RR–Lyrae–type pulsations from a 0.26–solar–mass star in a binary system

G. Pietrzyński1,2, J. B. Thompson3, W. Gieren4, D. Graczyk1, K. Śtepien2, G. Bono4,5, P. G. Prada Moroni6,7, B. Pilecki1,2, A. Udalski2, I. Soszyński2, G. W. Preston1, N. Nardetto8, A. McWilliam1, I. U. Roederer9, M. Górski1,2, P. Konorski1,2 & J. Storm9

RR Lyrae pulsating stars have been extensively used as tracers of old stellar populations for the purpose of determining the ages of galaxies, and as tools to measure distances to nearby galaxies1–3. There was accordingly considerable interest when the RR Lyrae star OGLE-BLG-RRLYR-02792 (referred to here as RRLYR-02792) was found to be a member of an eclipsing binary system3, because the mass of the pulsator (hitherto constrained only by models) could be unambiguously determined. Here we report that RRLYR-02792 has a mass of 0.26 solar masses (M☉) and therefore cannot be a classical RR Lyrae star. Using models, we find that its properties are best explained by the evolution of a close binary system that started with 1.4M☉ and 0.8M☉ stars orbiting each with an initial period of 2.9 days. Mass exchange over 5.4 billion years produced the observed system, which is now in a very short-lived phase where the physical properties of the pulsator happen to place it in the same instability strip of the Hertzsprung–Russell diagram as that occupied by RR Lyrae stars. We estimate that only 0.2 per cent of RR Lyrae stars may be contaminated by systems similar to this one, which implies that distances measured with RR Lyrae stars should not be significantly affected by these binary interlopers.

Using high-resolution spectra obtained with the MIKE spectrograph at the 6.5-m Magellan Clay telescope at the Las Campanas Observatory in Chile, and the UVES spectrograph attached to the 8.2-m VLT telescope of the European Southern Observatory on Paranal, we confirmed that RRLYR-02792 is a true physical, well detached, double-lined eclipsing binary system very well suited for deriving the masses of its two components with very high accuracy.

Analysis of the spectroscopic and photometric observations (Figs 1 and 2) results in the determination of the astrophysical parameters of our system presented in Supplementary Table 1. Realistic errors of the derived system parameters were determined using Monte Carlo simulations. The resulting masses of the components turned out to be very unexpected. The dynamical mass of the RR Lyrae component, (0.261 ± 0.015)M☉ is much smaller than the mass required for helium ignition, and therefore completely at odds with the predictions of all theoretical models of RR Lyrae stars5–7. Moreover, if the pulsating component of RRLYR-02792 (star 1, temperature T1) were indeed a classical RR Lyrae star, as suggested by its light curve and pulsation period, the nature of the more massive, cooler (at T1 = 6,000 K, T2 = 0.68 × T1) and fainter (by some two magnitudes in the V band) secondary component (star 2) would be extremely unusual. Assuming a typical temperature for the RR Lyrae star of 6,000 K, the temperature of the static secondary component (T2) would be only about 4,100 K, much too cool for a giant star with M2 = 1.67M☉ (whose temperature is expected to be close to 5,000 K).

A clue comes from the relatively short orbital period of 15.24 days, which suggests that mass exchange between the two components should have occurred during the evolution of this system. Inspired

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1Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile. 2Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warsaw, Poland. 3Carnegie Observatories, 813 Santa Barbara Street, Pasadena, California 91101-1292, USA. 4Dipartimento di Fisica ‘E. Fermi’, Università di Pisa, Largo B. Pontecorvo, 3, I-56127, Pisa, Italy. 5INFN, Sezione di Pisa, Largo B. Pontecorvo, 3, I-56127, Pisa, Italy. 6Laboratoire Lagrange, UMR7293, UNS/CNRS/OCA, 06300 Nice, France. 7Leibniz Institute for Astrophysics, An der Sternwarte 16, 14482 Potsdam, Germany.
by this possibility, we calculated a series of models for Algol-type binary systems\(^8,9\). We found that a system which initially contained two stars with \(M_1 = 1.4 M_\odot\) and \(M_2 = 0.8 M_\odot\) orbiting each other with an initial period of 2.9 days would, after 5.4 Gyr of evolution, have exchanged mass between the components as classical Algols do, and today would form a system very similar to RRLYR-02792 (with \(M_1 = 0.268 M_\odot\) and \(M_2 = 1.665 M_\odot\), and orbital period \(P = 15.9\) days).

We therefore conclude that the primary component of our observed system is not a classical RR Lyrae star with its well-known internal structure. Rather, it is a star that possesses a partially degenerate helium core and a small hydrogen-rich envelope (undergoing shell burning) that has lost most of its envelope during the previous red giant branch phase to the secondary star due to mass exchange in the binary system. It is now evolving towards the hot subdwarf region on the Hertzsprung–Russell diagram (see Fig. 3 and Supplementary Fig. 2).

