Studies of the Long Secondary Periods in Pulsating Red Giants. II. Lower-Luminosity Stars

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Abstract   We have used AAVSO visual and photoelectric V data and the AAVSO time-series package VSTAR and the Lomb-Scargle time-series algorithm to determine improved pulsation periods, "long secondary periods" (LSPs), and their amplitudes in 51 shorter-period pulsating red giants in the AAVSO photoelectic photometry program and in the AAVSO LPV (long period variable) binocular program. As is well known, radial pulsation becomes detectable in red giants at about spectral type M0, with periods of about 20 days. We find that the LSP phenomenon is also first detectable at about M0. Pulsation and LSP visual or V amplitudes increase from near zero to about 0.1 magnitude at periods of 100 days. At longer periods, the pulsation amplitudes continue to increase, but the LSP amplitudes are generally between 0.1 and 0.2 magnitude on average. The ratios of LSP to pulsation period cluster around 5 and 10, presumably depending on whether the pulsation period is the fundamental or first overtone. The pulsation and LSP phase curves are generally close to sinusoidal, except when the amplitude is small, in which case they may be distorted by observational scatter or, in the case of the LSP amplitude, by the pulsational variability. As with longer-period stars, the LSP amplitude increases and decreases by a factor of two or more, for unknown reasons, on a median time scale of about 20 LSPs. The LSP phenomenon is thus present and similar in radially pulsating red giants of all periods. Its cause remains unknown.

1. Introduction

In a previous paper (Percy and Deibert 2016), which is one of a series of our papers about pulsating red giants, we addressed the question of the nature and cause of the "long secondary periods" (LSPs) which occur in about a third of these stars, and whose cause is unknown. In the present paper, we look especially at shorter-period pulsating red giants in two samples: (1) stars in the AAVSO photoelectric photometry (PEP) program, which have both visual and PEP data; (2) shorter-period stars in the AAVSO LPV Binocular Program (www.aavso.org/lpv-section-file-downloads). These data, though not as precise as, for instance, MACHO and OGLE data, have the advantage that they have been sustained over many decades.

AAVSO PEP observations of pulsating red giants have already been analyzed by Percy *et al.* (1996). Now, there are an additional two decades of data. Robotic telescope PEP observations of similar stars were analyzed by Percy *et al.* (2001), and merged AAVSO and robotic observations were analyzed by Percy *et al.* (2008).

We hope to address scientific questions such as whether the LSPs occur in shorter-period, lower-luminosity red giants, and whether their amplitudes, and their ratio to the fundamental pulsation period are the same as in longer-period stars. Shorter-period stars have smaller pulsation and LSP amplitudes but, for the same length of dataset, yield more accurate values of the LSP, and the timescale of its amplitude variation. Since the pulsation periods are much less than a year, they are slightly less likely to be complicated by one-cycle-per-year aliases. Ultimately, we would like to make progress in identifying the nature and cause of the LSP phenomenon.

2. Data and Analysis

We used visual and PEP V observations from the AAVSO International Database (AID; Kafka 2016), and the AAVSO VSTAR time-series analysis package (Benn 2013), which includes both a Fourier and a wavelet analysis routine. Co-author HL was interested in comparing the results of VSTAR with those from the Lomb-Scargle algorithm (implemented here with the astropy.stats.LombScargle routine within PYTHON (www.python.org)) so we used that also for some of the analysis. Figure 1 shows the period spectrum of the visual data on T Cen, obtained with the Lomb-Scargle algorithm. The best period, the one-year aliases, and the harmonics are present and marked.

Our two samples of stars have some selection effects. Those in the PEP program were pulsating red giants which were in the AAVSO visual program in the early 1980s, but had small
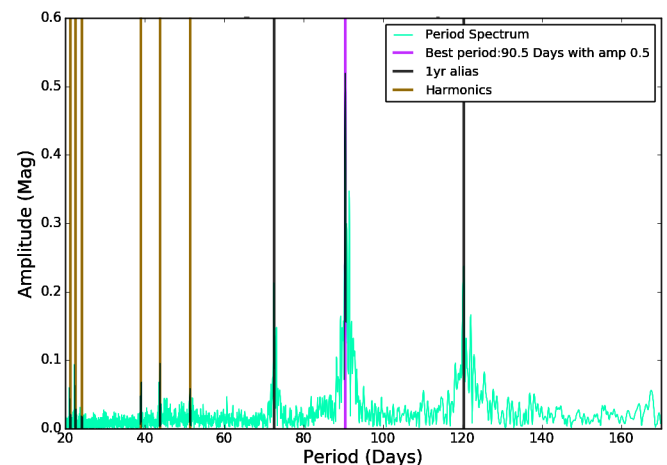

