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Cepheids with giant companions

II. Spectroscopic confirmation of nine new double-lined binary systems composed of two Cepheids[⋆],[⋆⋆]

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ABSTRACT

Context. Binary Cepheids with giant companions are crucial for studying the physical properties of Cepheid variables, in particular providing the best means to measure their masses. Systems composed of two Cepheids are even more important, but to date, only one such system has been identified, in the Large Magellanic Cloud (LMC).

Aims. Our current aim is to increase the number of these systems known tenfold and to provide their basic characteristics. The final goal is to obtain the physical properties of the component Cepheids, including their masses and radii, and to learn about their evolution in the multiple systems, also revealing their origin.

Methods. We started a spectroscopic monitoring campaign of nine unresolved pairs of Cepheids from the OGLE catalog to check if they are gravitationally bound. Two of these so-called double Cepheids are located in the LMC, five are in the Small Magellanic Cloud (SMC), and two are in the Milky Way (MW).

Results. We report a spectroscopic detection of the binarity of all nine of these double Cepheids with orbital periods ranging from 2 to 18 years. This increases the number of known binary double (BIND) Cepheids from 1 to 10 and triples the number of all confirmed double-lined binary (SB2) Cepheids. For five BIND Cepheids, the disentangled pulsational light curves of the components show anti-correlated phase shifts due to orbital motion. We show the first empirical evidence that typical period–luminosity relations (PLRs) are rather binary Cepheid PLRs, as they include light of the companion.

Conclusions. The statistics of pulsation period ratios of BIND Cepheids do not agree with those expected for pairs of Cepheids of the same age. These ratios together with the determined mass ratios far from unity suggest a merger origin of at least one component for about half of the systems. The SMC and MW objects are the first found in SB2 systems composed of giants in their host galaxies. The Milky Way BIND Cepheids are also the closest such systems, being located at about 11 and 26 kpc.

Key words. binaries: spectroscopic – stars: evolution – stars: oscillations – stars: variables: Cepheids

1. Introduction

Classical Cepheids (also referred to as simply Cepheids hereafter) form probably the most important class of pulsating stars. Because of the period–luminosity relation they obey, they are important distance indicators in the local Universe, providing a fundamental step of the cosmic distance ladder and connecting our Milky Way galaxy to galaxies in the Local Group and beyond. They are also key objects for testing the predictions of stellar evolution and stellar pulsation theories. There are almost 15 000 known classical Cepheids (Pietrukowicz et al. 2021), mostly in the MW (Pojmanski et al. 2005 and references therein, Soszyński et al. 2020) and the Magellanic Clouds (Soszyński et al. 2017). Although 80% of these Cepheids are expected to be members of binary systems (Kervella et al. 2019), only about 0.1% of them have been found in eclipsing systems, and even fewer in double-lined spectroscopic binaries. Finding such systems is of great interest, because both of these characteristics can be used to provide indispensable information about the physical properties of Cepheids.

Our study of these objects in eclipsing binary systems have already brought a wealth of data regarding the physical

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[⋆] Based on observations collected at the European Southern Observatory, Chile.

[⋆⋆] This paper includes data gathered with the 6.5 m *Magellan Clay* Telescope at Las Campanas Observatory, Chile.

properties of Cepheids, with accuracies of 0.5−2% for the most interesting Cepheid masses and radii (e.g., Pietrzyński et al. 2010; Pilecki et al. 2015, 2018). As part of these study, several interesting cases were identified, including an extremely rare system composed of two Cepheids, OGLE-LMC-CEP-1718 (Gieren et al. 2014). Having two Cepheids in one system allowed important constraints to be put on models as their ages have to be equal, and physical parameters similar and related to their pulsation periods. We can also assume they were born with the same chemical composition. Moreover, a subsequent study of OGLE-LMC-CEP-1718 by Pilecki et al. (2018) showed that the more evolutionary advanced component is actually slightly less massive, which may provide important information for the ongoing discussion on the origin of the Cepheid mass discrepancy (Cassisi & Salaris 2011; Anderson et al. 2016).

Although the first unresolved pairs of Cepheids (dubbed double Cepheids) were identified almost 30 years ago (Alcock et al. 1995)[1], to date, only one has been spectroscopically confirmed as a binary system and analyzed, which makes any statistical analysis impossible. The very limited parameter space would also render any theoretical study inconclusive. A larger set of such stars occupying wider parameter space would provide the opportunity to gain valuable insight into the pulsation and evolution of Cepheids through a comparative analysis of the differences between the components. All models would have to predict correct mass and period ratios (together with other observables) of the same-age and similar-composition components for several systems at the same time.

Factors that hinder spectroscopic confirmation of the binarity of double Cepheids are their relative faintness and long expected orbital periods. One of the aims of the present study is to confirm and monitor a statistically significant sample of such systems in different environments and provide their basic orbital and physical parameters. Such a sample will be of significant use for many future studies, including comparisons with model predictions of evolution and pulsation theories.

It is important to note that such systems will always be double-lined spectroscopic binaries (SB2) in visual bands, as their Cepheid components are both giant stars with similar brightness and atmospheric properties. A reliable mass determination (using Kepler's laws) is practically only possible for SB2 systems, but until recently only five such double-lined binary systems containing Cepheids were known (Pilecki et al. 2018). The rest of the known systems with Cepheids are single-lined binaries (SB1), which makes mass estimates for their components very uncertain, with typical accuracies of 10−20% (Evans et al. 2018). For a few of them, great effort has been put into their observation from space in far-UV, where companion lines are detectable and velocities can be measured (Gallenne et al. 2018). In the present paper, we only use the term spectroscopic double-lined binary (or SB2) to refer to objects for which lines of both components are identified in the same spectrum and the same wavelength range.

In the first paper of the series (Pilecki et al. 2021, hereafter P21) we proposed a new method of identification of Cepheids in SB2 systems according to which Cepheids that are excessively bright for their periods, have similar or redder colors, and have lower pulsation amplitudes are strongly suspected to form binaries. Using the first collected data for a limited sample, we showed that this method is about 95% efficient, confirming SB2 status for 17 out of 18 analyzed Cepheids in the Large Magellanic Cloud (see P21 and Pilecki 2022). Currently, the whole sample for this galaxy consists of 47 objects. It is interesting to note that two of the Cepheid candidates for SB2 systems selected in P21 are in fact double Cepheids. These systems were not analyzed there and are presented here together with systems from the Milky Way and the Small Magellanic Cloud.

Here, we present nine candidate binary double (BIND) Cepheids and show the first results of our observing program, which prove their binarity. We note that we treat only those binary systems composed of two Cepheids for which the anticorrelated orbital motion is confirmed either spectroscopically or astrometrically as BIND Cepheids. In Sect. 2 we describe the sample and present the photometric and spectroscopic data used in this study. In Sect. 3 we show the results from our analysis of the presented data, including the preliminary orbital solutions. In Sect. 4 we draw conclusions from these results and describe the prospects of our ongoing project.

2. Data

2.1. Object selection

From the latest catalogs of classical Cepheids of the OGLE project (Soszyński et al. 2017; Udalski et al. 2018), we selected nine that are classified as double Cepheids; these are objects where the presence of two Cepheids was detected at exactly the same coordinates. These objects are our candidates for binary systems composed of two Cepheids. An alternative possibility is that these stars are simply a superposition (a blend) of two unrelated stars. This is unlikely as even a slight difference in coordinates would result in a variable shift in the photocenter at different pulsation phases. Nevertheless, to unequivocally confirm that the two Cepheids that form a double Cepheid are gravitationally bound, spectroscopic confirmation of their anticorrelated orbital motion is necessary. In order to obtain such confirmation, we aim to seek out, together with the published OGLE-LMC-CEP-1718 system, a relatively large number of ten BIND Cepheids for follow-up studies.

In our sample, two objects are located in the Milky Way (MW), five in the Small Magellanic Cloud (SMC), and two in the Large Magellanic Cloud (LMC), and therefore the sample covers a significant range of metallicities. None of them have been studied before, but it is reassuring that the LMC targets were identified in P21 as having similar properties to other overbright Cepheids, for which evidence of their binarity was shown (see also Pilecki et al. 2022). We note here that the Cepheids of the Magellanic Clouds were listed by Szabados & Nehéz (2012) as known binaries but this was only based on them being double, with no direct evidence of their binarity provided. As all the objects come from the OGLE catalog, in the remainder of the text we omit the "OGLE" prefix in their IDs.

