Discovery of a new group of double-periodic RR Lyrae stars in the OGLE-IV photometry

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ABSTRACT
We report the discovery of a new group of double-periodic RR Lyrae stars from the analysis of the Optical Gravitational Lensing Experiment - IV (OGLE-IV) Galactic bulge photometry. In 11 stars identified in the OGLE catalogue as first overtone pulsators (RRc stars), we detect additional longer period variability of low amplitude, in the mmag regime. One additional star of the same type is identified in a published analysis of the Kepler space photometry. The period ratio between the shorter first overtone period and a new, longer period lies in a narrow range around 0.686. Thus, the additional period is longer than the expected period of the undetected radial fundamental mode. The obvious conclusion that addition periodicity corresponds to a gravity or a mixed mode faces difficulties, however.

Key words: stars: horizontal branch – stars: oscillations – stars: variables: RR Lyrae.

1 INTRODUCTION
RR Lyrae stars are classical pulsators of great astrophysical importance. They serve as excellent distance indicators and tracers of the old stellar populations, enabling galactic structure, kinematics and evolution studies. Majority of these stars are radial, single-periodic pulsators, pulsating either in the fundamental mode (F mode, RRab stars) or in the first overtone (1O mode, RRc stars). Double-mode pulsators pulsating simultaneously in the fundamental and in the first overtone modes (RRd stars) are also known and numerous. In the Petersen diagram, i.e. a diagram of shorter-to-longer period ratio versus the longer period these stars form a well-defined group with characteristic period ratio in a range 0.725–0.747 (depending on the period; open circles in Fig. 1; Soszyński et al. 2014). In all groups the Blazhko effect, quasi-periodic modulation of pulsation amplitude and phase is observed (for a review see Szabó 2014). The effect is more frequent in RRab stars than in RRc stars. Only recently the effect was discovered in RRd stars (Jurcsik et al. 2014; Soszyński et al. 2014; Smolec et al. 2015). RRc stars are prone to fast and irregular period changes on a time-scales shorter than predicted from stellar evolution theory (e.g. Catelan & Smith 2015).

Recently, new groups of double-periodic RR Lyrae stars were identified, thanks to precise and nearly continuous photometry of the space missions, CoRoT and Kepler. The discoveries include fundamental plus second overtone radial mode pulsators (e.g. Benkő et al. 2010, for a review see Moskalik 2014; diamonds in Fig. 1) and mysterious group of double-mode radial–non-radial pulsators. In this group, we observe the dominant pulsation in the first overtone mode and additional variability with a shorter period. In the Petersen diagram (triangles in Fig. 1), these stars seem to form two groups with period ratios clustering around ≈0.61 and ≈0.63. Space photometry (Szabó, Benkő & Paparó 2014; Molnár et al. 2015; Moskalik et al. 2015) indicates that this form of pulsation must be common among RRc stars, as 13 out of 14 RRc stars observed from space show the phenomenon. Majority of the 0.61 stars plotted in Fig. 1 however, were detected only recently in the third phase of the Optical Gravitational Lensing Experiment (OGLE; see e.g. Udalski et al. 2008) photometry of the Galactic bulge by Netzel, Smolec & Moskalik (2015). We also note that in RRc stars observed from space other low-frequency signals were detected and interpreted as non-radial gravity modes (Moskalik et al. 2015).

In this Letter, we describe the discovery of a new group of double-periodic pulsators among stars identified as RRc. In the analysis of a top-quality sample of OGLE-IV photometry of the Galactic bulge (Soszyński et al. 2014), we have found 11 stars that show yet another period ratio that cannot be explained with simultaneous excitation of two radial modes. These stars are marked with filled circles in Fig. 1. The additional periodicity is longer than the first overtone period and, as comparison with RRd stars clearly reveals, much longer than the expected period of the undetected radial fundamental mode. A literature search revealed yet another member of the group in the Kepler photometry of RRc stars (Moskalik et al. 2015). In the following sections, we describe our analysis and summarize the properties of the new group. In Section 5, we briefly consider possible explanation for the group.

