First Overtone RR Lyrae Stars in the OGLE Collection

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We present the preliminary results of the analysis of the Optical Gravitational Lensing Experiment (OGLE) data for the first overtone RR Lyrae stars (RRc) from the Galactic bulge. In the OGLE collection of variable stars, there are more than 10 000 RRc stars with six seasons of observations available. We analyzed this sample in order to detect non-radial modes and to study the Blazhko phenomenon, which is a quasi-periodic modulation of amplitude and/or phase.

We found new members of the group in which, besides the first overtone, there is another short-period signal, forming a characteristic period ratio of around 0.61 with the first overtone period. Previous analysis of the selected stars from the OGLE collection resulted in a discovery of more than 200 stars. After our analysis of all the RRc stars observed by OGLE, the number of known such stars exceeds 700.

In the previous analysis of the selected RRc stars, we discovered an entirely new double-periodic group in which, besides the first overtone, there is another signal. It has a period longer than the period of the first overtone, and forms a characteristic period ratio around 0.68. Before the present study, this group consisted of 19 stars found in the OGLE data and one star found in the *Kepler* data. The analysis of the whole sample of RRc stars resulted in a discovery of almost 70 new members of this group.

Additionally, in several stars with non-radial modes, we detected the Blazhko phenomenon.

1 Introduction

RR Lyrae stars are low-mass, low-metallicity stars from the classical instability strip. The dominant form of pulsations for RR Lyrae stars is single-periodic radial pulsation in either fundamental mode (RRab) or first overtone (RRc). Some stars can pulsate in two radial modes simultaneously: in the fundamental mode and first overtone (RRd) or fundamental mode and second overtone. Observations from the last few years, both from ground and space, revealed the presence of another periodicity in frequency spectra of first overtone RR Lyrae stars (RRc or RRd). The additional signal has a period shorter than the period of the first overtone and forms a period ratio from 0.60 to 0.64 with the first overtone. AQ Leo (RRd) was the first star in which this additional signal was detected (Gruberbauer et al., 2007). Currently, we know around 300 stars forming this double-mode group, $RR_{0.61}$, both from space

(Moskalik et al., 2015, and references therein; Moskalik et al., these proceedings) or ground (Netzel et al., 2015b,c, and references therein).

Additionally, during the previous analysis of a selected sample of Galactic bulge first overtone RR Lyrae stars, we detected a new double-periodic group of stars (Netzel et al., 2015a; Netzel & Smolec, 2016). The period of the additional variability is longer than the period of the first overtone and even longer than the period of the fundamental mode, which is never detected in these stars.

Here we present the analysis of all Galactic bulge RRc stars observed in the fourth phase of the OGLE project. We detected 696 members of the $RR_{0.61}$ group and 88 members of the $RR_{0.68}$ group.

2 Method

We used the Optical Gravitational Lensing Experiment (OGLE) data for the RR Lyrae stars in the Galactic bulge (Soszyński et al., 2014). We used six observational seasons from the fourth phase of the project. This sample consists of 10 826 RRc stars. For all these stars, we used an automatic procedure in order to extract significant frequencies present in the power spectra. The procedure used a standard consecutive prewhitening method and checked the prewhitened spectra for additional signals. We used the criterion of signal-to-noise ratio S/N>4 to decide whether the signal is significant. In a high fraction of RRc stars, we observed period changes, which caused remnant power in the prewhitened power spectra. As a result, the noise level in the power spectra is higher, and it hampers detection of additional peaks. In order to get rid of the period changes, we used time-dependent prewhitening (see Moskalik et al., 2015). As a result of our approach, we obtained lists of significant frequencies for all stars. Based on the frequency lists, we selected stars in which one of the additional signals is in the interesting frequency range (either corresponding to 0.61 signal or 0.68 signal). A full description of the method and classification criteria will be described elsewhere (Netzel et al., in prep).

3 Results

Our analysis of the whole data set of OGLE resulted in a detection of 696 $RR_{0.61}$ and 88 $RR_{0.68}$. We found 524 $RR_{0.61}$ and 69 $RR_{0.68}$ are new detections. The full table of stars with additional modes will be published in a dedicated paper. In Fig. 1 we present the Petersen diagram with double-mode RR Lyrae stars. We plotted all known $RR_{0.61}$ and $RR_{0.68}$ stars with blue and magenta asterisks, respectively.

