At the crossroads of astrophysics and cosmology: Period–luminosity relations in the 2020s
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Cepheids with giant companions: A new, abundant source of Cepheid astrophysics

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Abstract. We present a progress report of our project aiming to increase the number of known Cepheids in double-lined binary (SB2) systems from six to 100 or more. This will allow us, among other goals, to accurately measure masses for a large sample of Cepheids. Currently, only six accurate Cepheid masses are available, which hinders our understanding of their physical properties and renders the Cepheid mass–luminosity relation poorly constrained. At the same time, Cepheids are widely used for essential measurements (e.g., extragalactic distances, the Hubble constant). To examine Cepheid period–luminosity relations, we selected as binary candidates Cepheids that are too bright for their periods. To date, we have confirmed 56 SB2 systems, including the detection of significant orbital motions of the components for 32. We identified systems with orbital periods up to five times shorter than the shortest reported period to date, as well as systems with mass ratios significantly different from unity (suggesting past merger events). Both features are essential to understand how multiplicity affects the formation and destruction of Cepheid progenitors and what effect this has on global Cepheid properties. We also present eight new systems composed of two Cepheids (only one such system was known before). Among confirmed SB2 Cepheids, there are also several wide-orbit systems. In the future, these may facilitate independent accurate geometric distance measurements to the Large and Small Magellanic Clouds.

Keywords. Cepheids, binary systems, physical properties, P-L relation

1. Introduction

Classical Cepheids are perhaps the most important objects in astrophysics, given that they are crucial to gain improved physical insights in various fields, including as regards stellar oscillations and the evolution of intermediate-mass and massive stars. They wield enormous influence on modern cosmology. Since the discovery of the relationship between their pulsation period and their luminosity more than a century ago (the Leavitt Law; Leavitt and Pickering 1912), Cepheids have been used extensively to measure distances both within and outside of our Galaxy. The recent local Hubble constant determination accurate to 1.8% (Riess et al. 2022), which shows a significant discrepancy with the value inferred from *Planck* data, depends sensitively on this period–luminosity (P–L) relation.

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

Masses covering a wider range would be of the utmost importance to resolve these issues, but we in practice can measure them 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 (exhibiting few and broad lines) which 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.

One good source for more binary Cepheids would be to look for eclipses, but this solution has three serious limitations. First, such systems are not numerous, because a very specific orbital orientiation is needed for eclipses to occur. Second, according to current statistics, only about half of eclipsing systems involving Cepheids are double-lined, and third, the best places to look for them (the Galactic disk, Magellanic Clouds) have already been examined, and we do not expect many more such binaries to be found there any time soon. Therefore, we decided to look for another possible source that had not yet been considered and remained unexplored.

In the first paper of the series (Pilecki et al. 2021) we described such a source, highlighting its potential, and we presented the first results for the Large Magellanic Cloud (LMC). Here, we present the current stage of the project, providing updates based on new observations and expansion of the sample to the Small Magellanic Cloud (SMC) and the Milky Way (MW).

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 their spectra. To meet these conditions, one has to find Cepheids accompanied by stars of similar luminosity and preferentially of late spectral types, i.e., subgiants or later stages of stellar evolution. To identify such candidates, we considered three observable features caused by such companions. Compared with single Cepheids (or Cepheids with significantly fainter companions), for Cepheids with giant companions we expect:

- their total observed brightness to increase significantly;
- their photometric pulsation amplitude to decrease; and
- their color to be either similar or redder.

Looking at the P–L diagram for LMC Cepheids (Figure 1), we noticed that all previously confirmed eclipsing giant–giant SB2 systems including Cepheids (Pilecki et al. 2018) lie significantly above the corresponding P–L relation, being at least 50% (0.44 mag) brighter than a typical Cepheid for its period. At the same time, their amplitudes are about half the typical ones, and their colors are typical or redder. From the number of known eclipsing binary Cepheids we also estimated how many similar binary Cepheids may exist but have not yet been detected in photometric studies due to a lack of eclipses. Assuming random inclinations, we expected on the order of 50 SB2 systems composed of a Cepheid and a giant companion exhibiting a range of orbital periods from 1 to ∼5 years, i.e., similar to the periods for eclipsing Cepheids.

