What Are the SRd Variables?

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Abstract SRd variables are semiregular pulsating variable giants or supergiants of spectral type F, G, or K. But why are they not regular? This paper presents a detailed study, using light curve analysis, and Fourier and wavelet analysis, of data from the All-Sky Automated Survey for Supernovae (ASAS-SN), on 37 arbitrarily-selected SRd variables to examine the possible causes of their non-regularity. Of the 37 variables, 30 showed significant variations in pulsation amplitude, 11 showed significant "wandering" of the period, 6 showed abrupt period shifts, 7 showed a possible long secondary period (LSP), 8 showed possible bimodal pulsation, and 4 showed otherwise complicated behavior. Variable pulsation amplitude is therefore the most common of several phenomena which lead to their non-regularity. It also occurs in RV Tauri variables and pulsating red giants, but its physical cause is not known, nor is the cause of period wandering. Because there was some previous evidence that LSPs were rare among SRd variables, 13 SRd stars with the longest ASAS-SN periods were similarly analyzed. That analysis, and examination of the light curves of several dozen other SRd variables with long ASAS-SN periods showed clearly that LSPs are common in SRd variables. In longer-period SRd variables in the ASAS-SN variable star catalog, the catalog period is usually the LSP, rather than the pulsation period. LSPs in RV Tauri variables and in red giants have been ascribed to binarity; that may be the case in SRd variables also. A dozen W Virginis variables and 30 RV Tauri variables were also analyzed to study the overlap and possible relationship between CW, RV, and SRd stars. There is considerable overlap between these types.

1. Introduction

Yellow giants and supergiants lie in the upper middle of the Hertzsprung-Russell (H-R) diagram, which plots the luminosity of the stars against their surface temperatures. They are unstable against pulsation, and are classified according to the character of their variability: W Virginis (CWA) stars or Population II Cepheids have periods of 8 to 35 days, and generally regular light curves. RV Tauri (RV) stars have periods of 30 to 150 days and are defined by their alternating deep and shallow minima. According to the *General Catalogue of Variable Stars* (Samus *et al.* 2017), SRd stars are *semiregular* giants and supergiants of spectral type F, G, or K, with amplitudes in the range 0.1 to 4 mag, and periods in the range 30 to 1,100 days. Miller Bertolami (2016) and Bono *et al.* (2020) have carried out important studies of the evolution of variable stars in this part of the H-R diagram, and Bódi and Kiss (2019) have determined the physical properties of galactic RV Tauri stars from *Gaia* data, but there has been very little study of the SRd variables specifically. RV and SRd variables appear to be post-AGB stars. They are relatively rare.

Most Population I and II Cepheids are regular; their phase curves show little or no scatter. Why are SRd stars non-regular? Because their pulsation amplitude varies with time? Because their period "wanders" sufficiently to produce scatter in the phase curve? Because they have two or more pulsation periods? Because they have long secondary periods (LSPs), as many RV stars do? Or some combination of these? Or something else?

The purpose of this paper is to investigate these questions by carrying out a careful analysis of two samples of SRd stars in the All-Sky Automated Survey for Supernovae (ASAS-SN) variable star catalogue (Shappee *et al.* 2014; Jayasinghe *et al.* 2018, 2019). Some RV stars and long-period CW stars were also analyzed to put the SRd variables in context, in the hope of clarifying the relationship between these different types. This paper builds upon the results of an earlier limited study using AAVSO visual data (Percy and Kim 2014).

2. Data and analysis

From the ASAS-SN variable star website and catalog (Shappee *et al.* 2014, Jayasinghe *et al.* 2018, 2019), data on the following star samples were downloaded and analyzed with light curve analysis and time-series analysis: 37 arbitrarily-chosen SRd stars, 13 SRd stars with the longest ASAS-SN periods (348–477 days), and 4 CWA stars with the longest ASAS-SN periods. In addition, the light curves and phase curves of the following star samples were inspected on the ASAS-SN variable star website: several dozen more SRd stars with the longest periods, a dozen CW stars with periods of 40–80 days, and 30 RV variables from Bódi and Kiss (2019). The ASAS-SN data and light curves are freely available on-line (asas-sn.osu.edu/variables). The error bars on the ASAS-SN observations are typically 0.02 mag, and this is consistent with the noise level in the Fourier analyses.

