Two unusual, radially pulsating stars

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We present the results of pulsation modelling of two unusual radially pulsating stars OGLE-BLG-T2CEP-279 and OGLE-BLG-RRLYR-02792. The former variable is the first BL Her-type star showing the period doubling effect. The second variable is a member of well-detached eclipsing binary system and the first member of a new class of variable stars that mimic RR Lyrae pulsation, but have unusually small masses.

1 Introduction

Massive photometric sky surveys, such as Optical Gravitational Lensing Experiment (OGLE; Udalski et al., 2008), led to the discovery of thousands of classical pulsators: RR Lyrae stars and Cepheids. They also provide the best opportunity to search for rare and new phenomena, like classical pulsators in eclipsing binary systems or variables/phenomena predicted on theoretical grounds, but not observed yet. In this paper we briefly describe two such interesting objects. The first star, OGLE-BLG-T2CEP-279 is a type-II Cepheid of BL Her type, with pulsation period, $P \approx 2.4\,$d. However, the light variation cycle repeats after $2P$ – the star shows a clear period doubling effect, which manifests as alternations of brighter and dimmer maxima. The effect is characteristic for longer period, more luminous type-II Cepheids of RV Tau type. Non-linear radiative models of Buchler & Moskalik (1992) predicted the existence of period doubling effect also in BL Her-type stars, with periods in a range 2.0–2.6 d. The discovery of OGLE-BLG-T2CEP-279 by Soszyński et al. (2011) and detailed analysis of Smolec et al. (2012) confirmed this prediction. Modelling of the star is briefly described in Section 2.

The second star, OGLE-BLG-RRLYR-02792, is a member of a well detached eclipsing binary system. Its pulsation period, $P = 0.627\,$d, and light variation resemble that observed in fundamental mode RR Lyrae stars. Interestingly, the analysis of the system by Pietrzyński et al. (2012) revealed its unusually small mass, $0.26\mathrm{M}_\odot$, roughly half of what is expected for RR Lyrae pulsator. The star is believed to be a product of mass transfer during the evolution of binary system. Pulsation models for the star are presented in Section 3.

All models discussed in this paper were computed with non-linear, convective pulsation code described in detail in Smolec & Moskalik (2008).

2 OGLE-BLG-T2CEP-279 – first BL Her star with period doubling

BL Her stars are a subgroup of type-II Cepheids. They are regular pulsators, pulsating in the fundamental mode, with periods between 1 and 4 d. In the radiative models of these stars, with periods between 2.0 and 2.6 d, Buchler & Moskalik (1992) found

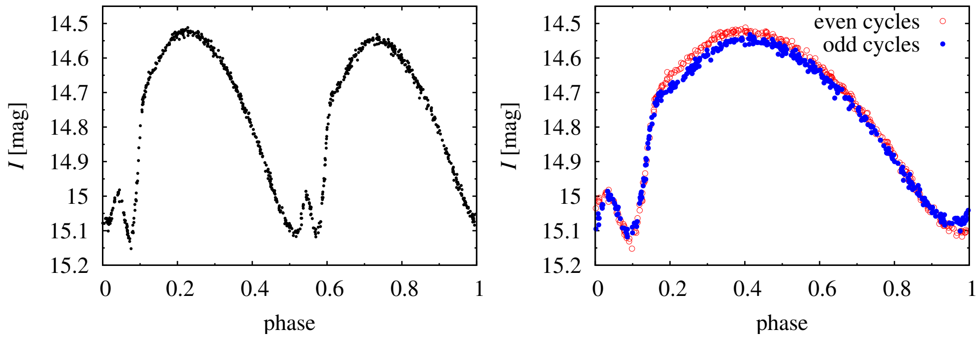

Fig. 1: I-band light curve of OGLE-BLG-T2CEP-279. In the left panel data was phased with twice the pulsation period. In the right panel we demonstrate the period doubling effect folding the data with pulsation period, but plotting the even/odd pulsation cycles with different colors and symbols.

a period doubling effect. Its origin was traced to the half-integer resonance between the fundamental mode and the linearly damped first overtone, $3P_{1O} = 2P_{F}$. The resonant mechanism leading to such behaviour was described by Moskalik & Buchler (1990). Since the period doubling effect detected in the models was robust, Buchler & Moskalik predicted its further discovery. It took 20 years however, till the first period-doubled BL Her star was found (Soszyński et al., 2011). The light curve of the star is plotted in Fig. 1. The effect is not very strong and is best visible when even and odd pulsation cycles are over-plotted (right panel). In the frequency spectrum, signal at subharmonic frequencies is clearly detected, which is characteristic for period doubling.

