OGLE-BLG-RRLYR-12245: An RR Lyrae Star that Switched from a Double- to Single-mode Pulsation

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ABSTRACT

We report the discovery of an RR Lyrae star that experienced a switching of its pulsation mode. OGLE-BLG-RRLYR-12245 was discovered as a double-mode RR\(\text{d}\) star from the observations conducted in years 2001-2006 during the third phase of the Optical Gravitational Lensing Experiment (OGLE-III). The OGLE-IV observations carried out since 2010 reveal that this object is now a fundamental-mode RR\(\text{ab}\) star, with no sign of the first-overtone pulsation. The analysis of the OGLE photometry shows that the final stage of the mode switching occurred on a relatively short timescale of a few months in 2005. We study the behavior of the star during this process, showing changes of the pulsational amplitudes and periods. We also discuss possible causes for the mode switching in RR Lyr stars.

Key words: Stars: variables: RR Lyrae – Stars: oscillations – Stars: Population II – Stars: horizontal-branch

1. Introduction

Mode switching in RR Lyr stars is a very rarely observed phenomenon. So far, only one RR Lyr variable that changed its pulsation mode has been detected. Vari-
Fig. 1. Upper panel: unfolded $I$-band light curve of OGLE-BLG-RRLYR-12245 obtained by the OGLE survey in the years 2001-2013. Lower panels: OGLE-III (left panel) and OGLE-IV (right panel) light curves of OGLE-BLG-RRLYR-12245 folded with the fundamental-mode periods. Note the difference in the periods before and after the mode switching.

able star V79 in the globular cluster M3 was known for decades as a fundamental-mode RR Lyr star (RRab), however in 1992 V79 became a double-mode pulsator (RRd) with the first-overtone mode dominating (Clement et al. 1997, Kaluzny et al. 1998, Clement and Goranskij 1999). Then, in 2007 this star again changed its pulsation mode and returned to the sole fundamental mode (Goranskij 2010). The mode switches in V79 were accompanied with significant changes of the pulsational period.

In this paper, we report the discovery of another RR Lyr star that recently switched its pulsation modes. OGLE-BLG-RRLYR-12245 was identified in the Galactic bulge by Soszyński et al. (2011) as an RRd star on the basis of the observations collected in years 2001-2006 during the third phase of the Optical Gravitational Lensing Experiment (OGLE-III). Double-mode RR Lyr stars are very rare in the Galactic bulge. Among 16 836 RR Lyr stars detected in the OGLE-III fields toward the Galactic center only 91 objects (0.5% of the total sample) were classified as RRd stars (Soszyński et al. 2011).

Recently, we searched for RR Lyr variables in the OGLE-IV bulge fields, photometrically monitored since 2010, and we significantly increased the number of known stars of this type in the central regions of the Milky Way. This new collection of RR Lyr variables and other pulsating stars will be presented in forthcoming papers. We also inspected the OGLE-IV light curves of the already known RR Lyr stars and noticed that OGLE-BLG-RRLYR-12245 drastically changed its pulsational properties. This metamorphosis is clearly visible in Fig. 1 presenting the OGLE-III and OGLE-IV light curves of our target folded with the fundamental-
mode periods. Observations collected in the years 2010-2013 show that OGLE-BLG-RRLYR-12245 is currently a typical RRab star, with no sign of the first-overtone period or any other secondary variability, including the Blazhko modulation. The period of the fundamental-mode oscillations increased by 0.000489 d (0.12%) between 2005 and 2010. Table 1 provides information about the identification, position and brightness of OGLE-BLG-RRLYR-12245.

Table 1
Properties of OGLE-BLG-RRLYR-12245

| OGLE-III field and star’s number | BLG175.1 144525 |
| OGLE-IV field and star’s number  | BLG514.03 97374 |
| Right ascension (J2000)          | 18°03'54.05'' |
| Declination (J2000)              | -31°25'10.8'' |
| Galactic longitude              | 359°846102    |
| Galactic latitude               | -4°663256     |
| Mean apparent luminosity ⟨I⟩    | 15.525 mag    |
| Mean apparent luminosity ⟨V⟩    | 17.277 mag    |

2. Observations and Data Analysis

All the photometric data discussed in this paper were obtained with the 1.3-m Warsaw Telescope located at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution for Science. The OGLE survey began regular photometric monitoring of the stellar field around OGLE-BLG-RRLYR-12245 at the beginning of the OGLE-III phase, in August 2001. The field was continuously observed (with the seasonal breaks) till February 2006. In total, 380 observing points in the Cousins I-band filter and a few measurements in the Johnson V-band were collected. Observations of these regions were resumed at the beginning of the OGLE-IV project, in March 2010, and are continued to this day with 959 I-band measurements already collected. Detailed descriptions of the instrumentation, photometric reductions and astrometric calibrations of the OGLE data are available in Udalski (2003) and Udalski et al. (2008).

