Semi-Regular Yellow (SRd) Variables: New Results

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Introduction: SRd stars are semi-regular yellow supergiant pulsating variables, of spectral type F, G, or K, mostly low-mass stars (like the sun) in an advanced (post-red-giant) stage of evolution. They have amplitudes of up to 4 magnitudes, and periods in the range of 30 to several hundred days. They are closely related to the better-known RV Tauri (RV) variables, which are characterized by alternating deep and shallow minima. Despite their abundance, interest and importance, SRd stars have been rather neglected by astronomers. AAVSO observers, however, have been productively observing both SRd and RV stars for many decades (e.g. Percy and Ursprung 2006, Percy and Haroon 2021).

A recent paper (Percy 2022) investigated the cause of the semi-regularity of SRd stars: variable pulsation amplitude (of unknown cause) in almost every case, but also period shifts and "wandering", bimodal pulsation, and "long secondary periods" (LSPs), an order of magnitude longer than the pulsation period P. See Figure 1 for a typical light curve. In the present paper, we use ASAS-SN data, and build on these results, and previous results for SRd variables based on AAVSO and other observations.

We are especially interested in the possible relation between the pulsation period and the luminosity (P-L relation), and the relation between LSP and the luminosity (LSP-L relation). Period-luminosity relations are well-known in Cepheids and, more recently, in RV Tauri stars (Bodi and Kiss 2019).

We are also interested in the behavior and cause of the LSPs in SRd stars, which may be due to binarity – a dust-enshrouded companion (Pollard et al. 1996, Vega et al. 2021). LSPs are also found in the RVb sub-class of RV stars, and in pulsating red giants (Soszynski et al. 2021).

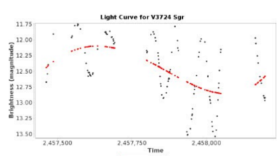

Figure 1. The ASAS-SN light curve of the SRd star V3724 Sgr, showing an LSP of about 900 days (red dotted curve), on which is superimposed a pulsation period of about 82 days, with variable amplitude.

Data and Analysis: We use V observations from the All-Sky Automated Search for Supernovae (ASAS-SN) on-line public database (asas-sn.osu.edu), light-curve analysis, and the AAVSO's time-series analysis package VSTAR to investigate light curves, pulsation periods and LSPs and their amplitudes, in a sample of 50 stars. A very few stars showed evidence for double-mode pulsation. As emphasized by Kim and Percy (2022), it is important to first look carefully at the light curve e.g. Figure 1 to "see what the star is doing". In some stars, the pulsation period was dominant; in others, the LSP was dominant. The pulsation periods and LSPs can first be measured from the light curve to a reasonable degree of accuracy, before using time-series analysis. We use mean V magnitudes and GAIA distances from the ASAS-SN variable star catalog to determine absolute magnitudes Mv. We then correct these for interstellar extinction, using the interstellar reddening data on the ASAS-SN catalog. From these absolute magnitudes, P-L and LSP-L relations are derived (Figure 2).

We used the LSPs in the ASAS-SN catalog. They are given to 8-10 significant figures, but are probably accurate to 10 percent. We estimate that the pulsation periods, determined by us, are accurate to 5 percent. The absolute magnitudes can be in error by up to 0.5 because of the error in parallax.

Results and Discussion: Figure 2 shows the P-L and LSP-L relations. The points on the left (in blue) are for pulsation periods. The points on the right (in red) are for LSPs. With some imagination, you can perhaps see two "sequences" for the pulsation periods, the longer pulsation periods being fundamental mode pulsators, and the shorter ones being first overtone

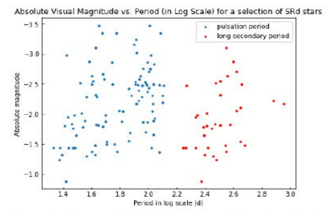

Figure 2. The period-luminosity (log P vs. Mv) relation for the SRd stars in our sample. The blue points on the left are for pulsation periods. The red points on the right are for LSPs. There is weak evidence for sequences for the pulsation periods

pulsators. The separation of the "sequences", about 0.3 in log P or a factor of two, is consistent with these modes. There is no clear sequence for the LSPs. Compare with the red giants in Figure 4 in which there are clear sequences for both. There are several possible explanations for the scatter in the P-L relation: errors in periods or Mv (see above), a simplistic approach to determining Mv, as compared with Bodi and Kiss (2019), the effect of a binary companion on the Mv, or a range of masses or metal abundances in the stars, for instance. The slopes of our "sequences" are roughly parallel to those of the RV stars (Figure 3), which is a heartening result.