In Smolec et al. (2012) we modelled the light variation of the star with convective pulsation hydrocodes (Smolec & Moskalik, 2008). We computed a large grid of models along a line of constant period, equal to the pulsation period of the star, assuming different masses, luminosities and metallicities. Our goal was to reproduce the light variation as closely as possible, with the focus put on reproducing the pulsation amplitude and amplitude of the alternations.

Light curves of our best models are plotted in the left panel of Fig. 2. All these models have the same metallicity, $Z = 0.01$, but three different masses, 0.5 $M_\odot$, 0.55 $M_\odot$ and 0.6 $M_\odot$. Based on pulsation calculations only we cannot pick the best model. Fortunately, all three models are located at nearly the same place in the Hertzsprung-Russel (HR) diagram, Fig. 2 right panel. Hence, confrontation with stellar evolution calculation allows to choose the best model, which is clearly model A, of the lowest mass.

The model calculations confirmed that the 3:2 resonance is essential for the period-doubling effect observed in OGLE-BLG-T2CEP-279.

3 OGLE-BLG-RRLYR-02792 – Binary Evolution Pulsator

OGLE-BLG-RRLYR-02792 is the first member of new class of variable stars, Binary Evolution Pulsators (or BEPs). Evolutionary models show that it evolved from a 1.4 $M_\odot$ star, member of a close binary system with initial orbital period of 2.9 days (Pietrzyński et al., 2012). Because of mass exchange, now it has only 0.26 solar masses and pulsates with a single period of 0.627 days. Its light and radial velocity curves,

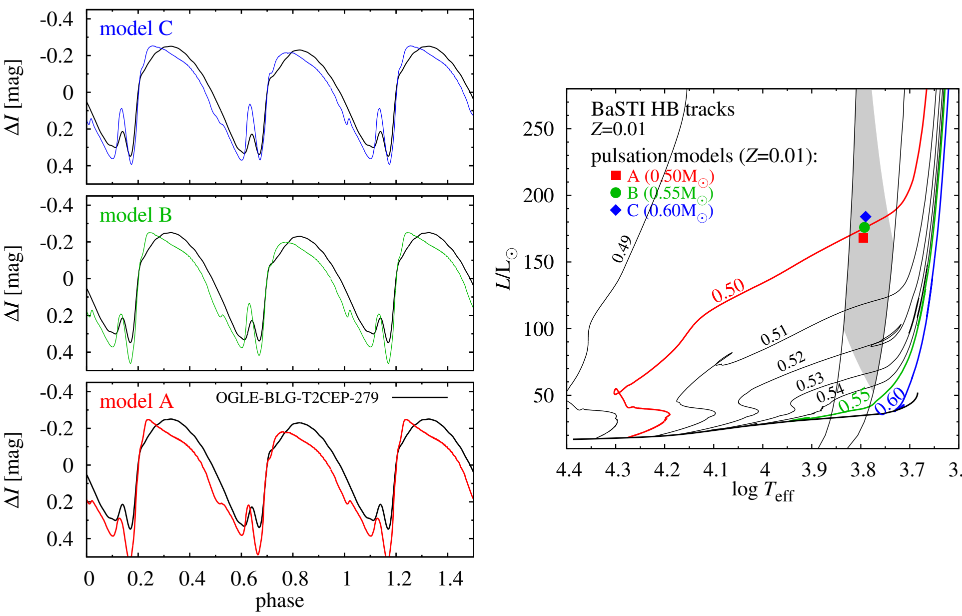

Fig. 2: Light curves for the three best pulsation models for OGLE-BLG-T2CEP-279 (left panel). Comparison with the BaSTI stellar evolutionary tracks (Pietrinferni et al., 2006, right panel) allows to rule out models B and C.

plotted in Fig. 3, mimic that of RR Lyrae star pulsating in the fundamental mode, except for the bump in the middle of the ascending branch of the radial velocity curve.

