# PULSATION MODES OF LONG-PERIOD VARIABLES IN THE PERIOD-LUMINOSITY PLANE

I. Soszyński<sup>1</sup>, P. R. Wood<sup>2</sup>, and A. Udalski<sup>1</sup>

<sup>1</sup> Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland; soszynsk@astrouw.edu.pl, udalski@astrouw.edu.pl
<sup>2</sup> Research School of Astronomy and Astrophysics, Australian National University, Cotter Road, Weston Creek ACT 2611, Australia; wood@mso.anu.edu.au *Received 2013 September 19; accepted 2013 October 26; published 2013 December 3* 

# ABSTRACT

We present a phenomenological analysis of long-period variables (LPVs) in the Large Magellanic Cloud with the aim of detecting pulsation modes associated with different period–luminosity (PL) relations. Among brighter LPVs, we discover a group of triple-mode semi-regular variables with the fundamental, first-overtone, and second-overtone modes simultaneously excited, which fall on PL sequences C, C', and B, respectively. The mode identification in the fainter red giants is more complicated. We demonstrate that the fundamental-mode pulsators partly overlap with the first-overtone modes. We show a possible range of fundamental mode and first overtone periods in the PL diagram.

Key words: infrared: stars - stars: AGB and post-AGB - stars: late-type - stars: oscillations (including pulsations)

## 1. INTRODUCTION

Stars that evolve on the first-ascent red giant branch (RGB) and asymptotic giant branch (AGB) show, with no exception, variability due to oscillations. The amplitudes of the photometric variations increase with the bolometric luminosity of giant stars—from micromagnitudes in stars at the base of the giant branch (Hekker et al. 2009; Bedding et al. 2010), through millimagnitudes in OGLE small-amplitude red giants (OSARGs; Wray et al. 2004; Soszyński et al. 2004), tenths of a magnitude in semi-regular variables (SRVs), to several magnitudes in Mira stars at the tip of the AGB. Recently, Bányai et al. (2013) showed that it is possible to distinguish between solar-like oscillations low on the RGB and larger-amplitude pulsations that are characteristic of the more luminous OSARGs, SRVs, and Miras, i.e., the OSARGs, SRVs, and Miras all seem to be self-excited pulsators rather than solar-like oscillators.

It is important to emphasize that there is no break in the overall red giant evolutionary sequence, so one can expect to see a continuity between the OSARGs, SRVs, and Miras (collectively known as long-period variables—LPVs). In the past, the OSARGs have sometimes been considered to be a class of variables separate from the SRVs and Miras (e.g., Soszyński et al. 2004, 2007).

Such continuity is clearly visible between the classically defined SRVs, especially the SRa stars, and Miras. Both groups follow the same period–luminosity (PL) sequence, labeled C by Wood et al. (1999). The difference between SRa stars and Miras lays in their amplitudes of variability and in the number of excited pulsation modes. Miras are usually single-mode pulsators, probably oscillating in the fundamental mode, while SRa stars usually exhibit two modes—fundamental and first overtone—so they occupy two sequences in the PL diagram, labeled C and C'.

However, LPVs display much more complex patterns in the PL plane. Recently, Soszyński & Wood (2013) showed that SRb stars (smaller amplitude and less regular that SRa stars) can be found in the space between the PL sequences C and C'. A theoretical analysis suggests that SRb stars do not follow a separate PL sequence, but that they form a continuity with SRa stars and Miras on sequence C. All of these stars are thought to pulsate in the fundamental mode.

OSARG variables form a series of PL sequences (e.g., Soszyński et al. 2007) of which the longest-period ridge roughly overlaps with sequence C'. Even so, it is not clear which modes of pulsation correspond to different PL relations of OSARGs. For example, Dziembowski & Soszyński (2010) in their theoretical work assumed that the longest-period PL sequence of OSARGs corresponds to the fundamental mode. On the other hand, Takayama et al. (2013) argued that the same PL relation is associated with the first overtone. From the phenomenological point of view, the identification of pulsation modes would be possible, if one detects LPVs with the fundamental mode (a period lying on sequence C), first overtone (sequence C'), and higher radial modes simultaneously excited in one star. Up to this time, such a configuration has not been observed in pulsating red giants. LPVs with periods identified on sequence C have been either single-mode (Miras) or double-mode (SRVs) pulsators.

In this paper, we report the discovery of a small group of triple-mode LPVs with the fundamental mode, first overtone, and second overtone simultaneously excited. Our sample populates exclusively the brighter part of the PL diagram and unambiguously assigns the pulsation modes to the PL relations in this region. For fainter LPVs, we found no distinct counterparts of these triple-mode variables. We argue that sequence C' in its fainter part is populated by both fundamental mode and first overtone variables.