In the OGLE-III catalog of RR Lyr stars in the Galactic bulge (Soszyński et al. 2011), OGLE-BLG-RRLYR-12245 was classified as an RRd star. Its position in the Petersen diagram (period ratios versus logarithm of the longer periods) is shown in Fig. 2, in which we included also other RRd stars detected by OGLE-III and OGLE-IV in the Galactic bulge and Large Magellanic Cloud (LMC, Soszyński et al. 2009). As can be seen in Fig. 2, the first-overtone/fundamental-mode period ratio in OGLE-BLG-RRLYR-12245 is quite typical for RRd stars in the Galactic
Fig. 2. Petersen diagram for RRd stars in the Galactic bulge (large grey circles) and LMC (small grey dots). Large black star shows the position of OGLE-BLG-RRLYR-12245. The blue lines represent calculated period ratios for selected models covering the instability strip. The metal abundance parameters, $Z$, are given next to each model. The blue triangles show the loci of the $2/P_{1O} = 1/P_F + 1/P_{2O}$ resonance. Theoretical periods were calculated for the envelope models with $M = 0.6M_\odot$, and luminosity in solar units satisfying the $\log L = 1.6 - 0.057 \log(Z/0.002)$ relation. The effective temperature at the blue edge is $\log T_{\text{eff}} = 3.853 - 0.19 (\log L - 1.6)$ and at the red edge is by 0.02 dex lower.

bulge, although it is smaller than period ratios observed in RRd stars from the LMC and other studied galaxies and clusters. Such low period ratios in the bulge double-mode RR Lyr stars are likely to be due to their exceptionally high metallicities. According to the linear pulsation models similar to those used in Soszyński et al. (2011), OGLE-BLG-RRLYR-12245 has metal abundance parameter $Z$ between 0.0020 and 0.0024. The exact value depends weakly on the adopted mass.

The morphology of the studied light curve substantially changed during 4.5 years of the OGLE-III monitoring. To investigate this behavior, we divided the light curve into parts covering shorter time spans. In each part, the fundamental- and first-overtone modes were separated by fitting of the double-frequency Fourier sum.
Fig. 3. Evolution of the fundamental-mode (upper panels) and first-overtone (lower panels) I-band light curves of OGLE-BLG-RRLYR-12245. Both pulsation modes have been separated with the Fourier techniques. First three panels in each mode present light curves obtained within the years 2002, 2003, and 2004, respectively. The remaining panels show observations collected in 2005 – from left to right: between February and June, from July to August, and from September to October 2005.

The periods of the modes were also optimized during the fitting. The resulting light curves obtained in the years 2002-2005 are presented in Fig. 3. Light curves obtained in 2001 and 2006 were omitted due to a small number of measurements collected in these years.

3. Period and Amplitude Changes of OGLE-BLG-RRLYR-12245

Fig. 3 illustrates the process of the mode switching in OGLE-BLG-RRLYR-12245. In 2002, our target was a double-mode pulsator with the first overtone as the
dominant mode. In the subsequent two years, the fundamental-mode oscillations increased in strength, while the amplitude of the first-overtone mode decreased in 2003 and slightly increased in 2004. In the years 2002-2004 both pulsation periods remained constant within the uncertainties.

The phenomenon of mode switching accelerated in 2005, thus the light curve obtained in that year was divided into three parts. The time spans of each part are provided in different panels of Fig. 3. One can see a rapid increase of the fundamental-mode amplitude and decrease of the first-overtone amplitude. By the end of 2005, the first-overtone mode disappeared completely. At the same time, the fundamental-mode period noticeably changed, namely increased from 0.409486 d to 0.409606 d.

In Fig. 4, we demonstrate the amplitude variations during the mode switching. Unfortunately, in the 2006 season, when OGLE-BLG-RRLYR-12245 probably stabilized as a fundamental-mode pulsator, OGLE project collected only two observing points at the beginning of the season (in February). However, these two points can be phased with the RRab light curve observed from 2010 by the OGLE-IV survey, assuming a pulsation period of 0.409969 d – only slightly shorter then the period observed today: 0.409975 d. Taking this into account, in Fig. 4 we assumed that the amplitude of the fundamental mode reached the final value at the beginning of 2006.
4. Discussion

OGLE-BLG-RRLYR-12245 is the second, after V79 in M3 (Clement et al. 1997), RR Lyrae star where the transition from double- (F+1O) to mono- (F) mode pulsation was observed, and the first one for which we had the opportunity to follow in detail this process. The OGLE time-series data confirm suggestions that changes in double-mode RR Lyr stars may occur in a one-year time-span (e.g. Clement et al. 1997, Clementini et al. 2004). Clementini et al. (2004) mentioned a number of RRd stars showing change of the dominant mode from usual 1O to F. Although we do not know (except for V79) whether ultimately the 1O mode will disappear, it seems natural to include all these objects together with our star in one class.

