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ABSTRACT
Despite their importance, very few RR Lyrae (RRL) stars have been known to reside in binary systems. We report on a search for binary RRL in the OGLE-III Galactic bulge data. Our approach consists in the search for evidence of the light-travel time effect in so-called *observed minus calculated* (O−C) diagrams. Analysis of 1952 well-observed fundamental-mode RRL in the OGLE-III data revealed an initial sample of 29 candidates. We used the recently released OGLE-IV data to extend the baselines up to 17 yr, leading to a final sample of 12 firm binary candidates. We provide O−C diagrams and binary parameters for this final sample, and also discuss the properties of eight additional candidate binaries whose parameters cannot be firmly determined at present. We also estimate that $\gtrsim 4$ per cent of the RRL reside in binary systems.

Key words: methods: data analysis – techniques: photometric – binaries: general – stars: fundamental parameters – stars: oscillations – stars: variables: RR Lyrae.

1 INTRODUCTION

RR Lyrae (RRL) stars play a key role in astrophysics. They are important distance indicators, allowing us to determine the distance to the closest galaxies (e.g. Cacciari 2013; Dambis et al. 2013), and thus providing an important step in the calibration of the extragalactic distance scale. Their importance in the context of galaxy formation and evolution is also being increasingly recognized (e.g. Catelan 2009). RRL stars being unmistakably old, their distribution in the Galactic halo provides evidence of the early Milky Way formation history (Drake et al. 2013a,b; Sesar et al. 2013; Torrealba et al. 2015). They also help trace the spatial distribution, and even the age, of some of the Milky Way's oldest stellar populations (Lee 1992; Catelan & de Freitas Pacheco 1993; Dékány et al. 2013).

Despite their usefulness, there are still important uncertainties affecting the fundamental parameters and physical properties of these stars. Trigonometric parallaxes of even the closest RRL are notorious for their large error bars (Benedict et al. 2011). To complicate matters further, the exact evolutionary status of even RR Lyr itself is uncertain, with indications that it may be significantly overluminous, compared to the zero-age horizontal branch (HB) level at its metallicity (Catelan & Cortés 2008; Feast et al. 2008).

RRL variables occupy a fairly narrow strip – the so-called *instability strip* – at intermediate temperatures along the HB. As such,

their exact mass value is crucial in establishing whether an HB star will ever become an RRL, or instead, a non-variable blue or red HB star. In this sense, theory predicts that the masses of RRL stars should decrease with increasing metallicity, with little scatter at any given [Fe/H] (e.g. Catelan 1992; Sandage 2006). Direct empirical confirmation of this important result is, however, still lacking. Most of the available information regarding RRL masses comes from the so-called *Petersen diagram* (Petersen 1973) of double-mode RRL (RRd) stars. RRd stars are observed to pulsate simultaneously in the fundamental and first overtone radial modes, and their distribution in the period ratio versus period (Petersen) diagram is predicted to be a strong function of the pulsating star's mass, in addition to other parameters, such as metallicity (e.g. Popielski, Dziembowski & Cassisi 2000). RRL star masses can thus be derived by comparing the observed positions of RRd stars in this diagram with those predicted according to stellar evolution and pulsation theory (e.g. Bono et al. 1996; Dékány et al. 2008). However, this method can only be trusted to provide accurate masses if the theoretical framework upon which it is based is itself accurate. To constrain the theories themselves, it is imperative to obtain a model-independent mass measurement.

Binary systems allow the derivation of the masses of their components, if the orbital parameters are known. In the case of binary systems containing classical Cepheids, analysis of their orbital parameters has played a crucial role in accurately establishing their physical properties, including their masses (Pietrzyński et al. 2010). Furthermore, Cepheid-bearing binary systems are relatively

common (Szabados 2003), and even systems in which *both* components are Cepheids are now known to exist (Gieren et al. 2014).

The situation regarding RRL stars could hardly be more different, as for long only one RRL, TU UMa, has been known to reside in a binary system (see Saha & White 1990 and Wade et al. 1999, for very detailed analyses of this star). Recently, eclipsing binary RRL candidates have been found by the OGLE project in the Galactic bulge (Soszyński et al. 2011), as well as in the LMC (Soszyński et al. 2009). However, follow-up observations and modelling of the bulge candidate have shown that the pulsating component of this system has too low a mass to be a bona fide RRL star (Pietrzyński et al. 2012; Smolec et al. 2013). Other candidate eclipsing RRL found by the OGLE-II project in the LMC (Soszyński et al. 2003) have turned out to be optical blends (Prša et al. 2008). Careful analyses of the RRL light curves (LCs) of the *Kepler* mission have uncovered only three possible binary candidates (Guggenberger & Steixner 2014; Li & Qian 2014).