The OGLE catalog provides individual pulsation modes of the components, which were obtained through the Fourier decomposition technique (Simon & Lee 1981). Using these modes, we can see that our targets represent all combinations of fundamental (F) and first-overtone ($1O$) Cepheids, i.e. pairs of F+F, F+$1O$ and $1O$+$1O$ Cepheids. Their periods range from 1.1 to 4.6 days, with period ratios between the components (P_2/P_1) of 0.56 to 0.99. For comparison, the only known binary double Cepheid, LMC-CEP-1718, is composed of two $1O$ Cepheids, with periods of about 2 and 2.5 days ($P_2/P_1 \sim 0.79$). The monitoring of our proposed sample may therefore not only lead to a ten-fold increase in the number of double binary Cepheids with

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[1] We ignore here a pair of Cepheids, CE Cas AB, which were classified as double Cepheid (Sandage & Tammann 1969) but form a visual pair separated by 2.5″.

Table 1. Basic data for known double Cepheids.

		Component A		Component B					
OGLE ID	Modes	P_1 [days]	P_1^F [days]	P_2 [days]	P_2^F [days]	P_2^F/P_1^F	V [mag]	I [mag]	Refs.
BLG-CEP-067	$1O+1O$	2.610721	3.827	1.692381	2.444	0.639	16.33	14.51	(3)
GD-CEP-0291	$F+F$	3.667693	3.668	3.398977	3.399	0.927	14.65	12.70	(3)
LMC-CEP-0571	$F+1O$	3.079937	3.080	2.100885	3.057	0.992	15.70	14.86	(1), (2)
LMC-CEP-0835	$F+F$	4.562781	4.563	2.750956	2.751	0.603	15.25	14.46	(1), (2)
LMC-CEP-1718	$1O+1O$	2.480909	3.649	1.963683	2.869	0.786	15.19	14.51	(1), (2), (4)
SMC-CEP-1526	$F+F$	1.804311	1.804	1.290234	1.290	0.715	16.83	16.16	(2)
SMC-CEP-2699	$1O+F$	2.562225	3.772	2.117341	2.117	0.561	16.06	15.38	(2)
SMC-CEP-2893	$F+F$	1.321549	1.321	1.135859	1.136	0.860	16.93	16.38	(2)
SMC-CEP-3115	$F+F$	1.251945	1.252	1.159784	1.160	0.926	16.66	16.18	(2)
SMC-CEP-3674	$F+1O$	2.896089	2.896	1.827785	2.665	0.920	15.79	15.13	(2)

Notes. Period (P_i) and fundamentalized period (P_i^F) are given for each component ($i = 1, 2$) of a given double Cepheid. LMC-CEP-1718 is the only one already spectroscopically confirmed. References are given in the last column.
References. (1) Alcock et al. (1995), (2) Soszyński et al. (2017), (3) Udalski et al. (2018), (4) Pilecki et al. (2018).

known mass and radius ratios, but could also cover a considerably wide parameter space for Cepheids pulsating in different modes and located in environments with different typical metallicities. Such a sample will be of extreme value for testing pulsation and evolution theory models.

The basic parameters of the double Cepheids of our sample are summarized in Table 1. We name the component with the higher fundamental or fundamentalized (in case of first-overtone Cepheids) period component A, and the other component B. In P21, we provided a formula for fundamentalization for the LMC Cepheids, which on average maintains “luminosity”; that is, after the fundamentalization of periods, we wanted the $1O$ Cepheids to lie on average on the same period–luminosity relation (period–Wesenheit index in this case) as F-mode Cepheids. For the purposes of the present study, we obtained a formula for the Cepheids in the SMC in the same way. Both relations were applied to LMC and SMC objects, and are given below:

$$\begin{aligned} &(\text{LMC}) \quad P_F = P_{1O} * (1.418 + 0.115 \log P_{1O}), \\ &(\text{SMC}) \quad P_F = P_{1O} * (1.433 + 0.096 \log P_{1O}). \end{aligned} \tag{1}$$

As the difference between these two relations in terms of the resulting ratios P_F/P_{1O} is insignificant and our aim is mostly to make it easier to compare the stars, we decided to also use the LMC relation for one $1O+1O$ MW Cepheid (we note that period ratios between Cepheids of the same mode are very insensitive to the transformation used). It is worth mentioning here that in the approach typically used for fundamentalization, the relation P_F/P_{1O} comes from the period ratios in double-mode Cepheids (see e.g., Feast & Catchpole 1997; Kovtyukh et al. 2016) with no constraint on the luminosity. We used the approach described in P21 principally because it better enables us to compare luminosities.

As components of binary systems should have the same age, and Cepheids are mostly found in a very specific stage of evolution (the blue loop), they should also have a similar mass and a relatively similar radius (in a range allowed by the width of the instability strip and extent of the blue loop). For example, LMC-CEP-1718 ($P_2^F/P_1^F = 0.786$) has a mass ratio of 0.98 and a radius ratio of 0.84 (Pilecki et al. 2018). As pulsation period depends principally on the mass and radius, the existence of Cepheids with very different periods ($P_2^F/P_1^F \sim 0.6$) in the same system would be very intriguing, possibly meaning (1) a combination of a first-crossing (still on the subgiant branch) and a typical (on the blue loop) Cepheid, or (2) a stellar merger event in the past evolution of the system, which can lead to Cepheids of different masses having the same age. These options seem to have a rather low probability of occurrence, but both are possible scenarios for the double Cepheids with low period ratios listed in Table 1 (once their binarity is confirmed) and a spectroscopic mass ratio would be necessary to discriminate between them.

2.2. Photometry

The majority of the photometric data used in this work come from the OGLE project (Soszyński et al. 2017; Udalski et al. 2018). Specifically, we used both the V- and I-band light curves from the catalog of the OGLE-3 and OGLE-4 phases. I-band light curves have on average 1280 points in total, while V-band light curves have only about 119 points. Average V and I-band magnitudes are given in Table 1. In the periodicity analysis (Sect. 3.1), only the I-band data were used but, whenever possible (i.e., for the LMC objects), the photometry was extended with the R-band data[2] (600 points on average) from the MACHO project (Alcock et al. 2002).

2.3. Spectroscopy

Spectroscopic monitoring of our sample started in October, 2020, with the exception of BLG-CEP-067 for which the first spectrum was obtained almost a year later, in September, 2021. The observations were performed using three very efficient instruments mounted on telescopes located in three distinct observatories in Chile, and took place until January, 2024. Most of the acquired spectra were obtained with the MIKE spectrograph mounted on the 6.5 m *Magellan Clay* Telescope at the Las Campanas Observatory. We also obtained spectra (in service mode) with the UVES spectrograph on the 8.2 m VLT at ESO Paranal Observatory. The three brightest Cepheids ($V \leq 15.7$ mag) were also observed with the HARPS instrument mounted on the 3.6 m telescope at ESO La Silla Observatory.

For the analysis, we used the reduced HARPS spectra downloaded from the ESO Archive[3]. The MIKE data were reduced using Daniel Kelson’s pipeline, which is available at

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[2] Downloaded from `http://macho.anu.edu.au`

[3] `http://archive.eso.org`

the Carnegie Observatories Software Repository[4], and the UVES data were reduced using the ESO Reflex software and the official pipeline available at the ESO Science Software repository[5].

For the identification of components in the spectra and the measurement of radial velocities (RVs), we used the broadening function (BF) technique (Rucinski 1992, 1999) implemented in the RaveSpan code (Pilecki et al. 2017). This technique provides narrower profiles than the cross-correlation function method, which helps in the separation of components, increasing the chance of detecting a companion and improving the precision of the RV measurements.

3. Analysis and results

3.1. Period analysis

We looked for the periodicity of all selected objects using the I-band light curves from the OGLE project. We did not use the measurements in the V filter because of their insufficient number for this kind of analysis. In the case of the LMC objects, an additional analysis was carried out adding photometry from the MACHO project that precedes OGLE observations.

We analyzed all the data sets at the same time, fixing the phase coefficients at the same values for OGLE-3 and 4, while leaving the amplitude parameters free to vary. Using this approach, we made sure that there is no phase shift between the data sets from different phases of the OGLE project. As the shape of the R-band light curve is quite similar to that of the I-band – and we were not aiming for a high level of accuracy here –, we did the same for the MACHO data. Lack of discontinuity between the sets confirmed the validity of this choice of approach.

As the variabilities of the two components of the double Cepheids are superimposed on each other, we first disentangled them (by iteratively subtracting one periodic variability and fitting the other) and treated each component separately in the analysis. The separated light curves are presented in Fig. 1. Individual Cepheids are identified by -A or -B after the ID, where A marks the Cepheid with the longer fundamental (or fundamentalized) period, which we assume to be the more luminous of the two. In the analysis, we assumed two models, one with a constant period (P) and another with a linear period change ($\mathrm{d}P/\mathrm{d}t$). The determined periods and the period changes are given in Table 2. In the upper part, we show the results for all Cepheids (using the OGLE data only), while in the lower part we only show results for the LMC objects using the combined OGLE+MACHO photometric data.