Significantly: the ratio of LSP to P clusters around 8-10. Similar to the red giants, this can be interpreted as meaning that the stars are pulsating in the (shorter) first overtone mode. It also suggests that the periods that we have determined are reasonably accurate; the scatter in LSP/P is small. And, as with the red giants, it raises an interesting point: P depends on the radius of the star. LSP is an orbital period, which depends on the size of the orbit. Why should that be related to the size of the star (Kim and Percy 2022)?

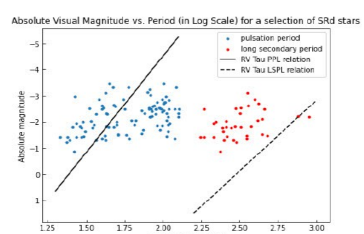

Figure 3. The same as Figure 2, but with the period-luminosity relations from RV stars superimposed. At the left is the relation for the pulsation periods. At the right is the relation for the LSPs. The latter forms an upper limit to the LSPs in the SRds.

Bodi and Kiss (2019) have recently used GAIA data to determine P-L relations for RV Tauri star pulsation periods and LSPs, though the latter is based on five stars only; other stars lie off the relation. Figure 3 shows, superimposed on Figure 2, the relations for the pulsation periods and the LSPs. The RV P-L relation, which is for the fundamental mode, is roughly parallel to the two "sequences" which may be present in Figure 2. However, it is offset from the longer-period SRd "sequence" – presumably the fundamental-mode sequence. This could reflect different masses, on average, for the RV and SRd stars.

The SRd LSPs tend to be shorter than RV LSPs, but that may be partly bias: our ASAS-SN datasets are less than 2000 days long, so longer LSPs will be harder to identify in our data. However, it does seem that SRd LSPs are somewhat shorter, implying that the companions' orbits are smaller, relative to the size of the star. Or to put it another way: the LSP-L relation for the RVb stars is the long-period limit for the LSPs of the SRd stars in Figure 3. Certainly one of the reasons to continue the study of LSPs in SRds is to learn more about the companion and its orbit.

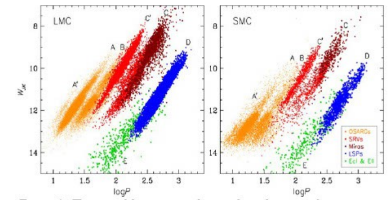

Figure 4. The period-luminosity relations for pulsating red giants in the Large and Small Magellanic Clouds. At left (yellow and red) are sequences for different pulsation modes -- fundamental and first overtone and possibly higher. At right (blue) is the sequence for LSPs (Soszynski et al. 2021).

Finally: we compare the behavior of the SRd stars with that of semi-regular red giant (SRa/SRb) variables. Figure 4 shows the period-luminosity relations for the pulsation period(s) and LSPs of red giants in the Large and Small Magellanic Clouds. Because the stars in each galaxy are at the same distance, the absolute and apparent magnitudes are directly related. In each galaxy, there are two or three pulsation sequences, presumably corresponding to different pulsation modes. What is more interesting are the well-defined LSP sequences. The pulsation period is determined by the radius of the star; the LSP is determined by the radius of the companion's orbit. As explained in Kim and Percy (2022), the existence of a LSP sequence implies that there is a relation – approximately a factor of two – between the radius of the companion's orbit and the radius of the star. It is not immediately clear why that should be. In the SRd stars, the orbital radii are less than twice the radii of the pulsating star. Perhaps it's because the atmospheres of the SRd stars are less extended than those of the red giants.

Concluding Remarks: SRd Stars. In our search for P-L relations for SRd stars, we have encountered the limitations of ASAS-SN data. AAVSO data may still be able to help. And we have found that LSPs are common in SRd stars, contrary to previous results using the AAVSO data. There are about a hundred SRd stars in VSX, many of them under-studied. Of the 229 SRd stars in the ASAS-SN catalogue, all those with periods greater than about 150 days are LSPs. They are not rare! Further study may help us to learn about the nature of the companion, and its dusty envelope, if any.

Concluding Remarks: LSPs in Red Giants. At least a third of red giants have observable LSPs. If they are due to eclipses by dust-enshrouded, former planetary companions (Soszynski et al. 2021), then geometrical considerations require that half or more pulsating red giants have such companions; many will have orbits which are flat-on. But what determines the amplitude of the LSP? How does the amplitude depend – if at all – on the size of the dust-enshrouded companion, and the red giant? Does the amplitude and shape of the LSP phase curve change with time? Again, AAVSO data can help to answer this.

Acknowledgements: We thank the ASAS-SN team for making the observations available, the AAVSO for creating VSTAR and making it available, and the University of Toronto Work-Study Program and Dunlap Institute for financial support.

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