Revealing a numerous population of double-lined binary Cepheids

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Masses of classical Cepheids of 3 to 11 $M_\odot$ are predicted by theory but those measured clump between 3.6 to 5 $M_\odot$. As a result, their mass-luminosity relation is poorly constrained, impeding our understanding of basic stellar physics and the Leavitt Law. Here we present and summarize the first results of the project to study a new, numerous group of Cepheids in double-lined binary (SB2) systems with the aim to provide their mass determinations in a wide mass interval and learn about their evolution. We analyzed a sample of 41 candidates binary LMC Cepheids spread along the P-L relation and presented evidence that they are in majority accompanied by luminous red giants. In a spectroscopic study of a subsample of 18 brightest candidates, for 17 we detected lines of two components in the spectra, already quadrupling the number of Cepheids in SB2 systems.

1 Introduction

Classical Cepheids are perhaps the most important objects in astrophysics, crucial for various fields of astronomy like stellar oscillations and evolution of intermediate and massive stars, and with the enormous influence on modern cosmology. Since the discovery of the relationship between their pulsation period and luminosity over a century ago (the Leavitt Law, Leavitt & Pickering 1912), the Cepheids are extensively used to measure distances both inside and outside of our Galaxy. The recent local Hubble constant determination accurate to 1.8% (Riess et al., 2021), that shows a significant discrepancy with the value inferred from the Planck data, highly depends on the aforementioned relation.

Although theoretical studies of Cepheids are quite advanced (e.g. Bono et al. 1999, 2005; Valle et al. 2009), our observational data are still very limited. Theory predicts masses of Cepheids in a range of 3–11 $M_\odot$ but their measured masses clump between 3.6 and 5 $M_\odot$, with only one higher but uncertain value of 6 $M_\odot$ (Pilecki et al., 2013, 2018; Gallenne et al., 2019; Evans et al., 2018). This makes the mass-luminosity relation very poorly constrained (Anderson et al., 2016), while it is crucial for the theoretical understanding of the period-luminosity (P–L) relation and the basic stellar physics regarding, e.g. the convection, mass-loss, and rotation. Moreover, the blue loops predicted by the evolution theory are too short to explain the existence of low-mass short-period Cepheids.

Masses in a wider range would be of utmost importance to solve these issues, but we can measure them practically only for Cepheids in spectroscopic double-lined binaries (SB2), for which lines of companions are easily detectable. Unfortunately, such systems are very rare. Most binary Cepheids, and all found in the Milky Way, have an early-type main sequence companion (i.e. with few and broad lines) that is typically 2–5 mag fainter in the V-band, making it extremely hard to determine its velocity and thus the mass of the Cepheid.

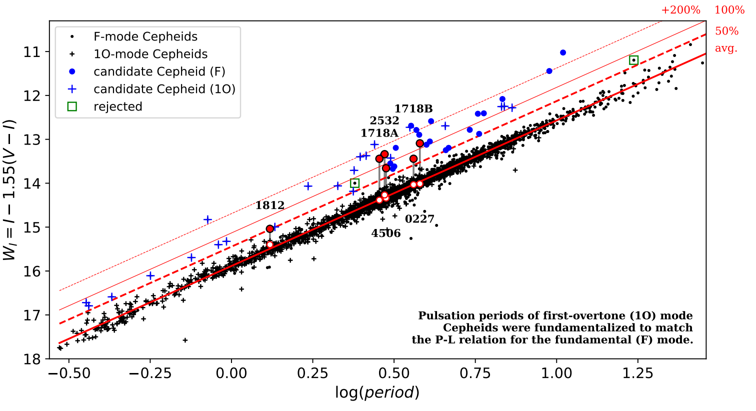

Fig. 1: P–L relation for reddening free Wesenheit index. Filled red circles show known eclipsing binaries with Cepheids, while empty circles mark their brightness without the companion light. Our candidates for binary Cepheids are ≥50% brighter than an average Cepheid for its period. Note that their distribution parallel to the P–L relation advocates strongly against blending by a random star.