3.2. O–C analysis

To test if these double Cepheids are gravitationally bound, for each disentangled pulsational variability we performed an O−C analysis, calculating instantaneous phase shifts along the collected photometric observational data. We then looked for any sign of light travel-time effect (LTTE) due to the common binary motion of the components. The O−C diagrams and a binary motion fit (when applicable) are shown in Fig. 2. As the amplitude of the phase variability in such an analysis depends on the size of the projected orbit and the precision depends on the pulsation period, the best results are achieved for long orbital periods and Cepheids with short pulsation periods. Moreover, intrinsic period changes of Cepheids may result in additional erratic shifts, which makes the detection of the orbital motion very hard or even impossible.

To improve the detection and the model fit, we tried to fit the anticorrelated binary motion to both components at the same time. To compensate for the intrinsic period changes, we tried to subtract a varying-order polynomial from the data before the model fit in an attempt to minimize the correlation coefficient; that is, looking for the highest possible anticorrelation. The results are presented in Fig. 3 and the fitted ephemeris data in Table 3.

With such a procedure, we eventually detected convincing anticorrelated cyclic phase shifts due to binary motion for five double Cepheids. For SMC-CEP-1526, the binary motion is extremely clear, with a correlation factor of $r = -0.97$ and an orbital period of about 2260 days. For two other Cepheids (SMC-CEP-2699 and SMC-CEP-3674), the anticorrelated cyclic behavior is less significant but also continues for at least two cycles ($P_{\mathrm{orb}} = 2600$ and 2400 days); for the first one, we had to subtract a polynomial from the data, and so the amplitudes are affected, while the second exhibits more noisy data. For SMC-CEP-3115, the anticorrelation is clear ($r = -0.94$) but the orbital period is unknown because the orbital cycle has not yet been covered.

The results for the LMC objects using only OGLE data were inconclusive, and so we decided to repeat the analysis with the addition of the available MACHO data. For LMC-CEP-0835, this resulted in somewhat distorted O−C data for the secondary but globally the anti-correlated behavior is easy to see. Although slightly more than one cycle is covered and formal errors are small, because of additional intrinsic period changes, the accuracy is probably much lower than that (at least two cycles are needed to obtain more accurate results). Nevertheless the orbital period is probably very long. Regarding LMC-CEP-0571, the results are similar from OGLE-only and OGLE+MACHO data analysis. In both cases, approximately parabolic anticorrelated variability is detected. Unless a very long orbital period is assumed, such O−C results can be best explained with a simple linear period change of opposite sign. Treating this variability as a pure effect of binary motion also yields unfeasibly high Cepheid masses for their pulsation periods. For SMC-CEP-2893, we are not able to detect any significant LTTE, and so we expect a shorter orbital period. For the MW objects, we do not have enough data and the time span is too short for the O−C analysis.

3.3. Spectroscopic analysis

The spectroscopic analysis of the double Cepheids from the sample was a very challenging task because of the three (assuming additional binary motion) independent variabilities involved. To begin with, we did not know which set of lines belonged to which Cepheid, and because of line changes (depth, width) along the cycle, it was hard to trace the components from one spectrum to another. Large pulsation amplitudes frequently resulted in an interchange of their positions; that is, one could not trust that the component with higher velocity was always the same Cepheid. This was further complicated by the lack of information about the orbital phase, period, and amplitude, which was adding unknown and variable velocity to all the measurements, including a possible interchange of components in terms of average pulsational velocity. To make the task even harder, the widths of the line profiles and average velocity separations frequently led to a blending of the line profiles. However, in the case of three SMC systems with well-determined O−C variability (at

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[4] `http://code.obs.carnegiescience.edu`

[5] `http://www.eso.org/sci/software.html`

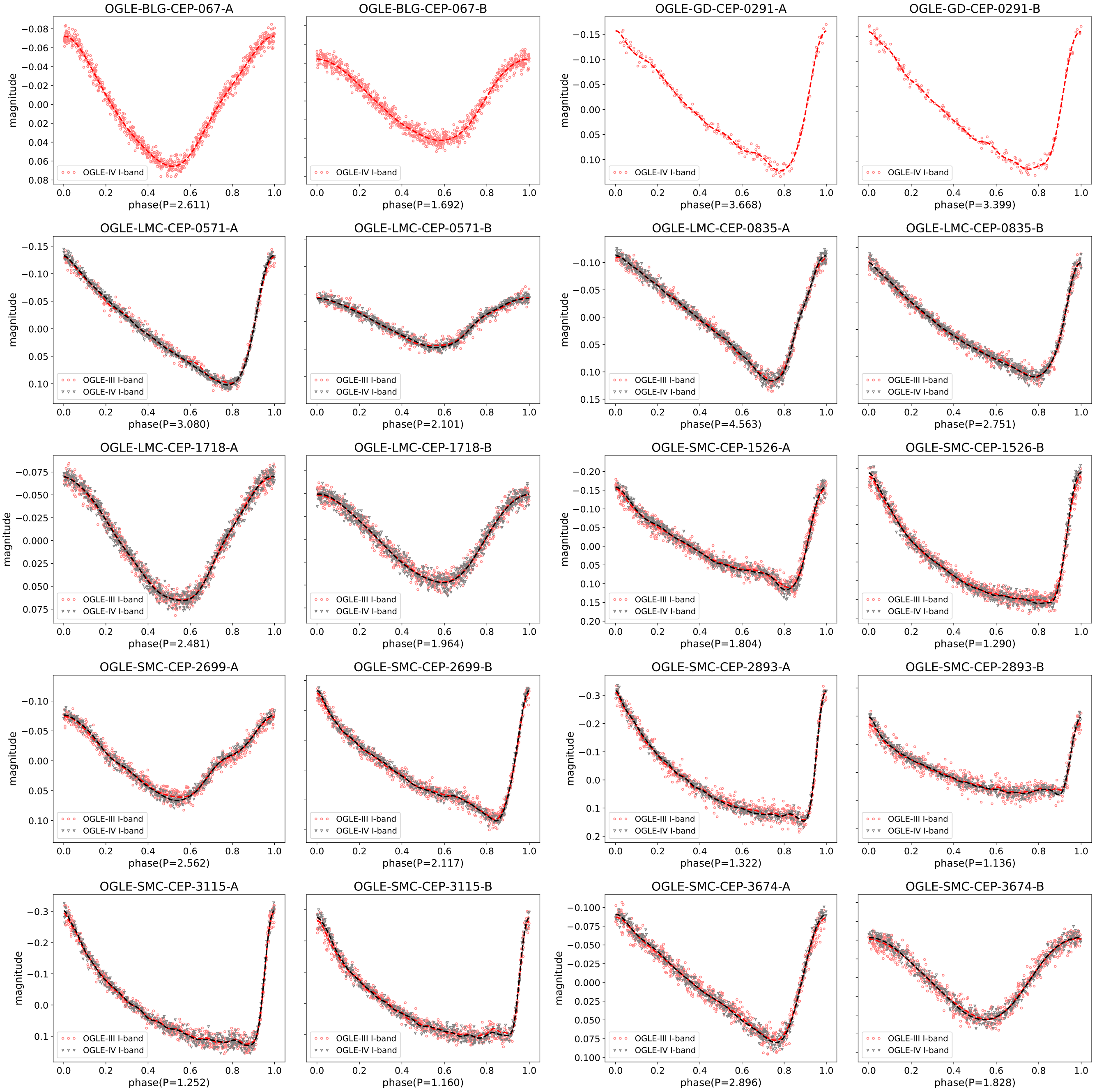
OGLE-BLG-CEP-067-A
OGLE-BLG-CEP-067-B
OGLE-GD-CEP-0291-A
OGLE-GD-CEP-0291-B
OGLE-LMC-CEP-0571-A
OGLE-LMC-CEP-0571-B
OGLE-LMC-CEP-0835-A
OGLE-LMC-CEP-0835-B
OGLE-LMC-CEP-1718-A
OGLE-LMC-CEP-1718-B
OGLE-SMC-CEP-1526-A
OGLE-SMC-CEP-1526-B
OGLE-SMC-CEP-2699-A
OGLE-SMC-CEP-2699-B
OGLE-SMC-CEP-2893-A
OGLE-SMC-CEP-2893-B
OGLE-SMC-CEP-3115-A
OGLE-SMC-CEP-3115-B
OGLE-SMC-CEP-3674-A
OGLE-SMC-CEP-3674-B

Fig. 1. Pairs of OGLE I-band light curves for both components of ten double Cepheids phased with the ephemeris from Table 2 for linear period change. Span of Y-axis is the same for each pair for easier comparison of pulsation amplitudes. In general, components A (with longer periods) have higher amplitudes, with the exception of OGLE-SMC-CEP-1526 ($F + F$) and OGLE-SMC-CEP-2699 ($1O + F$).

least two cycles), we had some advantage from knowing approximate orbital periods and phases.

