Amplitude Variations in Pulsating Red Supergiants

John R. Percy
Viraja C. Khatu
Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada; john.percy@utoronto.ca

Received October 16, 2013; revised December 5, 2013; accepted December 6, 2013

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 forty-four red supergiants. Of these, twelve stars had data which were too sparse and/or had low amplitude and/or were without conspicuous peaks in the Fourier spectrum; six stars had only a long (2,500–4,000 days) period without significant amplitude variation. The other twenty-six 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 to 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. We discuss possible explanations for the amplitude variations, including the effects of pulsation, rotation, convection cells, and stochastically-excited pulsations.

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 α Ori (Betelgeuse; Kervella *et al.* 2013), α Sco (Antares; Pugh and Gray 2013a, 2013b), and α Her (Moravveji *et al.* 2010) 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 forty-six pulsating red supergiant stars. They found periods in most of them, and two periods in eighteen 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, in the sense that the pulsations may be stochastically-excited. 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*: twenty-nine single-mode and thirty double-mode SR stars, ten Mira stars, and the LSPs in twenty-six SR stars. In each case, the amplitude varied significantly, on a time scale (L) which was about 30 to 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. Christensen-Dalsgaard *et al.* (2001) have pointed out that the pulsations of SR stars may be stochastically-excited, in which case amplitude variations may be due to growth and decay of pulsation modes. In the present paper, we extend Paper 1 to forty-four 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 section 3.2. for remarks on some of these. Our data extend a few years longer than those 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 to 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 Δt (50 days). The results are sensitive to the former, but not to the latter. Templeton *et al.* (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 as a function of 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.

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

**See note in section 3.2.*

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 ≤ 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, and 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*, RV Hya*, XY Lyr*, AD Per*, and 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* (3,600 days), BU Gem (2,500 days), RS Per* (4,000 days), KK Per (3,030 days), PR Per* (3,090 days), and FZ Per* (3,440 days).

Figure 1 shows the light curve and amplitude variation for S Per. Figures 2 and 3 show the light curves and amplitude variations of the "short" and "long" periods of μ Cep and α Ori, respectively. Figure 4 shows the light curve and amplitude variation for VY CMa. Paper 1 shows the amplitude variations for several pulsating red giants; these are similar to those in the red supergiants. The cycles of amplitude change are by no means sinusoidal, but have varying amplitudes themselves.

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 (1,850 ± 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.

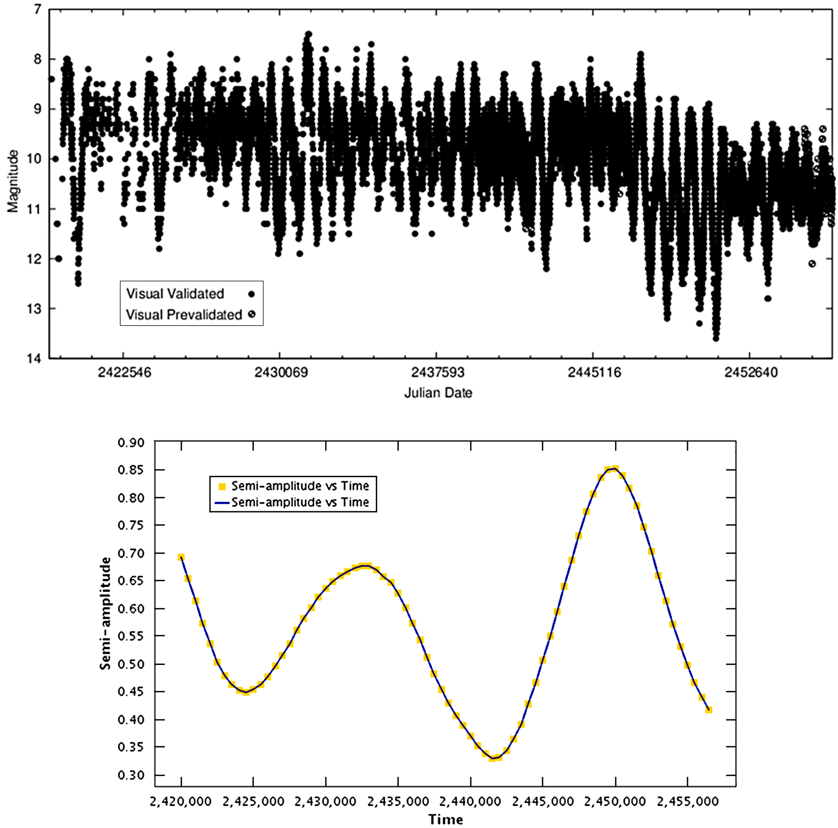

Figure 1. The changing visual amplitude (AAVSO data) of the pulsating red supergiant S Per, with a pulsation period of 813 days. The amplitude varies between 0.35 and 0.85, and there are approximately 2.25 cycles of increase and decrease.