Indeed, when we investigated the P–L diagram for all Cepheids from the OGLE-3 catalog (Soszyński et al. 2008), we identified 41 additional Cepheids that lie 0.44 mag (4.7σ) above the P–L relation, but for which eclipses were not detected (Figure 1). Virtually all Cepheids selected this way have low amplitudes and colors that are on average redder than typical by 0.12 mag in the $(V - I)$ index. As stated above, these three features together clearly indicate that the overbright Cepheids have luminous, late-type giant companions. This, in turn, made them perfect candidates for SB2 systems

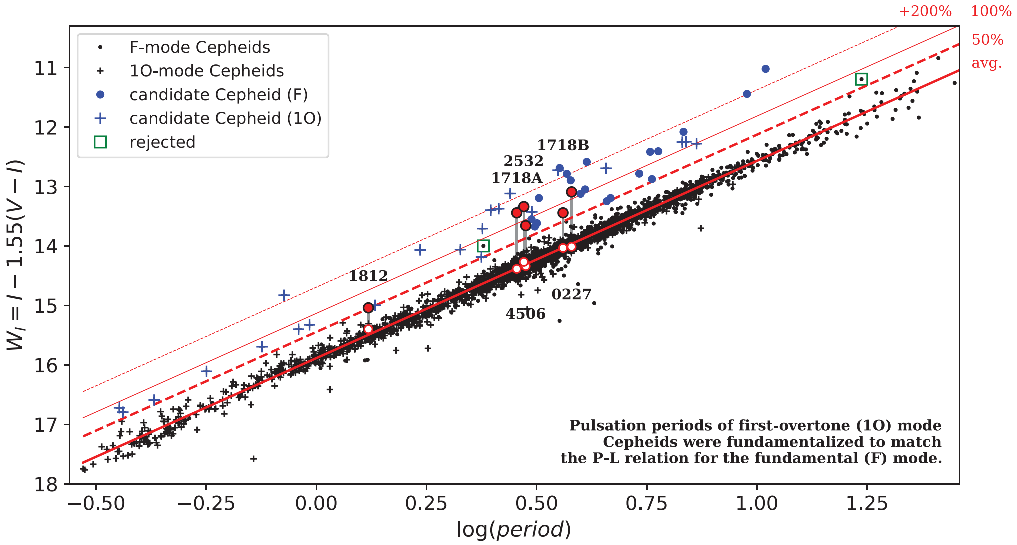

Figure 1. P–L relation based on the reddening-free Wesenheit index. Filled red circles show known eclipsing binaries involving Cepheids, while empty circles mark their brightness without any companion light. Our candidates for binary Cepheids are ≥50% brighter than an average Cepheid for a given period.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

composed of giants, for which lines of both components could be easily detected and their radial velocities (RVs) measured.

The Cepheids in our sample are distributed along the full P–L relation, with periods 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 Figure 1 the periods of 1O Cepheids (P_{1O}) were fundamentalized to match the periods of F-mode Cepheids (P_F) using the prescription of Pilecki et al. (2021).

Meanwhile, the project has been expanded by inclusion of new candidates in the LMC from the OGLE-4 catalog (Soszyński et al. 2017) and a dozen candidates in the SMC (Soszyński et al. 2010). In the samples selected as described above we found all seven known double Cepheids (i.e., objects for which pulsation of two Cepheids was detected at the same coordinates), which were all selected as candidates. This statistical result suggests that they share the same properties as other P–L-overbright Cepheids. This allows us to add to our SB2 candidate list double Cepheids from the MW, where the P–L relation method of detecting SB2 Cepheids cannot be applied directly (individual distances to the objects are needed to do so).