The $RR_{0.61}$ group is very populated. Three sequences formed within this group are very well visible. They are almost parallel. The lowest sequence is the most populated and is located at the period ratio 0.613. The top sequence is located at the period ratio 0.632. The middle sequence is the least populated. This sequence was identified for the first time by Netzel et al. (2015c) and now is fully confirmed. The most interesting stars among the $RR_{0.61}$ group are stars with signals corresponding to all three sequences at the same time. So far, this was observed mostly in OGLE stars (Netzel et al., 2015b,c). We detected three signals in 21 stars from our sample. In 95 stars, we detected signals corresponding to two of the three sequences.

Another feature observed in power spectra of $RR_{0.61}$ stars are signals close to subharmonic frequencies, i.e. $(n + 1/2)f_{1O}$. They were detected in most stars ob-

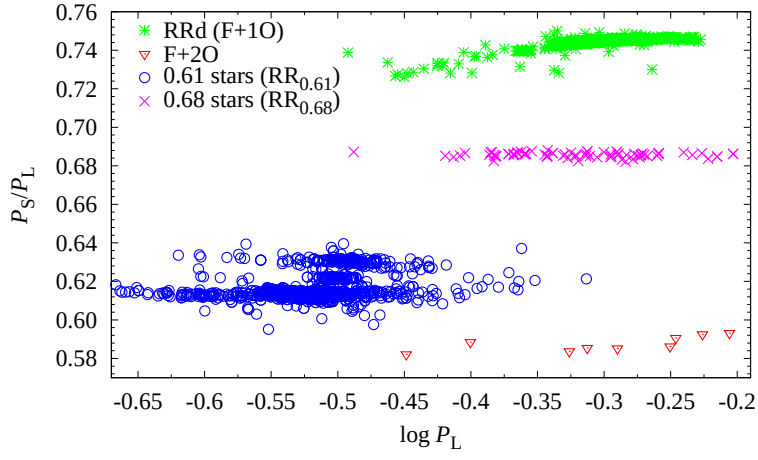

Fig. 1: Petersen diagram with double mode RR Lyrae stars detected in this study. $RR_{0.61}$ stars are plotted with blue asterisks. $RR_{0.68}$ stars are plotted with magenta asterisks. For the reference we plotted RRd stars with green symbols and stars pulsating in fundamental mode and second overtone with red symbols.

served from space. Usually, structures of subharmonic frequencies are broad and complicated (see examples in Netzel et al., 2015c). We also checked for these signals during a visual inspection of power spectra, and we found them in 57 stars, which corresponds to 8 percent of the $RR_{0.61}$ sample. An example of a star with three sequences and subharmonics is presented in Fig. 2.

An explanation of $RR_{0.61}$ stars was proposed and discussed in detail by Dziembowski (2016). It involves excitation of non-radial modes of degrees $\ell = 8, 9$. In this scenario, the excited mode is located at the $0.5f_{\rm x}$ frequency, where $f_{\rm x}$ corresponds to a signal forming the period ratio with the first overtone, $P_{\rm x}/P_{1\rm O}$, in the $0.6 - 0.64$ range.

The $RR_{0.68}$ group is tightly clustered around the period ratio 0.686. We do not observe a large scatter around the sequence or any correlation between the period and the period ratio. Currently, we know 89 $RR_{0.68}$ stars. We found 88 stars in the OGLE data, and one star was detected in the *Kepler* data (Moskalik et al., 2015). The additional signal, as opposed to additional signals in the $RR_{0.61}$ group, is always coherent. The amplitudes of the additional signal are small – in a mmag regime. The $RR_{0.68}$ group is puzzling, because the additional signal has a period longer than the (undetected) fundamental mode. We still lack a satisfying explanation of this group. For a discussion of the origin of this signal, see Dziembowski (2016).

3.1 Blazhko Effect

The Blazhko effect is a quasi-periodic modulation in some RR Lyrae stars. We analyzed the Blazhko effect in RRc stars from the Galactic bulge[1]. We have detected the Blazhko effect in 606 stars. In addition, we found 103 stars are multimode pulsators. They are marked in the Petersen diagram in Fig. 3 with red symbols.