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 to 950 days.

CL Car There are comparable peaks at 500 and 1,350 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 2441500–2443500. The

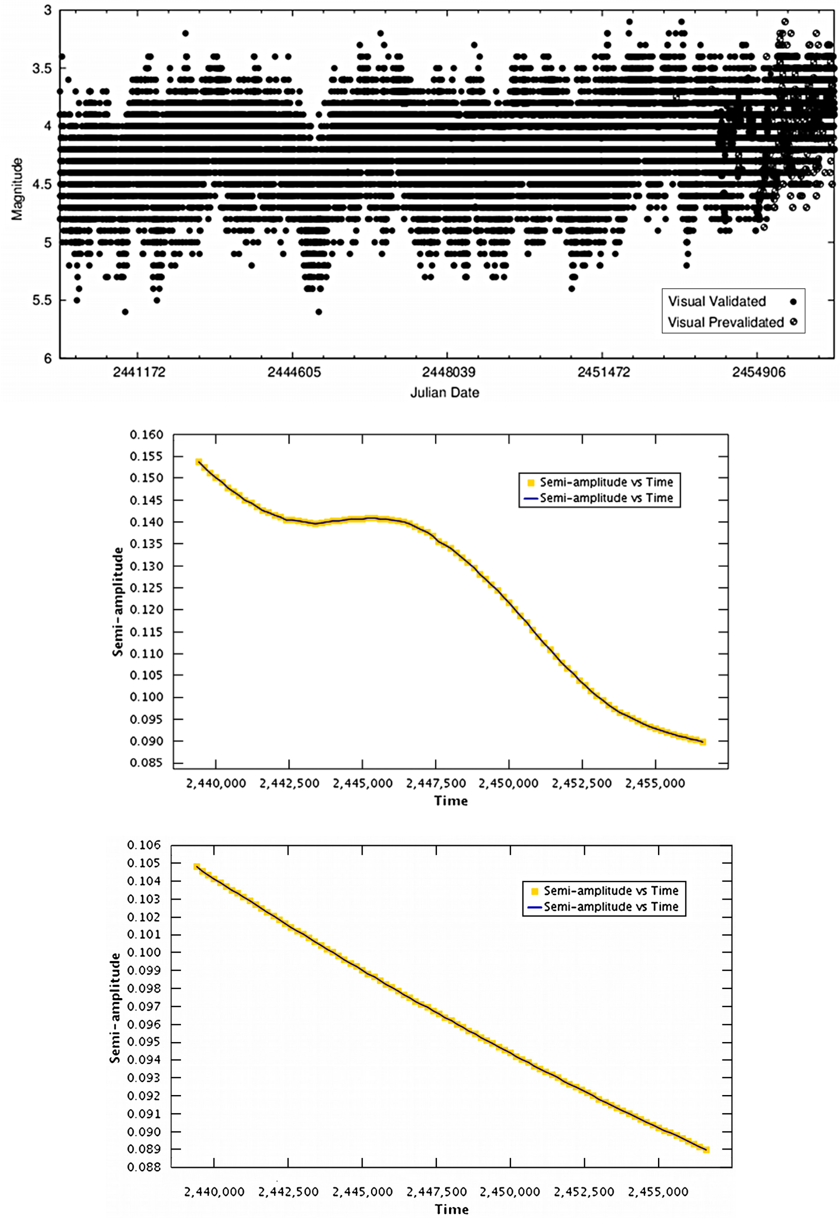

Figure 2. The AAVSO light curve of μ Cep (top), the amplitude of the 870-day period (middle), and the amplitude of the 4,525-day period (bottom).

