

Pulsating Red Giants in a Globular Cluster: ω Centauri

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Abstract We have carried out light-curve and time-series analysis of a sample of 16 pulsating red giants (PRGs) in the globular cluster ω Cen, using observations from the ASAS-SN database, and the AAVSO software package VSTAR. Of the 16 stars, 1 was classified by ASAS-SN as Mira (M), 5 as semiregular (SR), and 10 as “long secondary period” (LSP), i.e. the dominant period was an LSP. We have determined pulsation periods (P) for all of them, secondary pulsation periods for 3, possible secondary pulsation periods for 4, and LSPs for 8. This confirms that LSPs are common in Population II stars. In the context of a recent model for LSPs, this implies that many Population II PRGs had planetary companions which accreted gas and dust to become brown dwarfs or low-mass stars, now enshrouded by dust. In this model, the LSP is the orbital period of the hypothetical companion. The amplitudes of the pulsation periods vary by up to a factor of 3.4 on a median time scale of 18 pulsation periods, for reasons unknown. The ratios of LSP/P cluster around 4 and 8, presumably depending on whether P is a fundamental mode or first overtone period. We have augmented our sample with a few stars from the literature to plot period-luminosity relations. Sequences for LSPs, fundamental, and first-overtone pulsation periods are visible. Our results show that the complex variability of the PRGs in ω Cen is similar to that of red giants in other stellar systems, and in the field. In Appendix 1, we give results for a few red giants in NGC 6712, which we obtained as a prelude to the ω Cen project.

1. Introduction

Red giants vary in brightness in complex ways. They may pulsate in one or more radial modes, with variable pulsation amplitudes. About a third have a “long secondary period” (LSP), 5 to 10 times greater than the dominant pulsation period, and whose cause was uncertain until recently. The large convective cells in their outer layers and shock waves in their atmospheres may produce additional random variability. Soszyński *et al.* (2021) have made a strong case that LSPs are a result of binarity. The companion was initially a planet, which accreted matter from the red giant’s strong stellar wind, and “grew” into a brown dwarf or low-mass star, which produces the observed LSP velocity variations. The now-dust-enshrouded companion eclipses the red giant, producing the LSP. At infrared wavelengths, the dust-enshrouded companion can be seen to be eclipsed by the red giant about half a cycle later.

It is therefore interesting to note that LSPs exist in red giants in globular clusters (GCs), which are among the oldest objects in our galaxy and which are metal-poor. Studies of the variability of red giants in 47 Tuc have been published by Lebzelter and Wood (2005) and Percy and Gupta (2021), among others. In this paper, we study the variability of red giants in ω Cen. We use data from the All-Sky Automated Survey for Supernovae (ASAS-SN). The data are publicly available at <https://asas-sn.osu.edu/variables>. Unfortunately, ASAS-SN cannot observe and measure stars in the dense cores of globular clusters, so only a small fraction of the red giants in the cluster can be studied. We have supplemented our results with some of those of Lebzelter and Wood (2016). Our datasets are somewhat longer than those of Lebzelter and Wood (2016) and, unlike those authors, we have identified more than one pulsation period in some of our stars, estimated the LSPs, and also studied their variable pulsation amplitudes.

The automated process which ASAS-SN uses to classify and to establish the main pulsation period is often poorly suited to the analysis of PRGs (Percy and Fenaux 2019). The data and the properties which ASAS-SN establish must, therefore, be confirmed by a visual inspection of the light curves and by a more quantitative analysis (Percy and Fenaux 2019) of, for instance, its Fourier spectrum and period-time contour plots.

In this paper, we perform a detailed analysis of ASAS-SN observations of PRGs in ω Cen, the largest known globular cluster in the Milky Way at a distance of 5,240 parsecs (pc) from the Earth. This is a rather complex cluster. It may have undergone more than one wave of star formation, and may even have initially been a dwarf galaxy.

