Continued Search of RR Lyrae Binary Systems Towards the Galactic Bulge

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Binary systems provide the most straightforward way of measuring the mass of individual stars, and through it, constraining the models of stellar evolution. Unfortunately, very few binary candidates containing RR Lyrae variables have been found previously. We continue our search for such systems in the photometric data of the OGLE survey towards the Galactic bulge, finding more than 30 such candidates. Furthermore, we show that our ongoing radial velocity follow-up observations have the potential to confirm or refute some of our candidates in the near future.

1 Introduction

Direct mass measurements, achieved through the analysis of binary stars, are indispensable to constrain the models of stellar evolution. Furthermore, binary systems containing pulsating variable stars provide additional constraints to stellar pulsation theories, as well. Despite their large numbers, for a long time, only one RR Lyrae, TU UMa has been known to reside in a binary system with high confidence (Wade et al., 1999). The situation was especially startling due to the apparent profusion of Classical Cepheids in binary systems, where even a binary composed of two Cepheids had been found previously (Gieren et al., 2014). This had changed drastically when we announced 20 binary candidates, located in fields towards the Galactic bulge (Hajdu et al., 2015). Interestingly, multiple independent projects started around the same time looking for RR Lyrae binary systems either with photometry (Li & Qian, 2014; Guggenberger & Steixner, 2015; Liška et al., 2016) or spectroscopy (Guggenberger et al., 2016), but the candidates found by these studies either have supposed orbital periods too long for feasible follow-up (Liška et al., 2016), or the assumed projected semi-major axes are tiny, resulting in very low expected radial velocity signals (Li & Qian, 2014; Guggenberger & Steixner, 2015). As new RR Lyrae binaries are still of great interest, we are continuing our search for them in the data provided by the OGLE project (Soszyński et al., 2014).

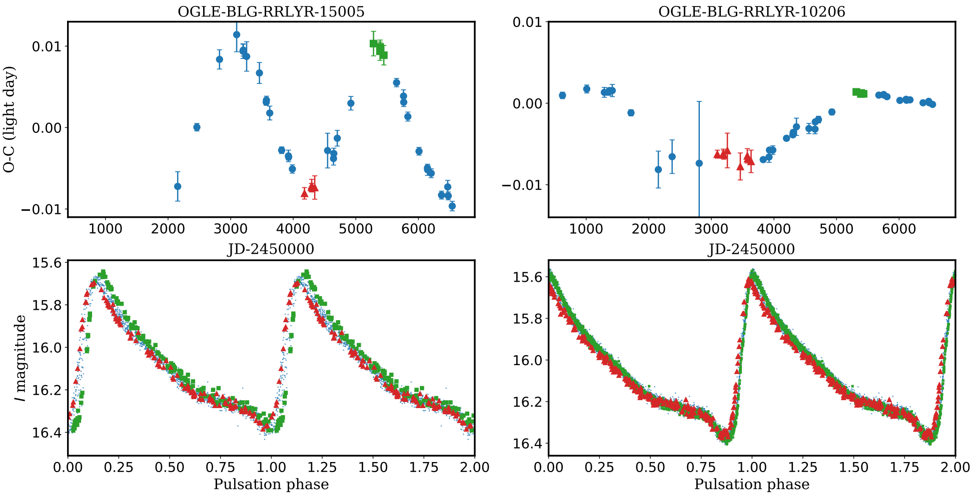

Fig. 1: *Top:* $O-C$ diagrams of two RR Lyrae stars from our sample, initially considered as RR Lyrae binary candidates, based on the shapes of their $O-C$ diagrams. *Bottom:* Folded I-band light curves. Comparison of specific parts of the light curves (where the corresponding timespans are marked with the appropriate symbols on the $O-C$ diagrams) reveals amplitude modulation, indicating the presence of the Blazhko effect.