[1]Full results will be published elsewhere (Netzel el at., submitted)

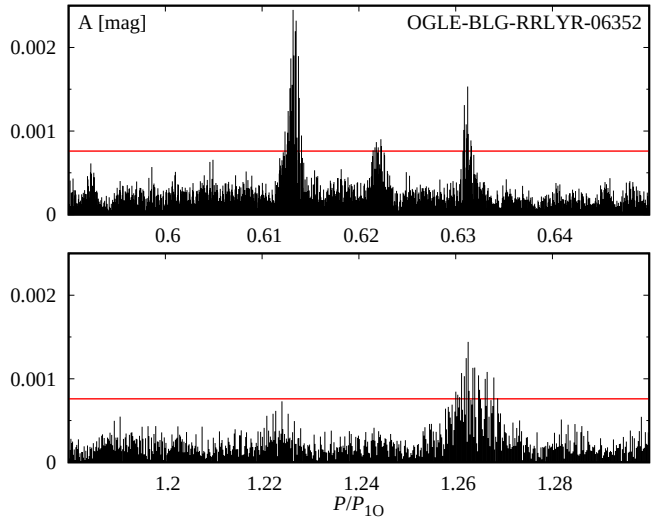

Fig. 2: Power spectrum of RRLYR-06352. The top panel shows frequency range of the additional frequency. To allow a direct comparison with the Petersen diagram, we used the period ratio, P/P_{1O}, on the horizontal axis, instead of frequency. The bottom panel corresponds to the subharmonic frequency range. It is also scaled, so exactly underneath the signal from the top panel, its subharmonic, if present, is located. The red line corresponds to S/N=4 level.

The type of pulsation is indicated by different markers and explained in the key. Some of them fit very well to already defined groups in the Petersen diagram. One star falls close to the RRd sequence. It might be modulated RRd star with an atypical period ratio – anomalous RRd star, see Soszyński et al. (2016). Eighteen stars fall into the $RR_{0.61}$ group. Interestingly, there are more Blazhko stars fitting the $RR_{0.68}$ sequence, despite it being much less populated. We detected the Blazhko effect in 24 of them. The incidence rate of the Blazhko effect is 3 percent and 27 percent for $RR_{0.61}$ and $RR_{0.68}$ stars, respectively.

4 Conclusions

We have presented the preliminary results of the search for non-radial modes in the full sample of the Galactic bulge RRc stars observed in the fourth phase of the OGLE project, which consists of 10 826 RRc stars. We detected 696 $RR_{0.61}$ stars and 88 $RR_{0.68}$ stars, where 524 and 69 are new detections. Our study shows that the Blazhko effect and excitation of these modes can coexist in the same star.

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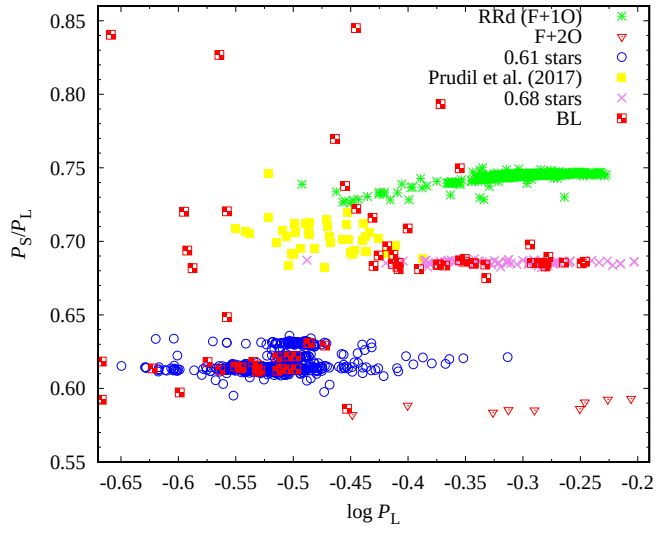

Fig. 3: Petersen diagram for multi-mode RR Lyrae stars. Blazhko stars with additional signals are marked with red symbols.

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