Because of the complexity of the variability in many of the stars, and the different time scales involved, careful visual light curve analysis proved to be especially useful.

Fourier and wavelet analysis was then done using the AAVSO time-series analysis package VStar (Benn 2012). Note that the amplitudes which are given in this paper are actually semi-amplitudes—the coefficient of the sine curve with the given period—rather than the full amplitude or range.

Two caveats: First, the star samples analyzed and inspected here are based on the classifications in the ASAS-SN catalog, with all their limitations and possible biases. Second: the datasets are only a few years long. The ASAS-SN classifications are based on a variety of measured properties of the stars. Other classifications of the stars in our sample—most based on limited data—range from SRd to SR, SRa, SRb, to L, I, and even Cep:.

3. Results

3.1. The cause of non-periodicity.

Table 1 summarizes the analysis of 37 randomly-chosen SRd variables from the ASAS-SN catalog with mean V magnitudes between 11 and 13. The columns give: the variable star name, the ASAS-SN period in days, the ASAS-SN mean V magnitude, the *fractional* variation or wander (ΔP/P) in the period during the interval of observation, the range (variation) in pulsation amplitude ΔA as determined by wavelet analysis, and various notes. These include apparent presence of LSPs, and additional periods which may or may not be due to a second pulsation mode. MP indicates that there were more than two peaks of appreciable strength in the Fourier spectrum, i.e. the spectrum was complex, and VM indicates that, in the phase curve, the minimum showed noticeably more scatter than the maximum—a common occurrence. An asterisk (*) indicates that there is a note about the star in section 3.1.

Of the 37 stars, 30 showed variations of more than 10 percent in the pulsation amplitude, 11 showed a fractional period "wander" of more than 0.03, 6 showed an apparent abrupt period shift, 7 showed a probable or possible LSP, 8 showed two peaks, possibly due to bimodal pulsation, 4 showed multiple peaks (usually more than 3, and not necessarily statistically significant), and 5 showed the variable minimum phenomenon. These can all contribute to producing a phase curve with much scatter, and thereby lead to a classification of SRd. Keep in mind, however, that these conclusions are based on only a few seasons of ASAS-SN data, with seasonal gaps.

Clearly the most common phenomenon which leads to semiregularity is variable pulsation amplitude. Figure 1 shows a specific example—BP Her—whose amplitude varies by a factor of two over the interval of the dataset. The cause of the amplitude variation is not known. There is no obvious correlation between the period and the mean amplitude, or between the period and the fractional variation in amplitude in the stars in Table 1. The following are notes on some specific stars.

HL And The period switches between 104 and 92 days.

V578 CrA The period switches between 62 and 78 days. In the light curve, the cycle lengths range from 50 to 70 days.

V537 Dra The period switches between 30 and 49 days. The ASAS-SN period of 221 days is presumably an LSP.

FQ Her The period "wander" is unusually large.

KQ Lyr Some very faint, presumably-spurious observations were omitted.

LV Lyr There are many peaks with amplitudes less than 0.05 mag. There is also a possible LSP of 352 days, with an amplitude of 0.08 mag. The data on this star in the AAVSO International Database give a possible period of 57.44 days, but the 352-day period does not appear in the AAVSO data.

V1183 Sgr According to the wavelet analysis, the period switches between about 50 and 65 days, each having a variable amplitude (Figure 2).

V1991 Sgr In the light curve, there are cycles of many lengths between 50 and 120 days but, in the Fourier spectrum, no peak is dominant. The highest is the 74.46-day period in Table 1.

V2221 Sgr The period switches between 62 and 75 days.