Recently, a number of metal-poor, carbon-rich RRLs have been identified via spectroscopy (e.g. Kennedy et al. 2014). The anomalous C abundance of these stars can be explained by mass accretion from a more massive companion, which has evolved through the asymptotic giant phase (Stancliffe et al. 2013), suggesting that these RRLs might be members of binary systems in which the other component has already evolved to the white dwarf stage. However, the binary nature of these RRLs has not yet been directly established.

In this Letter, we describe our search for periodic phase variations caused by the light-travel time (LTT) effect (Irwin 1952) in the LCs of a subsample of well-observed RRL stars from the OGLE-III survey towards the Galactic bulge (Soszyński et al. 2011). We augment the LCs of the binary candidates thus obtained with newly published photometry from the OGLE-IV survey (Soszyński et al. 2014), in order to increase the observational baseline. We derive binary parameters for the best candidates. Furthermore, we discuss the RRL binary fraction, as well as the detectability of such systems through the LTT effect.

2 DATA AND ANALYSIS

Our initial analysis is based on the *I*-band OGLE-III LCs for bulge RRL (Soszyński et al. 2011). We analyse stars with fundamental-mode pulsation (RRab subtype), as well as having an observational baseline covering more than 10 yr. These criteria define a subsample of 1952 RRab variables. For these, we have utilized the so-called *observed minus calculated* (O−C) diagrams (e.g. Sterken 2005), adopting a linear ephemeris (C) for the variables:

$$C(t) = t_0 + P_{\text{puls}}\, E, \tag{1}$$

where t_0 is the initial epoch, P_{puls} is the pulsation period, and E is the epoch number, or the number of elapsed pulsation cycles since t_0. Times have been transformed into Barycentric Julian Dates (BJD) in the Barycentric Dynamical Time standard (Eastman, Siverd & Gaudi 2010).

In the case of variable stars, the O−C diagram is most commonly constructed by subtracting the ephemeris (C) from timing observations (O) of particular features of the LCs, such as maxima or minima, and plotting this quantity as a function of time. Hertzsprung (1919) proposed utilizing the whole LC for deriving O−C points of a variable by fitting the phase of an LC template to the observations. Due to the generally sparse sampling of OGLE observations, determining the times of individual maxima at different epochs is unfeasible, making Hertzsprung's method vastly

superior for obtaining the required O−C measurements. We thus adopt the latter method in our analysis.

Fig. 1 illustrates the procedure for one of the binary candidates. First, we created an LC template by fitting the original LC with a Fourier series using LCFIT (Sódor 2012), as shown in Fig. 1(a). The LCs were divided into short sections corresponding to different observing seasons. Sections longer than 160 d were split in two, in order to achieve better time resolution. We have derived the O−C points by least-squares fitting the LC templates in phase to each of these segments. These phase shifts were then used to construct the O−C diagrams (Fig. 1b).
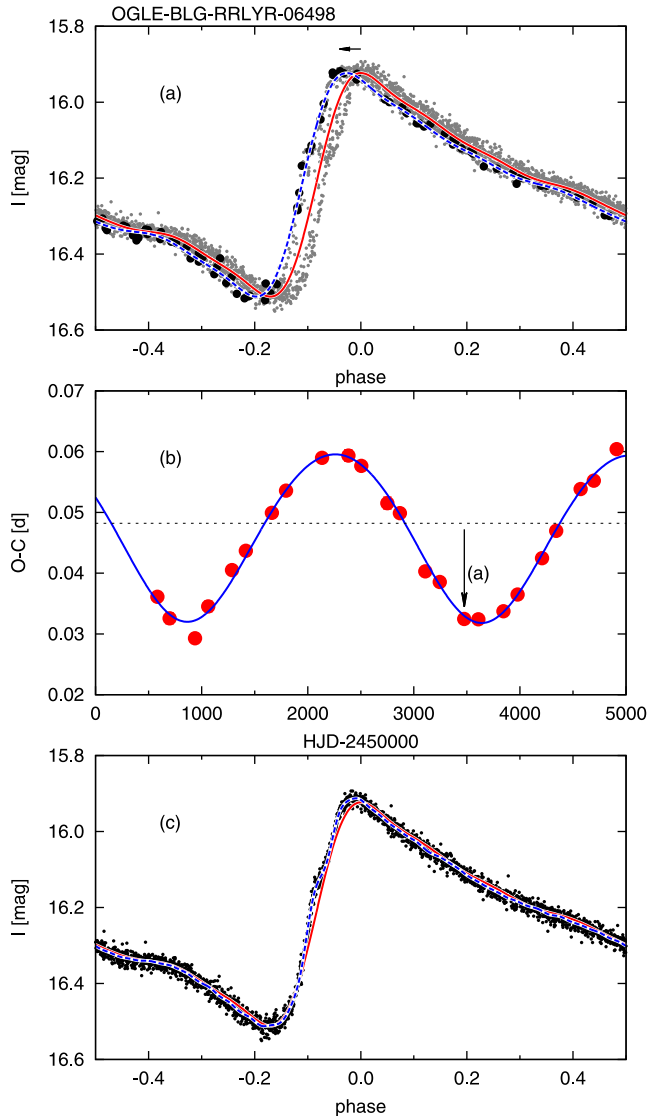