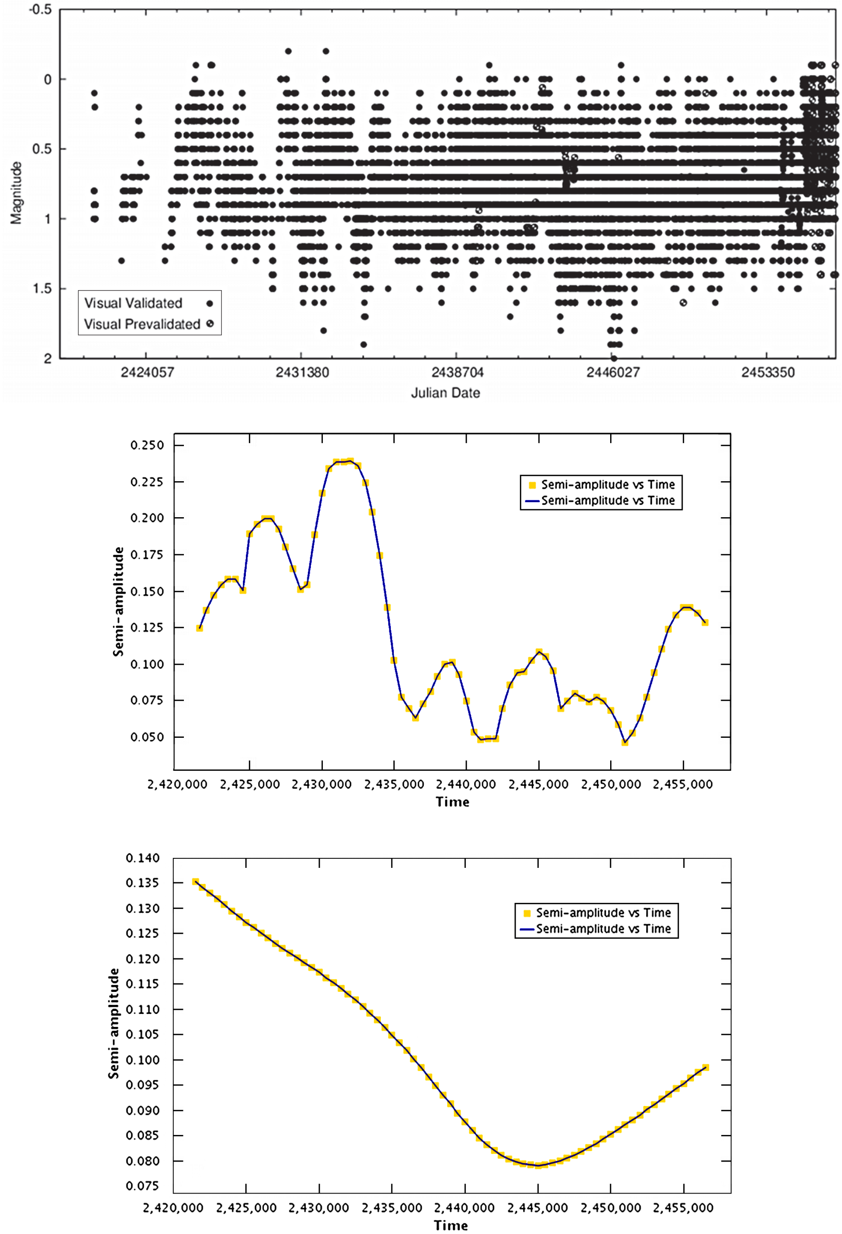

Figure 3. The AAVSO light curve of α Ori (top), the amplitude of the 388-day period (middle), and the amplitude of the 2,300-day period (bottom).