The light curves of stars therein are inspected and studied for the purposes of establishing its type, its pulsation modes and periods, including LSPs, and any complexities such as amplitude variability; Fourier and wavelet analysis are then used to refine and provide more quantitative estimates of these initial observations. This project extends the work of Lebzelter and Wood (2016), who obtained nearly two years of photometric measurements of dozens of red giants in ω Cen. As many exhibited significant irregularities or multiperiodicities in their light curves, only a small proportion of their periods and LSPs could be established well (Lebzelter and Wood 2016).

2. Data and analysis

We analyzed a sample of 16 stars (Table 1) from the ASAS-SN variable star catalogue within 30 arcminutes of the center of ω Cen, and classified by ASAS-SN as Mira stars (if their visual range exceeded 2.5 magnitudes), red semiregular (SR) variables, or long secondary periods (LSP)—or more properly, long-period variables with LSPs. The data can be found freely on-line (<https://asas-sn.osu.edu/variables>), reported to an error

of 0.02 mag (Shappee *et al.* 2014; Jayasinghe *et al.* 2018; Jayasinghe *et al.* 2019).

With a careful inspection of the light curves, the variabilities of the main pulsation period and amplitude, as well as the LSP, could be clearly observed. The main pulsation period(s) could be also estimated to an accuracy of a few percent by measuring a few intervals between maxima and minima and averaging them together. To refine this primary analysis, the Fourier analysis and wavelet routines in the American Association of Variable Star Observers (AAVSO) time-series package, VSTAR, were used (Benn 2013). The rough estimates of the pulsation period(s) from the light curve enabled the authors to determine the important peak(s) in the Fourier spectrum. Without these estimates, such an identification would have been more difficult, as the low amplitudes and the complexity of the variability suppressed the peaks to values close to the noise level of 0.02 mag. With these periods established, wavelet analysis was then used to study the rate and range of the pulsation amplitude variability. Lastly, the wavelet contour diagram was examined to detect the presence of multiple pulsation period(s) as well as any mode switching which subsisted between them. Note that our time-series analysis yields the semi-amplitude, rather than the full amplitude or range.

For more information about the WWZ (weighted wavelet z-transform), see the VSTAR manual. For a detailed account, see Foster (1996).

3. Results

Table 1 lists the name, type, period PA, mean V and K magnitudes, and the distance d in parsecs of the star, all taken from the ASAS-SN website, as well as the primary pulsation period PP, the secondary pulsation PS, the long secondary period LSP, and their respective semi-amplitudes, derived by the authors. The symbol “?”, wherever it appears, denotes uncertainty in the value given or in the existence of a pulsation mode. The errors in the distances d are usually between 6 and 15 percent, whilst the errors in the amplitudes A are near 0.02 mag. The accuracy of the periods is limited by the finite length of the datasets, as well as by the complexity of the variability. The pulsation amplitudes are in almost every case variable,

as has been found in many previous studies of pulsating red giants. The cause of the variable pulsation amplitudes is still unknown. The period in the ASAS-SN catalog is sometimes the pulsation period, sometimes the LSP, whichever is dominant. These results remind us that the variability of these stars is much more complex than can be expressed by a single average period and average amplitude.

Figure 1 shows the period-luminosity (PL) relations for all significant periods of the 16 stars in our sample as well as some of those studied by Lebzelter and Wood (2016). The K magnitudes are taken from the ASAS-SN website. The least-squares equations of the three sequences C', C, and D appearing in this figure are respectively given by

$$K_{\text{mag,C}'} = (-3.2 \pm 0.9) \log(P) + (13 \pm 2) \quad (1)$$

$$K_{\text{mag,C}} = (-3.5 \pm 0.3) \log(P) + (14.5 \pm 0.6) \quad (2)$$

$$K_{\text{mag,D}} = (-4 \pm 1) \log(P) + (17 \pm 3) \quad (3)$$

The general appearance of the figure is similar to that for other systems such as the LMC and SMC (Wood 2000; Soszyński *et al.* 2007), though our sample is much smaller than for those others. The ratios of LSP to P are, upon average, 6.5, but cluster around 4 and 8. Accordingly, the pulsation modes of stars in the sample must be primarily of the fundamental and first overtone, which respectively appear in the figure as sequences C and C'. The pulsation period ratios that we have found are also consistent with this conclusion.

The following are brief notes on individual stars in Table 1.