Figure 1. O−C analysis of the OGLE-III observations. (a) The original LC folded with the pulsation period (grey dots), its Fourier fit (red line), one section of the LC (black dots), and the least-squares template fit (blue dashed line). (b) The resulting O−C diagram (dots), and the corresponding binary-model fit (blue line). The point corresponding to the measurement shown in (a) is indicated by an arrow. (c) The folded LC, after correcting the times of observations for the binary motion (panel b). The Fourier fit (blue dashed line) now follows the real LC shape much more closely than the original fit (red line).

2.1 Selection of binary candidates

The LTT effect manifests itself as a strictly periodic phase modulation of the LC of a variable star, caused by its orbital motion around the common centre of mass in a binary system. The change in the observed times of particular features of the LC, and consequently in the corresponding O−C values, have the form

$$z(t) = a \sin i \; \frac{1-e^2}{1+e\cos(\nu)} \; \sin(\nu + \omega), \tag{2}$$

where a is the semimajor axis, i is the inclination, e is the eccentricity, and ω is the argument of the periastron. The true anomaly ν is a function of the time t, the orbital period P_{orb}, the time of periastron passage T_{peri}, and e.

We have visually inspected the O−C diagrams constructed as described previously, in search of O−C shapes allowed by equation (2) (e.g. Irwin 1959). In some cases, particularly when the period values found by Soszyński et al. (2011) have turned out to be inadequate, we have constructed the O−C diagrams with several different pulsation periods.

Fig. 1 shows one of the best candidates for a binary system containing an RRL thus obtained. In panel (b) of this figure, a preliminary orbital solution is also provided. Fig. 1(c) demonstrates the accuracy of the fit; the pre-whitening for the orbital solution results in an LC which has an rms deviation of only 12 mmag.

A large fraction of stars show erratic period changes, possibly connected to the Blazhko effect (Blažko 1907; see also Jurcsik et al. 2011). This effect manifests itself as an amplitude and phase modulation of the LC, and accordingly, variables affected by it have unreliable O−C diagrams for our purposes. For this reason, we have discarded binary candidates for which the LC shape and/or amplitude showed correlated changes with the phase variations, which might be indicative of the Blazhko effect. However, the presence of the Blazhko effect is unclear in some of the variables, as blending with another variable star and/or large photometric errors, together with the sparse coverage of the OGLE-III data, could mimic and/or mask the change of the LC shape/amplitude of Blazhko variables.

2.2 Analysis of the candidates

Following the above procedure, we have selected 29 potential binary candidates. In order to clarify the status of the stars in this sample, and also to refine the binary parameters of the candidates, we next combined the OGLE-III and IV data sets for these stars, thus increasing the baselines of their O−C diagrams. The full analysis of the combined OGLE-III and IV data sets will be reported in a future paper.

We have combined the OGLE-III and IV data sets for each of our 29 candidates by correcting for the difference between their average magnitudes, as given by Soszyński et al. (2009) and Soszyński et al. (2014). We then repeated the previous analysis on the data thus combined. We have inspected the new O−C diagrams and the combined LCs, and have found strong evidence that six of the candidates do in fact show the Blazhko effect, which was not evident from the relatively sparse OGLE-III data alone. The O−C variations of two additional candidates appear to be caused completely by their linear period changes, while for a third star, it is probably caused by irregular period changes. These discarded candidates are listed in Table 1, leaving us with a refined sample of 20 binary candidates.

