Amplitude Variations in Pulsating Red Supergiants

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Abstract We have used long-term AAVSO visual observations and Fourier and wavelet analysis to identify periods and to study long-term amplitude variations in 44 red supergiants. Of these, 12 stars had data which were too sparse and/or had low-amplitude and/or were without conspicuous peaks in the Fourier spectrum; 6 stars had only a long (2500-4000 days) period without significant amplitude variation. The other 26 stars had one or two periods, either “short” (hundreds of days) or “long” (thousands of days), whose amplitudes varied by up to a factor of 8, but more typically 2-4. The median timescale of the amplitude variation was 18 periods. We interpret the shorter periods as due to pulsation, and the longer periods as analogous to the “long secondary periods” found in pulsating red giants.

1. Introduction

Red supergiant stars are extreme and complex objects. Several dozen of them have been intensively studied over the years, on account of their brightness, complexity, and evolutionary importance. Long-term spectroscopic and photometric observations of individual objects such as Betelgeuse (Kervella et al. 2013) and Antares (Pugh and Gray 2013a, 2013b) show complex variability on several time scales, ranging from hundreds to thousands of days.

Kiss et al. (2006) have used long-term visual observations from the AAVSO International Database (AID) to study the variability of 46 pulsating red supergiant stars. They found periods in most of them, and two periods in 18 stars. The periods divide into two groups: periods of a few hundred days which are probably due to pulsation, and periods of a few thousand days which correspond to the “long secondary periods” (LSPs) in pulsating red giants; the nature of these LSPs is uncertain (Nicholls et al. 2009). The shapes of the peaks in the individual power spectra of these stars suggest that pulsation and convection interact strongly. The power spectra also exhibit strong 1/f noise, suggestive of irregular photometric variability caused by large convection cells, analogous to the granulation seen in the sun, but much larger. Percy and Sato (2009) used self-correlation analysis to determine or confirm LSPs in many of these same stars, using the same visual data.

Percy and Abachi (2013), hereinafter Paper 1, have recently used long-term visual observations from the AID to study amplitude variations in several samples of pulsating red giants: 29 single- and 30 double-mode SR stars, 10 Mira stars, and the LSPs in 26 SR stars. In each case, the amplitude varied significantly, on a time scale (L) which was about 30-45 times the pulsation period (P) or the LSP. The fact that L/P is approximately constant for these different groups of stars may be a clue to the origin of the amplitude variations. It suggests that either there is a causal relation between the two processes, or they are both linked to some property of the stars, such as its radius. In the present paper, we extend that study to 44 pulsating red supergiant stars.

2. Data and Analysis

We used visual observations, from the AAVSO International Database, of the red supergiant variables listed in Table 1. See ”Notes on Individual Stars” for remarks on some of these. Our data extend a few years longer than that of Kiss et al. (2006).
Paper 1 discussed some of the limitations of visual data which must be kept in mind when analyzing the observations, and interpreting the results. The present study is even more challenging than that of Paper 1, since the periods of red supergiants are even longer than those of red giants, and the timescales of the amplitude variations may be 20-40 times these periods.

The data, extending from JD(1) (as given in the table) to about JD 2456300 (except as noted in section 3.2), were analyzed using the VSTAR package (Benn 2013; www.aavso.org/vstar-overview), especially the Fourier (DCDFT) analysis and wavelet (WWZ) analysis routines. As noted by Kiss et al. (2006), the peaks in the power spectrum are complex, rather than sharp, and it is not always possible to identify an exact period.

For the wavelet analysis, as in Paper 1, the default values were used for the decay time $c$ (0.001) and time division $\Delta t$ (50 days). The results are sensitive to the former, but not to the latter. Templeton, Mattei, and Willson (2005) also used $c = 0.001$. We used the DCDFT routine to inspect the period spectrum of each star, but we were also guided by the results of Kiss et al. (2006) who determined periods for each star, and also listed other periods from the literature. For the WWZ analysis: around each of the true periods, we generated the amplitude versus JD graph, and determined the range in amplitude, and the number ($N$) of cycles of amplitude increase and decrease. As discussed in Paper 1, there was often less than one cycle of amplitude variation, in which case our estimate of $N$ is a crude and possibly unreliable one.