V826 Cen This is a *typical* star (Figure 2), which pulsates in two modes with periods of 89 and 51 days. As the ratio of these periods is 0.6, the star can be interpreted to be likely pulsating in the fundamental and first overtones (Xiong and Deng 2007). The presence, and superposition, of these two modes can be seen in its Fourier spectrum (Figure 3) and its wavelet contour diagram (Figure 4). An LSP of 542 days is also apparent in the light curve and the Fourier spectrum of the star. Based on the distance of this star, as given in the ASAS-SN catalog, this star may possibly be a non-member, or the error in the distance may be large.

Table 1. Period Analysis of ASAS-SN Observations of PRGs in ω Centauri.

Name	Type	PA (d)	(V)	K	d (pc)	PP (d)	A_{PP}	PS (d)	A_{PS}	LSP (d)	A_{LSP}
V826 Cen	LSP	661	10.87	6.829	3841	89	0.01	51	0.01	542	0.02
J132630.11-472428.2	LSP	156	11.23	7.071	4580	148	0.06	—	—	>2000?	?
V825 Cen	M	233	12.24	5.942	3898	232	1.05	—	—	—	—
J132617.98-473003.2	SR	45	11.02	7.696	4758	43	0.04	—	—	—	—
J132558.72-473609.8	SR	83	12.03	8.143	4617	82	0.23	40?	0.06?	—	—
J132616.14-473057.5	SR	82	11.27	7.763	4008	82	0.08	?	?	—	—
J132508.28-472020.6	SR	62	11.62	7.801	5598	62	0.04	—	—	—	—
J132709.16-472340.6	LSP	297	11.09	7.844	5047	41?	0.01?	?	?	296	0.03
J132712.06-472947.3	LSP	272	11.08	8.710	4040	46	0.01	—	—	271	0.03
J132521.33-473655.3	LSP?	49	11.55	7.694	5040	48	0.05	—	—	650?	0.04?
J132634.87-373410.2	LSP	71	11.97	8.185	3958	62	0.03	35	0.03	383	0.03
J132552.30-475612.3	LSP	308	12.86	7.521	4600	34	0.03	25	0.03	310	0.06
J132521.33-473655.3	LSP	49	11.55	7.694	5040	48	0.05	—	—	310	0.06
J132606.97-472518.9	SR	40	11.38	7.816	5029	40	0.02	?	?	—	—
J132844.02-470856.3	LSP	383	13.12	8.497	6295	30?	0.02?	—	—	383	0.06
J132656.73-472054.6	LSP	316	11.45	7.839	5297	38	0.02	—	—	383	0.06

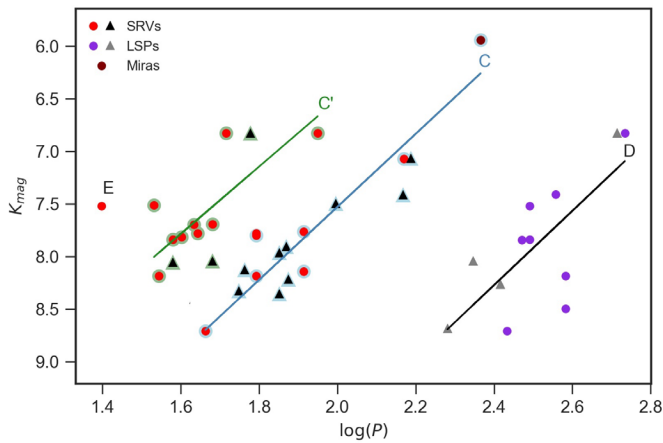


Figure 1. The period luminosity relations for red variables in ω Cen, where there is a point in the figure for each *significant* period found (that is, a point not marked by “?” in Table 1). The circular points are the measurements done by the authors; the triangular points are those found in Table 1 of “The Long Period variables in ω Centauri” by Lebzelter and Wood (2016). Sequences C', C, and D denote the sequences of first, fundamental, and LSP pulsators; the point E is perhaps the beginning of a sequence of second overtone pulsators. The points highlighted in blue and in orange are *considered* to belong to sequences C' and C, respectively, but there is some uncertainty in this classification. The least-squares equations of the sequences are given in Equations 1, 2, and 3 below.