Equation (2) does not take possible changes in the pulsation periods of the RRL stars into account. Such changes can significantly alter the O−C diagram, even on relatively short (∼10 yr) time-

Table 1. OGLE IDs[a] of uncertain RRL binary candidates.

| Likely non-binaries | | Likely binaries with poor fits | |
Symptom	ID	Symptom	ID
Blazhko effect	05075	$P_{orb} > 6000$ d	04522
	07773		05135
	10519		05152
	12027		10891
	13260		11683
	13698		12611
			12698
Period changes	05778	Very small amplitude	14852
	06876		
	12195		

[a]OGLE-BLG-RRLYR

scales. If the period changes linearly with time, the O−C diagram has the following shape:

$$(O-C)(t) = c_0 + c_1 t + c_2 t^2, \tag{3}$$

where $c_2 \equiv \beta$ is the linear period-change rate. The increased time-base of the combined data sets allows us to take this effect fully into account. We thus fit the O−C diagrams of the 20 remaining candidates with the sum of equations (2) and (3), and find that reliable parameters can be derived for 12 of them. The other eight variables either have orbital periods that are presumably comparable or longer than the baseline of the available observations (therefore the parameters of the fit are degenerate), or have very small O−C amplitudes. These stars, which may still be bona fide binaries and thus merit continued monitoring, are also listed in Table 1.

In order to derive the best possible parameters for this 12-star sample, we iterate the O−C solution once, by means of an improved Fourier fit to a (O−C)-subtracted LC. We also 3σ-clip the LCs, discarding the worst-quality (∼1 per cent) observations for each star. The final O−C points are determined by fitting these templates to the LC segments. The final diagrams, together with their fits, are shown in Fig. 2. Table 2 gives the fitted binary parameters for each star, as well as other relevant parameters of the fit.

3 DISCUSSION

We have completed the first systematic search for binaries in a subsample of OGLE Galactic bulge RRL stars utilizing the LTT effect. 20 probable binaries have been found analysing the O−C diagrams and LCs of 1952 OGLE-III bulge RRab variables, which represents about 1 per cent of this particular subsample (fundamental-mode pulsation, >10 yr observational baseline). This allows us to very roughly constrain the RRL binary fraction, as follows.