2 Binary RR Lyrae Search

We have analyzed a subset of the combined OGLE-III and IV I-band photometry of RR Lyrae variables towards the Galactic bulge (Soszyński et al., 2011, 2014) with the same implementation of the $O-C$ analysis (Sterken, 2005) method, as we have done in Hajdu et al. (2015). The main difference between the previous study and the current one is that we are analyzing more stars (5948 instead of 1952), by relaxing the requirements on the time span, number of observations per object, as well as the quality of light curves.

The generated $O-C$ diagrams had been inspected one by one, creating an initial list of stars with hints of cyclic variations. These variables had been analyzed in order to discard those which are affected by the Blazhko effect (see, e.g. Smolec 2016 and references within). We found many RR Lyrae stars with small amplitude modulations, coincident with the long-period $O-C$ variations, indicating that both are caused by the Blazhko effect. Figure 1 illustrates two of these Blazhko variables in the analyzed sample.

The remaining variables can be considered binary candidates. Figure 2 showcases two of our best candidates. Based on this sample, the main results are the following:

- we have found 17 new binary candidates with reliable binary periods, and 16 suspected binaries (where the suspected orbital period is generally longer than the observational baseline)
- none of the binary candidates have periods below 1000 days
- most new candidates have periods in the same $8-12$ yr period range, similarly to the candidates published by Hajdu et al. (2015), but this statistic is heavily

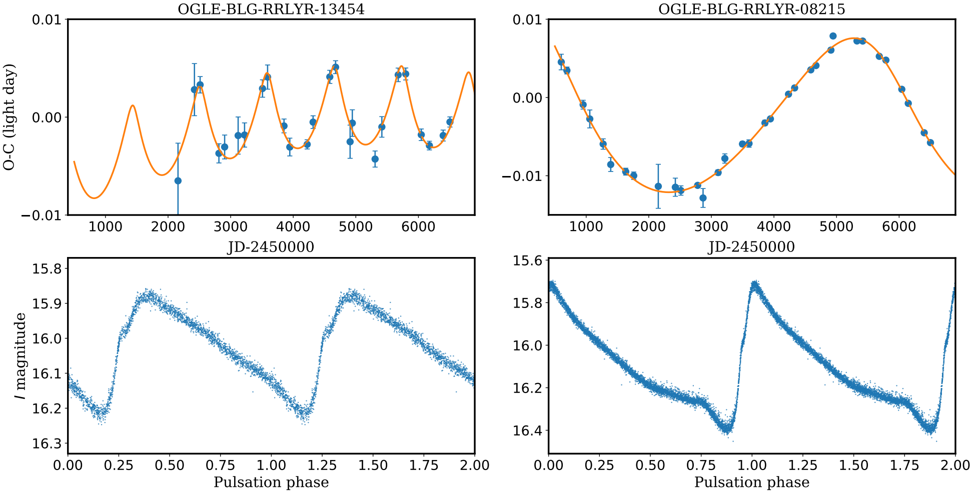

Fig. 2: *Top:* $O-C$ diagrams and preliminary orbital solutions of new RR Lyrae binary candidates. Note that the secular trend seen in OGLE-BLG-RRLYR-13454 is caused by the change of the pulsation period of the variable. Also note that for OGLE-BLG-RRLYR-08215 the observations are not long enough to determine an accurate binary period. *Bottom:* Folded light-curve of the variables. The $O-C$ variation has been subtracted from the timings of individual light-curve points, in order to showcase the stability and quality of the light curves.

biased by the observational baseline (12 years at most, depending on the star)