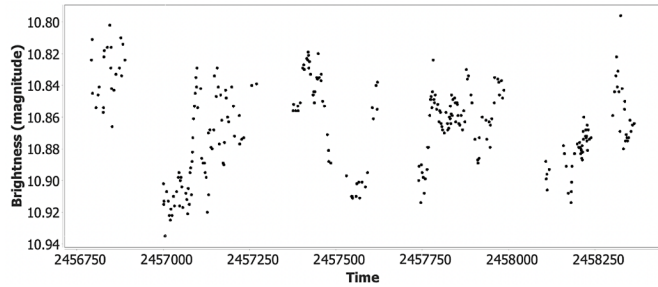


Figure 2. The V light curve of V826 Cen.

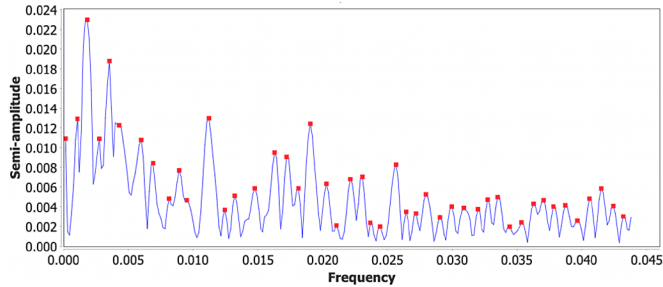


Figure 3. The Fourier spectrum of V826 Cen, in which is plotted the semi-amplitude against frequency (cycles/day). The two pulsation periods—51 days (0.01960 c/d) and 89 days (0.01123 c/d), the LSP—542 days (0.00185 c/d), and their aliases are visible. Its light curve is shown in Figure 2.

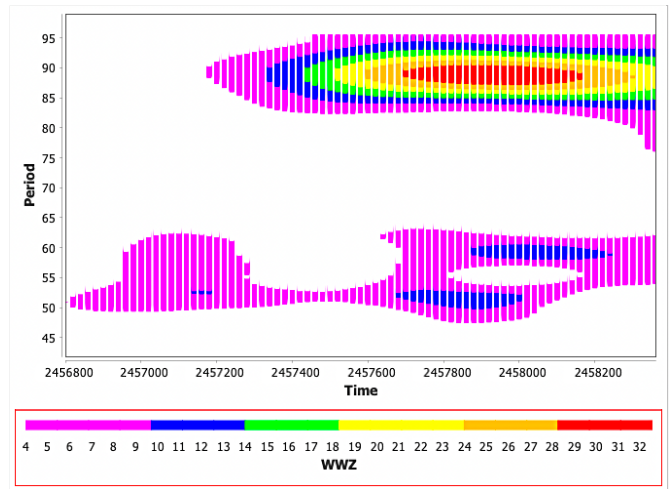


Figure 4. The wavelet contour diagram for V826 Cen, in which the period (d) is plotted against the Julian date, with WWZ amplitude in false color. It shows the presence of two pulsation modes with periods of about 50 and 90 days, each variable in amplitude. Its light curve is shown in Figure 2.

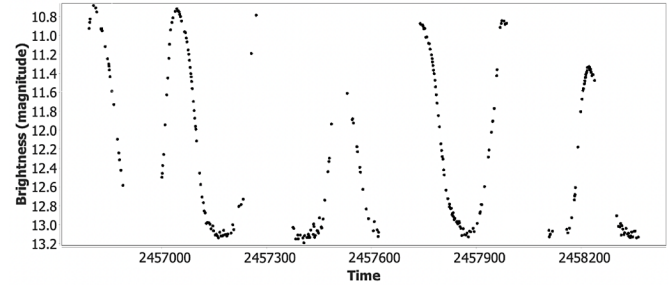


Figure 5. The V light curve of V825 Cen.