V3070 Sgr There is no significant period or amplitude variation, or LSP; the phase curve therefore has relatively little scatter. The light curve, however, shows some evidence of a second, shorter period— possibly due to an additional pulsation mode.

AO Sco The light curve is very complicated. The highest of many peaks in the Fourier spectrum is 99.33 days, with an amplitude varying between 0.12 and 0.25 mag. There is some suggestion, in the wavelet plot, that the period switches from 98 to 111 days for some time.

V830 Sco The period seems to switch between 50.6 and 57.7 days, each with an amplitude of 0.08. The phase curve is rather scattered.

3.2. Long secondary periods in SRd stars

Many RV variables have LSPs, 5 to 10 times longer than thepulsation period, and are subclassified as RVb. However, there seem to be few if any SRd variables with LSPs (Percy and Ursprung (2006); Percy (2015); Percy and Haroon (2021)). RU Cep and WW Tau are possible cases. Fourier analysis of AAVSO visual data on RU Cep shows a possible LSP of 520.17 days, with an amplitude of 0.06 mag, but no LSP is apparent in the AAVSO visual data on WW Tau.

The sample of SRd stars in Table 1 includes several with LSPs. Figure 3 shows a specific example—V3724 Sgr. The pulsational variability dominates, but a fourth-order polynomial, fitted to the data, shows the LSP clearly. But the period is long, and only one cycle is covered by the data, so one should technically not call it a period.

The ASAS-SN catalog includes 229 SRd variables, with periods ranging up to 476.74 days. The 12 with longest period were chosen for analysis and are listed in Table 2, along with ASAS-SN J192917.35+525332.8, whose period is almost as long, and whose light curve is shown in Figure 4. It was chosen because it was particularly illustrative. The columns in Table 2 give the star name, the ASAS-SN period in days, mean V magnitude, amplitude, and estimates of the pulsation period from the light curve (LC) and Fourier analysis (FA). A colon denotes uncertainty. Ten of the 12 longest-period stars in Table 2, with ASAS-SN periods of 348.13 to 476.74 days, also show shorter-period (typically 30–60 days) variability superimposed on the light curve, as shown in Figure 4. The shorter-period variability is presumably due to pulsation, as in the case of RVb stars and red giants with LSPs. The pulsation period in ASAS-SN J192917.+525332.8 is about 43 days from the light curve and 41 ± 1 days from Fourier analysis. The ASAS-SN catalog period is an LSP. The pulsation amplitude varies from 0.03 to 0.08 on a time scale of about 20 pulsation periods, as in other RV, SRd, and red SR variables.

3.3. Relation to CWA variables

There are 559 CWA variables in the ASAS-SN catalog. Most of these have short (10–20 day) periods, with saw-tooth

Table 1. Period Analysis of ASAS-SN Observations of some SRd Variables.