One good source for more binary Cepheids would be to look for eclipses, but this solution has two serious limitations. First, only about a half of eclipsing systems with Cepheids are double-lined, and second, the best places to look for them are already examined and we do not expect to find many more such binaries soon. This is why we had to look for another, perspective source that was not yet considered and remained unexplored up to now.

In the first paper of the series (Pilecki et al., 2021) we described such a source highlighting its potential and presented the first results for the Large Magellanic Cloud (LMC) galaxy. Here we summarize these results updating the information whenever obsolete.

2 The project

The basic idea of the project was to look for Cepheids in binary systems, for which lines of both components are present in the spectra. To meet these conditions, one has to find Cepheids accompanied by stars of similar luminosity, and preferentially of late spectral types, i.e. at a subgiant or later stage of evolution. To identify them, we can consider at least three observable features caused by such companions:

- the total observed brightness of a Cepheid should increase significantly
- its photometric pulsation amplitude should decrease
- its color should be either similar or redder

Looking at the period-luminosity diagram for the LMC Cepheids (Fig. 1) one can see that all of the previously confirmed eclipsing giant-giant SB2 systems with Cepheids (Pilecki et al., 2018) lie significantly above the corresponding P–L relation,

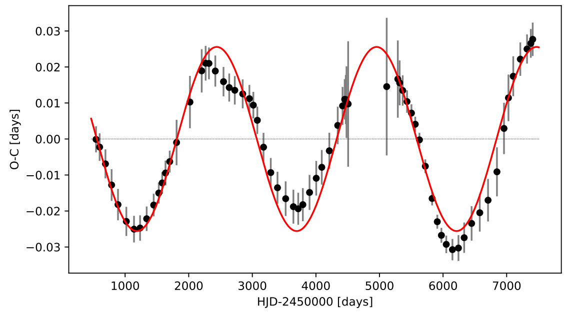

Fig. 2: O-C diagram for one of the SB2 Cepheid candidates. A clear LTTE modulation due to binary motion is present. Red line is the best fit to the Cepheid orbit.

being at least 50% (0.44 mag) brighter than a typical Cepheid for its period. At the same time, their amplitudes are about half of the typical ones for Cepheids with similar periods, and their colors are typical or redder. From the number of eclipsing binary Cepheids we have also estimated how many similar binary Cepheids exist, but have not been detected in the photometric studies due to the lack of eclipses. Assuming random inclinations, we can expect of the order of 50 SB2 systems composed of a Cepheid and a giant companion in a range of orbital periods of 1 to 4 years, i.e. similar to the one for the eclipsing Cepheids.

We investigated the P–L diagram for all the Cepheids from the OGLE catalog (Soszynski et al., 2008) and identified 41 more Cepheids that lie 0.44 mag (4.7σ) above the P–L relation, for which eclipses were not detected (Fig. 1). Virtually all Cepheids selected this way have low amplitudes and colors on average redder than typical by 0.12 mag in $V - I$ index. As stated above, these three features together clearly indicate that such overbright Cepheids have luminous late-type giant companions. This, in turn, makes them perfect candidates for SB2 systems composed of giants, for which lines of all components can be easily detected and their radial velocities (RV) measured.

The Cepheids in this sample are spread all over the P-L relation from 0.26 to 10.5 days. Among them 20 pulsate in the fundamental (F) mode and 21 in the first-overtone ($1O$) mode. Three of the latter are actually double-mode Cepheids pulsating in the second-overtone ($2O$) as well. In Fig. 1 periods of the first-overtone mode Cepheids (P_{1O}) were fundamentalized to match the periods of fundamental mode Cepheids (P_F) using the formula from Pilecki et al. (2021).