#### 2. A SAMPLE OF LPVs IN THE LARGE MAGELLANIC CLOUD

In our analysis, we use a large collection of LPVs detected by the OGLE project in the Large Magellanic Cloud (LMC; Soszyński et al. 2009). The stars were observed between 2001 June and 2009 May with the 1.3 m Warsaw telescope at the Las Campanas Observatory in Chile. The telescope was equipped with an eight-chip mosaic camera (Udalski 2003), covering approximately  $35' \times 35'$  on the sky with a scale of  $0'.26 \text{ pixel}^{-1}$ . Most of the images were obtained in the *I*-band with an exposure time of 180 s. The light curves consist typically of 700 points.

The photometry of LPVs in the central region of the LMC was supplemented with the OGLE-II measurements collected

between 1997 January and 2000 November. We also added observations obtained in the course of the ongoing OGLE-IV project from 2010 March to 2013 May. Thus, the time baseline of observations in some stars exceeded 16 yr and typically it was 12 yr, with over 1000 observing points.

Our sample of LPVs was cross matched with the 2MASS Point Source Catalog (Cutri et al. 2003). We left on our list only those stars that had both J- and  $K_s$ -band measurements. For each object, we derived the reddening-independent, near-infrared Wesenheit index, defined as

$$W_{JK} = K - 0.686(J - K).$$

The distribution of LPVs in the period- $W_{JK}$  and period-K diagrams look essentially the same for most SRVs and OSARGs. The main difference between both diagrams concerns Miras with heavy circumstellar extinction, which dominate the long-period end of sequence C. In the period-K plane, sequence C is significantly broadened by the Miras that are obscured by their circumstellar dust shells and lay far below the linear PL relation (e.g., Ita & Matsunaga 2011). This effect may be practically cancelled by using the reddening-independent Wesenheit index,  $W_{JK}$ . Also, the oxygen-rich and carbon-rich giants follow nearly the same PL relations in the period- $W_{JK}$  plane (Soszyński et al. 2007), so our conclusions are valid for both spectral types.

All the *I*-band light curves were searched for periodicities using the Fourier-based Fnpeaks code by Z. Kołaczkowski (2003, private communication). For each star, we detected five periods with an iterative procedure of fitting a third-order Fourier series and subtracting this function from the light curve. For each period, we also recorded the amplitude of the light variations, defined as a difference between the maximum and minimum value of the third-order Fourier series fit to the observed light curve.

The OGLE-III Catalog of LPVs in the LMC (Soszyński et al. 2009) counts 91,995 objects, of which 79,200 were classified as OSARGs, 11,128 were classified as SRVs, and 1667 were classified as Mira stars. Miras were distinguished from SRVs on the basis of their *I*-band amplitudes larger than 0.8 mag. In this study, we do not separate OSARGs and SRVs, since we are trying to find the continuity between both groups. We also had no effective method to completely separate RGB and AGB OSARGs fainter than the tip of the RGB, so we kept both these populations on the list of objects. RGB LPVs obey PL relations that are somewhat shifted (in log *P*) relative to the AGB giants (Kiss & Bedding 2003). However, this offset does not change the conclusions of this work and in particular the identification of the pulsation modes is valid for OSARGs on both the RGB and AGB.

#### 3. ANALYSIS

Figure 1 shows the period-Wesenheit index diagram for LPVs in the LMC. Each star is represented by only one point corresponding to the primary period (first period detected by the Fnpeaks code—usually associated with the largest amplitude). Different colors of the points code different ranges of *I*-band amplitude—from OSARGs with A(I) < 0.01 mag represented by blue symbols to Miras (A(I) > 0.8 mag) indicated by brown points. Sometimes the automatically detected periods are spurious, which is particularly evident for some of the smallest-amplitude variables (blue points), which show pseudo-periods longer than sequence D. However, most of the shorter periods are real and trace in Figure 1 the clearly visible PL sequences, which



**Figure 1.** PL diagram for LPVs in the LMC. Each star is represented by one point, corresponding to the primary period. Different colors refer to different amplitudes: blue points show LPVs with A(I) < 0.01 mag, green points show LPVs with 0.01 mag  $\leq A(I) < 0.05$  mag, orange points show LPVs with 0.05 mag  $\leq A(I) < 0.2$  mag, red points show LPVs with 0.2 mag  $\leq A(I) < 0.8$  mag, and brown points indicate Mira stars defined as LPVs with  $A(I) \geq 0.8$  mag. The gray solid line shows the fit to the PL sequence C'.

are labeled according to the scheme introduced by Wood et al. (1999) and other authors. Mira stars follow sequence C, SRVs follow sequences C and C', and OSARGs follow sequences A, A', and B. The gray line overplotted in Figure 1 has a slope  $dW_{JK}/d \log P = -4.444$  and it is a rough fit to sequence C'.