3. Data

Spectroscopic monitoring of our first SB2 candidates started in October 2020, with new objects added subsequently. Observations were performed using three of the world's best instruments mounted on telescopes located at observatories in Chile. The brightest targets ($V \leq 15.7$ mag) were observed with the High Accuracy Radial velocity Planet Searcher (HARPS) instrument mounted on the 3.6 meter telescope at the La Silla observatory. Most of the acquired spectra were obtained with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph mounted on the 6.5 m Magellan Clay telescope at the Las Campanas observatory. A significant fraction of data were also acquired with the

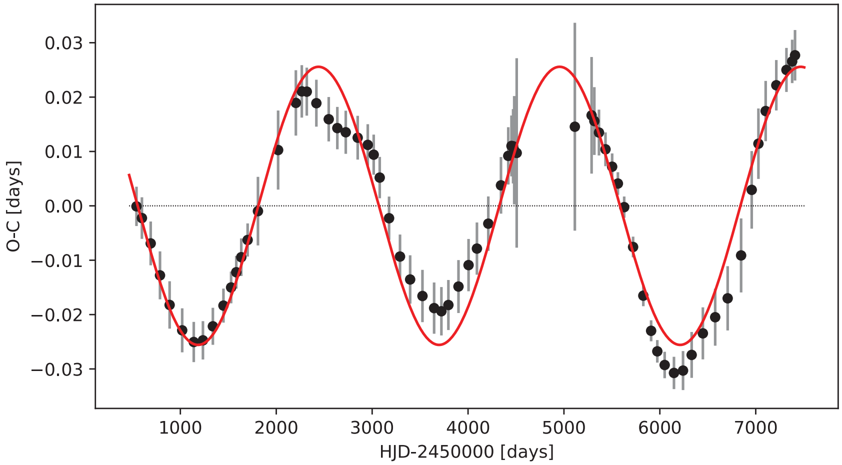

Figure 2. O–C diagram for one of the SB2 Cepheid candidates. A clear LTTE modulation due to binary motion is present. The red line is the best fit to the Cepheid's orbit.

European Southern Observatory's UV–Visual Echelle Spectrograph (UVES) on the 8.2 m Very Large Telescope (VLT) at Paranal Observatory. HARPS and MIKE were used in visitor mode, so that the observations were confined to the specific nights of the corresponding runs. UVES observations were obtained in service mode and could thus cover the orbital cycles more uniformly, while several-day-long HARPS runs were useful for covering pulsation phases of bright, long-period Cepheids.

4. Results

In a preliminary study, we analyzed photometric data from the OGLE catalogs for our initial sample of 41 Cepheids. The study of their O–C diagrams led to detection of the light travel-time effect (LTTE) due to binary motion for four candidates. One example, with an orbital period of about 2500 days, is shown in Figure 2.

4.1. *Double-lined binary Cepheids*

During the pilot program, we found 16 of 18 (∼90%) of our brightest candidate Cepheids to be components of SB2 systems, showing that the majority of these overbright pulsators are normal Cepheids with luminous giant companions. Additional observations of fainter candidates led to the discovery of a Cepheid in a binary system with an orbital period of only 59 days, five times shorter than any measured before for a firmly confirmed binary Cepheid. For a more detailed description of the system, please refer to Pilecki et al. (2022). Updated RV curves for this object are shown in Figure 3.

The observations have continued and, to date, 56 candidate Cepheids in the LMC, SMC, and MW have been confirmed as members of SB2 systems. For 32 of them, the anticorrelated orbital motions of the Cepheid and its companion were detected, which represents the ultimate proof that they are gravitationally bound. For 23, preliminary orbital solutions could be obtained, although in general the data coverage is not yet satisfactory due to long orbital periods and the complexity of the variabilities involved. For a few cases we managed to cover the orbital cycles well, and the solutions are not expected to change significantly (see Figure 4). Moreover, eight of the confirmed systems are composed of two Cepheids (see the next subsection).

