A Note on Bimodal Pulsating Red Giants

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Abstract ASAS-SN data and the AAVSO time-series analysis package VSTAR have been used to determine the pulsation periods of a sample of 23 bimodal pulsating red giants. The results have been combined with results from the literature to determine period ratios and pulsation modes, and how these vary systematically with the observed pulsation period(s). The results are consistent with previous results, and with theoretical predictions: most longer-period bimodal stars pulsate in the fundamental mode (period P0) and the first overtone mode (period P1), with P1/P0 decreasing slightly with increasing P0; most shorter-period bimodal stars pulsate in the first-overtone mode and the second-overtone mode (period P2), with P2/P1 decreasing slightly with increasing P1. Stars with period 100 to 200 days show a mixture of the two behaviors.

1. Introduction

Red giants are unstable to radial pulsation. Some red giants pulsate in two modes, usually the fundamental and first overtone mode in longer-period stars. Such bimodal pulsating red giants (PRGs) are useful in that they yield two observed periods which can be compared with theoretical predictions to provide information about the physical parameters of the star. Conventionally, Pb/Pa is plotted against log Pa in a so-called Petersen diagram (Petersen and Jorgensen 1972), where Pa and Pb are the longer and shorter periods, respectively.

Previous studies of individual bimodal PRGs (as opposed to surveys) have analyzed mostly stars with periods of 100 days or more (Mattei *et al.* 1997; Kiss *et al.*1999; Percy and Huang 2015; Fuentes-Morales and Vogt 2014). For these stars, P1/P0 is approximately 0.5. In this case, the first overtone period can be confused with the first harmonic period (P0)/2 which occurs if the light curve is not sinusoidal (Percy and Huang 2015). Theoretical models (Xiong and Deng 2007) suggest that, for shorter-period PRGs, P1/P0 increases to about 0.65 with decreasing period, and then decreases for the shortest-period stars. Short-period PRGs, studied with photoelectric photometry, have period ratios closer to 0.7 (Percy *et al.* 2008, Table 1).

The discontinuity between longer-period (greater than 100 days) PRGs with P1/P0 ~ 0.5, and shorter-period PRGs with P1/P0 ~ 0.7 might indicate that, for the shorter-period stars, the modes are not P0 and P1, but are P1 and P2. This would be consistent with recent models (Xiong *et al.*2018) which investigate the non-adiabatic oscillations and stability of PRGs in the presence of turbulent convection. They find that, for low-luminosity stars, lower-order modes are stable, while intermediate and high-order modes are unstable. As the luminosity increases, lower-order modes become unstable, and intermediate and high-order modes become stable.

In addition to the "classical" studies of indivual stars, described above, there is a large literature on Magellanic Cloud PRGs using data from the OGLE and MACHO surveys. These studies of multi-periodicy in PRGs have tended to interpret their results in terms of sequences in the period-luminosity diagram (e.g. Kiss *et al.* 1999; Wood 2000; Fuentes-Morales and Vogt 2014). Different sequences presumably correspond to stars pulsating in different modes. The horizontal spacings between the sequences are then related to period ratios. This is an extremely powerful way of visualizing the behavior of a large sample of stars.

Here, we express our results for individual stars, directly as period ratios which can be compared with theoretical values (Xiong and Deng 2007). We present period ratios Pb/Pa for a selection of PRGs with periods from 10 to 200 days, either from new analyses or from the literature. These would span the discontinuity, if indeed it was present, and choose between the two possible explanations for it. The results are then compared with theoretical predictions from Xiong and Deng (2007) and Xiong *et al.*(2018).

2. Data and analysis

Data were taken from the All-Sky Automated Survey for Supernovae (ASAS-SN: Jayasinghe *et al.* 2018, 2019) and analyzed using the AAVSO VSTAR time-series package (Benn 2013). Stars were selected to have an ASAS-SN classification of SR, periods between 10 and 200 days, and a sufficient amplitude. The light curves were first inspected for signs of bimodality; most stars were either monoperiodic or unduly scattered.

One drawback of the ASAS-SN data is that they extend for only about 2000 days—much less than e.g. the visual data of the American Association of Variable Star Observers. This limits the accuracy of any periods which are determined from the data.

Percy and Fenaux (2019) have discussed some of the problems with the automatic ASAS-SN analyses and classifications of PRGs. By carrying out the analyses manually, rather than automatically as the ASAS-SN team did, we can deal more effectively with the challenges which are presented by these complex stars.

A sample of stars with the properties described at the beginning of this section was analyzed using VSTAR. Some of the stars had many peaks of comparable height in the Fourier spectrum, and could not be interpreted. Those in Table 1 showed two clear peaks which appeared to be pulsation modes.

Those results were augmented with results for bimodal PRGs in the literature: a few shorter-period stars from Mattei *et al.* (1997) and Kiss *et al.* (1999), non-carbon stars from Percy and Huang (2015), and short-period PRGs observed by the AAVSO Photoelectric Photometry Program and by an Automated Photometric Telescope (Percy *et al.* 2008). For the purpose of plotting a Petersen diagram, the ratio of the periods and the logarithm of the longer period was calculated, and listed in Table 1. The Petersen diagram is shown in Figure 1.

