

Non-radial Pulsations in RR Lyrae Stars from the OGLE Collection

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RR Lyrae stars are classical pulsating stars. They pulsate mostly in the radial fundamental mode (RRab stars), in the radial first overtone mode (RRc stars), or in both modes simultaneously (RRd stars). The Collection of variable stars from the Optical Gravitational Lensing Experiment (OGLE) contains more than 38 000 RR Lyrae stars from the Galactic bulge. We analysed these data for RRc and RRd stars. We have found new members of radial–non-radial double-mode RR Lyrae stars, with characteristic period ratio of the two modes around 0.61. We increased the number of known RR Lyrae stars of this type by a factor of 8.

We have also discovered another group of double-mode RR Lyrae stars. They pulsate in the first overtone and in another, unidentified mode, which has period longer than period of the undetected fundamental mode. The period ratios tightly cluster around 0.686. These proceedings are focused on this puzzling group. In particular, we report eight new members of the group.

1 Introduction

RR Lyrae stars pulsate mostly in the radial fundamental mode or in the radial first overtone mode. Double-mode radial pulsators are also known. They pulsate simultaneously either in the fundamental mode and in the first overtone (green asterisks in Fig. 1), or in the fundamental mode and in the second overtone (red triangles in Fig. 1). Observations revealed another group of double-mode RR Lyrae stars. These stars pulsate in the first overtone (RRc or RRd) and have another signal of higher frequency (shorter period). Period ratio of the additional mode to the first overtone is around 0.61. The additional variability cannot correspond to any radial mode (Moskalik et al., 2015). Until recently, this group was not numerous: 23 stars were discovered in various stellar systems both in ground and in space observations (for a summary see Moskalik et al., 2015). Additional 18 stars of this type were discovered in M3 by Jurcsik et al. (2015).

We have analysed photometry for RRc stars from the Galactic bulge collected by the OGLE project (Udalski et al., 2015). We have significantly increased the number of double-mode stars with $P_x/P_{10} \approx 0.61$ (Netzel et al., 2015b,c). Thanks to our analysis, three separate sequences formed by these stars in the Petersen diagram were revealed (blue asterisks in Fig. 1). Explanation for this puzzling group of double-periodic pulsators was proposed recently by Dziembowski (2015).

These proceedings are focused on another exciting discovery we have made in the OGLE data (Netzel et al., 2015a). We have detected additional, unexpected signals in

a group of RRc stars (magenta crosses in Fig. 1). The additional signal has a frequency lower than the frequency of the first overtone; even lower than the frequency of the fundamental mode, which is undetected in these stars. Explanation of the nature of these signals faces difficulties. For short discussion see Netzel et al. (2015a) and Dziembowski (2015).

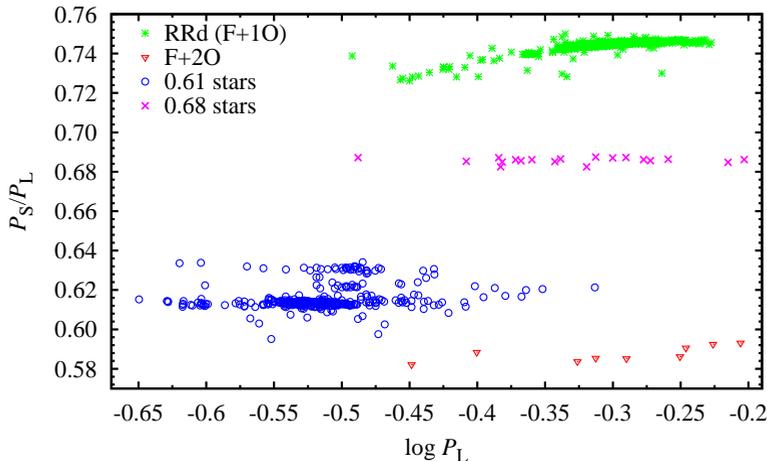


Fig. 1: Multi-mode pulsations of RR Lyrae stars in the Petersen diagram.