Figure 1. The Lomb-Scargle period spectrum for T Cen visual data, showing the best period (90.5 days), the one-year aliases, and the harmonics.

amplitudes, and would therefore benefit from PEP observations. The stars in the binocular program were presumably stars which were reasonably bright, and had moderate to high amplitudes. We chose to analyze stars from this program with shorter periods, since we were especially interested in the LSP phenomenon in such stars.

3. Results

3.1. Periods and amplitudes

We have determined improved periods and amplitudes in these 43 stars. Table 1 lists stars in the AAVSO LPV Binocular Program with periods less than about 120 days, for which there were sufficient data for analysis, along with our results. The columns give: the star name, the pulsation period PP, the LSP, the ratio of LSP to PP, and the pulsation and LSP visual amplitudes in magnitudes. In this and Table 2, some LSPs are close to one year and, if their amplitudes are small, there is some possibility that they are spurious (Percy 2015). Table 2 lists stars in the AAVSO PEP program for which there were sufficient visual and PEP V data to determine periods (see Notes on Individual Stars), along with our results. The columns give: the star name, the pulsation period PP, the LSP, the ratio of LSP to PP, and the pulsation and LSP amplitudes. In deciding on the value of the amplitude, we have usually given greater weight to the photoelectric V data. In any case, the PP and LSP amplitudes of these stars vary with time (Percy and Abachi 2013). Note that, although we concentrated on stars with shorter periods, there were stars in the PEP program (RS Cnc, η Gem, and SW Vir) which had longer periods. In the binocular program, X Her was listed as having a period of 102 days, but was found to have a longer one; Y Lyn was listed as having a period of 110 days, but was also found to have a longer one.

There were six stars (TV Psc, Z Eri, RR Eri, TV UMa, FP Vir, and V1070 Cyg) which were common to both programs. The two authors decided to analyze them independently. For Z Eri, this yielded two different results for the pulsation period —78.5 and 118.4 days. For this star, the Fourier spectrum yielded *several* peaks of comparable height, including those mentioned. In the V data, the highest was 239–243 days. We conclude that, with the present data, the pulsation period is indeterminate. For RR Eri, we obtained two different results for the LSP—366 and 742 days. In the Fourier spectrum of the V data, 742 days is marginally higher, whereas 366 days could well be a spurious period. Aside from these marginal differences, VSTAR and Lomb-Scarge gave equivalent results.

3.2. Long secondary periods

For the stars in Table 1, Figure 2 plots the ratio of LSP to pulsation period LSP/PP against PP. The shaded area is a histogram projected on the y-axis, with the scale on the top. Percy and Deibert (2016) found the ratio LSP/PP to be about 5 when the pulsation period was the fundamental period, and about 10 when the pulsation period was the first overtone. Figure 2 also shows clustering at about 5–6 and 8–10 and also some stars with a ratio of 12–14. The latter have short pulsation periods, and may be pulsating in the second overtone. This is consistent with previous studies of pulsation modes in short-

Table 1. Shorter-period stars in the AAVSO LPV binocular program.