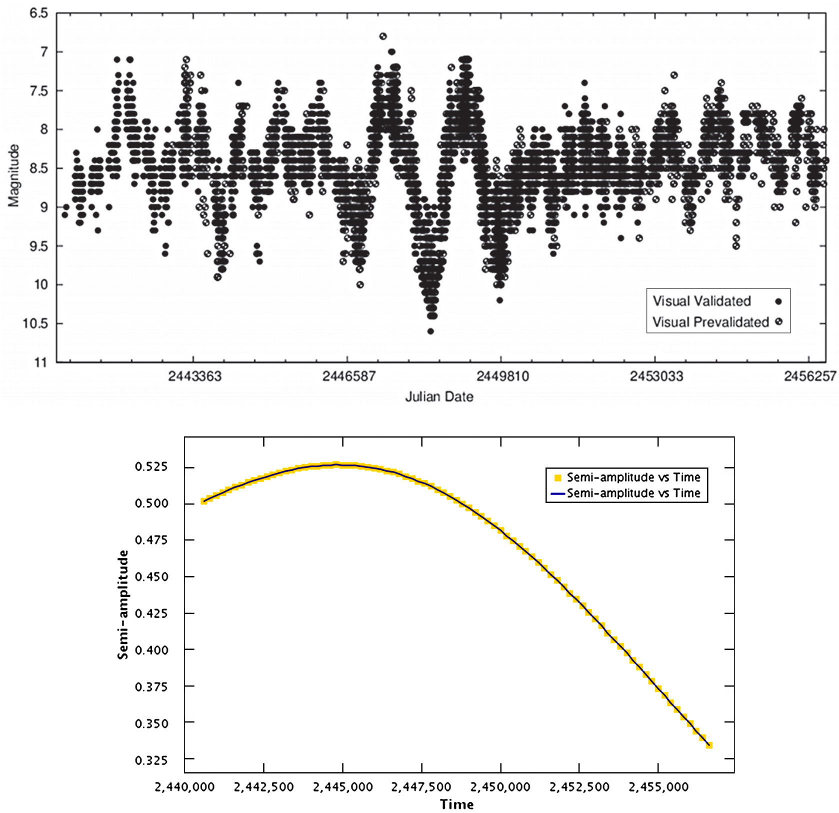

Figure 4. The AAVSO light curve of VY CMa (top), and the amplitude of the 1,440-day period

light curve shows a very slow rise and fall from beginning to end. The DCDFT spectrum shows several peaks between 2,000 and 10,000 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 2,000 and 10,000 days which may simply be a way of mathematically representing the slow, probably-irregular variations.

μ *Cep* This is a well-observed (visually and photoelectrically) star which is not excessively bright, and therefore much easier to observe than α Ori or α 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 2,000 and 5,500 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 2,550-day periods given by Kiss *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 magnitude. This includes the 353-day period reported by Kiss *et al.* (2006), which may be spurious.

α *Her* The period of about 124 days given by Kiss *et al.* (2006) has an amplitude less than 0.03 in our data. The highest peaks are in the range 1,300–1,600 days, and the WWZ results suggest that the long period is in the range 1,500–1,600 days. Moravveji *et al.* (2010) analyzed fifteen years of V-band and three-filter Wing (near infrared) data, and found an LSP of 1,343 days, and other periods around 125 days.

RV Hya The data are very sparse.

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

XY Lyr The literature period of 120 to 122 days has an amplitude less than 0.03 magnitude in our data. The highest peaks, 1850 ± 100 days, have amplitudes less than 0.05 magnitude.

α *Ori* This is the brightest and best-studied pulsating red supergiant, though both visual and photoelectric observations are difficult because of the lack of convenient comparison stars. A workshop about this star has recently been held (Kervalla *et al.* 2013). The period of 388 days (Kiss *et al.* 2006) is present in the V data, but is not prominent in the visual data.

S Per The star fades by about a magnitude towards the end of the dataset.

W Per Our periods agree with the literature periods. The 2,875-day period is clearly visible in the light curve.

RS Per There is a period of 224 days in the V data which does not appear to be present in the visual data.

XX Per The literature periods are 4,100 and 3,150 ± 1,000 days; the latter is not inconsistent with our period of 2,400 days.

AD Per Peaks are at the long period of 3,240 days, and at one year; the latter is not present in the V data, and is probably spurious.

BU Per There is a large gap in the middle of the dataset. There are peaks near a year, which are probably spurious. In the table, we have given results for the 381-day period (which may not be real). There are peaks at 3,700 and 5,500 days (which are possibly aliases of each other); a time scale of about 5,500 days appears to be present in the light curve.

FZ Per The V data do not support a period of about a year, which is present in the visual data, and is almost certainly spurious.

PP Per The only peak is at one year.

PR Per Peaks are at the long period of 3,090 days, and at one year. The amplitude of the long period increases only slightly.

α 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 magnitude. The WWZ contours suggest that both of these periods are present, with variable amplitude, with N ~ 1.0.

4. Discussion

All of the twenty-six stars in Table 1 show amplitude variations although, 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. As noted above, the cycles of amplitude variation are not sinusoidal, but have varying amplitudes themselves.

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 α Sco A 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, although the exact relation between these two time scales depends on the distributation 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 31,000 $(\sin i)/(v \sin i)$ and 39,000 $(\sin i)/(v \sin i)$ days, respectively. The measured values of $(v \sin i)$ are very uncertain; for α Ori, the value is probably a few km/s (Gray 2000, 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 21,500 and 11,900 days, respectively, with considerable uncertainty.