For systems with preliminary orbital solutions we calculated the mass ratios of the components and the minimum Cepheid masses, $M_{\rm Cep} \sin^3(i)$. The minimum masses obtained

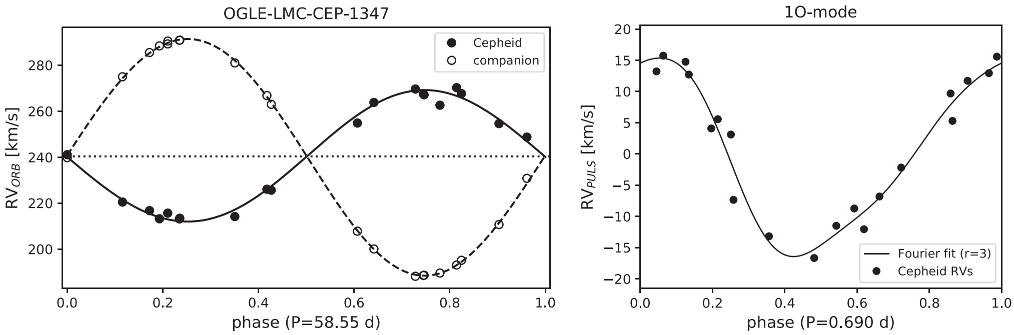

Figure 3. Updated RV curves for OGLE-LMC-CEP-1347. The scatter in the Cepheid RVs is due to unaccounted-for 2O-mode pulsations.

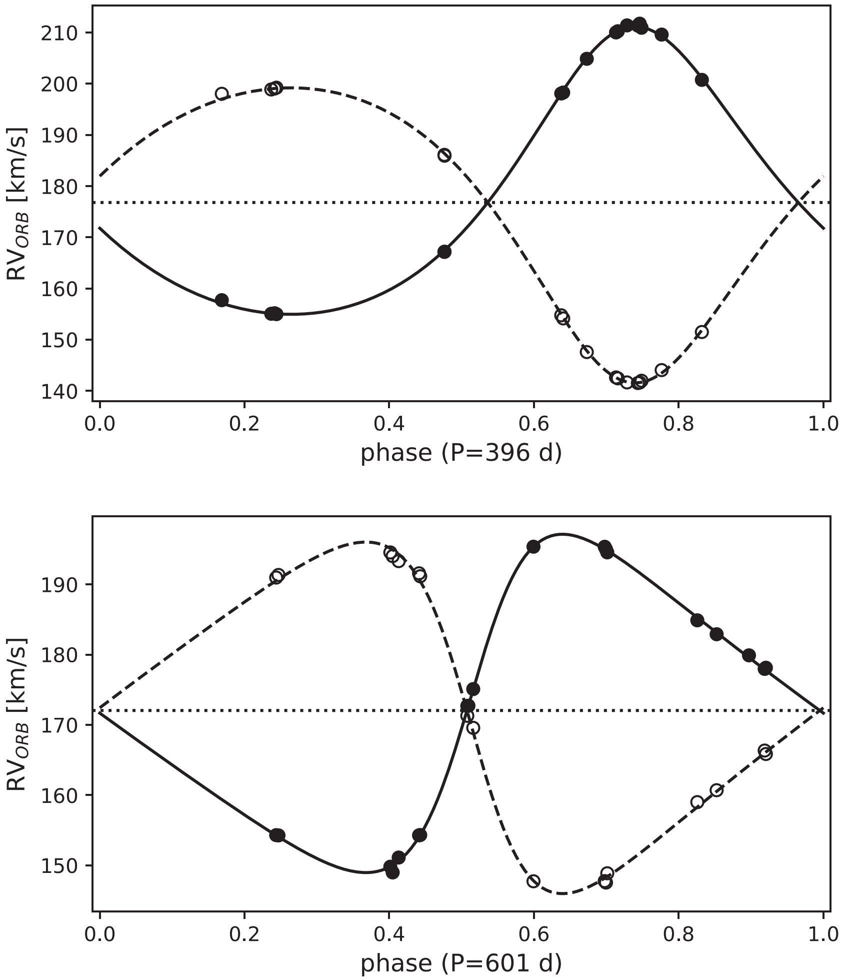

Figure 4. Preliminary orbits for two example double-lined binary Cepheids with best-covered orbital cycles. More data are still needed to cover the pulsation curves and improve the precision of the derived orbital parameters but no major change is expected to the solution.