Name	*PA(d)*	*mean V*	*ΔP/P*	*ΔA*	*Notes*
HL And	101	11.01	—	0.07–0.19	LSP = 417d, *
V389 Aps	108	11.15	0.024	0.50–0.55	
V555 Cen	73	12.53	0.011	0.24–0.26	MP, LSP?
V652 Cen	86	11.80	0.023	0.16–0.22	also P = 48.71d
V1387 Cen	98	11.28	0.030	0.20–0.33	Cepheid-like LC
V578 CrA	—	11.95	—	—	LSP = 443d?, *
V651 CrA	81	12.40	0.019	0.22–0.44	VM
V654 CrA-	85	12.74	0.035	0.15–0.19	LSP = 760d
V340 Dra	99	11.03	0.105	0.10–0.13	
V537 Dra	30:	11.78	—	0.03–0.10	also P = 50d and 221d, *
AR For	126	11.16	0.030	0.35–0.39	also P = 75.9d
BP Her	82	11.98	0.025	0.19–0.41	
FQ Her	128	11.21	0.066	0.22–0.37	also P = 89.4d, *
V361 Her	95	11.18	0.041	0.18–0.29	VM
KQ Hya	96	11.54	0.013	0.22–0.28	sawtooth LC
DP Lyr	88	11.79	0.029	0.18–0.28	
KQ Lyr	84	12.90	0.013	0.36–0.52	*
LV Lyr	—	12.31	—	0.06–0.12	P = 40d, 60d, 352d?, *
V2844 Oph	103	12.11	0.025	0.19–0.30	also harmonic?
V1183 Sgr	—	12.92	—	—	complex; P = 50d and 65d, *
V1991 Sgr	74	12.45	0.075	0.10–0.28	MP, *
V2221 Sgr	73	12.21	—	0.05–0.20	MP, *
V2336 Sgr	92	12.56	0.008	0.16–0.21	also harmonic
V3070 Sgr	101	12.08	0.001	0.22–0.22	MP, ampl. constant, *
V3101 Sgr	81	12.45	0.042	0.24–0.26	also P = 56.24d
V3724 Sgr	82	12.48	0.011	0.43–0.62	LSP = 900d
V4061 Sgr	91	11.42	0.014	0.12–0.15	also P = 185.2d?
AO Sco	99	12.37	—	0.12–0.25	plus harmonic; *
V830 Sco	51	12.04	—	0.08–0.11	also P = 57.70d, *
V1039 Sco	83	11.15	0.017	0.26–0.33	VM
V1633 Sco	79	11.92	0.032	0.21–0.30	sparse
CD TrA	85	11.87	0.034	0.14–0.16	
GN Vir	48	11.91	0.015	0.13–0.17	also harmonic
OO Vir	111	12.69	0.016	0.55–0.64	VM
NSV 10702	106	12.04	0.009	0.23–0.29	VM, also P = 66.2d
NSV 11150	96	12.38	0.001	0.33–0.34	VM
NSVS 16356719	83	12.73	0.030	0.20–0.23	long-term variation

** An asterisk indicates a note in section 3.1.*

Table 2. Period Analysis of ASAS-SN Observations of some Long-period SRd Variables.

Name: ASAS-SN-V	*P(ASAS)*	*mean V*	*A(ASAS)*	*Pulsation period*
J202338.34-431055.9	476.74	12.37	0.20	LC: 40d; FS: 42:d
J010054.02-725136.8	458.29	11.91	0.53	unusual LC
J171232.57+580052.9	456.11	12.22	0.18	LC: 40d; FS: 39.9d
J075241.54+031701.9	442.94	12.49	0.24	LC: 55d; FS: 50.9d
J120428.99+583354.0	416.52	11.09	0.20	LC: 40d; FS: 62.3d
J010601.38-725243.3	406.50	12.77	0.31	no evidence of pulsation
J205705.36-452412.0	396.72	11.82	0.18	LC: 75–80; FS: 38.5d
J170819.10+024921.3	374.53	13.41	0.22	LC: 40d; FS: 42.8d
J174744.53+453435.9	359.26	13.37	0.21	LC: 40d; FS: 40d:
J195314.29-391128.9	353.41	12.40	0.25	LC: 50d; FS: 42.4d
J051419.34-400423.9	349.65	13.69	0.41	LC: 40d; FS: 42 ± 1
J021014.93-752861.7	348.13	13.39	0.39	LC: 60d; FS: 57.1d
J192917.35+525332.8	322.39	12.13	0.37	LC: 43d; FS: 41 ± 1d