With the exception of Mira stars, LPVs are known to be multi-periodic variable stars. A widely used tool for studying multi-mode variables is the so-called Petersen diagram, in which the ratio of two selected periods is plotted against the logarithm of the longer period. However, LPVs form a quite fuzzy picture on the classical Petersen diagram because periods and period ratios corresponding to different PL sequences overlap with each other.

To circumvent this problem, we plot a somewhat different diagram (Figure 2) that we call a modified Petersen diagram. In this diagram, the ordinate shows (as in the classical Petersen diagram) the ratio of the shorter to longer periods  $P_S/P_L$  selected from the five most significant periods determined in every star, while the abscissa shows the horizontal distance (in log  $P_L$ ) of a star from the gray solid line plotted in Figure 1. In the modified Petersen diagram, different pairs of periods corresponding to different PL relations form distinct groups of points. In Figure 2, the colors of the points indicate amplitudes associated with the longer periods. Since Mira stars are usually single-mode pulsators, they are not included in the modified Petersen diagram.

## 4. PULSATION MODES OF LPVs

Assignment of the pulsation modes to different PL relations formed by LPVs is a matter of debate (e.g., Wood & Sebo 1996; Wood et al. 1999; Kiss & Bedding 2003; Ita et al. 2004; Takayama et al. 2013). There is a consensus today that Mira stars pulsate in the fundamental mode. Miras are generally single-mode variables and lie on sequence C in the PL plane, so other LPVs with one of their periods falling on this sequence are also considered to be fundamental-mode pulsators. Most SRVs are double-mode variables with the fundamental mode and first overtone simultaneously excited. The first-overtone



**Figure 2.** Modified Petersen diagram for LPVs in the LMC.  $P_S/P_L$  is the ratio of the shorter to longer periods selected from up to five periods determined for each star.  $\Delta \log P_L$  indicates the horizontal distance of the longer period from the gray line plotted in the PL diagram (Figure 1).

periods of SRVs delineate sequence C' in the PL diagram. In the modified Petersen diagram (Figure 2), type SRa SRVs (red points) concentrate at period ratios between 0.45 and 0.6. SRb stars with smaller amplitudes (orange points) exhibit on average larger ratios of the first-overtone to fundamental-mode periods. Their fundamental-mode periods can be found somewhere between sequences C and C'. Soszyński & Wood (2013) labeled this fundamental-mode sequence of SRb stars by the letter F, although it seems that sequences C and F constitute one wide sequence populated by the fundamental-mode pulsators.

The identification of the pulsation modes associated with the shorter-period PL relations obeyed by LPVs remains a subject of controversy. A definite answer would be given by multi-mode LPVs with the fundamental, first overtone, and higher overtones simultaneously excited. However, no such objects have been reported so far. LPVs with one of their periods lying on sequence C (fundamental mode) have been found to be either single-mode Miras or double-mode SRVs.

In this regard, we performed a search for SRVs with at least three radial modes simultaneously excited. We divided the PL plane into three regions: one covering the fundamental-mode periods (sequences C and F), the second comprising the firstovertone periods (sequence C'), and the third region covering the shorter-period sequences (A', A, and B). As discussed above, we derived five periods for each star from our sample of LPVs in the LMC. From this sample, we selected those objects that had at least one period in each of these regions. From our analysis, we excluded periods longer than those making up sequence C: still unexplained long secondary periods that comprise sequence D, periods that populate a newly discovered dim sequence located between sequences C and D (Soszyński & Wood 2013), and sequence E consisting of binary systems.

Since some of the automatically derived periods are spurious, we visually inspected all the selected light curves. For each period, we pre-whitened the light curves with four other detected periods and subjectively decided whenever the remaining period was real. Two examples of such light curves are shown in Figures 3 and 4. In the upper panel of these figures, we show the unfolded light curves; the middle panels show the original light curves folded with three periods corresponding to three pulsation modes and the bottom panels present pre-whitened light curves folded with the same periods.