Detailed modelling of the star is presented in Smolec et al. (2013). Models prove that it is a fundamental mode pulsator driven by the classical kappa mechanism. We computed a grid of non-linear models along a line of constant period ($P = 0.627\,\mathrm{d}$) with fixed mass (0.26 $\mathrm{M}_\odot$) and varying luminosity and chemical composition. Then, we selected the models that reproduce the light and radial velocity curves of OGLE-BLG-RRLYR-02792 best. The comparison was done using the lowest order Fourier decomposition parameters. Independent of chemical composition (and adopted parameters of the turbulent convection model) the best models fall within a narrow

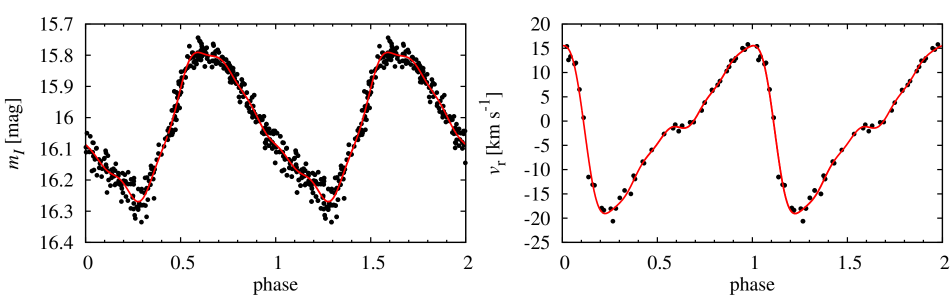

Fig. 3: Disentangled light (left) and radial velocity (right) curves of OGLE-BLG-RRLYR-02792.

luminosity ($31 - 36$ $L_\odot$) and effective temperature ($\sim 6850 - 7050$ K) range, at the blue edge of the instability strip. The best agreement between the model and observed curves is obtained for metal rich model depicted in Fig. 4. In the right panel of the figure we show its location in the HR diagram (diamond). The model reproduces both light and radial velocity curves very well. In particular, the bump in the middle of the ascending branch of the radial velocity curve is reproduced. The bump is caused by the 2:1 resonance between the fundamental mode and the second overtone $P_F/P_{2O} = 2:1$ – the same resonance that shapes the Hertzsprung bump progression in classical Cepheids (see e.g. Buchler et al., 1990). Loci of this resonance is plotted with dotted line in the right panel of Fig. 4. Indeed, model sequence computed along a line of constant period, and hence with different P_{2O}/P_F ratios, show a prominent bump progression as illustrated in Fig. 5.

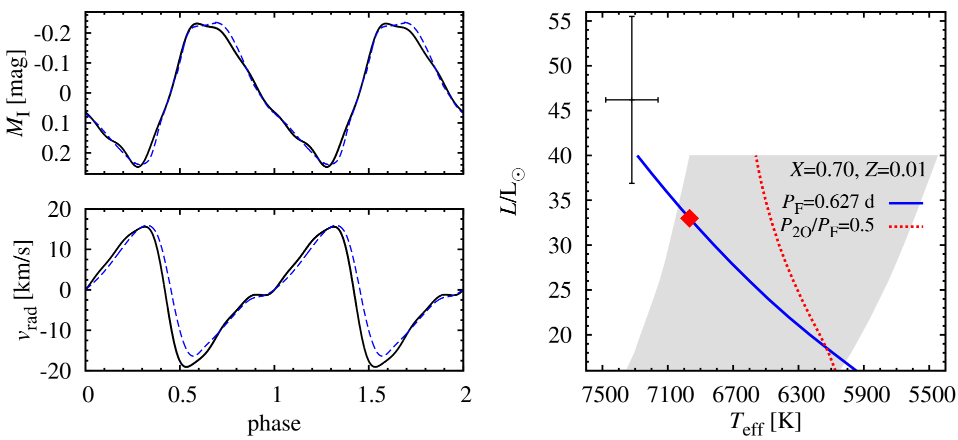

Fig. 4: Left: light and radial velocity curves for the best hydrodynamic model (dashed blue) compared with observations (black, Fourier fit to observational data). Right: Location of the best model in the HR diagram (diamond) confronted with parameters of OGLE-BLG-RRLYR-02792 derived from analysis of eclipsing system (cross).