3 Results

For the whole sample of 41 Cepheids we performed the analysis of photometric data, including the study of O–C diagrams. We obtained one clear detection of the light travel-time effect (LTTE) due to a binary motion (see Fig. 2) with a period of about 2500 days, and three others for which a periodic ($P_{\rm orb}$ from 700 to 1700 days) behavior was observed but with smaller amplitudes. The binary parameters obtained from the analysis of the best case suggest a high mass ratio and the merger origin of

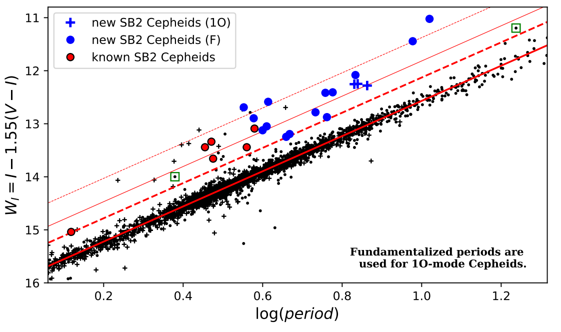

Fig. 3: Similar to Fig. 1 but for periods longer than 1.15 days and showing the newly confirmed Cepheids in SB2 systems. Almost all of them have periods longer than those of the known SB2 Cepheids, spreading up to 10.5 days.

the companion, in similarity to the scenario depicted by Neilson et al. (2015). First spectroscopic observations of this system are consistent with such a model. For one of the systems one eclipse was observed during the whole observation time span of the OGLE project, which makes it a very interesting and valuable object to follow up.

For a subsample of 18 candidates with the longest periods, we performed spectroscopic observations during four consecutive nights using the HARPS spectrograph mounted on a 3.6-meter telescope in La Silla Observatory (ESO). With these observations, for 16 Cepheids, we have detected additional components in the spectra, i.e. lines of stable companions, using the Broadening Function technique (Rucinski, 1999). More details regarding the spectroscopic analysis can be found in Pilecki et al. (2021). Subsequent observations confirmed the presence of a companion for one more candidate from this group resulting in almost 95% efficiency in detecting double-lined binary Cepheids with the presented method. For some objects the orbital motion of the companion has already been detected, which is another and direct evidence of binarity of our candidates.

4 Conclusions

The analysis of spectroscopic data we have collected so far clearly shows that the Cepheids selected as described in Section 2 are indeed double-lined binary systems. This has important implications for the interpretation of period-luminosity relations and for our general knowledge of Cepheids and their evolution. We know now that overbright Cepheids, which were often being rejected as P–L relation outliers, are in great majority Cepheids with red, luminous giant companions. These conclusions can be also likely extended to other pulsating stars with well-defined P–L relations like, for example, Type-II Cepheids or RR Lyrae stars.

With the 17 confirmed candidates, we have already quadrupled the number of Cepheids in spectroscopic double-lined binaries. In Fig. 3 one can see that most of these new Cepheids have periods longer than those of known SB2 Cepheids, spreading up to 10.5 days. The extrapolation of the number of confirmed cases to the whole sample suggests that about 39 new Cepheids in SB2 systems can be expected once all 41 selected objects are studied. This would mean a huge almost 8-fold increase in the number of this type of systems.

In the long run our study will bring firm mass estimates for a large sample of Cepheids, including long-period, high-mass Cepheids for which lack of data is the most severe, and probing the uncertain low-mass end at the same time. A similar stage of evolution of both components implies mass ratios close to one. Any significant deviation from unity will be extremely interesting, indicating a very probable merger event in the Cepheid's past. And this is the only way merger Cepheids can be unambiguously detected (as compared to e.g. dubious chemical composition peculiarities) and characterized. From the analysis of Sana et al. (2012) we can estimate that even 30% of Cepheids may be the product of a merger.

We identified a significant number of similar Cepheid candidates in the Small Magellanic Cloud, which we have already started to observe. First results bring the same conclusions as for Cepheids in the LMC. Moreover, Gaia eDR3 provides sufficient precision to look for such candidates in the Milky Way. Extension of our project to these two galaxies will further increase the number of Cepheids in SB2 systems leading toward an order of magnitude improvement in our knowledge of the physical properties of these interesting pulsators.

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