Figure 3. Light curve of a triple-mode SRV OGLE-LMC-LPV-32911. The upper panel shows an unfolded light curve, the middle panels present the same light curve folded with tree pulsation periods, and lower panels show the light curves pre-whitened with the four other detected periods. Periods and mode identifications are given in the panels.



Figure 4. Light curve of a triple-mode SRV OGLE-LMC-LPV-65344. The upper panel shows an unfolded light curve, the middle panels present the same light curve folded with tree pulsation periods, and the lower panels show the light curves pre-whitened with the four other detected periods. Periods and mode identifications are given in the panels.

As a result of the visual examination, we detected a limited number of about 50 candidates for triple-mode LPVs—with fundamental mode, first, and second overtones excited. The locations of these stars in the PL diagram and modified Petersen diagram are shown in Figure 5. The fundamental-, first-, and second-overtone modes fall on sequences C, C', and B, respectively. The most important aspect of this result is that it unambiguously links together the SRVs and Miras from sequences C and C' and the OSARG variables from sequence B (as well as A and A').

It is striking that in spite of the fact that we analyzed the entire sample of LPVs, we identified reliable candidates for triple-mode pulsators exclusively among brighter stars. Only one star in our sample is fainter than  $W_{JK} = 10$  mag. In the lower part of the PL diagram, we found a number of LPVs with the longest period falling on sequence C and two closely spaced periods located roughly on sequence C'. Such closely spaced periods were also detected in the OSARG variables populating sequences A and B (Soszyński et al. 2004, 2007). Such a phenomenon may be caused by non-radial pulsation modes or by small variations of the pulsation periods, but not by consecutive radial modes.

Thus, in the lower part of the PL diagram, we found no reliable examples of triple-mode pulsators, at least with the longest period falling on sequence C or F. This result complicates the identification of the pulsation modes in this region. Most SRVs have two periods: one falling on sequence C and the second lying on sequence C'.

Figure 6 shows the modified Petersen diagram for LPVs fainter than  $W_{JK} = 11$  mag. The gray contour in this diagram roughly surrounds the area where  $P_F/P_{10}$  and  $P_{20}/P_{10}$  ratios were observed for brighter SRVs. As can be seen, there is no natural boundary that separates both groups; fundamental-

mode/first-overtone and first-overtone/second-overtone pulsators overlap in the modified Petersen diagram. This fact means that the PL sequence associated with the fundamental mode extends much further toward the shorter periods than shown in the paper by Soszyński & Wood (2013). Probably some of the fundamental-mode periods fall on sequence C', which had previously been associated with the first-overtone mode.

So, where is the short-period limit of the fundamental pulsation mode of LPVs? The definitive answer cannot be given just on the basis of the photometric observations, because it seems that different modes of pulsations of LPVs may overlap in the PL, Petersen, and other empirical diagrams. This is because in the LMC we observe a mixture of red giants with different masses and in different evolutionary stages.

A clue about the range of the fundamental mode (and other modes) in the PL diagram can be obtained by analyzing the longest pulsation periods of various LPVs (the upper panel of Figure 7). As previously noted, fundamental-mode periods of SRVs and Miras populate sequence C and the space between sequences C and C' (the red and brown points in Figure 7). OSARG variables obey a series of PL relations, of which the longest-period sequence roughly coincides with sequence C' (ignoring sequence D, which is not associated with any radial pulsation mode). However, the exact position of this PL relation depends on other pulsation periods of these multi-periodic variables. If we select OSARGs that do not have a period falling on either sequence A or sequence A' and we plot them in the PL diagram, we can see two ridges, of which the longer one is located slightly to the right of sequence C' (the orange points in Figure 7). OSARG stars that have a detectable period on sequence A but do not have a detectable period on sequence A' have their longest period more or less at the location of sequence C' (the green points in Figure 7). Finally, OSARG variables



Figure 5. PL diagrams (upper panel) and modified Petersen diagram (lower panel) for triple-mode SRVs with the fundamental-, first-, and second-overtone modes excited. Different symbols indicate different periods (upper panel) and period ratios (lower panel). Gray points in the background indicate all LPVs in the LMC.

with at least one of their periods on sequence A' follow four PL relations, of which the longest one is located to the left from sequence C' (the blue points in Figure 7). Although we are not sure that the longest period in all these LPVs corresponds to the fundamental mode, this continuity in the position of the longest-period sequences suggests that the longest period is the fundamental mode.

In the lower panel of Figure 7, we plot the PL sequences of the same stars but using the second longest pulsation period (with the exception of Miras, which are single-mode variables). These are candidates for first-overtone mode pulsation. As one can see, the fundamental mode and first overtone LPVs significantly overlap in the PL diagram.