2 Data analysis

Our analysis of RR Lyrae stars was focused on a search of additional low-amplitude signals. In the OGLE collection of variable stars there are more than 10 000 RRc stars (Soszyński et al., 2014). First, we decided to focus on stars which were most frequently observed. These stars are located in the OGLE fields 501 and 505 (see position of observational fields in Fig. 15 in Udalski et al., 2015). Selected stars have more than 8 000 data points from four observational seasons of OGLE-IV. There are 485 RRc stars in the sample. They were analysed manually, using standard consecutive prewhitening technique, with the dedicated software written by the authors. For some stars, after prewhitening with the first overtone and its harmonics, residual signal at the frequency of the first overtone remained. It may correspond to long-term period changes in these stars or to long-term amplitude and/or phase modulation (the Blazhko effect). For these stars, to increase the frequency resolution, we combined OGLE-IV data with data available from the previous phases of the OGLE project (Soszyński et al., 2011). Increased data length allowed us to resolve close frequencies and to detect long-period modulation in a few stars.

Analysis of the whole sample of more than 10 000 RRc stars in the Galactic bulge is ongoing. Some of preliminary results are reported in these proceedings.

3 New group of double-mode stars

During the analysis of the selected sample of 485 RRc stars, we detected an additional signal in 11 stars (2 per cent of the analysed sample). The frequency of the additional signal is lower than the frequency of the fundamental mode, which is not detected in

these stars. In the Petersen diagram in Fig. 1, stars of the new group are marked with magenta crosses. They form a horizontal sequence and tightly cluster around 0.686. Typical amplitude of the additional signal corresponds to few per cent of the first overtone amplitude (and does not exceed 10 per cent).

A literature search revealed one additional RRc star of this type, KIC945311, which was observed with *Kepler* space telescope and analysed by Moskalik et al. (2015). In this star the additional 0.61 mode was discovered. For one of the additional low-amplitude periodicities (designated as f_5 in tab. 7 in Moskalik et al., 2015) we have found $P_{10}/P_5 = 0.6867$. Thus, this star fits the progression in the Petersen diagram very well and is also a member of the new group. These results were described in details by Netzel et al. (2015a).

Preliminary analysis of the full sample of 10 826 OGLE RRc stars stars revealed eight new stars that belong to this group. They are reported here for the first time. Altogether there are 19 members of the new group discovered in the OGLE data and one star discovered in the *Kepler* data. Basic properties of all stars are collected in Tab. 1. The first part of the table contains stars described in Netzel et al. (2015a), including one star observed with *Kepler* telescope. The second part of the table contains data on 8 newly discovered stars. We note that in all these stars we detect signals at combination frequencies with the first overtone, which proves that the additional signal is intrinsic to these stars and is not due to contamination.

In Fig. 2, we show the Petersen diagram with all known stars of the discussed type. No specific structures are present within this group.

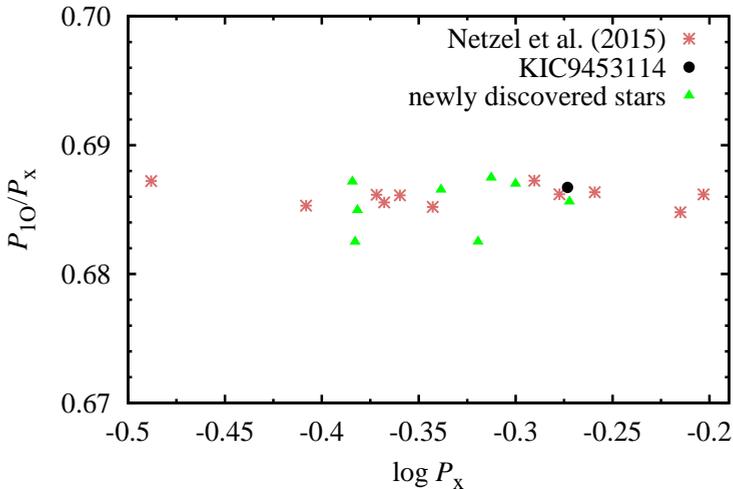


Fig. 2: Petersen diagram for RRc stars with additional, long-period signal. New detections reported in these proceedings are marked with filled triangles. Stars discovered earlier in the OGLE data are marked with asterisks and single star observed with *Kepler* is marked with filled circle.