Star	PP (d)	LSP (d)	LSP/PP	PP amp (mag)	LSP amp (mag)
θ Aps	108.8	1023	9.4	0.14	0.11
RT Cnc	89.3	371:	4.1	0.06	0.10
TU CVn	44.8	363:	8.1	0.03	0.03
V465 Cas	97.2	895	9.3	0.07	0.18
T Cen	90.5	—	—	0.54	—
SS Cep	100.3	958	9.5	0.06	0.09
RR CrB	55.5	630	11.3	0.04	0.05
AF Cyg	94	1439	15.3	0.13	0.08
V1070 Cyg	62.4	640	10.3	0.04	0.05
U Del	118	1166	9.9	0.05	0.21
CT Del	80.7	372:	4.6	0.06	0.12
TX Dra	77.5	712	9.2	0.09	0.15
Z Eri	118.4	725	6.2	0.05	0.11
RR Eri	92.6	366:	3.9	0.06	0.10
X Her	176.0	667	3.8	0.06	0.08
g Her	87.6	877	10.0	0.03	0.16
UW Her	106.8	985	9.3	0.09	0.07
IQ Her	76.1	624	8.2	0.05	0.12
RX Lep	100.7	572	5.6	0.06	0.07
Y Lyn	133.2	1257	9.5	0.08	0.33
SV Lyn	67.6	545	8.1	0.06	0.08
XY Lyr	121.4	1235	10.2	0.04	0.04
GO Peg	74.9	473	6.3	0.05	0.07
TV Psc	55.1	403	7.4	0.03	0.04
τ4 Ser	111.1	1159	10.5	0.04	0.11
W Tri	105.5	765	7.3	0.05	0.08
ST UMa	90.2	625	6.9	0.04	0.07
TV UMa	53.8	653	12.2	0.03	0.06
V UMi	72.9	759	10.5	0.12	0.08
FP Vir	62.8	384	6.1	0.08	0.11

Table 2. Red giants in the AAVSO PEP program.

Star	PP (d)	LSP (d)	LSP/PP	PP amp (mag)	LSP amp (mag)
χ Aqr	40.2	229	5.7	0.03	0.03
RZ Ari	56.5	507	9.0	0.05	0.05
W Boo	25	360::	14.4	0.02	0.04
RS Cnc	240.8	2050	8.5	0.19	0.12
FZ Cep	81.8	743	9.1	0.11	0.10
FS Com	55.7	680	12.2	0.06	0.06
W Cyg	132	(259)	(2)	0.20	0.17
AB Cyg	69	525	7.6	0.10	0.13
V1070 Cyg	62.8	639	10.2	0.04	0.05
V1339 Cyg	34.1	—	—	0.04	—
EU Del	62.5	626	10.0	0.12	0.08
AZ Dra	44	359:	8.2	0.04:	0.10:
Z Eri	78.5	730	9.3	0.10	0.13
RR Eri	92.5	742	8.0	0.12	0.10
η Gem	232	—	—	0.07	—
IN Hya	87.8	693:	7.9	0.09	0.10
R Lyr	53	380:	7.2	0.04	0.04
V533 Oph	58	400	6.9	0.08	0.10
ρ Per	55	723	13.1	0.05	0.06
TV Psc	55.0	400:	7.3	0.03	0.04
CE Tau	105	1280	12.2	0.03	0.08
TV UMa	54	640	11.9	0.06:	0.07
VW UMa	66	621	9.4	0.06	0.07
VY UMa	122	1180	9.7	0.05	0.06
SW Vir	155	1647	10.6	0.50	0.21
FH Vir	59.6	360:	6.0	0.09	0.15:
FP Vir	65	375:	5.8	0.07	0.10

period, small-amplitude red giants, which showed that many of these pulsate in the first or second overtone (e.g. Percy and Bakos 2003).

3.3. Amplitudes

Figure 3 plots the visual or V pulsation amplitude in magnitudes against the pulsation period. As is well-known (see Percy and Guler 1999 and the review by Kiss and Percy 2012, for instance), pulsation sets in at about M0 spectral type, which corresponds to periods of about 20 days. The pulsation amplitude then increases with period, as seen in Figure 4.

Figure 4 plots the PP amplitude against the LSP amplitude, both visual or V, in magnitudes. The two are approximately equal for periods less than about 100 days. For longer periods, the LSP amplitude is typically 0.05–0.2 magnitude (Percy and Deibert 2016). The LSP phenomenon thus becomes detectable at the same spectral type as radial pulsation.