Following van Albada and Baker (1973) seminal idea, the type of RR Lyr star pulsation is being linked to evolution along the horizontal branch. Stars evolving in the blueward direction in the H-R diagram pass successively through the F-mode, either-or (EO), and 1O-mode domains of the instability strip. Those evolving redward stars pass these domains in the reverse order. In the EO domain, the choice of the pulsation mode depends on the direction of evolution. The Osterhoff dichotomy is thought to arise from this dependence. Although the cause of double mode pulsations is still debated (see e.g. Szabó et al. 2004, Smolec and Moskalik 2010) there is agreement that they occur in the EO domain. This also agrees with the positions of RRd pulsators in the period–luminosity diagrams for Magellanic Clouds (Soszyński et al. 2009, 2010).

It is possible that the event observed in OGLE-BLG-RRLYR-12245 is connected with crossing the EO/F boundary during the redward evolution. A significant growth of the F-mode amplitude may occur with the rate similar to the linear growth rate which may be faster than 1/d. However, the 6 × 10^{-5} d/yr rate period increase, inferred from numbers given in Fig.1, is by more than two orders of magnitude higher than the evolutionary rate (see e.g. Le Borgne et al. 2007). The most likely cause of the period increase is a nonlinear shift resulting from the increase of the pulsation amplitude.

Clement et al. (1997) used the systematic growth of the F-mode and decline 1O-mode in two RRd stars in M3 as an evidence for the redward evolution. However, the behavior of one of them (V79) turned out more complicated. According to Goranskij et al. (2010), who made use of old photographic data, the star was an F-mode pulsator between 1895 until 1992. Then, it switched quickly to F+1O pulsation, which lasted to 2007, when the star became again a pure F-mode pulsator. Such a behavior cannot be caused by consecutive crossings of the F/EO and EO/F boundaries. They came too soon one after another. In the pure F-mode phases, pulsation in this star exhibits fast changes. Before 1992, the period of V79 varied significantly and for a short time in 1992 the star stopped to show any detectable pulsation. In data taken after 2007, the Blazkho-type modulation was found in V79. As we may see in Fig. 1, the pulsation amplitude in OGLE-BLG-RRLYR-12245 does not show any changes in the F-mode phase.
Goranskij et al. (2010) blamed the peculiarities of V79 pulsation to resonances between different radial modes. This is possible. There are numerous examples of dynamical systems where resonances lead complicated behaviors without external cause. Buchler and Kolláth (2011) suggested that the 9:2 resonance between F- and 9O-modes is responsible for the Blazkho effect. The possibility that the occurrence of RRd pulsators in the EO domain is due to the \(2\nu_{1O} = \nu_F + \nu_{2O}\) has been already mentioned by Soszyński et al. (2011). The loci of this resonance in the Petersen diagram are depicted in Fig. 2. We can see there that the model of OGLE-BLG-RRLYR-12245 lies very close to the resonance center. We do not know whether the switching between the RRd and RRab pulsation type is due to this or any other resonance.

For our star, the interpretation of the mode switching as a consequence of passing through the EO/F boundary during the evolution across the instability strip cannot be excluded. However, it seems more likely that this phenomenon results from the specific development of the instability in the EO domain. In the similar manner the Blazkho effect may arise in the F domain and fast period changes found in many RRc stars (e.g., Jurcsik et al. 2001). Complex variations in time do not need external cause nor do they require resonances. The Lorentz strange attractor is the most famous example. However, looking for the necessary conditions for various forms of pulsation remains a valid task. These conditions may help us explain why only 0.5% of the Galactic bulge RR Lyr stars are double-mode pulsators (Soszyński et al. 2011), while in other environments this percentage is much higher. For example, in the Large and Small Magellanic Clouds RRd stars represent, respectively, 4% and 10% of the total sample of RR Lyr stars (Soszyński et al. 2009, 2010). Maybe we will understand why in spite of much larger number of RRc stars we have not yet seen the RRc/RRab mode switching? Furthermore, if the \(2/P_{1O} = 1/P_F + 1/P_{2O}\) resonance is indeed the condition for double-mode pulsation we get a new constrain on the star parameters.

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