Advances in Astronomy and Space Physics, **2**, 135-138 (2012)

Binary evolution pulsating star – new evolutionary channel to produce RR Lyr-like pulsations

*P. Karczmarek**

Centre for Astronomy, Nicolaus Copernicus University, 11 Gagarina st., 86-100 Toruń, Poland

In 2011 a promising candidate for an RR Lyrae star in an eclipsing binary system was found. Till that time not even one case of RR Lyrae star in a binary system has been known. The pulsator's mass is $0.26\,M_\odot$ which is not enough to burn helium in the core, as RR Lyrae stars do. The presence of a more massive companion is a clue that the mass transfer had to occur in the past. Therefore, Binary Evolution Pulsating (BEP) star, while having RR Lyr-like light curve, has completely unlike internal structure. The bulk of the star's mass was lost during the red giant phase due to mass transfer and the partially degenerated helium core with thin hydrogen burning shell was revealed. The BEP object has been captured inside the instability strip (IS) in the RR Lyrae area and thus it is confused with classical RR Lyrae pulsators. Therefore, the BEP star is the evidence of a new evolutionary channel to produce RR Lyr-like oscillations. In simulations made with `StarTrack` code we trace the evolution of a sample of binaries and examine properties of the system required for pulsation phase to occur. We suggest that the stars created via this new evolutionary channel can in part explain the existence of UV up-turn, low-mass C-O WD and He WD.

Key words: stars: variables: RR Lyrae — binaries: eclipsing — stars: evolution

INTRODUCTION

Eclipsing binaries are perfect stellar laboratories to determine the most important stellar parameters: age, mass, radius, metallicity. The light curve and radial velocities analysis of binary components now provide the stellar parameters with the accuracy of 1% [1]. Moreover, thanks to pulsating stars in eclipsing binaries, the problem of dynamical mass of the classical Cepheids was solved – the result was in a better agreement with the predictions of the stellar pulsation theory than the stellar evolution one [6]. Determination of the parameters of other types of eclipsing pulsators, as δ Scuti stars or classical Cepheids, improves the understanding of stellar physics and imposes the constraints on the key stellar parameters. In case of standard candles, it allows for a better calibration of the cosmic distances. The growing number of discoveries of the eclipsing pulsating stars is being reported nowadays, yet no RR Lyrae star has been found.

THE DISCOVERY

In 2011, Soszyński et al. [8] observed an eclipsing binary with the RR Lyrae component, named OGLE-BLG-RRLYR-02792, with an orbital period $P_{\rm orb} = 15.24$ d and the pulsation period $P_{\rm pul} = 0.627$ d. The method used to untangle the pulsation and eclipse curves is based on fitting a function to the data via the Fourier series. The program designed for this task finds the best fit of the light curve phased with pulsational period (with already removed "eclipse points") to the data, subtracts the newly-found function from the light curve which contains all points ("eclipse points" present). Subtraction eliminates the pulsation variability and retains only eclipses.

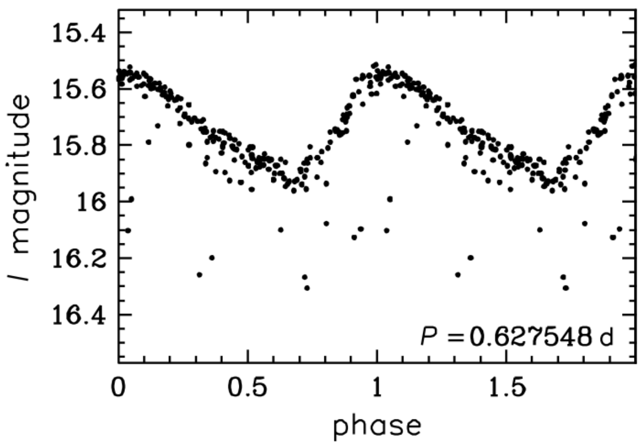

Fig. 1: Pulsational I-band light curve of the primary component of the binary system OGLE-BLG-RRLYR-02792, folded on a pulsation period of 0.627548 days. The shape of the light curve is mimicking that of a classical RR Lyr star. The outlier points are responsible for the eclipsing variability. The figure excerpted from [8].