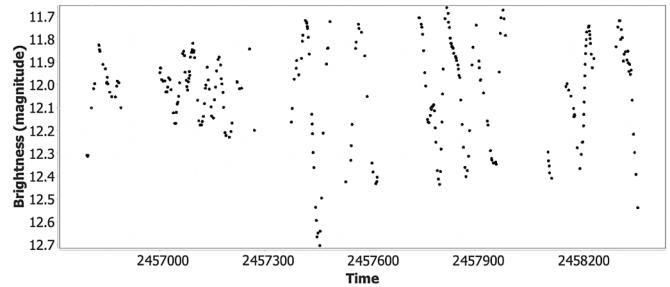


Figure 6. The V light curve of J132558.72-473609.8.

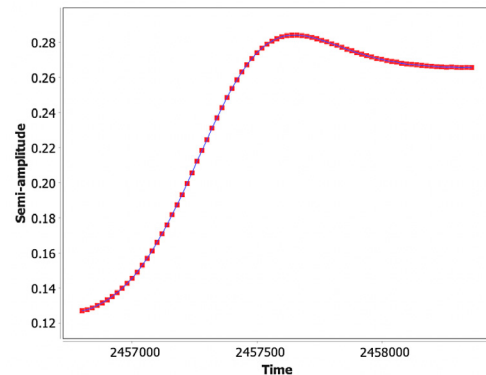


Figure 7. The variable pulsation semi-amplitude of J132558.72-473609.8, as determined by wavelet analysis. The amplitude doubles over a time interval of about 600 days. Its light curve is shown in Figure 6.

J132630.11-472428.2 The light curve shows a slow, linear ascent, perhaps owing to the presence of an LSP. The variations within are sawtooth, with momentary triangular blips that may arise from the presence of a shorter period mode of about 15 days, or from some non-pulsational process such as shock waves.

V825 Cen This is a Mira star with a period of 232 days (Figure 5). Though the maximum brightness varies from cycle to cycle, the minimum brightness remains constant, perhaps owing to the presence of a thirteenth-magnitude companion, observed in the same photometric aperture as the Mira star.

J132558.72-473609.8 The light curve is unusual, with a variable amplitude that doubles between the start of the second and third seasons (Figures 6 and 7). Like *J132630.11-472428.2*, the variations within are sawtooth, with momentary triangular blips arising perhaps from the presence of a shorter period mode of about 15 days. The light curve suggests the presence of two pulsation modes, with periods of 82 and 40 days, but as the amplitude of the latter is so small compared to the former and as it is less significant than several other peaks in the Fourier spectrum, the authors are not certain of its existence. It is also possible that it is a harmonic.

J132616.14-473057.5 There are three discordant points in the last season, owing presumably to instrumental effects. In the light curve and in the Fourier analysis, there is mild evidence of a shorter period mode of about 40 days superposed upon the primary mode of 82 days. It is also possible that this is a harmonic.

J132709.16-472340.6 The star pulsates with a period of 41 days in its first two seasons and has an LSP of 296 days. Though its period-time graph suggests that its period rises from 40 to 70 to 90 days, the semi-amplitudes of its peaks near 70 and 90 days in the Fourier spectrum are below the noise level and so make the authors uncertain of the existence of other pulsation modes.

J132552.30-475612.3 The star pulsates in two modes with periods of 34 and 25 days. As the ratio of these periods is 0.7, and as the first period falls upon sequence C' and the second upon the point labelled E in Figure 1, it is suspected that the star should be pulsating in its first and second overtones.

J132521.33-473655.3 There is a discordant point in the last season. Like *J132630.11-472428.2* and *J132558.72-473609.8*, the variations within are sawtooth, with momentary triangular blips arising perhaps from the presence of a shorter period mode of about 25 days. The Fourier spectrum suggests the presence of an LSP with a period of 650 days, but the modulation of the mean V magnitude in the light curve is too slight to confirm this number to be reasonable.

J132606.97-472518.9 Observing the star to lie on sequence C' of Figure 1, the star can be deduced to be a first overtone pulsator with a steady pulsation period of about 40 days. Though the Fourier spectrum suggests the presence of a second pulsation period with a period of 63 days and a (small) semi-amplitude of 0.02, no evidence of it exists in the light curve or in the WWZ contour diagram.