3. Results

3.1 Summary of Results

Interpreting the results is challenging because of the complexity of the stars, the low amplitudes in many stars, and the long time scales involved. Some stars had several low-amplitude peaks in the DCDFT spectra which could not be shown to be significant, unless there was also V data. When the peaks were about a year, and with amplitudes less than 0.1, they might be spurious results of the Ceraski effect (see below). The reality of very long periods was also uncertain if the dataset was short and/or the star showed very long-term irregular variations. In the end, we have been conservative about which stars to include in Table 1, and which to use to draw conclusions.

Table 1 lists the results for each star: the name, period $P$ in days, initial JD, amplitude range, number $N$, and length $L$ in days of cycles of amplitude variation, and the ratio $L/P$. An asterisk in the table, or in the following paragraphs indicates that there is a note about the star in section 3.2. Especially for the stars with $N \leq 1$, the amplitude range is a lower limit.

The following stars were rejected as supergiants by Kiss et al. (2006): UZ CMa, T Cet, IS Gem, Y Lyn, and are not listed in the table.

Almost all of the stars showed signals at a period of about one year, with an amplitude of a few hundredths of a magnitude. This was most likely due to the Ceraski effect, a physiological effect of the visual observing process. Unless the signal was also present in V data (which would not be subject to this effect), we assumed that the signal was spurious. It is possible, of course, that one or two of these stars had a real low-amplitude period of about a year.

For the following stars: either the data were too sparse, and/or the amplitude was too small, and/or the DCDFT spectrum showed no conspicuous peaks: NO Aur*, CK Car*, IX Car*, W Cep, ST Cep*, AO Cru*, BI Cyg*, WY Gem*, WY Hya*, XY Lyn*, AD Per*, PP Per*.

The following stars showed possible long (thousands of days) periods, but without any significant variation in amplitude over the timespan of the data: AZ Cyg* (3600 days), BU Gem (2500 days), RS Per* (4000 days), KK Per (3030 days), PR Per* (3090 days), and FZ Per* (3440 days).

Figure 1 shows the amplitude variation for S Per. Paper 1 shows the amplitude variations for
Figure 1: The changing visual amplitude of the pulsating red supergiant S Per, with a pulsation period of 813 days. The amplitude varies between 0.35 and 0.85, and there are approximately 2.25 cycles of increase and decrease.

several pulsating red giants; these are similar to those in the red supergiants.

3.2 Notes on Individual Stars

SS And: In Table 1, we have given results using the literature period of about 120 days, even though that period has an amplitude less than 0.03 in our data. The highest peaks (1850±100 days) have amplitudes less than 0.05.

NO Aur: The star fades noticeably at the end of the (sparse) dataset.

VY CMa: The long period is quite conspicuous in the light curve. The DCDFT spectrum includes its aliases.

RT Car: A period of about 400± days is present in the V data, as well as in the visual data. The data are sparse after JD 2453000.

BO Car: The 330-day period is sufficiently different from a year that we have accepted it as probably real.

CK Car: There is a deep R CrB-like minimum at the start of the dataset, and a possible shallower fading, halfway through the dataset. This makes it difficult to identify any underlying period. There may or may not be a period around 900-950 days.

CL Car: There are comparable peaks at 500 and 1350 days which are aliases of each other; the shorter period is the one which seems to be present in the light curve, at least after JD 2452500. The variability before then is not well-defined.

EV Car: The data are sparse.

IX Car: There is a gap in the data between JD 2441500-3500. The light curve shows a very slow rise and fall from beginning to end. The DCDFT spectrum shows several peaks between 2000-10000 days which may simply be a mathematical way of representing the very slow variation.

ST Cep: The light curve shows very slow variations; the DCDFT spectrum shows several peaks between 2000 and 10000 days which may simply be a way of mathematically representing
the slow, probably-irregular variations.

\( \mu \) Cep: This is a well-observed (visually and photoelectrically) star which is not excessively bright, and therefore much easier to observe than \( \alpha \) Ori or \( \alpha \) Sco.

\( AO \) Cru: The 340-day period is close to a year, and of small amplitude; it may well be spurious.