3.4. Phase curves

For the stars in Table 1, the shape of the pulsation phase curve and the LSP phase curve were investigated by fitting them with a fifth-degree polynomial, and comparing the result to a sine curve using the scipy.stats.pearsonr module in PYTHON. The results are shown in figures 5 and 6. For the pulsation phase curves, there is a small dissimilarity for stars with visual amplitudes less than 0.1 magnitude. The simplest explanation is that, for these, the shape of the true (sinusoidal?) phase curve is being distorted by observational scatter. The LSP phase curves also tend to be less sinusoidal if the amplitude is less than 0.1 magnitude; again, the simplest explanation is that this is due to the distorting effect of observational scatter and of the pulsational variability. For the following stars, the LSP phase curve was flagged as being non-sinusoidal: V1070 Cyg, Z Eri, RX Lep, and XY Lyr. Only two of the four have amplitudes less than 0.10 magnitude. Percy and Deibert (2016) found, from visual inspection, that the LSP phase curve of Y Lyn was clearly sawtooth, rather than sinusoidal; here, we find it to be sinusoidal.

3.5. Amplitude variations

Table 3 lists stars from Table 1 which had sufficient data to investigate variations in the LSP amplitude using the wavelet routine in VSTAR. The columns list: the name of the star, the range of the LSP amplitude in magnitudes, the number N of cycles of LSP amplitude increase and decrease, and the ratio of the length L of these cycles to the LSP, where L is the length of the dataset divided by N. See our previous papers, especially Percy and Abachi (2013), for more discussion of the determination of these. In particular: note that N and L are very approximate, because there is often less than one cycle of increase and decrease in the dataset—even though the dataset may be many decades long.

The median ratio of cycle length L to LSP is 21, slightly lower than the value 30 found by Percy and Abachi (2013); the difference is probably not significant. The LSP amplitudes vary by typically a factor of two, again in agreement with the values found by Percy and Abachi (2013). Combining our results with those of Percy and Abachi (2013), there is no obvious
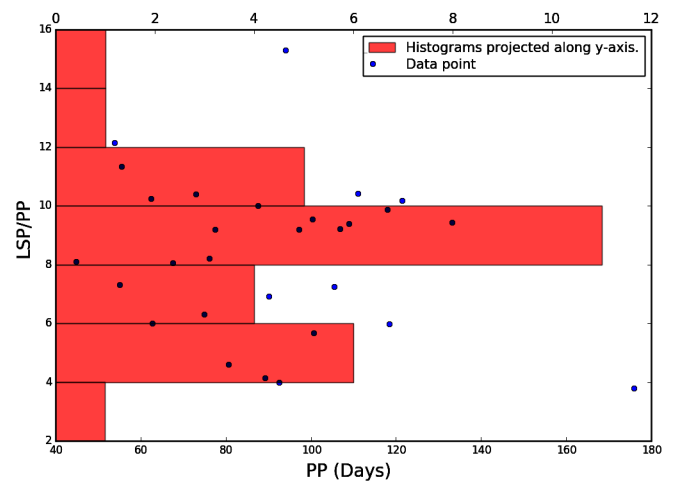

Figure 2. The ratio of LSP to pulsation period PP, as a function of PP, for the stars in Table 1. The shaded area represents a histogram of the data, with the scale at the top. The results are consistent with those of Percy and Deibert (2016), namely that the values cluster about 5 and 10, depending on whether the pulsation period is the fundamental period or the first overtone.
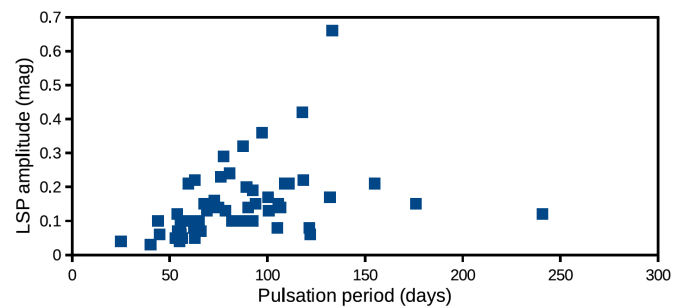

Figure 3. The visual or V pulsation amplitude in magnitudes versus pulsation period. As is well known from previous studies (reviewed by Kiss and Percy 2012), the shortest-period stars have the smallest amplitudes; radial pulsational instability sets in at spectral type approximately M0III.
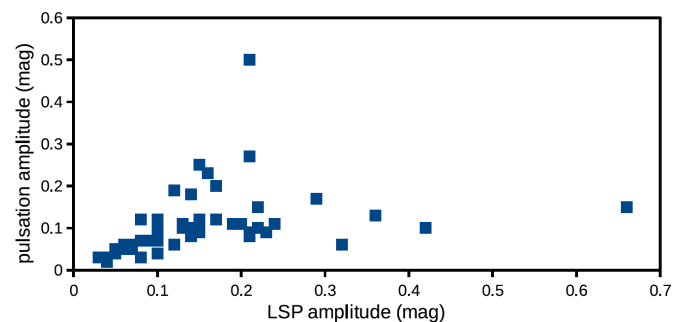