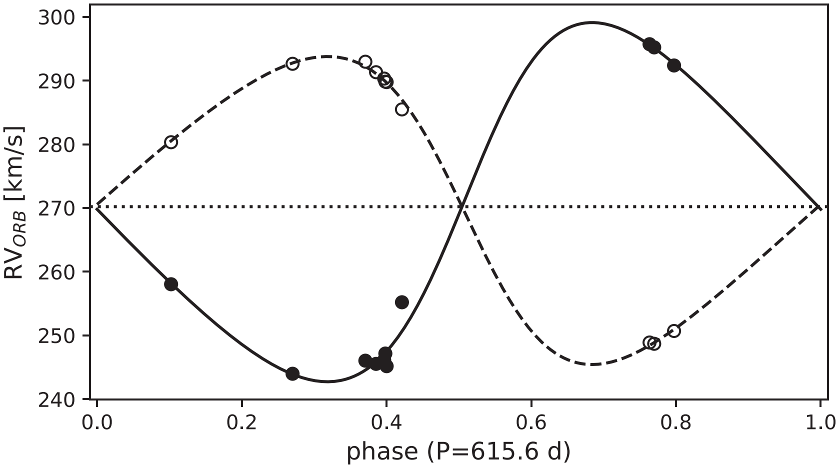

Figure 5. Example of a binary Cepheid with a preliminary mass ratio that is significantly different from unity.

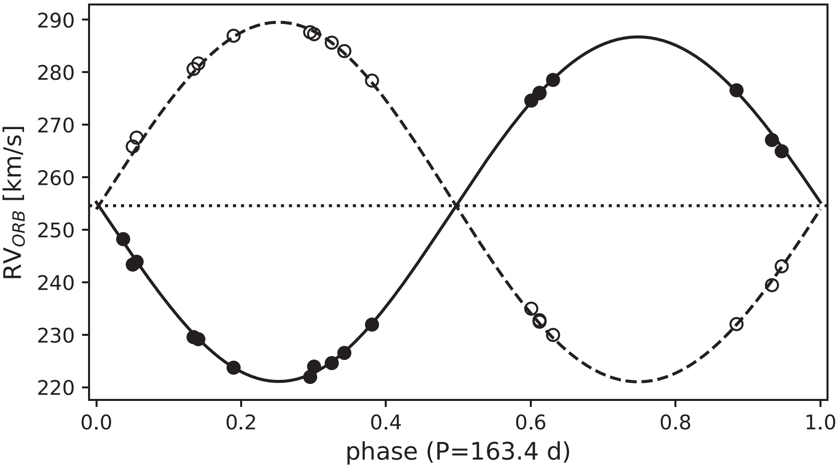

Figure 6. Another binary Cepheid with an orbital period below the 200-day limit.

for several systems are close to the masses derived for eclipsing Cepheids, showing that the inclinations of these systems are high and that they are good targets for accurate and precise mass measurements. Mass ratios obtained for some of the systems are different from unity. As $q = M_2/M_1 \sim 1$ is expected for components at similar evolutionary stages and the same age, which means that they could have passed through binary interactions in the past, either by means of a merger event or via mass transfer. One example of such a system is shown in Figure 5.

Among the binary Cepheids with orbital solutions, a new system was found with an orbital period below 200 days, which is the lower limit obtained by Neilson et al. (2015) for binary Cepheids that passed through their evolution on the RGB. As systems with periods below this limit would be destroyed at that evolutionary stage, their components are probably younger, and the Cepheids are likely on their first crossing through the instability strip (in the Hertzsprung gap). Our newly discovered system has a period of only 163 days, which is the second shortest period ever measured for a binary Cepheid (Figure 6).