During a long process of trial and error, and educated guesses, we gradually became able to identify components and characterize the underlying orbital motion corresponding to a given Cepheid in the system. Eventually, this led to the preliminary orbital solutions presented in Fig. 4. The expected orbital periods of most of the systems are longer than 5 years and we have not yet had the opportunity to cover a full orbital cycle for them. And to increase accuracy, slightly more than one cycle should be covered in order to have at least a marginal overlap in phase. We will thus continue spectroscopic monitoring of these systems until we are able to obtain a reliable solution; nevertheless, the analysis of our current data already bring important results.

The most important is the detection of the anticorrelated orbital motion of both components for all double Cepheids from the sample, which ultimately confirms their binarity. For the first eight objects shown in Fig. 4, the orbital velocities change considerably (by 10 km s^{-1} or more), a significant curvature of the orbital variability is observed (which helps to constrain models), and/or a velocity reversal in regard to the systemic velocity is observed. In cases where orbital periods are known from the O−C analysis, after confirming their consistency with the data they were adopted in the models. These periods will be kept until more precise ones from the spectroscopic analysis

Table 2. Pulsation ephemeris data for the components of double Cepheids.

			Constant P	Linear dP/dt		O−C		
OGLE ID	Mode	T_0 [days]	period [days]	period [days]	dP/dt	A_I [mag]	r	Flags
BLG-CEP-067-A	1O	6728.9156	2.610720(4)	2.610719(4)	2.1e−08 [2.0σ]	0.138	E+P	–
BLG-CEP-067-B	1O	6728.1099	1.6923770(29)	1.6923836(27)	−7.1e−08 [11σ]	0.086	−0.60	–
GD-CEP-0291-A	F	7241.9130	3.667699(13)	3.667720(17)	−7.8e−08 [2.0σ]	0.279	E+E	–
GD-CEP-0291-B	F	7239.6049	3.398977(14)	3.398970(14)	5.6e−08 [1.5σ]	0.275	−0.42	–
LMC-CEP-0571-A	F	5656.6539	3.0798876(21)	3.0798760(26)	−1.7e−08 [7.0σ]	0.230	P+E	–
LMC-CEP-0571-B	1O	5633.7415	2.100785(4)	2.100815(4)	4.4e−08 [11σ]	0.088	−0.94	–
LMC-CEP-0835-A	F	5062.4994	4.562725(4)	4.562714(5)	−2.5e−08 [3.5σ]	0.226	O+O?	LTTE
LMC-CEP-0835-B	F	4985.9788	2.7508653(16)	2.7508776(20)	2.3e−08 [9.0σ]	0.210	−0.83	–
LMC-CEP-1718-A	1O	3923.5083	2.4809134(14)	2.4809078(14)	−1.8e−08 [11σ]	0.134	P+E	ECL
LMC-CEP-1718-B	1O	3914.7558	1.9636626(11)	1.9636615(12)	−4.1e−09 [2.9σ]	0.096	0.33	–
SMC-CEP-1526-A	F	4038.4523	1.8043149(6)	1.8043146(6)	−1.1e−09 [1.6σ]	0.264	O+O	LTTE
SMC-CEP-1526-B	F	3751.2473	1.29022591(26)	1.29022616(25)	1.6e−09 [5.1σ]	0.334	−0.97	–
SMC-CEP-2699-A	1O	4942.2171	2.5622543(28)	2.5622527(29)	−8.5e−09 [2.2σ]	0.134	E+P	LTTE
SMC-CEP-2699-B	F	4780.6972	2.1174356(12)	2.1174265(10)	−3.9e−08 [29σ]	0.208	0.34	–
SMC-CEP-2893-A	F	5326.5241	1.32155113(30)	1.3215514(4)	3.7e−10 [0.8σ]	0.453	E+E	1C
SMC-CEP-2893-B	F	5292.0427	1.1358590(4)	1.1358595(4)	9e−10 [1.9σ]	0.245	0.44	–
SMC-CEP-3115-A	F	4558.5922	1.2519451(3)	1.25194563(29)	4.3e−09 [10σ]	0.420	O+O	LTTE
SMC-CEP-3115-B	F	4603.3492	1.15978962(26)	1.15978938(25)	−4.2e−09 [11σ]	0.372	−0.94	–
SMC-CEP-3674-A	F	5009.1460	2.8960253(25)	2.8960260(28)	2.3e−09 [0.7σ]	0.163	O+O	LTTE
SMC-CEP-3674-B	1O	5008.9881	1.8277750(19)	1.8277743(20)	−2.5e−09 [1.0σ]	0.108	−0.82	–
LMC-CEP-0571-A	F	4929.8173	3.0799661(9)	3.0798934(19)	−4e−08 [43σ]	0.228	P+E	–
LMC-CEP-0571-B	1O	4820.7063	2.1007583(13)	2.1007901(28)	1.9e−08 [13σ]	0.088	−0.76	–
LMC-CEP-0835-A	F	4556.0275	4.5627231(27)	4.562725(4)	1.3e−09 [0.5σ]	0.225	E+O	LTTE
LMC-CEP-0835-B	F	4232.2570	2.7508940(10)	2.7508739(14)	−1.8e−08 [21σ]	0.207	−0.55	–
LMC-CEP-1718-A	1O	3097.3722	2.4809333(10)	2.4809322(10)	−2.5e−08 [23σ]	0.134	P+E	ECL
LMC-CEP-1718-B	1O	3044.8611	1.9636670(8)	1.9636673(8)	−5.1e−09 [5.5σ]	0.095	0.81	–

Notes. Two ephemerides are presented, assuming either a constant period (P) or a linear period change (dP/dt). The same reference time (T_0, maximum brightness at I-band for a constant P) is used for both. Errors in the last digits are given in parentheses. For dP/dt, the significance in sigma is given in brackets. In the penultimate column, a different information is given in rows for each component. O−C means the type of O−C variability for both Cepheids (E – erratic, P – parabolic, O – orbital motion), r is the correlation parameter for these variabilities. Flags: 1C – at least 1 orbital cycle is covered, ECL – eclipsing system, LTTE – anticorrelated light travel-time effect detected. Results for the OGLE data only are given above the double horizontal line, while those using additional MACHO data are shown below.

are available. For SMC-CEP-2893, for which we expected a short orbital period given the lack of detection in the O−C analysis, indeed the preliminary results suggest a period of about 760 days. This is the only case for which our spectroscopic data cover more than one orbital cycle. For LMC-CEP-0571, a full cycle is almost covered but the solution is uncertain because of suboptimal phase coverage; its currently estimated period is the second shortest among the sample, which is consistent with the lack of detection in the O−C analysis (assuming the parabolic variabilities originate from period changes). For BLG-CEP-067, GD-CEP-0291, and SMC-CEP-3115, the orbital periods were set to match the available data and to not produce unphysical results (e.g., excessively high Cepheid masses).

For the last (ninth) object (LMC-CEP-0835) in Fig. 4, the results of the O−C analysis lead us to expect a very long orbital period (~6500 days) and small RV variation, and indeed the present RV measurements are consistent with this scenario. The orbital motion is clearly seen but because of the short phase range covered and small RV changes, the model is the least constrained in the sample. The presented model is one of many that fit the current data, and therefore new observations are highly anticipated to constrain the orbital parameters.

The preliminary orbital parameters and physical properties of BIND Cepheids and their components, including their minimum masses ($M_i \sin^3(i)$, where i is the orbital inclination), are given in Table 4. This table includes period ratios (for ease of comparison with mass ratios) and the radii ratios calculated using the period–mass–radius relation from Pilecki et al. (2018). For the first two objects (composed of F-mode Cepheids), period ratios come from Table 1, while for the F + 1O-mode Cepheid SMC-CEP-3674, we recalculated the period ratio using Eq. (2) from Szilàdi et al. (2018) for fundamentalization as this equation is more appropriate for deriving radius ratios. However, using the period ratio 0.920 from Table 1 for SMC-CEP-3674 we would obtain a similar (within errors) value of R_2/R_1 = 0.925.