Figure 4. The PP amplitude as a function of LSP amplitude (both visual or V, in magnitudes), for the stars in Table 2. For longer-period stars, Percy and Deibert (2016) found that the LSP amplitude was typically 0.2 magnitude. For the shorter-period stars, both the LSP amplitude and the pulsation amplitude are approximately equal. Both radial pulsation and the LSP phenomenon set in at spectral type about M0III.

correlation between L/LSP and pulsation period, i.e. with the radius of the star.

3.6. Notes on individual stars

χ Aqr The V data give periods of 40.2 and 229 days, but the amplitudes are small. The visual data do not give reliable periods.

RZ Ari The visual and V data give the same pulsation period (56.5 days) but the LSP (507 days) is present in the V data only.

W Boo This star switches modes between 25 and 50 days (Percy and Desjardins 1996). The present V data give a strongest period of 25.7 days. The visual and V data both give an LSP of 358–365 days, with small amplitude; it is suspiciously close to one year, and may be spurious.

VZ Cam There are no significant peaks in the visual or V data.

RS Cnc The pulsation period of 240.8 days is present in both the visual and V data. There is a possible LSP of 2,050 ± 100 days.

DM Cep No periods could be found.

FZ Cep The V data give periods of 81.8 and 743 days. The visual data are inconclusive.

T Cet The pulsation period may be 161 or 288 days; these are aliases. The LSP may be 1,908 days, but this too may be an alias.

FS Com The visual and V data both give a pulsation period of 55.7 days. The V data give an LSP of 689 days, in agreement with the result of Percy *et al.* (2008). The visual data do not show an LSP.

GK Com The results are uncertain.

W Cyg The visual data give periods of 132 and 259 days, as do the V data. We assume these to be the fundamental and first overtone periods. There is no evidence for an LSP.

AB Cyg The V data give periods of 69.3 and 521 days. The visual data give an LSP of 529 days, but the pulsation period is uncertain.

V973 Cyg The visual data give periods of 40.5 and 362 or 394 days. The V data give periods of 36.5 and 391 days. In each case, the amplitude is small.

V1070 Cyg The visual data give periods of 62.8 and 639 days. The V data are inconclusive.

V1339 Cyg The visual and V data both give pulsation periods of 34.06 days. The visual data give an LSP of 339 days, but the amplitude is only 0.02 magnitude, so it is uncertain.

EU Del The visual data give periods of 62.55 and 623.8 days. The V data give periods of 62.52 and 629.3 days. This star is a "prototype" of small-amplitude pulsating red giants.

VW Dra The data are noisy.

AT Dra Data are plentiful, but somewhat noisy. There are no significant peaks.

AZ Dra The visual data give a pulsation period of 44.4 days. The visual and V data both give an LSP of 357–360 days, with amplitudes about 0.10 magnitude. The period may be spurious.

Z Eri Both the visual and V data give periods of 78.5 and 730 days.

RR Eri The V data give periods of 92.5 and 742 days. The former is weakly present in the visual data, but not the latter. The GCVS period is 97 days.

IS Gem Non-variable.

η Gem The pulsation period (232 days) is present in both the visual and V data, but there is no obvious LSP.

X Her The General Catalogue of Variable Stars (GCVS; Samus *et al.* 2012) gives a period of 95 days; we find 176 days.

ST Her Both the visual and V data give periods of 151 or 257 days. These are aliases, and we cannot choose between them.

AK Hya The data are noisy; there are no convincing peaks.