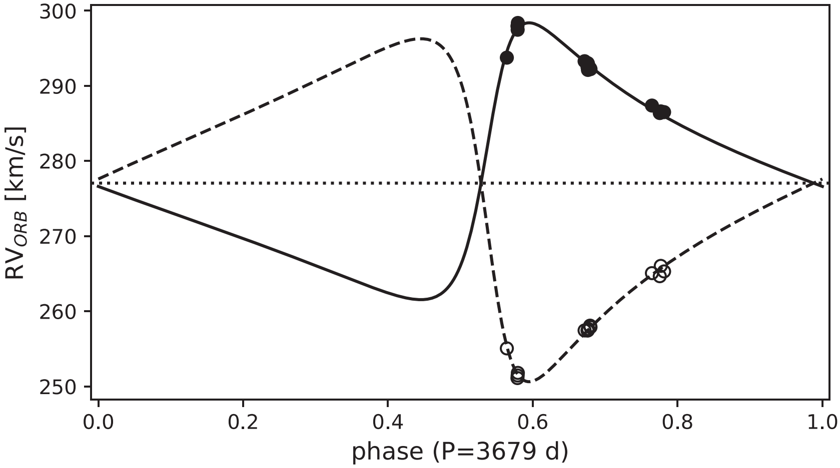

Figure 7. Example of a wide-orbit binary Cepheid with a long orbital period. The current solution suggests that its period may reach 10 years or even longer.

The longest orbital period measured so far for an extragalactic binary system is $P = 1550$ days (∼4 yr; Gieren et al. 2015). Meanwhile, preliminary solutions for some of our new systems suggest orbital periods longer than 4 years, even up to about 10 years or more (see Figure 7). These binary systems, for which we can obtain spectroscopic orbits, are currently the best candidates for direct geometric distance measurements using interferometric methods, offering the best possible accuracy. And although at the moment we do not expect high precision for extragalactic measurements, with upcoming improvements to instrumentation, such systems may eventually become our best and most direct tools for distance measurements to nearby galaxies, surpassing previously used methods (e.g., Pietrzyński et al. 2019).

4.2. *Binary double Cepheids*

An interesting subsample of double-lined binary Cepheids form those binary systems composed of two Cepheid components. As part of our project we observed nine candidates for such systems. Binary double (BIND) Cepheids are unique laboratories for pulsation and evolution studies. However, only one system of this kind was known before. To date, we have confirmed orbital motions for eight additional systems of a similar nature. Preliminary orbits for two are shown in Figure 8. Altough the orbital solutions may change once a full orbital cycle has been covered, the anti-correlated orbital motion of both components is already clear, proving binarity of these double Cepheids.

Interestingly, some preliminary solutions suggest mass ratios significantly different from unity, while for others the pulsation periods are very different (after fundamentalization of the 1O periods, for comparison). Both features may indicate past binary interaction events, which would affect the physical properties of the same-age components. Another interesting feature of the new BIND Cepheids is their long orbital periods. For most, periods longer than five years are expected according to the current models (based on only partially covered cycles). Although long periods make the observations more challenging, in the future these systems will also offer an opportunity to measure direct distances to their host galaxies, as described in the previous section.