For three BIND Cepheids with the best-covered pulsation cycles, we show the corresponding RV curves in Fig. 5. For other systems, the pulsation is taken into account in the model to reduce the scatter but the pulsational RV curves are either approximate (low order Fourier series) or over-fitted (high order Fourier series) depending on what serves better to recover the orbital motion. For example, for objects with steep RV changes, the latter produces more precise results.

3.4. Milky Way sample

GD-CEP-0291 is composed of two F-mode Cepheids. It is the brightest and the closest double Cepheid and is also the

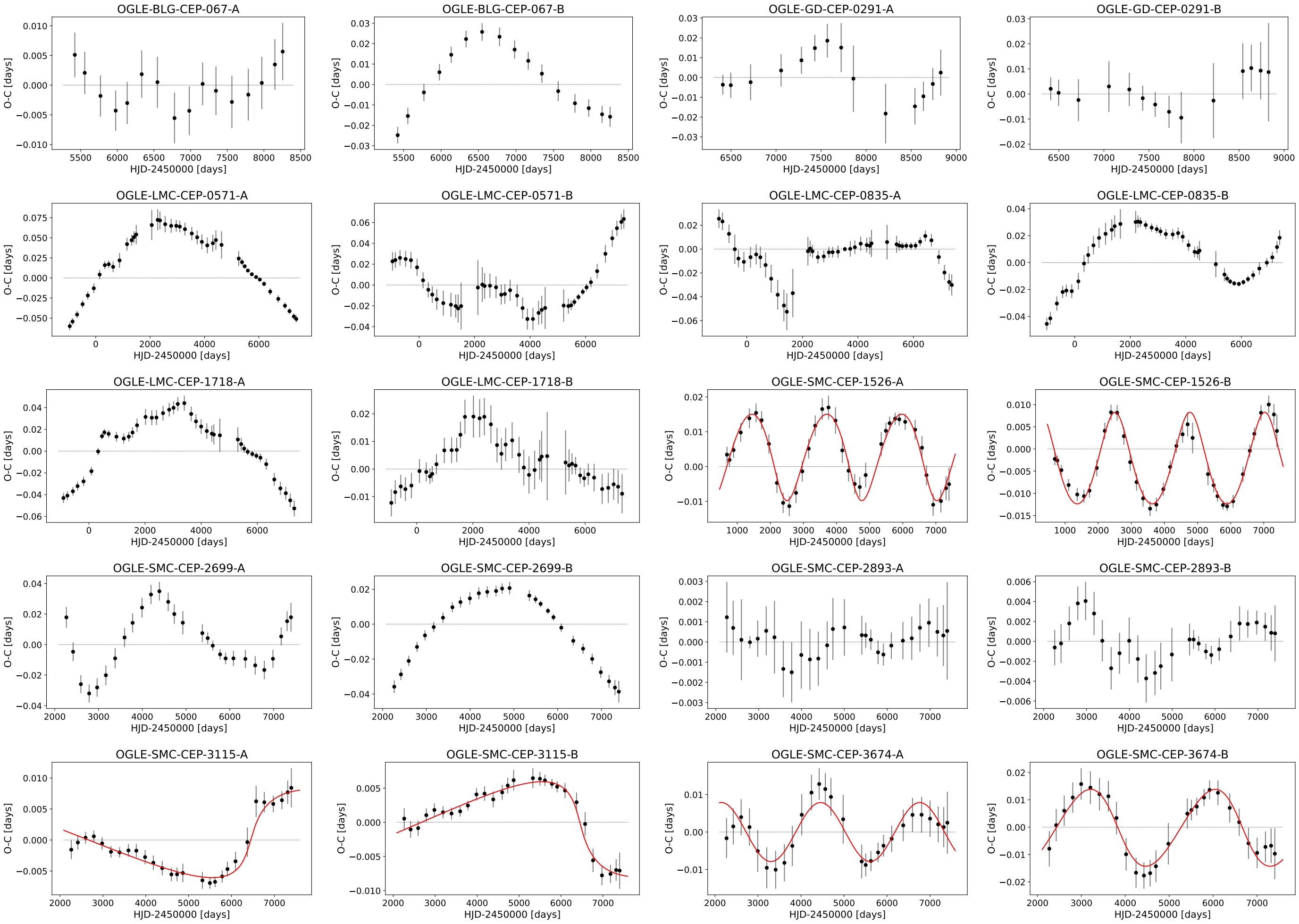

Fig. 2. Pairs of O−C plots for both components of candidate binary double Cepheids. The LTTE fit is shown with a red line for systems with a correlation parameter of O−C variations of $r < -0.8$. Three systems (OGLE-SMC-CEP-1526,3115,3674) show very strong evidence for LTTE. Two other stars (OGLE-LMC-CEP-0835,0571) show anticorrelated phase shifts, but the conclusions are less clear (see text). We show a common orbital solution for them in Fig. 3.

closest of any type of known double-lined binary Cepheid. Because distances from the *Gaia* mission (Gaia Collaboration 2016) were discrepant (4.3 kpc from GSP-Phot and 11 kpc from parallax; Lindegren et al. 2021), we calculated a distance to this star using the multiband method (Gieren et al. 2005), period–luminosity relations of Breuval et al. (2022), and additional photometric data from the *Gaia* (Gaia Collaboration 2023) and 2MASS surveys (Skrutskie et al. 2006). As our object is a double Cepheid, the method had to be slightly modified. From the P–L relations, we obtained the expected absolute magnitudes of individual Cepheids and calculated their combined absolute magnitudes. These values were then used as input for the multiband method together with the apparent magnitudes of the unresolved double Cepheid (see Fig. 6, left). Such a procedure yielded a distance of 10.7 ± 0.6 kpc, which is in agreement with that obtained from the parallax. As a byproduct, the reddening, $E(B-V) = 1.00 \pm 0.06$ mag, was also determined. We note that *Gaia* and OGLE photometry are not consistent. To be conservative, in order to determine the uncertainties, the original photometric errors were increased to obtain a reduced χ^2 of about 1.

Because of its wide orbit and proximity (it is located five times closer than the LMC systems), GD-CEP-0291 is probably the best target for future interferometric observations among all the binary Cepheids. From the current model, the expected maximum angular separation is about 1 mas, which is more than six times higher than for the currently widest orbit of the binary Cepheid LMC-CEP-4506 (Gieren et al. 2015). Once the astrometric orbit is obtained through interferometry, its combination with the known spectroscopic orbit will directly provide a geometrical distance to the object and the masses of the components.

BLG-CEP-067 is a double Cepheid composed of two 1O Cepheids with significantly different periods (see Table 1), which may suggest quite different component masses. Indeed, the mass ratio obtained from our RV data is consistent with the period ratio; that is, the shorter-period Cepheid is significantly less massive than the longer-period one. From the two options mentioned at the end of Sect. 2.1, this points to the merger scenario and not the combination of a first and a subsequent-crossing Cepheid. Using the multiband method mentioned above we determined a distance to this star of $d = 26.3 \pm 1.1$ kpc and a reddening of $E(B-V) = 0.90 \pm 0.04$ mag (Fig. 6, right). According to this measurement, this system is located in the disk far beyond the Galactic bulge, and only by coincidence is observed close to the Galactic center.

BLG-CEP-067 and GD-CEP-0291 are the first double-lined binaries with a Cepheid (two Cepheids in these cases) in the