J132844.02-470856.3 There are a few discordant points in the first three seasons. In its light curve and Fourier spectrum, there is evidence of a pulsation mode with low amplitude and with a period between 25 to 35 days.

J132656.73-472054.6 There are a few discordant points in the last season.

4. Discussion

Soszyński *et al.* (2007) have provided an explanation as to why the PL relations of the LSP are nearly parallel to those of the low-order radial pulsation modes. To account also for the *linearity* in the LSP PL relation, Soszyński *et al.* (2021) have proposed a mechanism of LSPs, in which a brown dwarf or low-mass star companion and its dusty cloud orbit the central PRG, eclipsing it once per orbit, with a period P_{LSP} . In this binary model, the ratio of the radius, R , of the central PRG to the orbital radius, A , of the companion can be presumed to be nearly constant for all stars in the cluster (but see discussion below), being given by

$$\frac{R}{A} \approx 0.24 Q_F^{-\frac{2}{3}} \left(\frac{P_F}{P_{LSP}} \right)^2, \quad (4)$$

where Q_F and P_F are the pulsation constant and period of the fundamental mode, respectively (Soszyński *et al.* 2007). Supposing the stars to possess a mass $M \approx M_\odot$, an effective temperature satisfying $\log(T_e) \approx 3.6$ (Persson *et al.* 1980) and a luminosity satisfying $\log(L/L_\odot) \approx 3.0$ (Persson *et al.* 1980), then Xiong and Deng (2007) should suggest $Q_F \approx 10^{-1.1} \approx 0.08$ and, therefore, $A \approx 2R$. With Kepler's Third Law,

$$P_{LSP} = \frac{2\pi}{\sqrt{GM}} (R + A)^{\frac{3}{2}} \approx \frac{2^{\frac{5}{2}}\pi}{\sqrt{G}} \sqrt{\frac{R^3}{M}}. \quad (5)$$

The value, quoted above, for Q_F is based on non-adiabatic models in the linear approximation. This would not be appropriate for large-amplitude stars such as Miras. But almost all of the stars in our sample are small-amplitude pulsators, for which the linear approximation is appropriate.

With the Luminosity-Radius-Temperature Relation, $R = \sqrt{L/4\pi\sigma T_e^4}$, where σ is the Stefan-Boltzmann constant,

$$P_{LSP} \approx \frac{2\pi^{\frac{5}{2}}}{\sigma^{\frac{3}{4}} T_e^{\frac{3}{2}} \sqrt{GM}} L^{\frac{3}{4}}. \quad (6)$$

Converting P_{LSP} into units of days, and taking the logarithm of both sides,

$$\text{Log}(L) \approx \frac{4}{3} \log(P_{LSP, \text{days}}) + \frac{4}{3} \log\left(\frac{4300 \sigma^{\frac{3}{4}} T_e^{\frac{3}{2}} \sqrt{GM}}{\pi^{\frac{5}{2}}}\right), \quad (7)$$

in which equation it is clear that the relation between $\log(L)$ and $\log(P_{LSP})$ must be *linear*, consistent with the relation given by sequence D in Figure 1. The slope is consistent with the observed value in Figure 1.

It is interesting that LSPs obey a reasonably *tight* period-luminosity relation in Figure 1, and in corresponding figures in Wood (2000) and in Soszyński *et al.* (2007, 2021). In the context of Soszyński *et al.* (2021)'s explanation of the cause of LSPs, the ratio of the radius A of the companion's orbit to the radius R of the star, which must be equal to or greater than 1, must, in fact, be relatively constant from star to star, as assumed above.

5. Conclusion

ω Cen is considered to be an anomalous globular cluster—massive, with multiple waves of star formation, and possibly even the core of a small galaxy that was absorbed by the Milky Way. Nevertheless, the complex variability of the red giants is similar to that in 47 Tuc (Percy and Gupta 2021), and other stellar systems, including the Milky Way. We identify period-luminosity relations for fundamental and first-overtone pulsators, and also for the LSPs in ω Cen. The pulsation amplitudes vary by a similar amount and on a similar time scale as those of the red giants in 47 Tuc. About half the stars show LSPs. Almost all the red giants in a sample of red giants in 47 Tuc did. About a third of red giants in other stellar systems do. It is possible that the incidence of LSPs in Population II stars is even greater than in Population I. The incidence of *companions* will be even higher still, since some companions' orbits will be seen flat-on, and will not produce LSPs. Studies of LSPs in other globular clusters would therefore be of interest.