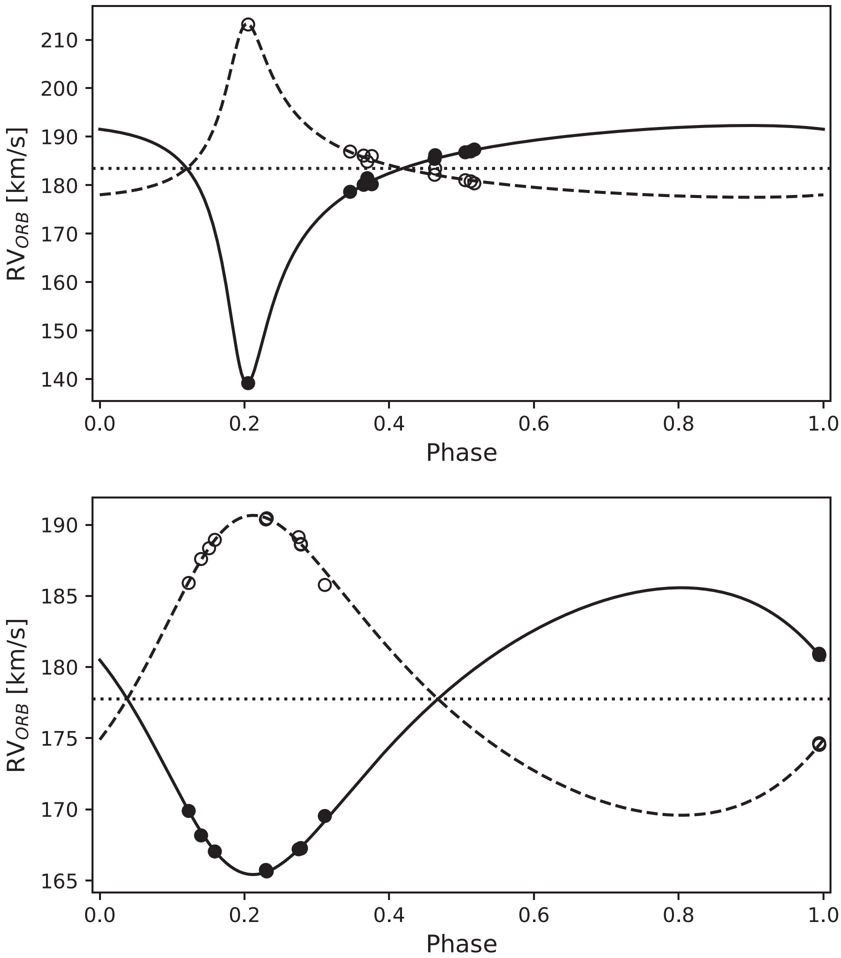

Figure 8. Preliminary orbits for two example binary double Cepheids show a clear change of the components' orbital velocities. However, as the orbital cycle has not yet been fully covered, the final, exact solutions (including the orbital periods) may change significantly.

5. Conclusions

Analysis of spectroscopic data we have collected so far clearly shows that the Cepheids selected as described in Section 2 are indeed components of 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 are often rejected as P–L relation outliers, are in the great majority Cepheids with red, luminous giant companions. These conclusions can also likely be extended to other pulsating stars with well-defined P–L relations, e.g., Type II Cepheids or RR Lyrae stars.

With 56 confirmed candidates, we have already ten-fold increased the number of Cepheids in spectroscopic double-lined binaries. This includes over 90% of all candidates in the LMC. In Figure 1 one can see that many of them have periods longer than those of known SB2 Cepheids, reaching up to 10.5 days. Extrapolation of the number of confirmed cases to the SMC suggests that about 50 new SMC Cepheids in SB2 systems can be expected once all SMC objects have been studied. This would increase the total number of known SB2 Cepheids by a further 80% (i.e., 20-fold compared with the state before we commenced the project).

Eventually, our study will yield firm mass estimates for a large sample of Cepheids, including long-period, high-mass Cepheids for which the lack of data is the most severe and for those from the uncertain low-mass end. Similar evolutionary stages for both components imply mass ratios close to unity. Any significant deviation from unity may indicate a probable past merger event. This is the only way merged Cepheids can be unambiguously detected (as compared with, e.g., dubious chemical composition peculiarities) and characterized. From the simulations of Sana et al. (2012) we can estimate that up to 30% of Cepheids may be merger products. In our study we will be able to estimate this fraction observationally and compare it with simulations.

Geometric methods provide the most accurate and direct distances to astronomical objects. One such method is based on the determination of both astrometric (angular) and spectroscopic (absolute) orbits of binary systems, which combined give directly the distance (see, e.g., Gallenne et al. 2019b). Unfortunately, at increasingly large distances, it becomes commensurately harder to measure orbital angular sizes, as one needs systems of increasingly higher luminosity and larger component separations. Using traditional methods, such systems are extremely hard to identify in other galaxies, as one needs decades of monitoring to find just a few. However, our method of detection of binary Cepheids is independent of the orbital size, and several systems with very wide orbits have already been identified. They are currently our best candidates for direct geometric distance determinations to the LMC and SMC, which can eventually lead to the ultimate calibration of the first rung of the cosmic distance ladder.

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