*paulina.karczmarek@astri.uni.torun.pl

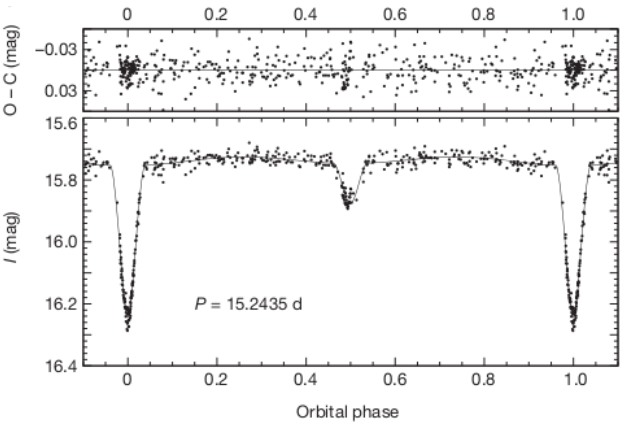

Fig. 2: Orbital I-band light curve (617 epochs collected over 10 years) of the binary system OGLE-BLG-RRLYR-02792, after removal of the intrinsic brightness variation of the pulsating component (data points), together with the solution (solid line), as obtained with the 2007 version of the standard Wilson-Devinney code [9, 10]. Top panel: the residuals of the observed magnitudes from the computed orbital light curve. The figure excerpted from [7].

Table 1: Orbital and physical parameters of the OGLE-BLG-RRLYR-02792 system, together with their uncertainties as obtained from the modelling of the spectroscopic and photometric data. The table excerpted from [7].

Parameter[a]	Primary (pulsating)	Secondary
M [$M_\odot$]	0.261 ± 0.015	1.67 ± 0.06
R [$R_\odot$]	4.24 ± 0.24	4.27 ± 0.31
$T_{\rm eff}$ [K]	7320 ± 160	5000 ± 150
a [$R_\odot$]	32.20 ± 0.32	
$P_{\rm orb}$ [d]	15.24350 ± 0.00021	
$P_{\rm pul}$ [d]	0.627548 ± 0.000008	
$\mathrm{d}P/\mathrm{d}t$	-2.3×10^{-8}	
e	0.0072 ± 0.0029	

[a] The parameters are as follows: stellar mass, stellar radius, effective temperature, orbit size, orbital period, pulsational period, rate of period change, eccentricity.

Figs. 1 and 2 give the general view on the star's variability. Collected data was carefully analysed by Pietrzyński et al. [7] to determine the orbital and physical parameters of the system (Table 1) and the type of pulsations using the Fourier parameters. All indicators: the Fourier parameters, the pulsational period and the location on Hertzsprung-Russel (HR) diagram, implied with no doubts that the pulsating component is RR Lyrae star but the pulsator's mass was not enough (0.26 $M_\odot$) for the star to undergo the helium flash and thus to burn helium in the core, as it is usually takes place in canonical RR Lyrae stars. The presence of the companion could explain the troublesome mass of the pulsating component. In the past the system has undergone the mass transfer episode and as a result the donor has stripped its almost entire hydrogen envelope off revealing the hot helium core. The physical properties of the pulsator happen to place it in the same instability strip (IS) of the HR diagram occupied by RR Lyrae stars. It is noteworthy that the pulsations were generated not as a result of the single star evolution but due to the evolution of the binary system, therefore the new type of binary star gained the name Binary Evolution Pulsator (BEP). BEPs are considered to pass the IS two orders of magnitude faster than canonical RR Lyrae stars, and always towards higher temperatures.

SIMULATIONS

The simulations made with the `StarTrack` code (manual to the code is available in [2]) enables to track the evolution of the binary from Zero Age Main Sequence (ZAMS) till the white dwarf (WD) phase. If at any time of the evolution, any of two components crosses the RR Lyrae instability strip while having the mass $M < 0.5\,M_\odot$, this object at this particular stage of its evolution is called BEP and initial parameters of the binary system (masses of both components, orbital period) are collected. The RR Lyrae instability area is determined in the terms of effective temperatures ($T_{\rm eff}$) and luminosities (L) as follows [3]:

$$\begin{gathered} 16\,L_\odot < L < 100\,L_\odot \\ 5000\,\mathrm{K} < T_{\rm eff} < 7400\,\mathrm{K}. \end{gathered} \tag{1}$$

Two different kinds of BEP objects crossing the IS were found:

(i) $M \lesssim 0.3\,M_\odot$. The primary component starts its evolution as a main sequence (MS) star and ends as He WD after 5-7 Gyrs. While being red giant (RG) it transfers the mass to the companion (MS star). After the mass transfer ended, primary component enters the Horizontal Branch without going through the helium flash. The luminosity remains the same as the radius decreases and the temperature increases. The primary component pulsates as BEP while crossing the IS in the time interval of about a million years. The secondary component goes through the RG phase, expands and overfills its Roche Lobe. The unstable mass transfer to the primary leads to the common envelope episode. At the final stage the binary consists of two helium white dwarfs. Fig. 3 shows the evolutionary track of the primary.