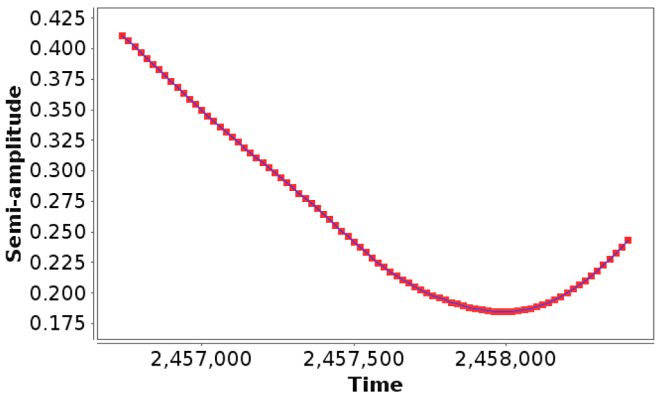

Figure 1. The pulsation amplitude variability of BP Her, determined from ASAS-SN data by wavelet analysis. The pulsation period is 81.64 days. The amplitude varies by a factor of two, on a time scale of about 20 pulsation periods. This behavior is similar to that of other SRd, RV, and red SR variables.

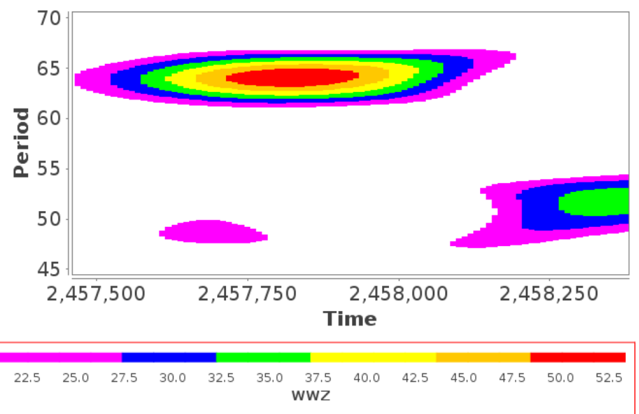

Figure 2. The wavelet contour diagram of V1183 Sgr, determined from ASAS-SN data, showing the presence of two pulsation periods of about 50 and 65 days, with variable pulsation amplitudes, resulting in apparent mode-switching.

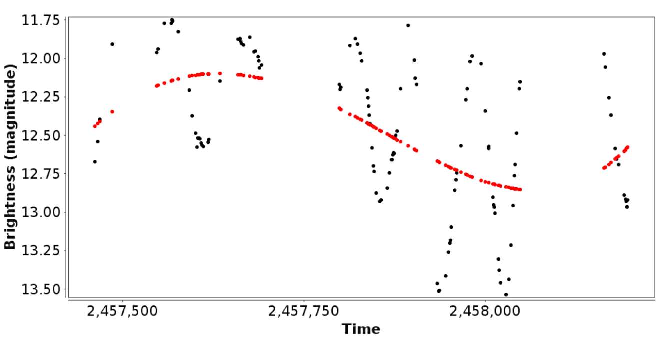

Figure 3. The V light curve of V3724 Sgr, from ASAS-SN data, showing a pulsation period of 81.77 days, with variable amplitude, and an LSP of about 900 days. The model (red line) is a fourth-order polynomial fit.

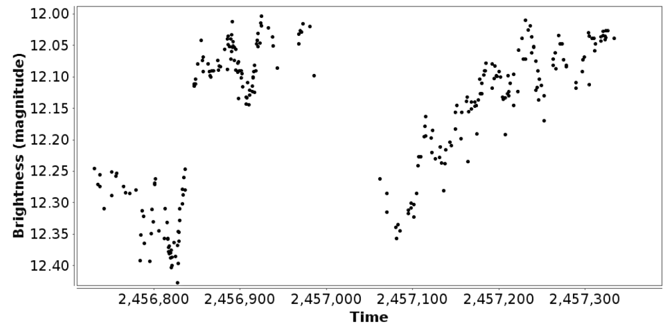

Figure 4. Part of the V light curve of ASAS-SN J192917.35+525332.8, showing the presence of both an LSP of 322 days (the ASAS-SN period), and a pulsation period of 41 days. This star was chosen because the pulsation period and the LSP are both clearly visible.