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2 DATA AND ANALYSIS

Data used for analysis were collected during the fourth phase of the OGLE project (Udalski, Szymański & Szymański 2015). For some stars we used additionally data from the third phase. OGLE-IV collection of variable stars (Soszyński et al. 2014) contains 38 257 RR Lyrae stars, including 10 825 RRc stars and 174 RRd stars. Our goal is to search for additional, low-amplitude signals in stars pulsating in the first overtone (RRc and RRd). Detecting weak signals requires possibly the lowest noise level, which is best met by stars with the largest number of observations. Hence, for our analysis we chose stars located in the most frequently observed fields, their numbers are 501 and 505 in OGLE-IV. For each star in these fields we have more than 8000 data points. Altogether, there are 485 RRc and 4 RRd stars in these fields, which is also a reasonable number for manual analysis. We used observations of the I band only (more numerous than the V-band data). In publically available OGLE-IV data there are four observational seasons available. Length of the data is about 1334 d for most stars.

Data were analysed manually using standard consecutive pre-whitening method. Discrete Fourier transform allow us to find significant frequencies in the spectrum. We considered only those frequencies for which signal-to-noise ratio was S/N ≥ 4. All detected frequencies were fitted to the data in the form:

\[ m(t) = m_0 + \sum_{k=1}^{N} A_k \sin(2\pi f_k t + \phi_k), \]  

where \( f_k \) are frequencies, \( A_k \) and \( \phi_k \) are amplitudes and phases. Only resolved frequencies are included in equation (1). We consider two frequencies unresolved if separation between them \( \Delta f < 2/T \), where \( T \) is length of the data. When all significant frequencies were included in the sum, we removed points deviating from the fit by more than 4\( \sigma \).

In the data of many stars slow trend is present. It manifests in the frequency spectrum as a signal at low frequencies and gives rise to daily aliases at integer frequency values. We model the slow trends either with a long-period (≈50,000 d) sine function or with low-order polynomial.

In many stars, after pre-whitening with the frequency of the first overtone, \( v_{1O} \), and its harmonics, close peaks were detected at \( k v_{1O} \), forming either equidistant triplets (multiplets) or close doublets. These are a signature of the Blazhko effect. We fitted these signals in the form \( k v_{1O} \pm \Delta v \), where \( \Delta v \) is a separation between main frequency and the side peaks.

In other stars, after pre-whitening, unresolved signal remains at the location of \( v_{1O} \) and/or its harmonics. It indicates that first overtone is not stationary, but its amplitude and/or phase change with time on a time-scale comparable to or longer than the data length. Such signals increase the noise level in the transform and may hide the additional low-amplitude signals, which we search for. To get rid of the non-stationary signals, we used time-dependent pre-whitening method proposed by Moskalik et al. (2015), see Netzel et al. 2015 for application to OGLE data). Whenever possible, in order to investigate long-term variation of the first overtone, we combined OGLE-IV data with OGLE-III data (Soszyński et al. 2011), which, in some cases revealed a long-period Blazhko modulation. Irregular phase (period) changes of the first overtone are also very frequent.

3 RESULTS

As a result of our study, we identified several interesting and well-known phenomena: Blazhko effect, period-changing stars and double-periodic stars with additional non-radial, shorter period mode, with characteristic ≈0.61 period ratio to the first overtone period. These results will be described elsewhere (Netzel et al., in preparation). In addition, we found a group of 11 stars (2 per cent of the sample) with additional low-frequency signal. Corresponding period is longer than first overtone period; period ratios, \( P_{1O}/P \), fall within a narrow range from 0.6848 to 0.6872 with average value of 0.6860. Such period ratios were not reported in the literature before. Properties of the stars are summarized in Table 1.