Approximately 50 per cent of RRab stars show the Blazhko effect (Jurcsik et al. 2009; Kolenberg et al. 2010). Due to their LC phase and shape changes, determining their binarity through the O−C method is impossible. Therefore, all of the Blazhko binaries have necessarily been missed, and so the total binary fraction must be closer to 2 per cent than to 1 per cent. We assume that the fraction of stars whose binarity was missed due to erratic pulsation period changes is small in comparison. Binaries with very low inclinations and very long periods are also missed. As we have no information about the fraction of long-period binaries in the sample, and as our method is more sensitive to stars with high inclination (because the O−C amplitude is proportional to $a \sin i$), we conservatively assume that at least half of the binaries are still missed due to these two selection effects. Based on these arguments, presumably at least
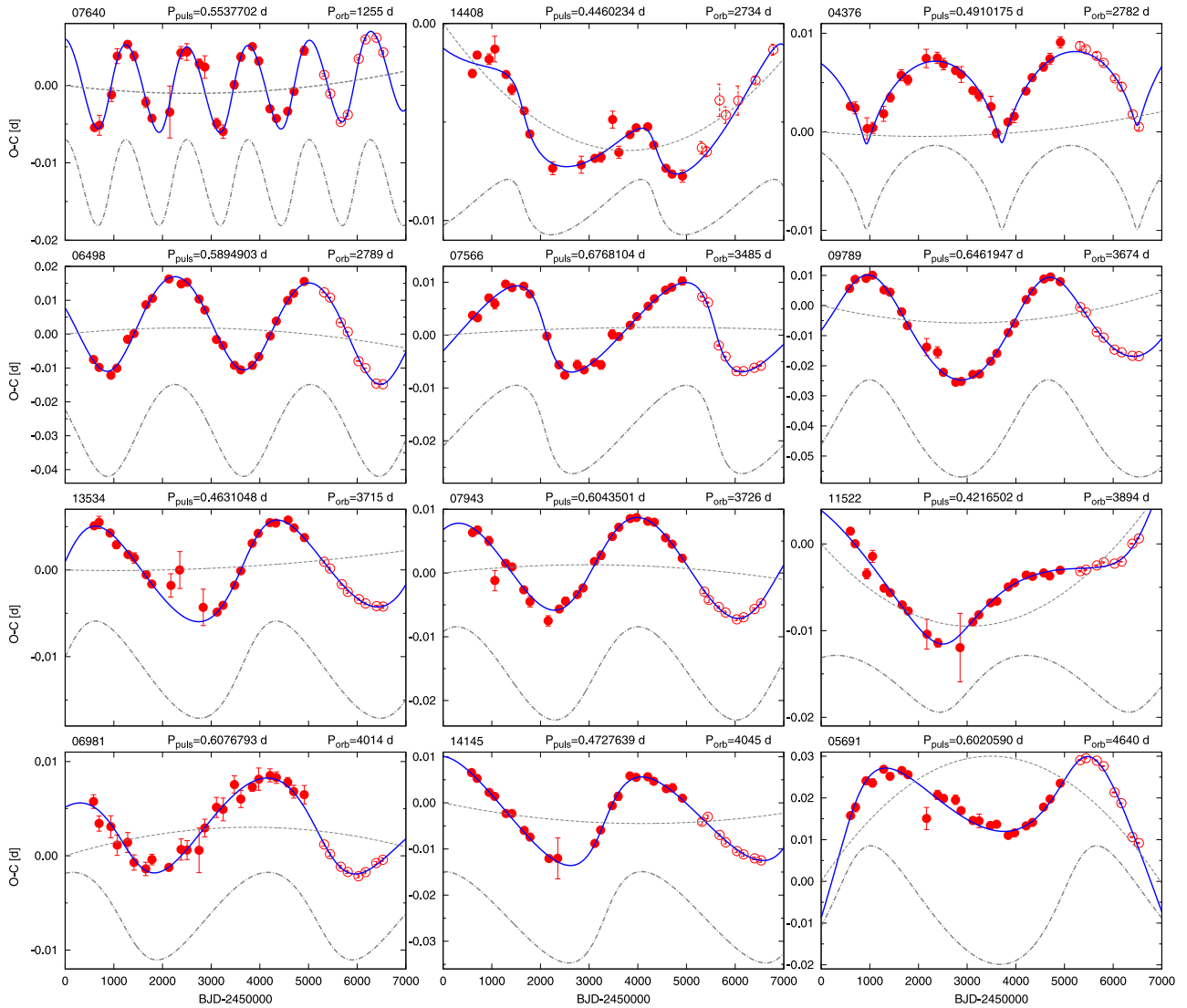
Figure 2. O−C diagrams of RRL binary candidates. The O−C points (filled circles: OGLE-III data; empty circles: OGLE-IV data) are fitted with the sum of a linear period change [equation (3), dashed line] and the binary orbit [equation (2), dot–dashed line, shifted downwards for clarity]. For each star, the OGLE ID, pulsation period, and orbital period are given on top of the upper *x*-axis.

4 per cent of RRL variables reside in binary systems in the sample. The recovery rate using the O−C method is thus ∼25 per cent, or perhaps lower.

Very few RRL stars have been reported to reside in binary systems yet (see Section 1). The current sample allows us to assess the observational requirements to discover additional such systems. The period distribution of the binary candidates is highly skewed: we find no binaries with orbital periods shorter than ∼3.5 yr, and there is a clustering of stars with orbital periods around ∼10–11 yr. Due to the long time-scale, currently OGLE is the only survey capable of discovering these variables, as high-precision (0.01–0.02 mag), long-baseline data are indispensable. Indeed, the increased baseline achieved by incorporating the OGLE-IV data greatly improved the quality of the fits, as we were able to disentangle the effects of the change in the RRL pulsation periods from the effect of binarity on the O−C diagrams, thus leading to more robust binary parameters. Note that we have succeeded in recovering RRLs with Blazhko periods as short as ∼0.5 yr, which is close to the limit of period detection set by the data sampling – thus indicating that binary RRLs with similarly short periods would have been

found through our analysis. The apparent lack of RRL variables in short-period binary systems puts a tight constraint on the inclination (due to the wide orbits) of eclipsing RRL binary systems, making our method much superior for the detection of RRL binaries.

Their faintness (15–17 mag in *I*) makes the follow-up of our binary candidates challenging. Still, two of them (06498 and 09879) have *higher* minimum masses (calculated from the parameters in Table 2 for reasonable mass assumptions for the RRL) than the RRL itself. The secondaries in some of these systems may be stars which have evolved off from the main sequence, therefore bright enough to contribute significantly to the light of the systems. If such a favourable case could be found, the mass ratio between the two stars could be measured through the ratio of their orbital radial velocities.