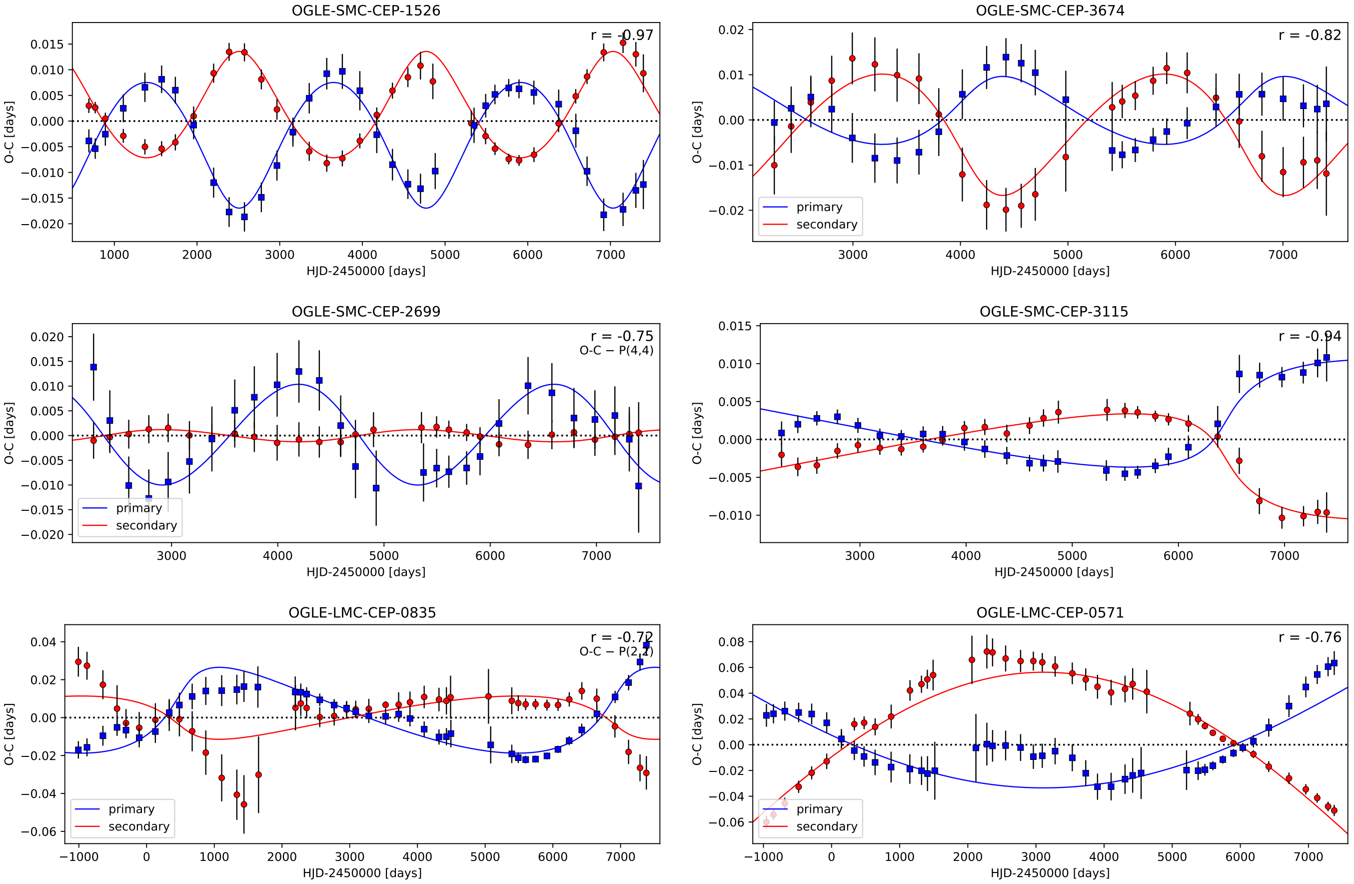

Fig. 3. O−C plots for both components of double Cepheids with anticorrelated phase shifts ($r < -0.7$). A common orbital fit is shown. The first four objects show clear LTTE, although for OGLE-LMC-CEP-2699, a fourth-order polynomial had to be subtracted from the O−C curves. Anticorrelated variability can also be seen for OGLE-LMC-CEP-0835 (after subtraction of a parabola) but the secondary shows strong deviation at 1500 days. The phase shifts of OGLE-LMC-CEP-0571 can be explained by an anticorrelated linear period change of the components and do not prove binarity.

Table 3. Orbital ephemeris from the O−C data.

OGLE ID	$T_{0,\rm orb}$ [days]	$P_{\rm orb}$ [days]
SMC-CEP-1526	5907 ± 17	2260 ± 12
SMC-CEP-3674	4500 ± 40	2630 ± 70
SMC-CEP-2699	4160 ± 60	2400 ± 80
SMC-CEP-3115	8900 ± 800	9300 ± 2300
LMC-CEP-0835	1760 ± 50	6440 ± 70

Notes. Orbital period ($P_{\rm orb}$) and reference time ($T_{0,\rm orb}$) for double Cepheids with anitcorrelated variability of the components (marked LTTE in Table 2). For OGLE-SMC-CEP-3115, the full cycle is not covered and the parameters are highly uncertain.

MW, where both components are giant stars. There are many other MW binary Cepheids known but all of them are composed of a Cepheid and an early-type main sequence component[6]. This opens up the possibility to obtain the first accurate mass determinations for Cepheids in SB2 systems composed of giants in our galaxy.

3.5. Large Magellanic Cloud

LMC-CEP-0571 is one of the three mixed-mode ($F+1O$) double Cepheids. The period ratio (after fundamentalization of the $1O$ period) is very close to unity, and so we expect a similar value for the mass ratio, but we cannot confirm this at the moment as the current solution is very uncertain. Both Cepheids in the system exhibit high period change rates of opposite sign (see Fig. 2). The preliminary orbital period of this system ($P \sim 1310$ d; we do not have a reliable value from the O−C analysis) is the second shortest in the sample.

LMC-CEP-0835 is composed of two F-mode Cepheids with a very low period ratio of about 0.6. It contains a Cepheid with the longest pulsation period in the sample. Both the O−C analysis and our spectroscopic data confirm that it is a binary system with a very long orbital period (∼18 yr) and small amplitude, which made the observations and analysis very challenging. More data spanning at least a few more years are needed to determine the mass ratio and to find a reason why the pulsation periods are so distinct.

3.6. Small Magellanic Cloud

The largest group of BIND Cepheids belongs to the SMC. These Cepheids are also the first to be confirmed spectroscopically as members of SB2 systems in this galaxy.

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[6] There are some visual pairs of Cepheids, such as CE Cas AB, but even if they are eventually found to be gravitationally bound, in practice we would have little to gain from that as their orbits would be extremely wide, impeding a meaningful analysis of their orbital motion.

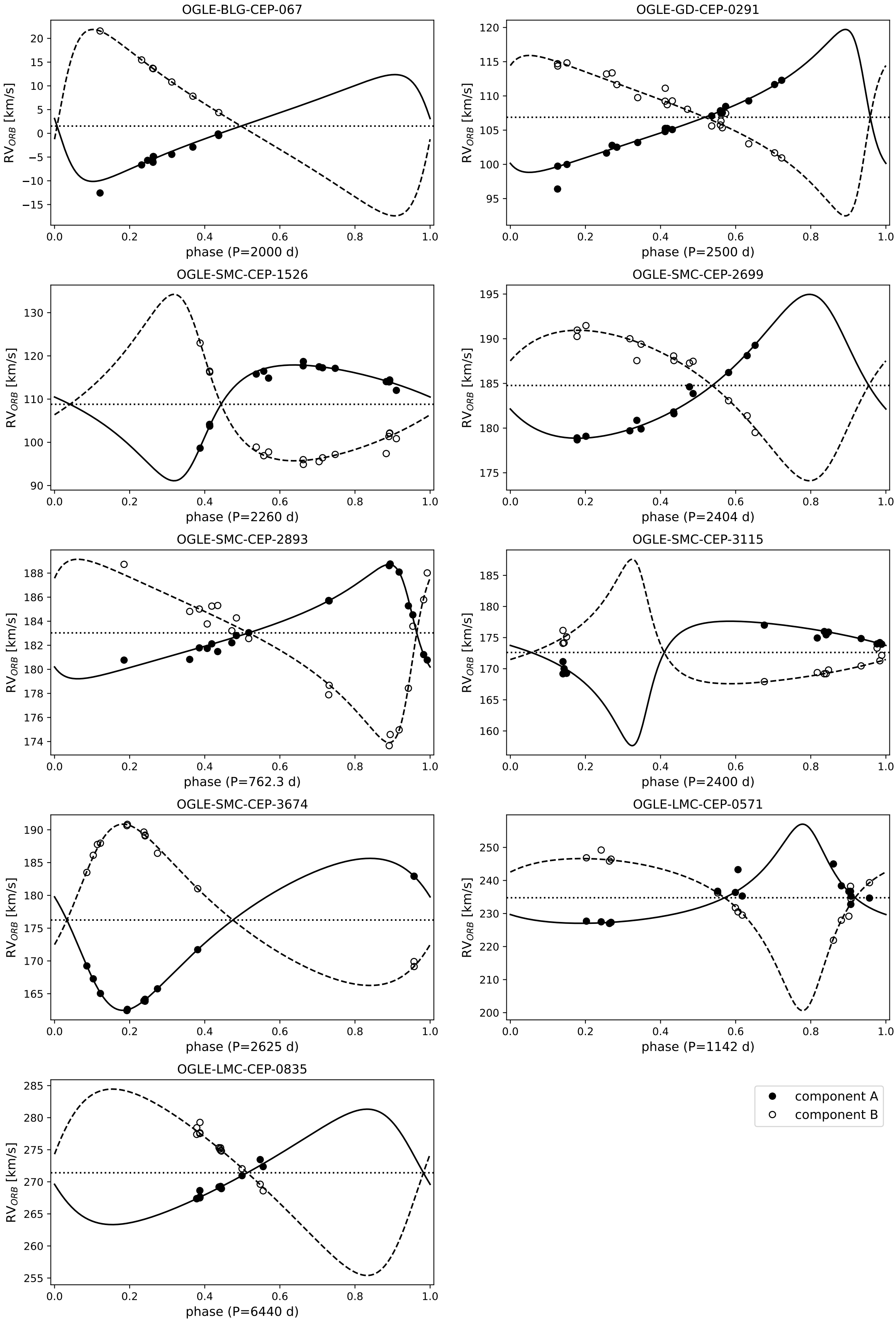

Fig. 4. Preliminary orbital RV curves. Only for OGLE-SMC-CEP-2893 and OGLE-LMC-CEP-0571 do the orbital periods come from an orbital solution. For three SMC systems (1526, 2699, 3674) and one in the LMC (0835), the period is taken from the LTTE model, while for the rest it is set to roughly match the data and to not produce unphysical results.