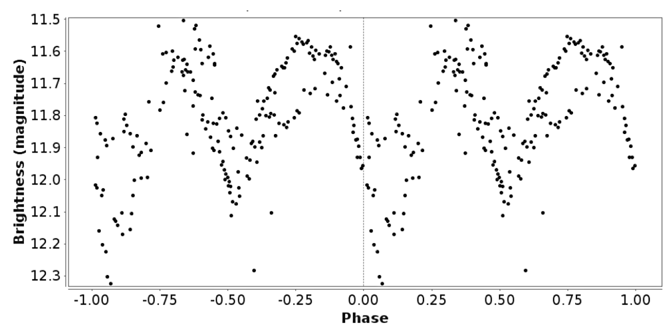

Figure 5. The phase curve of the SRd star V652 Cen, using a period of twice the value in Table 1, showing the mild tendency of alternating deep and shallow minima.

phase curves with minimal scatter. There are, however, 43 with periods greater than 50 days, and 8 with periods greater than 75 days. Of the latter, 4 stars were either too bright or too faint for analysis. ASAS-SN J054347.27-663509.1 has the same kind of low-scatter, saw-tooth phase curve as shorter-period CWA variables, but ASAS-SN J074929.27+530753.2, J130634.33+185820.7, and J093857.44-092132.8 have more scattered phase curves, mostly due to variability in the pulsation amplitude. Indeed, the same seems to be true of most of the other CWA stars with periods greater than 50 days. It is therefore not clear why ASAS-SN did not classify them as SRd stars. There is clearly some overlap.

3.4. Relation to RV variables

Five stars in Table 1 had two periods in a ratio close to 2: V555 Cen, V652 Cen, V2844 Oph, V2221 Sgr, and V2336 Sgr. Of these, V652 Cen (Figure 5) and V2844 Oph had phase curves which were marginally RV-like; alternating minima were of slightly different depths.

Out of curiosity, I looked up the ASAS-SN data on the 11 high-confidence Galactic RV stars in Table 1 of Bódi and Kiss (2019). Four were not in the ASAS-SN catalog, 4 were misclassified as CWA stars, and 4 were correctly classified as RVa stars. For the 20 other Galactic RV stars listed in Table 2 of Bódi and Kiss (2019), only 7 were correctly classified by ASAS-SN as RVa stars. The ASAS-SN analysis and classification system is relatively limited and simple, and understandably has problems with complex variables like RV and SRd variables.

This should be kept in mind when using the classifications and analyses in that catalog.

Both these observations show that the boundary between SRd and RV stars is a rather fuzzy one.

4. Discussion

The most common phenomenon which leads to SRd non-regularity is variable pulsation amplitude. It is not clear why the RV and SRd stars show this behavior and the Cepheids do not. Some process which depends on the gravity or luminosity of the star must come into operation. Variable pulsation amplitudes are found in most pulsating red giants (Percy and Abachi 2013).

The period wander in SRd stars may be due to the same process which causes a similar phenomenon in pulsating red giants (Eddington and Plakidis (1929); Percy and Colivas (1999)). It can be modelled as random cycle-to-cycle period fluctuations, and may be due to the effect of the very large convective cells in the outer layers of these stars.

The defining characteristic of RV stars is the alternating deep and shallow minima, but this behavior is often irregular. Percy *et al.* (2003) analyzed a sample of 33 RV and SRd stars in the LMC using MACHO data, using self-correlation analysis. Using the results, and also simulations of RV light curves, they were able to emphasize that there is a range of behavior in RV stars—including the alternating minima phenomenon—which would make them overlap with SRd stars. One might imagine that there was a continuous sequence from the regular CW stars, to the RV and semiregular stars, to irregular stars—though Lebzelter and Obbrugger (2009) have shown that, when datasets are equivalent, there is no difference in regularity between the SRd variables and the supposedly-irregular Lb variables.

For the SRd stars with two distinct, non-LSP periods, most—but not all—have period ratios in the range 0.55 to 0.65, which could indicate that the periods are the fundamental and first overtone. Given the uncertainties in the models of these low-gravity stars, and the limitations of the observational datasets, we will not attempt to compare observed period ratios with theoretical values. However, the higher period ratios, found in a few stars, are interesting, and should be followed up. That would best be done with denser, longer datasets, such as AAVSO visual data.