The pulsational light curve of such a star very closely resembles that of a classical RR Lyrae star. However, variable stars produced this way are expected to cross the classical pulsational instability region on the Hertzsprung–Russell diagram about 100 times faster than do the RR Lyrae stars. Because the star is moving rapidly at a constant luminosity across the instability strip towards higher temperatures, its radius should become smaller and therefore its pulsation period should steadily decrease. Indeed, using our photometric data we have measured a period decrease of the pulsating component of \((8.4 \pm 2.6) \times 10^{-6}\) d yr\(^{-1}\), which is on average more than two orders of magnitude larger than the period change shown by canonical RR Lyrae stars\(^1\), and therefore strongly supports our interpretation. Moreover, we have detected hydrogen lines in the spectrum of the binary associated with the pulsating primary component (see Supplementary Fig. 1), which

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**Figure 2 | Change of brightness of the binary system caused by the mutual eclipses, and the intrinsic change of the brightness of the primary component caused by its pulsations.**

- **a** Main panel, orbital I-band light curve (617 epochs collected over 10 years) of the binary system 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\(^11,12\). Top panel, the residuals of the observed magnitudes from the computed orbital light curve. **b** Pulsational I-band light curve of the primary component of our binary system, folded on a pulsation period of 0.627496 days. The shape of the light curve is mimicking that of a classical RR Lyrae star. The following final ephemeris for our system was derived from the OGLE photometric data: \(P = 15.24350 \pm 0.00021\) d, \(T_0 = 2,452,108.3161 \pm 0.038\) d (orbital); \(P = 0.627496 \pm 0.000008\) d, \(T_0 = 2,455,000.355 \pm 0.005\) d (pulsation). Adopting the photometric ephemeris, and the mass ratio obtained from the analysis of the spectroscopic data (Fig. 1), we model our spectroscopic and photometric observations using the Wilson-Devinney code. We accounted for the intrinsic photometric variations of the pulsating star in the system by fitting a Fourier series of order 15 to the observations secured outside the eclipses and then subtract the corresponding variations in the eclipses in an iterative way, scaling the obtained fit according to the obtained Wilson-Devinney model.

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**Figure 3 | Positions of the two stars in the RRLYR-02792 binary system on the Hertzsprung–Russell diagram.**

The two stars are shown by filled circles (error bars, 1\(\sigma\)); \(L_\ast\) and \(L_\odot\), stellar and solar luminosity, respectively; \(T_{\text{eff}}\) stellar effective temperature. Solid lines show evolutionary models computed for 1.7, 1.6 and 1.5 \(M_\odot\) stars with the most recent version of the FRANEC evolutionary code adopting updated input physics\(^8\). Current evolutionary models were computed assuming a solar chemical composition (metals, \(Z = 0.0129\); helium, \(Y = 0.274\)). We adopted the recent heavy-element solar mixture\(^8\) and a mixing-length value of \(\alpha = 1.74\). Dashed lines proceeding horizontally from the luminosity axis show evolution of stellar structures with final masses of 0.26 \(M_\odot\) and 0.28 \(M_\odot\), computed by following the standard evolution of a 1.4 \(M_\odot\) structure from the pre-main sequence up to the beginning of the red giant phase. At \(\log\left(L/L_\odot\right) = 0.9\) we applied an enhanced mass loss rate of about \(10^{-7}\) \(M_\odot\) yr\(^{-1}\) until the final masses (that is, 0.26 \(M_\odot\) and 0.28 \(M_\odot\)) were approached. We computed the final evolutionary fate of these structures, at constant mass, down to the cooling phase of He-core white dwarfs\(^9\). The two short vertical dashed lines show the instability strip for typical RR Lyrae stars according to models for a solar chemical composition (\(Z = 0.02, Y = 0.28\))\(^10\), in which the pulsating component of our binary system is located. We adopted 300 K as the uncertainty of the calculated instability strip. Very good agreement between the evolutionary models and the observations is demonstrated.
confirms that the star possesses a hydrogen-rich envelope. In such a scenario, the secondary component is a typical red giant star currently evolving up the red giant branch, increasing its size and luminosity. During its future evolution, our system will turn into a binary system composed of two white dwarfs sharing a common envelope.

We have captured the RRLYR-02792 binary system in a very special and short-lived phase of its evolution, which constitutes just a small fraction ($10^{-4}$) of its current age. The system provides a number of strong observational constraints that have enabled us to track its past evolution unambiguously and in detail, and so discover a new evolutionary channel for the production of binary pulsating stars—these are the inhabitants of the pulsational instability strip on the Hertzsprung–Russell diagram that mimic classical RR Lyrae variables, but have a completely different origin. These low mass pulsating stars could principle increase the observed spread in luminosity of the RR Lyrae stars, hence affecting distance measurements based on them. Our calculations show that among 1,000 RR Lyrae stars one should expect just 2 such stars, so in practice they should not affect distance determinations to galaxies if these are made with relatively large samples of RR Lyrae stars.

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