3. Results

Table 1 lists the results of our time-series analysis of ASAS-SN bimodal PRGs. The columns give: the ASAS-SN name (minus ASAS-SN-V J), the longer period Pa in days and its amplitude Aa, the shorter period Pb in days and its amplitude Ab, the ratio Pb/Pa, and log Pa. Figure 1 shows a graph of Pb/Pa versus log Pa, including stars in Table 1, and from the sources mentioned in section 2.

Table 1. Pulsation properties of bimodal PRG stars from ASAS-SN V photometry.

Star Name—ASASSN-V J	*Pa (d)*	*Aa (mag)*	*Pb (d)*	*Ab (mag)*	*Pb/Pa*	*log Pa*
191142.71+474526.6	104.47	0.31	67.69	0.15	0.648	2.02
220237.54+631351.9	100.84	0.18	52.78	0.19	0.523	2.00
080848.62-613410.2	26.70	0.07	19.95	0.04	0.747	1.43
002626.14+501637.2	142.73	0.12	87.00	0.12	0.610	2.15
112717.23+533103.7	166.92	0.20	98.34	0.24	0.590	2.22
201740.06+703651.6	173.26	0.11	104.58	0.11	0.600	2.24
071224.39-705134.9	106.42	0.19	60.41	0.14	0.568	2.03
204430.16-714817.1	91.97	0.07	61.08	0.13	0.664	1.96
111558.88-720026.6	96.61	0.10	64.67	0.12	0.669	1.99
190457.78-723524.6	83.97	0.08	55.23	0.07	0.658	1.92
105411.56-765436.6	119.49	0.18	74.77	0.18	0.628	2.08
035911.54+720905.5	44.49	0.06	31.23	0.08	0.700	1.65
003011.09+734535.8	64.03	0.16	45.33	0.09	0.708	1.87
074108.86-213820.1	16.49	0.06	9.61	0.07	0.580	1.22
175048.61-305655.3	14.58	0.11	8.15	0.11	0.559	1.16
165737.81-375858.2	18.27	0.12	9.19	0.05	0.503	1.26
155730.72-752331.0	65.05	0.08	44.15	0.05	0.679	1.81
122643.81-870158.5	106.32	0.11	67.79	0.11	0.638	2.03
085542.14-830046.9	76.78	0.12	52.83	0.12	0.688	1.88
225936.37-774536.8	72.76	0.07	49.23	0.07	0.677	1.86
035911.54+720905.5	44.49	0.06	31.23	0.08	0.702	1.65
190836.86-180124.5	34.04	0.03	17.07	0.09	0.500	1.53
180025.09-533405.9	19.15	0.05	26.76	0.05	0.715	1.43

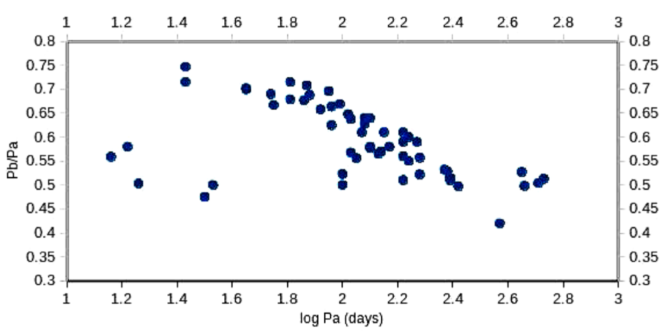

Figure 1. For bimodal PRGs: the ratio Pb/Pa of the shorter period Pb in days to the longer period Pa in days, as a function of log Pa.

4. Discussion

For stars with log Pa > 2.3, Pb/Pa is approximately 0.5, but decreases slightly from 0.52 to 0.50 or less. This is better seen in Figure 3 of Percy and Huang (2015). It is consistent with theoretical predictions if Pa and Pb are the fundamental and first overtone modes (Xiong and Deng 2007). For stars with log Pa < 2.0, Pb/Pa increases from 0.64 to 0.72 or greater with decreasing Pa. This is consistent with theoretical predictions if Pa and Pb are the first and second overtone modes (Xiong and Deng 2007). Stars with log Pa between 2.0 and 2.3 appear to be a mixture of these two groups. In that case, Pa will be a mixture of P0 and P1. Theoretical models also predict that longer-period stars should be unstable to lower-order modes, and shorter-period stars should be unstable to higher-order modes (Xiong *et al.* 2018), as we observe.

There are some shorter-period stars with Pb/Pa of about 0.5. For these, Pa and Pb may be fundamental and first overtone periods, or more likely first and third overtone modes. The latter would be more consistent with theory.

The longer-period star with a period of 350 days and Pb/Pa = 0.4 is RU Vul. This star underwent dramatic changes in both period (155 days to 100 days) and amplitude (0.85 to 0.10 magnitude), and is therefore anomalous.

The mode assignments that we have made give reasonable matches to the theoretical Petersen diagram of Xiong and Deng (2007). However, there is some ambiguity. The theoretical period ratios are moderately uncertain, especially at higher luminosities and periods, both because of uncertainties in the models, and because the period ratios are mass and composition dependent. Much depends on how well the models treat convection.