In the right panel of Fig. 4 we also show the location of OGLE-BLG-RRLYR-02792 in the HR diagram, as derived from the analysis of eclipsing system. It is located outside the instability strip. The effective temperature is higher by 350 K than in our best matching model. We note however, that effective temperature of OGLE-BLG-RRLYR-02792 estimated by Pietrzyński et al. (2012) relies on the assumed effective temperature of the secondary component – 5000 K – a typical temperature for a 1.67 $M_\odot$ giant, but not an actual measurement. A slight decrease of the secondary's temperature (by ~ 150 K) strongly improves the agreement between our best model and observations.

4 Summary

Both OGLE-BLG-T2CEP-279 and OGLE-BLG-RRLYR-02792 are very interesting pulsators, first members of new classes of pulsating stars, period-doubled BL Her stars, and binary evolution pulsators. Modelling of these stars with convective pulsation hydrocodes was successful, the qualitative features of the light (and radial velocity) curves were reproduced and estimation of physical parameters of the stars was

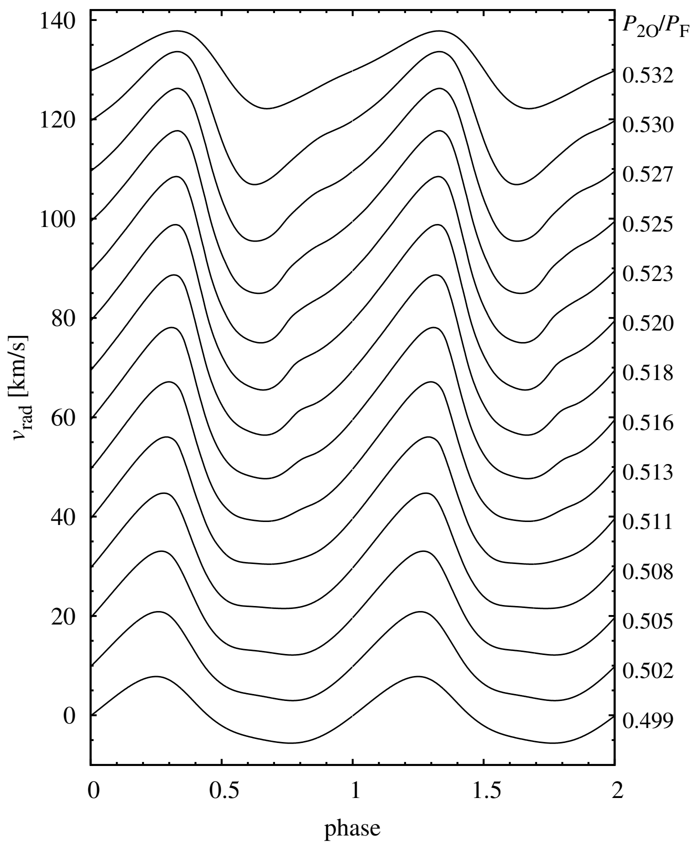

Fig. 5: Bump progression in radial velocity curves in a sequence of BEP models of constant period ($P_F = 0.627\,d$). The linear period ratio P_{2O}/P_F is given on the right hand side of each curve.

possible. In addition, the two stars nicely illustrate the effects of resonances among pulsation modes on stellar pulsation. In OGLE-BLG-T2CEP-279 the half-integer resonance causes the period doubled pulsation, while in OGLE-BLG-RRLYR-02792 the 2:1 resonance is responsible for the appearance of bump in the light/radial velocity curves.

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