A literature search revealed one additional RRc star observed by Kepler in which additional longer period was detected with period ratio falling in the same range (see \( f_5 \) in Table 7 in Moskalik et al. 2015). Data for the star are in the last row of Table 1.

Stars with the additional frequency are plotted with filled circles in the Petersen diagram in Fig. 1. Star found in the Kepler photometry is marked with a different symbol and it fits the progression formed by the OGLE stars very well. All stars form a tight horizontal sequence below RRd stars. Fig. 2 shows only the newly found stars. No clear structure is visible within the group.

We note that period ratios of RRd stars cover a wide range in the Petersen diagram with period ratio clearly correlated with the period of the fundamental mode. The large range of period ratios of RRd stars corresponds to the large metallicity spread in the Galactic bulge, as model calculations indicate (e.g. Soszyński et al. 2011). Without identification of the additional pulsation mode and appropriate pulsation models (see Section 5), we cannot infer about metallicities or relation between metallicity and location of the star in the Petersen diagram for the newly discovered group.

The analysed stars are located in the most dense stellar fields in the Galactic bulge, in which probability of blending is very high. The tight progression formed by a new group in the Petersen diagram and nearly constant period ratio with the first overtone period are a strong argument that the additional signal is real and intrinsic to the analysed RRc stars. Even more, in six stars we detect combination frequencies of the additional and first overtone frequencies which proves that the two signals originate from the same star. The form of the combination frequency is written in the penultimate column of Table 1. In three stars \( S/N > 4 \) for signal at combination frequency (marked with bold font). In other three stars we see a signal precisely at the position of combination frequency (within frequency resolution of the spectrum), but with \( 3 < S/N < 4 \).

The unknown period is longer than the period of the unseen fundamental mode (see Fig. 1). This has an immediate consequence:
Table 1. Stars with additional frequency. Subsequent columns contain periods of the first overtone and of additional signal, their ratio, amplitude of the first overtone and amplitude ratio. Two last columns contain form of the combination frequencies (if detected) and remarks.

| Star                        | \(P_{1O}\) (d) | \(P_x\) (d) | \(P_{1O}/P_x\) | \(A_{1O}\) (mag) | \(A_x/A_{1O}\) | Combination freq. | Remarks |
|-----------------------------|-----------------|--------------|-----------------|------------------|-----------------|-------------------|---------|
| OGLE-BLG-RRLYR-04994        | 0.362 2954(3)   | 0.527 97(1)  | 0.686 19        | 0.0799(4)        | 0.048           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-05080        | 0.299 6982(1)   | 0.436 810(5) | 0.686 11        | 0.1353(4)        | 0.048           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-06970        | 0.429 889 98(7) | 0.626 497(9) | 0.686 18        | 0.1272(1)        | 0.012           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-07127        | 0.377 8854(3)   | 0.550 57(1)  | 0.686 35        | 0.1009(5)        | 0.050           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-07653        | 0.311 188 79(6) | 0.454 151(6) | 0.685 21        | 0.1166(2)        | 0.025           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-08748        | 0.291 538 24(7) | 0.424 892(3) | 0.686 15        | 0.1185(3)        | 0.039           | \(v_{1O} + v_x\)  | a,b     |
| OGLE-BLG-RRLYR-09146        | 0.352 157 99(3) | 0.512 423(5) | 0.687 24        | 0.1474(1)        | 0.028           | \(v_{1O} + v_x\)  | a,c     |
| OGLE-BLG-RRLYR-09217        | 0.293 913 46(2) | 0.428 719(1) | 0.685 56        | 0.1083(2)        | 0.026           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-09426        | 0.223 391 20(4) | 0.325 069(6) | 0.687 21        | 0.0724(2)        | 0.016           | \(v_{1O} + v_x\)  | a,b     |
| OGLE-BLG-RRLYR-10100        | 0.417 3796(2)   | 0.609 497(8) | 0.684 79        | 0.1164(4)        | 0.060           | \(v_{1O} + v_x\)  | a       |
| OGLE-BLG-RRLYR-32196        | 0.267 7486(1)   | 0.390 699(7) | 0.685 31        | 0.1008(4)        | 0.039           | \(v_{1O} + v_x\)  | a       |
| KIC9453114                  | 0.366 0809      | 0.533 0831   | 0.686 72        | 0.206 64         | 0.004           | \(v_x - v_{1O}, v_x - 2v_{1O}\) | a |