Table 4. Preliminary properties of BIND Cepheids.

OGLE ID	$T_{0,\mathrm{prb}}$ [days]	P_{orb} [days]	q	$M_1 \sin^3(i)$ [$M_\odot$]	$M_2 \sin^3(i)$ [$M_\odot$]	$A \sin(i)$ [$R_\odot$]	e	P_2^F/P_1^F	R_2/R_1
SMC-CEP-1526	8271 ± 15	$2260^{(*)}$	0.70 ± 0.09	3.6 ± 0.7	2.5 ± 0.6	1320 ± 90	0.42 ± 0.06	0.715	0.70 ± 0.04
SMC-CEP-2893	9210 ± 6	762 ± 7	0.62 ± 0.06	0.05 ± 0.01	0.03 ± 0.01	154 ± 9	0.57 ± 0.03	0.860	0.73 ± 0.03
SMC-CEP-3674	9256 ± 21	$2625^{(*)}$	0.94 ± 0.13	1.7 ± 0.4	1.6 ± 0.3	1190 ± 80	0.31 ± 0.05	$0.864^{(+)}$	0.89 ± 0.06

Notes. Preliminary properties of BIND Cepheids. Preliminary orbital and physical properties of three BIND Cepheids with best defined orbits. For two of them periods are fixed to the values obtained from the O–C analysis (marked with asterisk). In the penultimate column period ratios are shown for easy comparison with mass ratios. Note that for SMC-CEP-3674 the period ratio (marked with +) was calculated using for fundamentalization Eq. (2) from Szilàdi et al. (2018). In the last column radii ratios calculated from period-mass-radius relation (Pilecki et al. 2018) are provided.

SMC-CEP-1526 has a very well determined orbital ephemeris (thanks to the O−C analysis) and therefore we can obtain a relatively reliable preliminary orbital solution despite the lack of a fully covered orbital RV curve. The ratio of pulsation periods for this $F + F$ double Cepheid ($P_2^F/P_1^F = 0.715$) suggests a mass ratio that is different from unity. Indeed, our spectroscopic data confirm that the secondary (with the shorter period) is significantly less massive than the longer-period primary (see Table 4), similarly to BLG-CEP-067, suggesting a merger origin of the primary component. The preliminary minimum masses ($3.6\,M_\odot$ and $2.5\,M_\odot$) are high and also suggest a high inclination of the orbit.

SMC-CEP-2699 is another mixed-mode ($1O + F$) double Cepheid. It has the lowest period ratio in the sample, $P_2^F/P_1^F = 0.561$. Surprisingly, our preliminary spectroscopic solution suggests that the shorter-period secondary is more massive. If this holds true, it would mean that the secondary may not only be of merger origin but also on the first crossing, trying to catch up with the more evolutionary advanced but currently lower-mass primary. The orbital period from the O−C analysis (2400 days) is consistent with the RV curves and is too long for the mass transfer to be the cause of the mass difference.

SMC-CEP-2893 is composed of two F-mode Cepheids with among the shortest pulsation periods of the Cepheids in the sample. The system has the shortest orbital period ($P \sim 760$ d) among all the BIND Cepheids, but this is nevertheless longer than that of the previously known eclipsing double Cepheid, LMC-CEP-1718. This is the only system for which we can determine all the orbital parameters – including orbital period – from the RVs alone. The derived minimum masses suggest a very low inclination of the system (it is seen almost face-on, with inclination below 20°). The period ratio is moderately lower than unity ($P_2^F/P_1^F = 0.860$), which leaves any option possible, but our preliminary mass ratio (0.62) is significantly different from unity, suggesting a merger origin of one of the Cepheids. However, we are still cautious with this solution because of low RV amplitudes and still poorly covered pulsational RV curves. Moreover, due to the close-to-integer orbital period of 2.09 years, most of the spectra were acquired around two suboptimal orbital phases (~0.4 and ~0.9).

SMC-CEP-3115 is also composed of two F-mode Cepheids with very short pulsation periods. According to the O−C data, the system has a long orbital period and is probably highly eccentric. Current RV data span far enough to confirm the binary motion but not enough to constrain the eccentricity. The preliminary solution is very uncertain but suggests similar masses of the components, which is in agreement with the pulsation period ratio (0.926) of the components.

SMC-CEP 3674 is the third mixed-mode ($F + 1O$) double Cepheid. It shows quite well-defined LTTE in the O−C diagram, with the orbital cycle covered about two times. The orbital period from the O−C diagram is consistent with the spectroscopic data. SMC-CEP 3674 is the third BIND Cepheid for which a more reliable orbital solution could be obtained. Moderate minimum masses suggest an orbital inclination of around 45°. The preliminary mass ratio is 0.94, which is consistent with the period ratio of 0.920.

3.7. Period ratios

We mention in Sect. 2.1 that period ratios very different from unity are suspicious and not expected if assuming no previous interaction between the components and excluding the uncommon combination of a first-crossing Cepheid and a Cepheid on a blue loop. As such ratios, we consider those with values of around 0.6 or lower, which is based on our evolutionary and pulsation theory models presented in Espinoza-Arancibia et al. (2024). Using these models, such different periods cannot be obtained for similar-mass Cepheids unless one of the Cepheids is still on the first crossing. However, to estimate the rarity of the period ratios measured for BIND Cepheids, a large and empirical comparison sample is necessary. To this end, we looked into the list of 24 Cepheids in the LMC star cluster NGC 1866 (Musella et al. 2016), which should all have roughly similar ages. We calculated all possible combinations of period ratios for these Cepheids, excluding two with uncertain membership and fundamentalizing periods for first-overtone Cepheids. A histogram of these period ratios compared with those for BIND Cepheids is shown in Fig. 7 (left). As can be seen there, P_2^F/P_1^F values for the NGC 1866 Cepheids of lower than 0.8 are very rare and values below 0.7 are absolutely nonexistent.

However, Cepheids in NGC 1866 have fundamentalized periods of between 2.64 and 3.52 days, while P^F of our BIND Cepheids ranges from 1.14 to 4.56 days. To increase the size of the comparison sample and the range of periods, we added 12 Cepheids (P^F from 2.66 to 4.43 days) from another LMC cluster, NGC 2031 (Bertelli et al. 1993), to the analysis. A histogram for the combined datasets is shown in the right panel of the same figure. According to this test, randomly taking a pair of Cepheids from any of the two clusters one would have little chance (~7%) of obtaining a ratio of lower than 0.8, and only about 2% have ratios of below 0.7. On the contrary, half of BIND Cepheids have these values lower than 0.8, and 30% of them show values of below 0.7.