The discovery of a low-mass Binary Evolution Pulsator (BEP, Pietrzyński et al. 2012), originally classified as a binary RR Lyrae candidate (Soszyński et al., 2011), raises the question whether our candidates are real bona-fide RR Lyrae variables, or products of stellar co-evolution. Recently, Karczmarek et al. (2017) simulated the evolution of a population of stellar binaries, in order to evaluate the significance of BEPs in the study of pulsating variables. The binary periods of their sample overlap with our binary RR Lyrae candidates, however, they have no BEPs above 2500 days. Furthermore, most of their long-period binaries are of the variety what they call AGB-core variables (panel f of fig. 6 of Karczmarek et al. 2017), which generally have masses in the $0.5-0.6\,\mathrm{M}_\odot$ range (panel a), but their radii are in the $10-50\,\mathrm{R}_\odot$ range (panel c). If these stars pulsate in the radial fundamental mode, their periods would be significantly longer than those of real RR Lyrae stars. Therefore, we can conclude that the possible contamination of our RR Lyrae binary candidates from BEPs is smaller than it would appear based solely on the overlapping period ranges of our study and that of Karczmarek et al. (2017). Finally, none of our stars have anomalous light-curve shapes at their respective pulsation periods, further enhancing the non-BEP argument for our binary candidates.

The lower 1000 day limit we find in the distribution of binary periods is most probably a side-effect of binary evolution: in shorter period binaries, Roche-lobe overflow leads to enhanced mass loss, and many would-be RR Lyrae stars become blue horizontal branch stars instead.

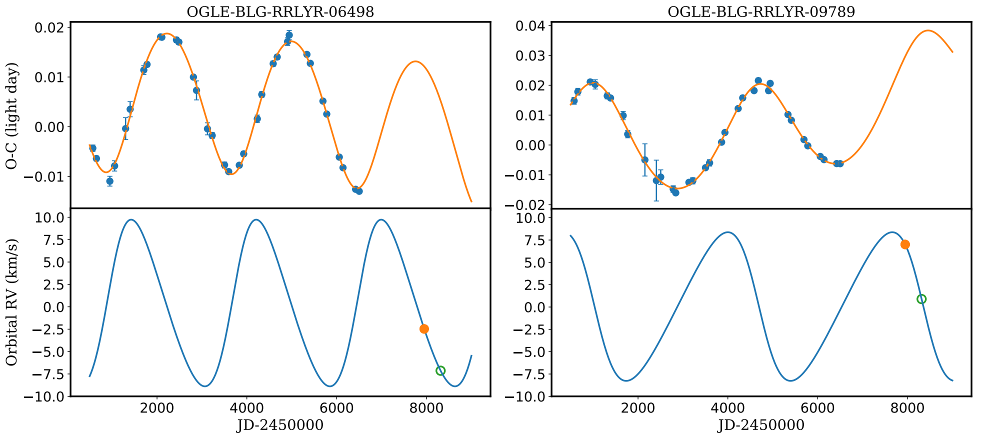

Fig. 3: $O-C$ orbital solutions (top) and derived orbital radial velocities (bottom) of two RR Lyrae variables. The filled and empty circles denote observations completed in 2017, and the middle of the 2018 Galactic bulge observing season, respectively. The expected radial velocity differences between the two seasons are -4.7 and $-6.1\,\mathrm{km\,s^{-1}}$ for 06498 and 09789, respectively. Radial velocity differences of this order should be detectable at the precision of our RV measurements, thus confirming the binarity of these stars. Note that the secular trend seen in the $O-C$ diagrams is caused by the slow change in the pulsation period of these stars.

3 Spectroscopic Follow-up

We have started a spectroscopic follow-up program, in order to verify the binary nature of our candidates. Unfortunately, many of them have low expected radial velocity changes (a few $\mathrm{km\,s^{-1}}$) due to their long periods and low $O-C$ amplitudes. Most of our candidates suffer from moderate extinction, affecting radial velocity follow-up, as most prominent metal lines are in the blue part of the spectra. Nevertheless, we have obtained spectra with the MIKE spectrograph of the Clay telescope at Las Campanas Observatory for eight of our candidates in the 2017 observing season.

Some of our candidates have expected velocity differences between the 2017 and 2018 seasons on the level of $5\,\mathrm{km\,s^{-1}}$. Figure 3 illustrates this for two variables, 06498 and 09789. The precision of our observations should be sufficient to decidedly confirm or refute the binarity of these variables, given successful observations in the 2018 observing season.

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