(ii) $0.3\,M_\odot \lesssim M \lesssim 0.5\,M_\odot$. The primary component starts its evolution as a MS star and ends as C-O WD after 1.5-2.5 Gyrs. While being RG it transfers the mass to the companion (MS star) until reaches the tip of the RG branch and ignites helium in the core. Then the mass transfer ends and the primary descend the RG branch and resides in the Horizontal Branch. The luminosity remains the same as the radius decreases and the temperature increases. The primary pulsates as BEP while crossing the IS in the time interval of about a million years. The secondary component goes through the Red Giant phase, expands and overfills its Roche Lobe. The unstable mass transfer to the primary leads to the common envelope episode. At the final stage the binary consists of two C-O WD or the C-O and hybrid WD. Fig. 4 shows the evolutionary track of the primary.

The first (i) "low-mass" case is available for initial parameters: the mass of the primary and the orbital period, in ranges

$$\begin{array}{c} 0.4\ \mathrm{M}_\odot \lesssim M_0 \lesssim 2.0\ \mathrm{M}_\odot \\ 1.4\ \mathrm{d} \lesssim P_0 \lesssim 9.0\ \mathrm{d}, \end{array} \quad (2)$$

while the (ii) "high-mass" case occurs when

$$\begin{array}{c} 2.0\ \mathrm{M}_\odot \lesssim M_0 \lesssim 3.0\ \mathrm{M}_\odot \\ 4.0\ \mathrm{d} \lesssim P_0 \lesssim 18.0\ \mathrm{d}. \end{array} \quad (3)$$

The constraints are fluent and require further examinations to be estimated more accurate.

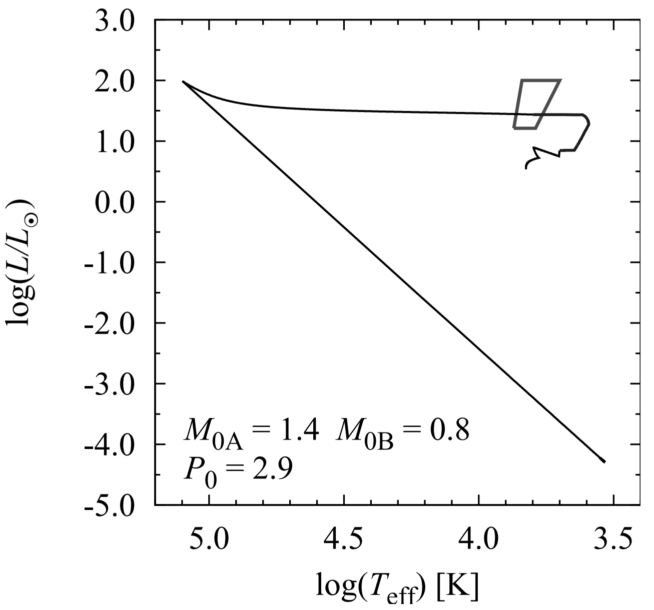

Fig. 3: Evolutionary track of the primary component which undergoes the BEP phase having the mass $M \lesssim 0.3\,\mathrm{M}_\odot$. Thick line on the evolutionary path indicates the mass transfer phase. The trapezium shaped area is the IS of RR Lyrae stars. The initial masses and period of the binary are given.

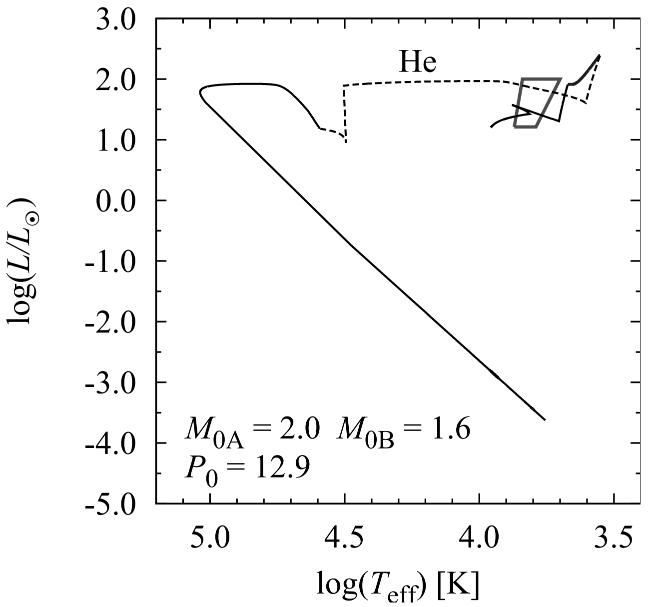

Fig. 4: Evolutionary track of the primary component which undergoes the BEP phase having the mass $0.3\,\mathrm{M}_\odot \gtrsim M \gtrsim 0.5\,\mathrm{M}_\odot$. Thick line on the evolutionary path indicates the mass transfer phase. Dashed line shows the helium core burning stage which starts on the tip of the RG branch just after the mass transfer episode ends. The trapezium shaped area is the IS of RR Lyrae stars. The initial masses and period of the binary are given.