\( AZ \) Cyg: The light curve shows slow, irregular variations; the DCDFT spectrum shows several peaks between 2000 and 5500 days which may simply be a way of mathematically representing the slow, probably-irregular variations. There is no evidence for a significant period around 500 days.

\( BI \) Cyg: There are many peaks in the range of hundreds and thousands of days, but none stand out.

\( TV \) Gem: The 426 and 2550-day periods given by Kiss \textit{et al.} (2006) are aliases of each other.

\( WY \) Gem: The data are dense, but there are no significant peaks with amplitudes greater than about 0.05 mag. This includes the 353-day period reported by Kiss \textit{et al.} (2006), which may be spurious.

\( \alpha \) Her: The period of about 124 days, given by Kiss \textit{et al.} (2006) has an amplitude less than 0.03 in our data. The highest peaks are in the range 1300-1600 days, and the WWZ results suggest that the long period is in the range 1500-1600 days.

\( RV \) Hya: The data are very sparse.

\( W \) Ind: There is very little visual data after JD 2451500, but there is extensive V data. A period of 198 days is present in both datasets.

\( XY \) Lyr: The literature period of 120-122 days has an amplitude less than 0.03 mag in our data. The highest peaks, 1850±100 days, have amplitudes less than 0.05 mag.

\( \alpha \) Sco: Both visual and photoelectric observations of this bright star are challenging, because of the lack of convenient comparison stars. The most recent long-term spectroscopic and photometric
studies of its variability are by Pugh and Gray (2013a, 2013b). We find evidence, in the WWZ analysis, for periods in the range of 1000-2000 days.

**W Tri:** The period of about 107 days, given by Kiss *et al.* (2006) has an amplitude less than 0.03 in our data. The highest peaks are at 595 and 765 days, both with amplitudes of about 0.07 mag. The WWZ contours suggest that both of these periods are present, with variable amplitude, with $N \sim 1.0$.

### 4. Discussion

All of the 26 stars in Table 1 show amplitude variations though, in some cases, they are small – a few hundredths of a magnitude. They are, of course, lower limits to what might be observed if the dataset was much longer. The timescales of the amplitude variation of the stars for which this timescale is reasonably well-determined – those with one or more cycles of increase and decrease – have a median value of 18 periods, with some uncertainty. This value is similar for the short periods and the long ones. In the pulsating red giants (Paper 1), this ratio was 30-45, which is significantly greater than for the supergiants.

Photometric observations of red supergiants in both the Milky Way and the Magellanic Clouds suggest that the “short” period is to be identified with pulsation, and the “long” period with the long secondary periods in red giants. Pugh and Gray (2013b) have identified an additional period of 100 days in $\alpha$ Sco A (Antares) which is present in long-term spectroscopic observations, but not in photometry. They suggest that it is a convection-driven non-radial p-mode.

Paper 1 raised the hypothesis that the amplitude variations might be associated with the rotation of a star with large-scale convective regions. Both simulations and observations show that red supergiants have such regions on their surfaces (Chiavassa *et al.* 2010). The approximate uniformity of the L/P values suggests that there is some link between the period P and the process which causes the amplitude variations. Stars which are larger pulsate more slowly, and rotate more slowly, though the exact relation between these two time scales depends on the distribution of mass and of angular momentum in the star. The rotation period of a star is $2\pi R (\sin i)/(v \sin i)$ where R is the radius and $(v \sin i)$ is the measured projected equatorial rotation velocity. Fadeyev (2012) gives the radii of SU Per and W Per as 780 and 620 solar radii, respectively. The rotation periods are therefore 31000 $(\sin i)/(v \sin i)$ and 39000 $(\sin i)/(v \sin i)$ days, respectively. The measured values of $(v \sin i)$ are very uncertain; for Betelgeuse, the value is probably a few km/s (Gray 2000, and private communication 2013). If this value also applies to SU Per and W Per then, using an average value of $\sin i$ of 0.7, the rotation periods are not inconsistent with the values of L, which are 21500 and 11900 days, respectively, with considerable uncertainty.

This paper also has an important education application: author VK is an astronomical sciences major at the University of Toronto, and this is her first formal research project – a useful contribution to science, and an interesting (we hope) example, for observers, of how their observations contribute to both science and education.