Soszyński *et al.* (2004) have plotted Petersen diagrams for PRGs in the LMC. The highest concentration of stars occurs when Pa is a long secondary period (LSP). The next largest concentration occurs for stars with log Pa < 2.0, and Pb/Pa of about 0.7. They interpret these periods as P3/P2; we interpret them as P2/P1. There is another concentration of stars with log Pa < 2 and Pb/Pa = 0.5. They interpret these as P3/P1; we could interpret them as P1/P0. We note that there are hardly any bimodal stars with log Pa > 2.0, except those with LSPs; there are no bimodal stars of the type studied by Mattei *et al.* (1997), Kiss *et al.*(1999), and Percy and Huang (2015). This suggests that there may be significant differences between the PRGs in the LMC and in our galaxy, perhaps due to composition differences.

Trabucchi *et al.* (2017) have calculated linear, radial, non-adiabatic models for PRGs in the LMC. These are reasonably successful in modeling the different sequences (corresponding to different overtones) in the PL sequences, though the theoretical periods of the higher-luminosity fundamental mode pulsators are too long. In these stars, convection and convective cells are particularly important, but difficult to treat theoretically.

A potential piece of useful information might be pulsation amplitudes. Trabucchi *et al.* (2017) showed that, in the LMC, essentially all third-overtone pulsators have amplitudes less than 0.01 mag. Similarly, in the LMC, the second-overtone pulsators have (I) amplitudes < 0.05 mag. In our Table 1, the amplitudes corresponding to fundamental, first, second, and third overtone pulsation do not have significantly different amplitudes, but average about 0.08 mag. However, the stars in Table 1 were chosen to show evidence of bimodality in their light curves, so they are not a random sample. We would not have chosen stars with amplitudes less than 0.01 mag.

Yet another approach to pulsation modes was carried out by Percy and Bakos (2003), who summarized results on 77 small-amplitude PRGs for which radii and masses could be estimated; these are stars with periods of a few tens of days, and would lie in the left third of our Figure 1. They found that most of the stars pulsate in the first overtone, some in the fundamental, and a few in the second or third overtone. This is consistent with our interpretation of Figure 1.

5. Conclusions

Analysis of individual bimodal PRGs (Figure 1) provides detailed information about the possible pulsation modes and period ratios of these stars, and how they vary with period. The results are consistent with previous results, and with theoretical predictions. They complement results from large-scale surveys (e.g. Wood 2000) which display the results as multiple sequences in the Petersen diagram. This study also reminds us that useful work can be done by analyzing stars from the vast ASAS-SN database, by students, amateur astronomers, and others.

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References

Benn, D. 2013, VSTAR data analysis software (http://www.aavso.org/vstar-overview).

Fuentes-Morales, I., and Vogt, N. 2014, *Astron. Nachr.*, **335**, 1072.

Jayasinghe, T., *et al.* 2018, *Mon. Not. Roy. Astron. Soc.*, **477**, 3145.

Jayasinghe, T., *et al.* 2019, *Mon. Not. Roy. Astron. Soc.*, **486**, 1907.

Kiss, L.L., Szatmáry, K., Cadmus, R. R., Jr., and Mattei, J. A. 1999, *Astron. Astrophys.*, **346**, 542.

Mattei, J.A., Foster, G., Hurwitz, L. A., Malatesta, K. H., Willson, L. A., and Mennessier, M. O. 1997, ESA SP-402, 269.

Percy, J. R., and Bakos, A. G. 2003, in *The Garrison Festschrift*, ed. R. O. Gray, C. J. Corbally, A. G. D. Philip, L. Davis Press, Schenectady, N.Y., 49.

Percy, J. R., and Fenaux, L. 2019, *J. Amer. Assoc. Var. Star Obs.*, **47**, 202.

Percy, J. R., and Huang, D. J. 2015, *J. Amer. Assoc. Var. Star Obs.*, **43**, 118.

Percy, J. R., Mashintsova, M., Nasui, C. O., Palaniappan, R., Seneviratne, R., and Henry, G. W. 2008, *Publ. Astron. Soc. Pacific*, **120**, 523.

Petersen, J. O., and Jorgensen, H. E. 1972, *Astron. Astrophys.*, **17**, 367.

Soszyński, I. Udalski, A., Kubiak, M., Szymanski, M., Pietrzynski, G., Zebrun, K., Szewczyk, O., and Wyrzykowski, L. 2004, *Acta. Astron.*, **54**, 129.

Trabucchi, M., Wood, P. R., Montalbán, J., Marigo, P., Pastorelli, G., and Girardi, L. 2017, *Astrophys. J.*, **847**, 139.

Wood, P. R. 2000, *Publ. Astron. Soc. Australia*, **17**, 18.

Xiong, D. R., and Deng, L. 2007, *Mon. Not. Roy. Astron. Soc.*, **378**, 1270.

Xiong, D. R., Deng, L., and Zhang, C. 2018, *Mon. Not. Roy. Astron. Soc.*, **480**, 2698.