A glimpse at the Petersen diagram (Fig. 1) shows that the additional signal cannot correspond to any radial mode. The corresponding period is longer than the fundamental mode period. Moreover, it cannot correspond to stellar rotation or presence of a companion (it is too short). It seems that the most likely explanation is excitation of non-radial mode of gravity or of mixed character. This explanation faces many difficulties, however (for a short discussion see section 5 in Netzel et al., 2015a). Re-

Table 1: RRc stars with additional long-period signals. Subsequent columns contain: periods of the first overtone and of the additional signal, their ratio and amplitude ratio. Last column contains remarks. First part of the table lists stars described in detail in Netzel et al. (2015a). Last part of the table contains recent discoveries in the OGLE data, reported here for the first time.

star	P_{10} (d)	P_x (d)	P_{10}/P_x	A_x/A_{10}	remarks
04994	0.3622954(3)	0.52797(1)	0.68619	0.048	a
05080	0.2996982(1)	0.436810(5)	0.68611	0.048	e
06970	0.42988998(7)	0.626497(9)	0.68618	0.012	a, e
07127	0.3778854(3)	0.55057(1)	0.68635	0.050	a
07653	0.31118879(6)	0.454151(6)	0.68521	0.025	a
08748	0.29153824(7)	0.424892(3)	0.68615	0.039	a, b
09146	0.35215799(3)	0.5124233(5)	0.68724	0.028	c, e
09217	0.29391346(2)	0.428719(1)	0.68556	0.026	a, e
09426	0.22339120(4)	0.325069(6)	0.68721	0.016	a, e
10100	0.4173796(2)	0.609497(8)	0.68479	0.060	a, e
32196	0.2677486(1)	0.390699(7)	0.68531	0.039	a
KIC 9453114	0.3660809	0.5330831	0.68672	0.004	e
01064	0.3148614(1)	0.458621(7)	0.68654	0.030	e
07673	0.3662894(1)	0.534248(4)	0.68562	0.060	a, e
08076	0.28448202(6)	0.415333(1)	0.68495	0.100	e
09671	0.28267093(4)	0.414171(4)	0.68250	0.020	a, e
10427	0.3442403(1)	0.501076(4)	0.68700	0.057	a, e
14775	0.3346791(1)	0.48682(1)	0.68748	0.025	e
30601	0.2836980(4)	0.412854(9)	0.68716	0.077	e, a, d
36675	0.3271380(1)	0.479323(6)	0.68250	0.048	e

a – additional signal close to f_{10} ; b – harmonic of f_x ;
 c – additional signal close to f_x ; d – additional signal in power spectrum
 e – combination frequency between the first overtone and additional signal

cently, Dziembowski (2015) noted that the additional periodicity could be attributed to the radial fundamental mode if these objects are low-mass striped giants rather than genuine RRc stars. This explanation has its own problems as well, as discussed by Dziembowski (2015). We have checked whether these stars are correctly identified as RRc pulsators. We investigated light curve shapes visually and quantitatively using the Fourier decomposition parameters (see Fig. 3 and 4 in Netzel et al., 2015a). They are typical for RRc stars. For a few stars we detect higher scatter of the phased light curve (see Fig. 3 in Netzel et al., 2015a). This is either due to the lower mean brightness of these stars or due to period change which is common among RRc stars. Based on these considerations, identification of these stars as RR Lyrae variables seems correct.

Two stars are interesting on their own and are discussed in more detail below.

In the frequency spectrum of OGLE-BLG-RRLYR-07653, after prewhitening with the first overtone and its harmonics, we detected residual unresolved signal at the position of f_{10} . We joined all available data for this star. Merged data are plotted in Fig. 3. The increased length of the data set allowed us to detect triplet structure in the frequency spectrum. The side peaks at f_{10} are presented in Fig. 4. We interpret this structure as a signature of the Blazhko effect (long-period amplitude and/or phase

modulation). Period of the Blazhko modulation is 1698 ± 4 d.