Table 3. Amplitude variations in the LSPs in shorter-period red giant stars.

| Star	LSP amp	N cycles	L/LSP
θ Aps	0.07–0.17	0.75	34
RT Cnc	0.05–0.15	4	8
TU CVn	0.02–0.06	2	50
SS Cep	0.07–0.16	1.5	26
AF Cyg	0.05–0.11	1.5	21
V1070 Cyg	0.04–0.06	1.5	16
U Del	0.14–0.26	0.5	21
CT Del	0.02–0.18	1.7	20
Z Eri	0.08–0.19	2	21
X Her	0.04–0.25	1	60
g Her	0.08–0.22	0.5	46
RX Lep	0.05–0.13	2	18
Y Lyn	0.15–0.40	0.5	32
SV Lyn	0.03–0.10	2	18
XY Lyr	0.03–0.07	1	16
TV Psc	0.02–0.10	1.25	40
τ4 Ser	0.07–0.12	1.25	17
W Tri	0.06–0.10	1.75	20
ST UMa	0.03–0.12	2	24
TV UMa	0.03–0.06	2	15
V UMi	0.03–0.20	0.75	26
FP Vir	0.06–0.17	1.5	33
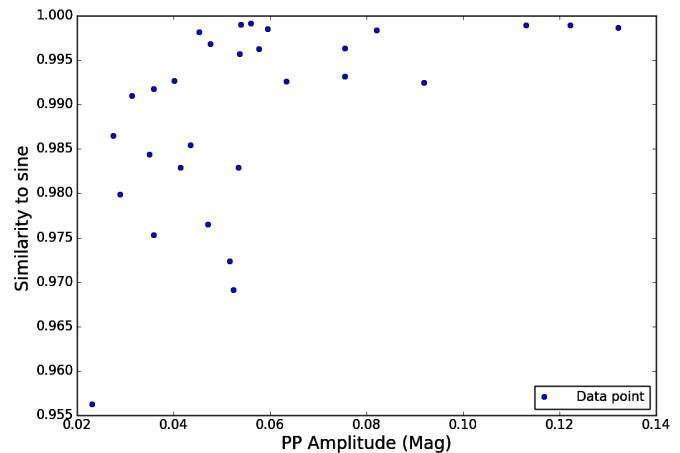
Figure 5. The similarity of the pulsation phase curve to a sine curve, as a function of pulsation amplitude in magnitudes. Stars with small pulsation amplitudes may have phase curves which differ slightly from sine curves, perhaps because observational scatter distorts the phase curve.
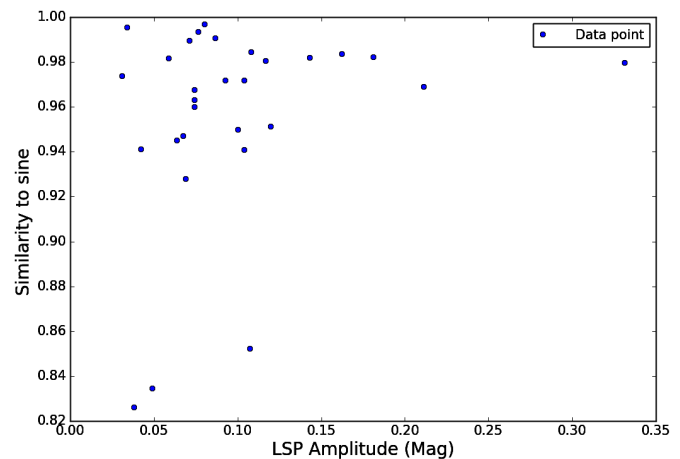

Figure 6. The similarity of the LSP phase curve to a sine curve, as a function of the LSP amplitude in magnitudes. Stars with smaller LSP amplitudes may have LSP phase curves which differ slightly from sine curves, perhaps because observational scatter and the pulsational variability distort the LSP phase curve.

IN Hya The V data suggest a pulsation period of 87.9 days and an LSP of 693 days. The visual data are less clear, but may indicate a pulsation period of 85.8 days.

SS Lep Probably non-variable.

Y Lyn GCVS gives a period of 110 days; we get 133.2 days.

R Lyr The visual and V data give a period of 53 ± 10 days. There is no LSP (Percy *et al.* 2008).

V614 Mon The pulsation period is unclear, and the LSP in both the visual and V data is dangerously close to one year.

V533 Oph The visual data give periods of 55.3 and 398 days. The V data give periods of 60.0 and 405 days.

ρ Per The visual and V data give the same pulsation period (55 ± 0.5 days) but the LSP (723 days) is visible in the V data only.