Bedding (2013) has suggested a simpler explanation for the amplitude variability in both the red supergiants, and the red giants (Paper 1): amplitude variability is to be expected for stochastic oscillations. Such oscillations are continuously excited by convection at the same time as being damped with a certain e-folding lifetime. Kiss *et al.* (2006) used Lorentzian fits to the power spectra of six red supergiants to estimate their mode lifetimes in days: W Per (1,200), TV Gem (286), α Ori (1,140), α Her (1,060), VY CMa (2,800), and S Per (2,240). These lifetimes are an order of magnitude shorter than the values of L—the lengths of the cycles of amplitude increase and decrease in Table 1.

Amplitude variations are also discussed explicitly by Christensen-Dalsgaard *et al.* (2001) in the context of semiregular (SR) pulsating red *giants*. They determined the rms scatter of the amplitudes of SR variables, using AAVSO visual data, and compared this with the mean amplitudes of the stars. For variables with visual amplitudes less than about 1.5 magnitude, they find that the scatter is proportional to the mean amplitude, which is what would be expected for stochastically-excited pulsations. For larger-amplitude stars, they find that the scatter is independent of the mean amplitude. This might be because the visual amplitudes of these stars are much higher than the bolometric amplitudes, or because a single mode is excited in more luminous stars (rather than two or more modes in the less luminous stars), or because pulsation in the more luminous stars is driven by the standard kappa mechanism, or a mixture of these reasons. The amplitude variations shown in Figure 2 of their paper, for an artificial time series for an oscillation with a period of 82 days, are not unlike those that we observe in pulsating red giants and supergiants. We note also that Fadeyev (2012) has constructed models of red supergiants, and found them to be unstable against fundamental-mode radial pulsation, the driving mechanism being the standard kappa mechanism in the hydrogen and helium ionization zones. The explanation for the complex variability behavior of red supergiants may therefore be a mixture of processes.

Our 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 twenty-six of forty-four 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 to 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.

6. Acknowledgements

We thank the hundreds of AAVSO observers who made the observations which were used in this project, and we thank the AAVSO staff for processing and archiving the measurements. We also thank the team which developed the VSTAR package, and made it user-friendly and publicly available. We are especially grateful to the referee, Professor Tim Bedding, for his comments on the manuscript, and his suggestion of a plausible explanation for the amplitude variations. This project made use of the SIMBAD database, which is operated by CDS, Strasbourg, France.

References

Bedding, T. R. 2013, private communication (November 18).
Benn, D. 2013, VSTAR data analysis software (http://www.aavso.org/node/803).
Chiavassa, A., Haubois, X., Young, J. S., Plez, B., Josselin, E., Perrin, G., and Freytag, B. 2010, *Astron. Astrophys.*, **515A**, 12.
Christensen-Dalsgaard, J., Kjeldsen, H., and Mattei, J. A. 2001, *Astrophys. J.*, 562, L141.
Fadeyev, Y. A. 2012, *Astron. Lett.*, **38**, 260.
Gray, D. F. 2000, *Astrophys. J.*, **532**, 487.
Gray, D. F. 2013, private communication (September 24).
Kervella, P., Le Bertre, T., and Perrin, G. (eds.). 2013, *Betelgeuse Workshop 2012*, EAS Publ. Ser. 60, EDP Sciences, Les Ulis, France.
Kiss, L. L., Szabó, G. M., and Bedding, T. R. 2006, *Mon. Not. Roy. Astron. Soc.*, **372**, 1721.
Moravveji, E., Guinan, E. F., Wasatonic, R., Sobouti, Y., and Nasiri, S. 2010, *Astron. Space Sci.*, **328**, 113.
Nicholls, C. P., Wood, P. R., Cioni, M.-R. L., and Soszyński, I. 2009, *Mon. Not. Roy. Astron. Soc.*, **399**, 2063.
Percy, J. R., and Abachi, R. 2013, *J. Amer. Assoc. Var. Star Obs.*, in press (http://www.aaavso.org/sites/default/files/jaavso/ej243.pdf).
Percy, J. R., and Sato, H. 2009, *J. Roy. Astron. Soc. Canada*, **103**, 11.
Pugh, T., and Gray, D. F. 2013a, *Astron. J.*, **145**, 38.
Pugh, T., and Gray, D. F. 2013b, *Astrophys. J.*, **777**, 10.
Templeton, M. R., Mattei, J. A., and Willson, L. A. 2005, *Astron. J.*, **130**, 776.