At the distance of the bulge, the binary candidate with the longest major axis (09789, ∼5.6 au) would have a projected major axis of about 0.7 mas. *Gaia* astrometry will unfortunately be hampered by the high crowding and the faintness of the candidates. However, Sahlmann et al. (2014) have demonstrated that 120 μas astrometry with FORS2@VLT is attainable on multiyear time-scales, for

Table 2. Fitted and derived parameters of the RRL binary candidates.[a]

ID	P_{orb} (d)	T_{peri} (d)	e	ω (deg)	$a\sin i$ (au)	σ (au)	β (d Myr^{-1})	K (km s^{-1})	$f(m)$ (M$_\odot$)
07640	1255 ± 4	9598 ± 54	0.16 ± 0.04	− 30 ± 15	0.97 ± 0.02	0.16	0.05 ± 0.01	8.5	0.0774
14408	2734 ± 38	8871 ± 78	0.60 ± 0.12	162 ± 8	0.30 ± 0.03	0.11	0.16 ± 0.01	1.5	0.0005
04376	2782 ± 19	8147 ± 53	0.79 ± 0.11	− 92 ± 6	0.74 ± 0.06	0.11	0.04 ± 0.01	4.7	0.0070
06498	2789 ± 18	8137 ± 134	0.12 ± 0.04	− 82 ± 16	2.35 ± 0.05	0.16	− 0.11 ± 0.03	9.2	0.2228
07566	3485 ± 15	8612 ± 33	0.54 ± 0.03	− 178 ± 3	1.72 ± 0.04	0.14	− 0.03 ± 0.02	6.4	0.0556
09789	3674 ± 30	7221 ± 81	0.18 ± 0.04	78 ± 10	2.80 ± 0.06	0.23	0.24 ± 0.03	8.4	0.2162
13534	3715 ± 27	6327 ± 73	0.26 ± 0.03	20 ± 5	1.00 ± 0.02	0.22	0.02 ± 0.01	3.0	0.0096
07943	3726 ± 40	9273 ± 150	0.14 ± 0.03	− 15 ± 13	1.28 ± 0.03	0.20	− 0.05 ± 0.02	3.8	0.0200
11522	3894 ± 153	8751 ± 411	0.30 ± 0.14	− 61 ± 24	0.57 ± 0.08	0.12	0.37 ± 0.04	1.7	0.0017
06981	4014 ± 85	7349 ± 206	0.25 ± 0.06	− 150 ± 11	0.82 ± 0.04	0.14	− 0.08 ± 0.03	2.3	0.0046
14145	4045 ± 100	9255 ± 81	0.41 ± 0.04	− 3 ± 7	1.88 ± 0.08	0.11	0.10 ± 0.02	5.5	0.0541
05691	4640 ± 119	6010 ± 314	0.35 ± 0.06	46 ± 12	2.54 ± 0.17	0.32	− 0.90 ± 0.14	6.3	0.1011

[a]The columns, in order, correspond to the following quantities: (1) OGLE ID, in the usual form OGLE-BLG-RRLYR plus the catalogue entry number; (2) orbital period; (3) time of periastron passage, in units of BJD − 2440000; (4) eccentricity; (5) argument of the periastron; (6) projected semimajor axis; (7) standard deviation of the fit $\sqrt{\mathrm{SSR}/[M-N]}$, where SSR is the sum of squared residuals, N is the number of data points and M is the number of free parameters; (8) rate of change of the pulsation period; (9) semi-amplitude of the radial velocity $K = 2\pi a \sin i / P_{orb} \sqrt{1-e^2}$; (10) mass function $f(m) = a^3 \sin^3 i / P_{orb}^2$, which is connected to the stellar masses through $f(m) = m_s^3 \sin^3 i / (m_{RR} + m_s)^2$, where m_{RR} is the mass of the RRL, and m_s is the mass of the secondary.

targets with similar magnitudes as here. A long-term astrometric follow-up programme might thus be feasible, in order to determine the inclination of these systems.

In this study of a subsample of OGLE LCs, we have demonstrated that RRL stars can be detected in long-period binary systems, provided that high-quality, extended photometric data sets are used. We plan to extend our analysis to the whole OGLE bulge RRL data set in the near future. Through long-term follow-up of the candidates, we will finally have a chance of determining the masses for a significant sample of RRL stars, and thereby directly constrain the theories of RRL star pulsation and evolution.

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