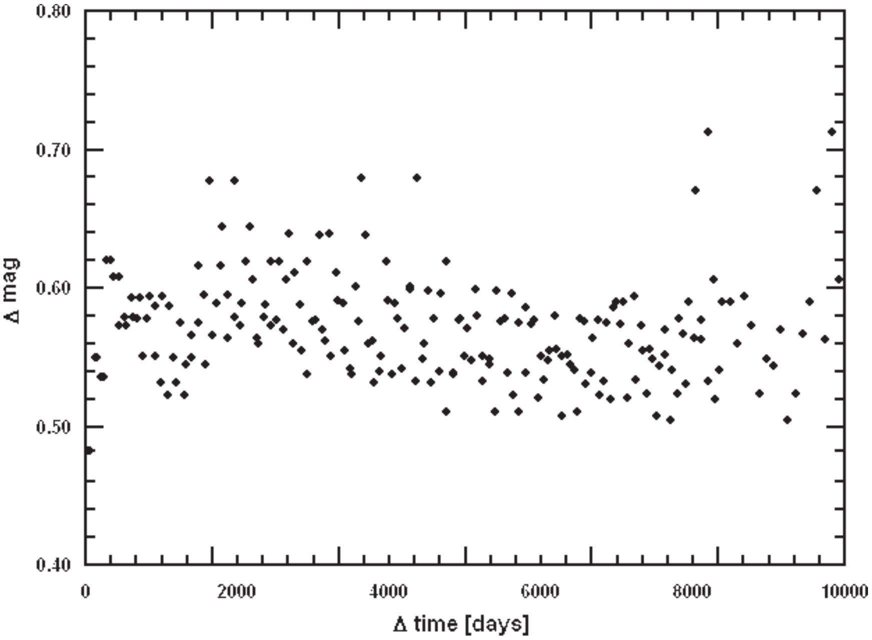

Figure 5. The self-correlation diagram for AG Aur, an SRd variable. There are no periodic or quasi-periodic minima, greater than a few tenths of a magnitude, on time scales of up to 10,000 days.

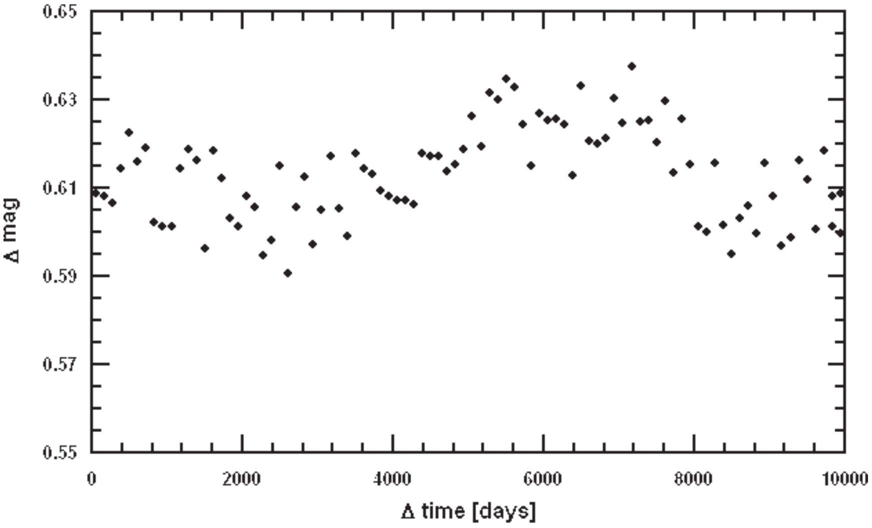

Figure 6. The self-correlation diagram for Z Aur, an SRd variable. There are no periodic or quasi-periodic minima, greater than 0.01 magnitude, on time scales of up to 10,000 days.

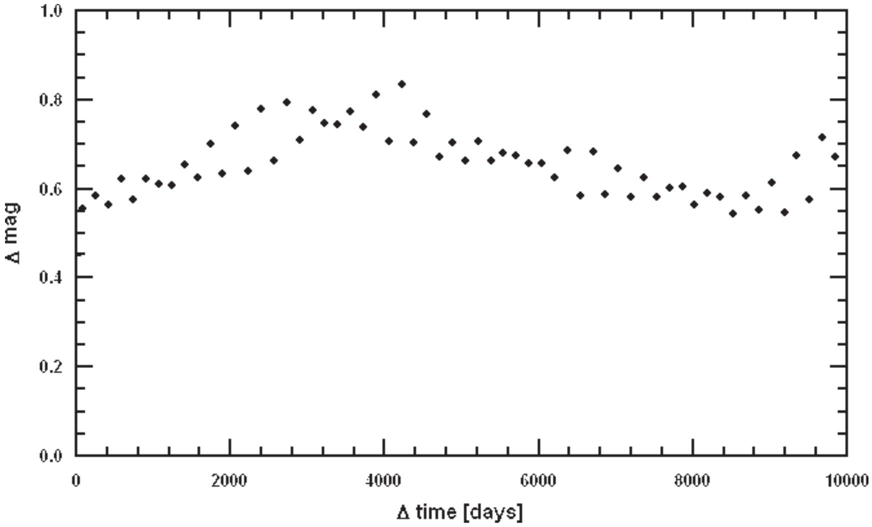

Figure 7. The self-correlation diagram for DE Her, an SRd variable. There are no periodic or quasi-periodic minima on time scales of 1,000 to 10,000 days, though there is a complex pattern which appears to be an interaction between the pulsation period (165 days), the bin size (which is chosen to be the same as the period), and the seasonal gaps in the data.

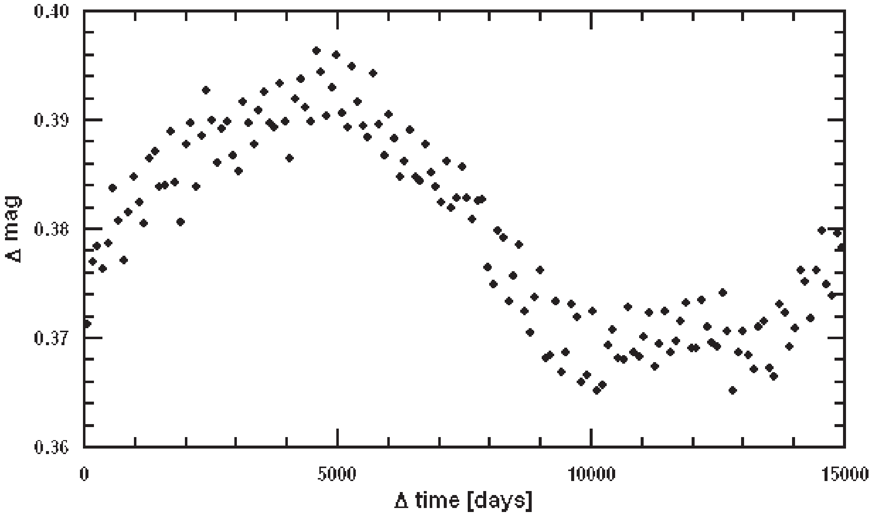

Figure 8. The self-correlation diagram for SX Her, an SRd variable. Any periodic or quasi-periodic minima, on time scales of up to 15,000 days, are much less than 0.01 magnitude. The very long-term (decades) non-periodic variations in this Figure may be due to subtle changes in how the data were obtained; see text.