Notes. a – additional signal close to \(v_{1O}\); b – harmonic of \(v_x\); c – additional signal close to \(v_x\).

Figure 2. Petersen diagram for stars with additional frequency.

if additional variability corresponds to pulsation mode, it cannot be radial. Even more, it cannot correspond to the purely acoustic mode, but must be a gravity mode or a mode of mixed character. As such explanation faces difficulties (Section 5), we analysed the light curves of the dominant pulsation mode to check whether the RRc identification in the OGLE catalogue is correct. The light curves folded with the first overtone period are plotted in Fig. 3 sorted by the increasing period. Shapes are typical for RRc stars including the characteristic bump-feature preceding the maximum light. Period change, well visible for some longer period stars, is also characteristic for RRc stars. It also contributes to the larger photometric dispersion of some of the light curves. The other factor responsible for different dispersion of the light curves presented in Fig. 3 is difference in mean brightness of the stars: dispersion is larger for fainter stars.

Light-curve shapes can be described quantitatively with the Fourier decomposition parameters, which display characteristic progression with the pulsation period, depending on the pulsation mode. In Fig. 4, we compare the Fourier decomposition parameters for our stars with parameters for RRc stars from the Galactic bulge and OGLE-III catalogue (Soszyński et al. 2011). Errors in determination of Fourier decomposition parameters for our stars are usually smaller than symbol size. Parameters for all 11 stars are within typical for RRc stars at given pulsation period. Based on the photometric data we have, we conclude that the dominant pulsation mode is indeed the radial first overtone.

In nine stars, we see a signal close to the primary frequency. Those stars are marked with ‘a’ in the remarks column, regardless of whether the signal is resolved or not. These stars were investigated for the Blazhko effect using combined OGLE-III and OGLE-IV data (see next section). Typically irregular phase changes were
Fourier decomposition parameters for RRc Galactic bulge stars (OGLE-III). Red points correspond to stars with the additional frequency. Rest of the RRc stars are marked with black dots.

detected. In one star, marked with ‘b’, we found harmonic of the additional mode. In one star, marked with ‘c’, signal close to additional frequency is seen (see next section). In all stars additional signal is stationary.

4 REMARKS ON INDIVIDUAL STARS
OGLE-BLG-RRLYR-05080. Part of the data in the first season of observations is vertically shifted. We removed these data and analysed the rest.

OGLE-BLG-RRLYR-07653. After pre-whitening the spectrum with a frequency of the first overtone and its harmonics, we still detect residual, unresolved signal at $v_{1O}$. Time-dependent analysis shows that amplitude and phase of the first overtone change with similar periodicity. We incorporate the OGLE-III data in the analysis to increase the frequency resolution. Length of the merged OGLE-III and OGLE-IV data is about 6042 d, which allow us to detect modulation period as long as 3020 d. Analysis of the combined data shows clear triplets at $v_{1O}$. The additional frequency, though lower than $v_{1O}$, is still well above the Keplerian frequency and this rules out all interpretations in terms of spots or a companion. We note that instability may extend below the frequency of the fundamental mode, as is the case for some dipole modes. A careful analysis of a grid of full evolutionary models is required, which is ongoing (Dziembowski, in preparation). Still, the expected driving rates (Van Hoolst, Dziembowski & Kawaler 1998; Dziembowski & Cassisi 1999) are orders of magnitude lower than driving rates (mode selection; e.g. Smolec 2014). Still, the expected driving rates are worrying.