# 5. CONCLUSIONS

In this paper, we have tried to assign pulsation modes to LPVs on different PL relations. For brighter SRVs, we showed that sequences C, C', and B are populated by the fundamental



**Figure 6.** Modified Petersen diagram for LPVs fainter than  $W_{JK} = 11$  mag. Different colors refer to different amplitudes, as in Figure 2. The gray contour indicates the area where  $P_{1O}/P_F$  and  $P_{2O}/P_{1O}$  ratios are expected.



**Figure 7.** PL diagrams for the potential fundamental-mode (upper panel) and first-overtone (lower panel) periods of LPVs in the LMC. The points in the upper panel are the longest pulsation periods detected in each star while the points in the lower panel are the second longest periods. Brown points indicate Mira stars (A(I) > 0.8 mag), red points indicate SRVs, orange points indicate OSARGs without a period on sequence A or sequence A', green points indicate OSARGs with one of their periods falling on sequence A but not on sequence A', and blue points indicate OSARGs with at least one period lying on sequence A'. The gray points in the background indicate the primary periods of all LPVs from our sample.

mode, first overtone, and second overtone, respectively. For fainter LPVs, the fundamental modes of some LPVs overlap with the first overtones of other pulsating red giants. The region of the PL plane occupied by the longest period of different types of LPVs forms a continuous wide ridge that spreads from OSARG variables (sequence C') through SRb stars (sequence F of Soszyński & Wood 2013) to SRa and Mira stars (sequence C). It is likely that all these periods are caused by the fundamental-mode pulsations, which is in agreement with the theoretical investigation of Dziembowski & Soszyński (2010) and is opposite to the mode identifications of Takayama et al. (2013). Similarly, the first-overtone pulsators (second longest periods) fall in a region that covers sequences B and C'. The exact position of different modes in the PL plane depends on the mass, metallicity, and evolutionary status of a star. Variations in the mass and metallicity are the likely cause of the broad PL sequences.

One of the most important results of this paper is our finding that OSARGs, SRVs, and Miras constitute a continuum with no break between these types of pulsating red giants. As a giant star evolves, it gradually changes from an OSARG to an SRV and finally to a Mira, increasing its pulsating periods, limiting the number of its excited modes, and increasing its variability amplitude. It seems that the boundary between OSARG variables and SRVs is arbitrary, as it is between SRVs and Miras (where the boundary is defined as the amplitude in the *V*-band equal to 2.5 mag). I.S. is indebted to Wojciech A. Dziembowski for many fruitful discussions on the topic of this paper. This work has been supported by the Polish Ministry of Science and Higher Education through the program "Ideas Plus" award No. IdP2012 000162. The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/ 2007-2013)/ERC grant agreement no. 246678.

#### REFERENCES

- Bányai, E., Kiss, L. L., Bedding, T. R., et al. 2013, MNRAS, 436, 1576
- Bedding, T. R., Huber, D., Stello, D., et al. 2010, ApJL, 713, L176
- Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, 2MASS All Sky Catalog of Point Sources (Pasadena, CA: NASA/IPAC)
- Dziembowski, W. A., & Soszyński, I. 2010, A&A, 524, A88
- Hekker, S., Kallinger, T., Baudin, F., et al. 2009, A&A, 506, 465
- Ita, Y., & Matsunaga, N. 2011, MNRAS, 412, 2345
- Ita, Y., Tanabé, T., Matsunaga, N., et al. 2004, MNRAS, 347, 720
- Kiss, L. L., & Bedding, T. R. 2003, MNRAS, 343, L79
- Soszyński, I., Dziembowski, W. A., Udalski, A., et al. 2007, AcA, 57, 201
- Soszyński, I., Udalski, A., Kubiak, M., et al. 2004, AcA, 54, 129
- Soszyński, I., Udalski, A., Szymański, M. K., et al. 2009, AcA, 59, 239
- Soszyński, I., & Wood, P. R. 2013, ApJ, 763, 103
- Takayama, M., Saio, H., & Ita, Y. 2013, MNRAS, 431, 3189
- Udalski, A. 2003, AcA, 53, 291
- Wood, P. R., Alcock, C., Allsman, R. A., et al. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lebre, & C. Waelkens (Cambridge: Cambridge Univ. Press), 151
- Wood, P. R., & Sebo, K. M. 1996, MNRAS, 282, 958
- Wray, J. J., Eyer, L., & Paczyński, B. 2004, MNRAS, 349, 1059