### 5. Conclusions

We have identified one or two periods in 26 of 44 red supergiants, using Fourier analysis of sustained, systematic visual observations. All these periods have amplitudes which vary by factors of up to 8 (but more typically 2-4) on time scales which are typically about 20 times the period. The “short” periods (hundreds of days) are presumably due to pulsation. The “long” periods are analogous to the long secondary periods in red giants; their cause is not known for sure. But there is observational and theoretical evidence for large-scale convection in these stars, so a combination
of pulsation, convection, and rotation may combine to produce the complex variations that are observed in these stars.

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Table 1: Amplitude Variability of Pulsating Red Supergiants.

| Star    | P(d)   | JD(1)      | A Range | N  | L(d)  | L/P |
|---------|--------|------------|---------|----|-------|-----|
| SS And*| 159    | 2429500    | 0.15-0.55| 9.5| 2789  | 18  |
| VY CMa*| 1440   | 2440500    | 0.33-0.52| 0.5| 41000 | 26  |
| RT Car*| 448    | 2437000*   | 0.07-0.31| 2.5| 6600  | 15  |
| RT Car*| 2060   | 2437000*   | 0.07-0.11| <0.5|>39000| >19 |
| BO Car*| 330    | 2439000    | 0.07-0.27| 3.5| 5000  | 15  |
| CL Car*| 500    | 2434800    | 0.08-0.43| 0.5| 43400 | 87  |
| EV Car*| 820    | 2440000    | 0.10-0.50| 0.5| 33000 | 40  |
| TZ Cas | 3100   | 2438000    | 0.11-0.16| <0.2|>86000| >28 |
| PZ Cas | 840    | 2440000    | 0.13-0.50| 0.5| 33000 | 39  |
| µ Cep* | 870    | 2394500    | 0.07-0.26| 5.0| 11800 | 14  |
| µ Cep* | 4525   | 2394500    | 0.07-0.09| 0.8| 80000 | 18  |
| RW Cyg | 645    | 2416000    | 0.09-0.19| 1.25|32400 | 50  |
| BC Cyg | 700    | 2439500    | 0.15-0.51| 0.5| 33000 | 46  |
| TV Gem*| 426    | 2431000    | 0.08-0.29| 2.5| 9600  | 23  |
| TV Gem*| 2570   | 2431000    | 0.16-0.21| <0.2|>96000| >38 |
| α Her* | 1550   | 2425000    | 0.05-0.09| 1.0| 31500 | 20  |
| W Ind* | 198    | 2440000    | 0.23-0.42| 3.75|2933  | 15  |
| α Ori* | 388    | 2420000    | 0.03-0.24| 5.25|6000  | 15  |
| α Ori* | 2300   | 2420000    | 0.08-0.14| 0.5| 73000 | 32  |
| S Per* | 813    | 2419000    | 0.32-0.85| 2.25|16670 | 21  |
| T Per* | 2500   | 2410000    | 0.05-0.10| <0.5|>93000| >37 |
| W Per* | 500    | 2415000    | 0.20-0.47| 3.5| 11857 | 24  |
| W Per* | 2875   | 2415000    | 0.17-0.19| 1.0| 41500 | 14  |
| SU Per | 450    | 2432500    | 0.07-0.22| 2.5| 21500 | 46  |
| SU Per | 3300   | 2432500    | 0.07-0.22| 0.75|32000 | 10  |
| XX Per*| 2400   | 2422500    | 0.05-0.10| <0.5|>113000| >47 |
| BU Per*| 381    | 2432500    | 0.13-0.15| <0.25|>66000| >173|
| VX Sgr | 754    | 2427500    | 0.55-1.35| <1.0|>29000| >38 |
| AH Sco | 765    | 2440000    | 0.38-0.53| 1.5| 11667 | 16  |
| α Sco* | 1750   | 2431000    | 0.10-0.40| 0.5| 51000 | 29  |
| CE Tau | 1300   | 2435000    | 0.06-0.13| 0.6| 35833 | 28  |
| W Tri* | 680    | 2431500    | 0.08-0.11| 1.0| 25000 | 37  |