We anticipate a further detection of stars with additional low-frequency periodicity during the ongoing K2 mission. The precise space photometry may shed more light on the nature of these mysterious RRc pulsators.

5 SUMMARY AND CONCLUSIONS
We have discovered a new group of double-periodic RR Lyrae stars with the dominant pulsation in the radial first overtone. Additional period is longer than the first overtone period and longer than the expected period of the unseen fundamental mode. Period ratios between the first overtone and additional period tightly cluster around 0.686, independently of the first overtone period (which covers a broad range from $\approx 0.22$ to $\approx 0.42$ d). Amplitude of the additional periodicity is in the mmag range and is only a small fraction of the first overtone amplitude (up to 6 per cent). The group counts 12 stars, 11 identified in the OGLE-IV Galactic bulge photometry and one in Kepler observations. In two stars we detect the Blazhko modulation. Irregular phase variation, which is typical for RRc stars, is detected in most cases. The signal corresponding to additional periodicity is always stationary.

Excitation of an additional oscillation mode in these RRc stars seems the only possible interpretation of the additional signal. The frequency, though lower than $v_{1O}$, is still well above the Keplerian frequency and this rules out all interpretations in terms of spots or a companion. We note that instability may extend below the frequency of the fundamental mode, as is the case for some dipole modes. A careful analysis of a grid of full evolutionary models is required, which is ongoing (Dziembowski, in preparation). Still, the expected driving rates (Van Hoolst, Dziembowski & Kawaler 1998; Dziembowski & Cassisi 1999) are orders of magnitude lower than driving rates for the radial modes. The driving rates are not a good predictors of the pulsation amplitude or of the form of the finite amplitude pulsation (mode selection; e.g. Smolec 2014). Still, the expected driving rates are worrying.

We anticipate a further detection of stars with additional low-frequency periodicity during the ongoing K2 mission. The precise space photometry may shed more light on the nature of these mysterious RRc pulsators.

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REFERENCES

Benkő J. M. et al., 2010, MNRAS, 409, 1585
Catelan M., Smith H. A., 2015, Pulsating Stars. Wiley, New York
Dziembowski W., Cassisi S., 1999, Acta Astron., 49, 371
Jurcsik J., Smitola P., Hajdu G., Nuspl J., 2014, ApJ, 797, L3
Molnár L. et al., 2015, MNRAS, submitted
Moskalik P., 2014, in Guzik J. A., Chaplin W. J., Handler G., Pigulski A., eds, Proc. IAU Symp. 301, Precision Asteroseismology. Cambridge Univ. Press, Cambridge, p. 249
Moskalik P. et al., 2015, MNRAS, 447, 1173
Netzel H., Smolec R., Moskalik P., 2015, MNRAS, 447, 2348
Smolec R., 2014, in Guzik J. A., Chaplin W. J., Handler G., Pigulski A., eds, Proc. IAU Symp. 301, Precision Asteroseismology. Cambridge Univ. Press, Cambridge, p. 265

Soszyński I. et al., 2011, Acta Astron., 61, 1
Soszyński I. et al., 2014, Acta Astron., 64, 177
Szabó R., 2014, in Guzik J. A., Chaplin W. J., Handler G., Pigulski A., eds, Proc. IAU Symp. 301, Precision Asteroseismology. Cambridge Univ. Press, Cambridge, p. 241
Szabó R., Benkő J. M., Paparó M., 2014, A&A, 570, A100
Udalski A., Szymański M. K., Soszyński I., Poleski R., 2008, Acta Astron., 58, 69
Udalski A., Szymański M. K., Szymański G., 2015, Acta Astron., 65, 1
Van Hoolst T., Dziembowski W. A., Kawaler S. D., 1998, MNRAS, 297, 536

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