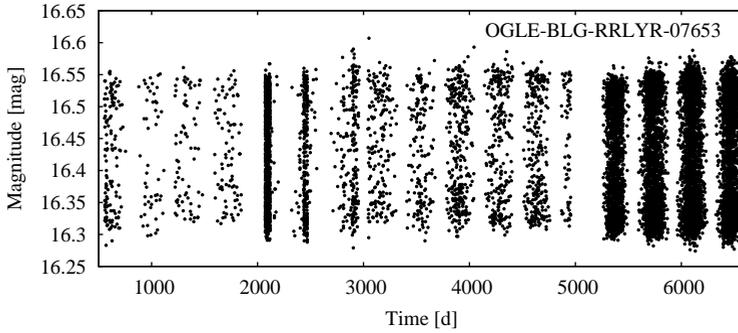


Fig. 3: Combined data from OGLE-IV, OGLE-III and OGLE-II for OGLE-BLG-RRLYR-07653. Total lengths of the data is 6042 d. There are 10 836 data points.

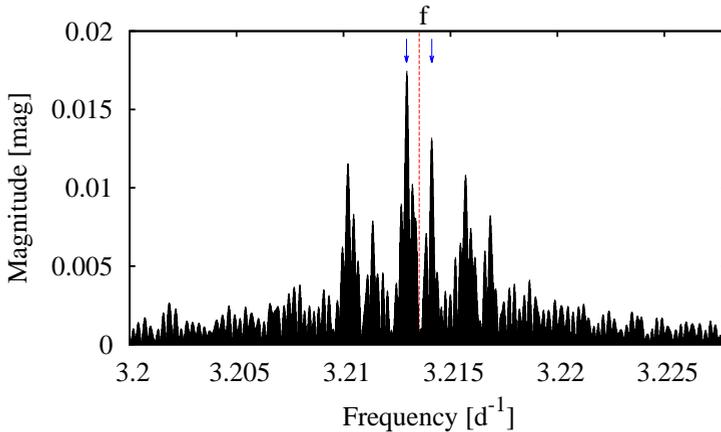


Fig. 4: Frequency spectrum of combined data for OGLE-BLG-RRLYR-07653 after prewhitening with the first overtone and its harmonics. Position of the first overtone is marked with f and with dashed line. Side peaks are marked with arrows.

In the frequency spectrum for OGLE-BLG-RRLYR-30601, we found more than one additional frequency. Additional long-period signal, f_X , with $P_{1O}/P_X \approx 0.687$, is clearly detected, together with the combination frequency with the first overtone. There is another signal in the frequency spectrum at $f_Y \approx 2.712544 \text{ d}^{-1}$. The period ratio, $P_{1O}/P_Y \approx 0.7695$, is too high to fit the RRd sequence in the Petersen diagram. The combination frequency, $f_Y + f_{1O}$, is also detected, which rules out possible contamination. Signal at f_Y has higher amplitude than signal at f_X . There are two other significant signals close to f_{1O} . Together with first overtone frequency they form unevenly spaced triplet. The separation between the low-frequency side peak and the first overtone is 0.07534 d^{-1} , which corresponds to a modulation period of 13.27 d. For the high-frequency side peak the separation is 0.07173 d^{-1} (modulation period of 13.94 d). This structure is not detected at harmonics of the first overtone. The light curve of this star and its Fourier decomposition parameters, are typical for RRc star.

4 Summary

We have analysed first overtone RR Lyrae stars located in the Galactic bulge from the OGLE collection of variable stars. We focused on a search for additional periodicities in these stars. We have significantly increased the number of double-mode stars with $P_X/P_{1O} \approx 0.61$. More than 260 stars were detected in the OGLE data (Netzel et al., 2015b,c). We have also discovered entirely new group of double-periodic stars, with dominant variation associated with the radial first overtone and additional periodicity of longer period (Netzel et al., 2015a). In the Petersen diagram, these stars form a horizontal sequence, with period ratios, P_{1O}/P_X , clustering around 0.686. So far we know 20 stars of this type. These stars still lack a satisfactory explanation.

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