RESULTS AND CONCLUSIONS

Long time-base observations of stars inside the IS allow to determine the rate of pulsation period change $\mathrm{d}P/\mathrm{d}t$. Because the star is moving at a constant luminosity across the IS towards higher (lower) temperatures, its radius should become smaller (larger) and therefore its pulsation period should steadily decrease (increase). For classical RR Lyrae stars $|\mathrm{d}P/\mathrm{d}t_{\mathrm{RR}}| \approx 10^{-11} - 10^{-9}$ (in alternative notation $0.01 - 1.0$ d/Myr) [5] and can be positive or negative as they cross IS two times, first going towards lower temperatures, next – towards higher temperatures. BEPs, in turn, cross the IS only once, always towards higher temperatures, that means $\mathrm{d}P/\mathrm{d}t_{\mathrm{BEP}} < 0$ and as they are moving rapidly, $-2.2 \times 10^{-8} \lesssim \mathrm{d}P/\mathrm{d}t_{\mathrm{BEP}} \lesssim -5.5 \times 10^{-9}$ (equals to $\mathrm{d}P/\mathrm{d}t_{\mathrm{BEP}} \approx 2 - 8$ d/Myr). This distinct difference can be used to distinguish BEPs from RR Lyrae stars, especially in case when the eclipses are not seen in a system.

BEP is just a part of life of the object which thereafter turns into He WD or C-O WD (depending on the initial mass). Such evolution can in part explain the abundance of He WD and low-mass C-O WD. The single star simulations show that these objects can be created from the red giant provided artificially high mass loss [4]. Simulations with `StarTrack` code performed for the binary case show that the high mass loss rate is fully explained by the mass transfer that happens exactly in the RG phase. As the result, the hot (helium or carbon) core stripped from hydrogen envelope tends to radiate in short-wavelength spectrum band. To sum up, the binary scenario accounts for existence of He WD, C-O WD and UV up-turn.

The contamination of RR Lyrae stars by BEPs was estimated to be 0.2% [7]. This means that for 1000 objects classified as RR Lyrae stars, two can actually be BEPs, only showing the RR Lyr-like light curve. Nevertheless, detailed calculations are required to confirm this number. The higher percent of contamination might increase the observed spread in luminosity of the RR Lyrae stars and affect distance measurements based on them. As the BEPs are much younger than the RR Lyrae stars, the age of old galaxies and globular clusters hosting them might be redefined as younger. It is also possible that the contamination by BEPs may concern not only the RR Lyrae stars but also the other pulsators in the IS, like classical Cepheids or δ Scuti stars.

The discovery of OGLE-BLG-RRLYR-02792 points to the new evolutionary channel to create RR Lyr-like oscillations. This encourages to improve both evolutionary and pulsation theories. The priority task is to proceed tracking pulsating binaries and to double check the stellar catalogues which can already contain the "fake" RR Lyrae stars and other binaries. Finally, it is a chance to enrich the evolutionary and pulsation codes with new aspects of binary evolution and to calibrate them for better predictions of stars' behaviour.

ACKNOWLEDGEMENT

It is a pleasure to thank G. Pietrzyński for supporting this project. I am grateful to K. Belczyński for sharing the `StarTrack` code and for many useful and valuable instructions. The research presented here was supported by the TEAM subsidies of the Foundation for Polish Science (FNP).

REFERENCES

[1] Andersen J., Clausen J. V., Nordstrom B., Tomkin J. & Mayor M. 1991, A&A, 246, 99
[2] Belczynski K., Kalogera V. & Bulik T. 2002, ApJ, 572, 407
[3] Bono G., Caputo F., Cassisi S., Incerpi R. & Marconi M. 1997, ApJ, 483, 811
[4] Castellani M., Castellani V. & Prada Moroni P. G. 2006, A&A, 457, 569
[5] Kunder A., Walker A. S., Peter B. et al. 2011, AJ, 141, 15
[6] Pietrzyński G., Thompson I. B., Gieren W. et al. 2010, Nature, 468, 542
[7] Pietrzyński G., Thompson I. B., Gieren W. et al. 2012, Nature, 484, 75 2
[8] Soszyński I., Dziembowski W. A., Udalski A. et al. 2011, Acta Astronomica, 61, 1
[9] Van Hamme W. & Wilson R. E. 2007, ApJ, 661, 1129
[10] Wilson R. E. & Devinney E. J. 1971, ApJ, 166, 605