TV Psc The periods from the visual (55.1 days) and V data (55.0 days) are consistent, even though the amplitudes are small—0.06 and 0.02 magnitude, respectively—but the LSP is uncertain: 403 days from the visual data, and 546 days from the V data, both seemingly well-determined.

TX Psc No reliable periods could be found.

XZ Psc No reliable periods could be found.

V449 Sco There are no significant peaks.

CE Tau The pulsation period (105 ± 2 days) and the LSP (1280 ± 10 days) are present in both the visual and V data.

TV UMa The visual data give periods of 53.8 and 656 days; the V data give periods of 50–60 and 627 days.

VW UMa The visual data give periods of 65.9 and 624 days; the V data give periods of 66.2 and 618 days.

VY UMa The visual data give periods of 121.8 and 1,200 days. The V data are less certain, but suggest periods of 125 and 1,160 days.

SW Vir The visual and V data give pulsation periods of 155.3 and 154 days, respectively. The LSP is uncertain, but may be 1647 days.

EV Vir The data are too sparse to yield a result.

FH Vir The V data give a pulsation period of 59.6 days, in reasonable agreement with the GCVS period of 70 days. The LSP may be about 350–370 days, but this is dangerously close to a year.

FP Vir The visual data give periods of 62.8 and 383 days; the V data give periods of 67.0 and 369 days.

4. Discussion

We must emphasize the challenges and consequent uncertainties of our work: the amplitudes of our stars are small; the data are primarily visual, so they have limited accuracy and the possibility of spurious signals. Despite the decades-long database, some of the phenomena that we are studying would benefit from an even longer one.

Our results should provide additional constraints on the cause of the LSP phenomenon. That cause must be able to act in lower-luminosity stars as well as higher-luminosity ones. At the same time, its amplitude must approach zero in the lowest-luminosity pulsators, as the pulsation amplitude does. And, whatever causes the cyclic changes in LSP *amplitudes* must operate over the entire period/luminosity range. Wood (2015) also shows (his Figure 1) that LSPs extend to the lowest luminosities—though sparsely—in the Large Magellanic Cloud.

It also appears that LSPs occur on both the red giant branch and on the asymptotic giant branch. The LSP mechanism must explain the tight correlation between the LSP and the fundamental pulsation period, and the consistency of the LSP amplitude variations over the entire LSP range. It must also explain the large prevalence of LSPs—over 30 percent at all luminosities. It cannot be dependent on some rare process or configuration in the star.

Several possible causes of LSPs have been suggested in the literature e.g. Nicholls *et al.* (2009). Some do not match all of the observations. Others are inconsistent with theoretical predictions, in their present form. Percy and Diebert (2016) discussed the possibility of some form of rotational variability, but there were significant problems with that hypothesis. It is possible, of course, that different mechanisms act in different stars. V Hya, for instance, may be a form of eclipsing binary.

Saio *et al.* (2015) proposed that oscillatory convective pulsation modes might be a possible explanation for the LSPs. This hypothesis had some problems, but they might be overcome by a better treatment of convection; the authors used the standard mixing-length theory of convection. Based on the constraints listed above, this hypothesis is very attractive, but the "problem of the LSPs" must be considered unsolved at this point in time.

Are there red giants with LSPs but no primary (pulsation) periods? Probably not, because almost all red giants cooler than M0III are unstable to pulsation. But it might be worth looking at late K giants to see if any of them varied with periods 5–10 times greater than the expected fundamental mode period.

5. Conclusions

We have used AAVSO visual and PEP data to determine improved periods and amplitudes of lower-luminosity, shorter-period pulsating red giants. Our results extend those of Percy and Deibert (2016) to stars with shorter periods—down to 20–30 days. As red giants expand, radial pulsation becomes detectable in early type giants, with periods of about 20 days. So does the LSP phenomenon. With increasing period, the pulsation and LSP amplitudes both increase, and are approximately equal on average. When the period is longer than about 100 days, the LSP amplitude levels off at 0.1 to 0.2 magnitude. The LSP is about five times the fundamental pulsation period in these shorter-period stars, as it is in longer-period ones, and the LSP amplitude rises and falls on a time scale of about 20 LSPs. The LSP phenomenon thus extends to the shortest periods. Its nature and cause, however, are still unknown, but it must be able to operate in stars with shorter periods, warmer temperatures, and lower luminosities.

6. Acknowledgements

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