The LSPs in RV stars are believed to be due to some aspect of binarity. This was proposed by Percy (1993), primarily on the basis of the long-term light curve of stars like U Mon. The LSP minima were periodic, but the depth and form of the minima were variable, suggesting a role for dust of varying opacity. The hypothesis was much strengthened by long-term systematic photometric and spectroscopic observations of RVb stars by Pollard *et al.* (1996), who also provided a clear discussion of RV stars in general. Fokin (1994) carried out a study of non-linear pulsations in models of RV stars, and provided an analytical critique of the binary and possible pulsation mechanism for the LSP, including an important discussion of the ratio of the pulsational periods to the LSPs. Van Winckel *et al.* (1999) concentrated specifically on the matter of binarity, the general observational characteristics of RV stars, how they support the binarity hypothesis, and how binarity actually produces the RVb phenomenon. Kiss and Bódi (2017) provided additional evidence based on how the apparent pulsation amplitude changed through the LSP cycle. Most recently, Vega *et al.* (2021) have carried out a detailed multiwavelength study of the RVb star U Mon, and explained the LSP phenomena in terms of binary interactions within a circumbinary disc.

The LSPs in SRd stars presumably have the same cause, since RV and SRd variables are similar in so many ways. There is also strong evidence (Soszyński *et al.* 2021) that the LSPs in red giants are due to binarity. According to this model, the red giant's low-mass companion is a former planet that accreted a significant amount of mass from the red giant wind, and grew into a brown dwarf or very low-mass star, enveloped in a dust cloud.

Red supergiants also have LSPs (Kiss *et al.* (2006), Percy and Sato (2009)), and some are spectroscopic binaries. In both Antares (Pugh and Gray (2013)) and Betelgeuse (Goldberg (1984)), the length of the LSP is not statistically different from the radial velocity period. For Antares, the spectroscopic period and LSP are 2170 and 1650 ± 640 days, respectively; for Betelgeuse, they are 2100 and 2050 ± 460 days, respectively. The radial-velocity curve of Antares is similar in amplitude and shape to those found for LSPs in red SR stars. Furthermore, during the "great dimming" of Betelgeuse in 2020, there was a dust cloud obscuring the disc of the star (Montargès *et al.* (2021). The "great dimming" may therefore not be a one-off event, but may occur periodically when the pulsation period and LSP are both at minimum, and at their largest amplitudes, as was the case in 2020 (Percy 2020).

Information about variable stars in catalogs such as ASAS-SN and the *General Catalogue of Variable Stars* (Samus *et al.* 2017) tends to be restricted to a (mean) period and (mean) amplitude, leading to a classification such as SRd. Detailed studies of individual stars, such as that done here, provide a much more complete picture. This same point was made by Pollard *et al.* (1996) many years ago. Surveys which determine mean periods and amplitudes for large numbers of variables are important, but it is also important to extract information about more complex stars (like SRd stars), if possible, especially if the nature and cause of the complications are poorly-understood. This is work that would be appropriate for students and amateur astronomers, as well as professionals.

5. Conclusions

For SRd variables, the period wanders by a few percent. The pulsation amplitude varies significantly on a time scale of 20 to 30 periods. An additional pulsation period may be present, or an LSP—all with variable amplitudes. All of these contribute to non-regularity when a phase diagram for the average period is plotted. Bimodal pulsation occurs in other types of stars, but not necessarily with variable amplitude. LSPs occur in RVb and red SR variables, as well as SRd variables.

An interesting and important question is what causes these phenomena which contribute to non-regularity. By analogy with the RV stars, the LSP in SRd stars is probably due to binarity. The causes of the period wander and amplitude variability remains unknown, but seem to be associated with the low gravity and high luminosity of the stars in which they occur, and with possible strong non-linear effects, and also with the presence of large convective cells in the outer layers of the stars.

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