The first author of this paper was an undergraduate astronomy and physics student. Projects of this kind are an excellent way for students to develop and integrate their science, math, and computing skills, motivated by (among other things) the knowledge that they are doing real science, with real data.

6. Acknowledgements

This paper made use of ASAS-SN photometric data. We wish to thank the ASAS-SN project team for their remarkable contribution to stellar astronomy, and for making the data freely

available on-line, as well as the AAVSO for creating and making available the VSTAR time-series analysis package.

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Appendix A:

Table 2 lists properties concerning the period analysis of PRGs in the field of the NGC 6712 Cluster. We did not include them in Figure 1 because we wanted that figure to show stars with similar ages, distances, and compositions.

The following are brief notes on individual stars, which were analyzed as a prelude to the ω Cen project.

AP Sct Though the mean magnitude of the star remains roughly the same, the amplitude of its variability increases with time (Figure 8).

CH Sct, MR Sct The *shapes* of the light curves are very regular. From season to season, however, their brightnesses vary over a wide range of one to two visual magnitudes and also undergo a slow, linear ascent (Figure 9). We might therefore suspect the presence of an LSP whose period is larger than the time of observation ($> 1,000$ d).

NSV 11456 Owing perhaps to an LSP, the mean magnitude of the star alters from season to season, rising from the first to the second and falling from the second to the third.

NSV 11484 Any variability appears to be insignificant, being under the level of the noise. The light curve shows a slow, linear ascent, as the star brightens by 0.2 visual magnitude.

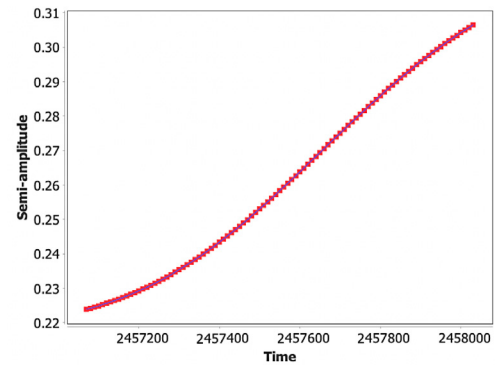


Figure 8. The variable pulsation semi-amplitude of AP Sct, as determined by wavelet analysis. The semi-amplitude undergoes a slow ascent.

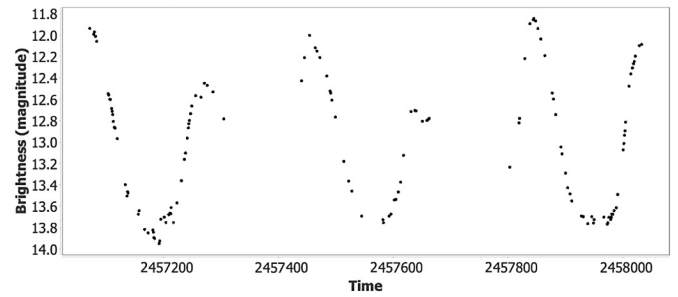


Figure 9. The V light curve of CH Sct.

Table 2. Period Analysis of ASAS-SN Observations of PRGs in NGC 6712.

Name	Type	PA (d)	(V)	K	d (pc)	PP (d)	A_{PP}	PS (d)	A_{PS}	LSP (d)	A_{LSP}
AP Sct	SR	112	12.45	8.15	6176	112	0.3	—	—	—	—
CH Sct	LSP?	192	13.01	8.126	5343	188	0.08	—	—	$> 1000?$?
MR Sct	LSP?	117	12.77	8.274	5197	118	0.3	—	—	$> 1000?$?
NSV 11456	LSP?	64	13.58	6.166	3402	64	0.08	—	—	$> 1000?$?
NSV 11484	L	--	13.86	10.084	3550	--	--	—	—	--	--