Taking into account the fact that the Cepheid membership for NGC 2031 is not as certain as for NGC 1866, we tested the

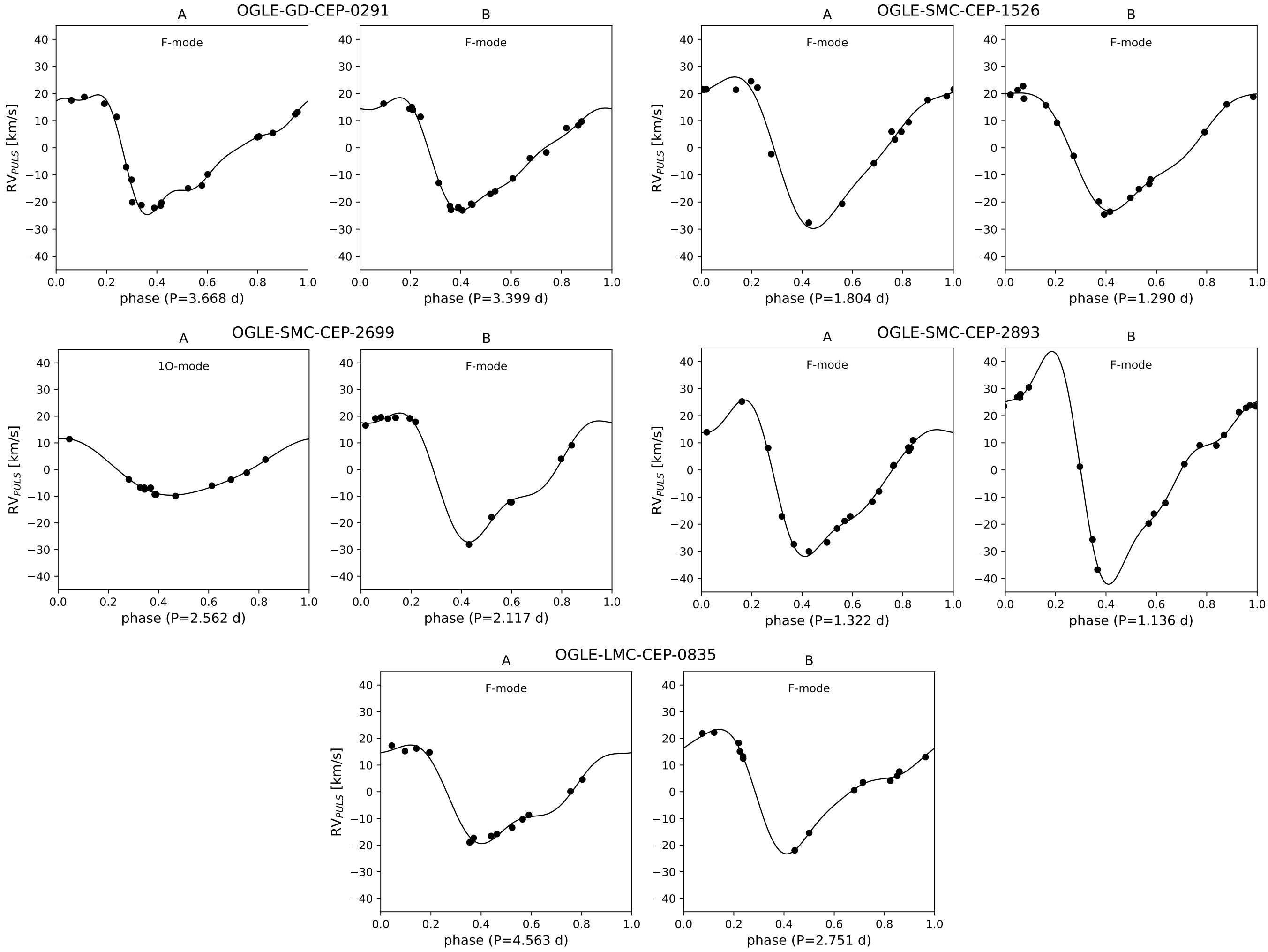

Fig. 5. Preliminary pulsational radial velocity curves for five binary double Cepheids with the best-covered pulsation cycles. For each system, RVs for both Cepheid components (A and B) are shown. The solid line is a Fourier series fit to the data (third to fifth order for F mode and second order for the 1O Cepheid). The span of the Y-axis is the same for all panels.

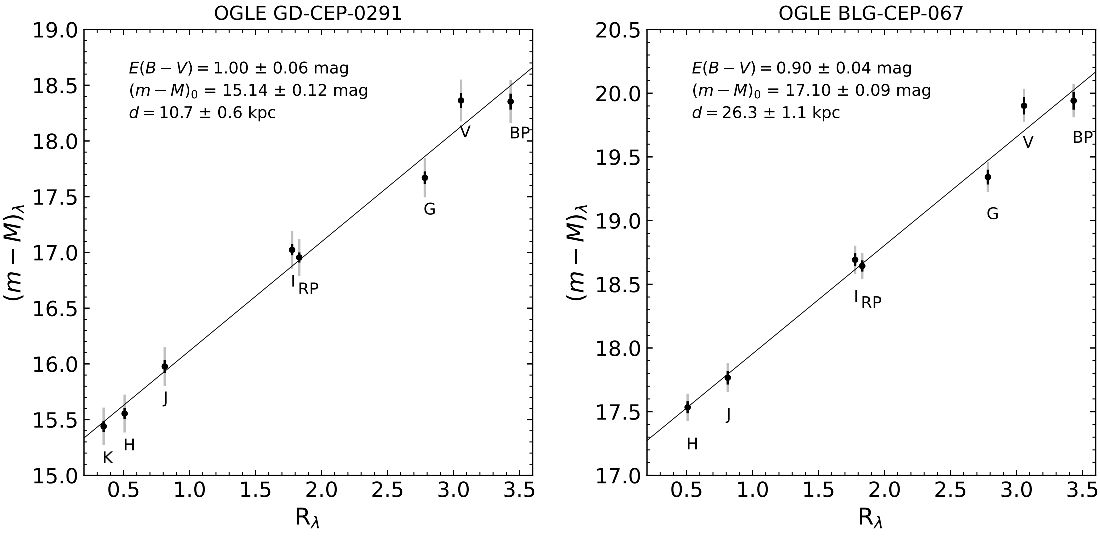

Fig. 6. Multiband method applied to the two MW Cepheids, providing distances and reddening values. OGLE-GD-CEP-0291 is found to be the closest double and also the closest known double-lined binary Cepheid of any type. BLG-CEP-067 is apparently far beyond the Galactic bulge. The original photometric errors are marked in black, while those increased to obtain the reduced χ^2 = 1 are marked in gray.

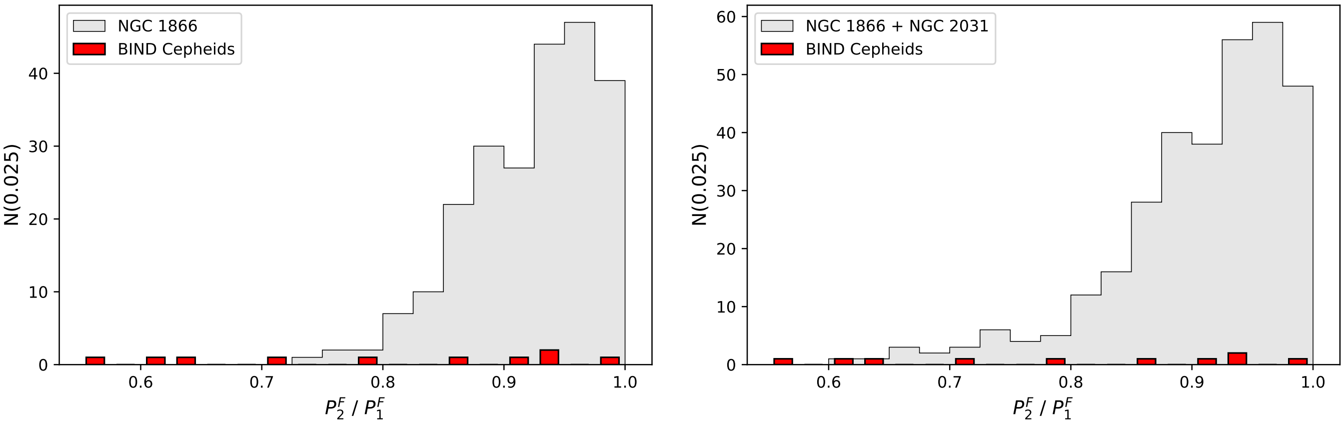

Fig. 7. Histogram of period ratios for all combinations of Cepheids in NGC 1866 and (separately) in NGC 2031 compared with period ratios of BIND Cepheids. Only for ~7% of these combinations are period ratios lower than 0.8, while half of the BIND Cepheids have a period ratio of below this limit.

effects of removing different NGC 2031 Cepheids from the list and repeating the analysis. For such variants, chances varied from 4% to 8% for period ratios of lower than 0.8 and from 0.3% to 2% for ratios lower than 0.7, meaning it would be hard to increase these values considerably above those determined in the previous paragraph. We also note that for the aforementioned visual pair of Cepheids, CAab Cas, the period ratio is 0.87 (Opal et al. 1988).

We can compare these results with what we know about the eclipsing binary double Cepheid, LMC-CEP-1718. For that Cepheid, the period ratio is 0.786. Although the mass ratio is close to unity, the slightly less massive Cepheid is more luminous and seems to be more evolutionary advanced, which points to some kind of disturbance in the past evolution of this double Cepheid. This could be a border case, where the components passed through a weak interaction that did not strongly change the mass ratio. We note that this is the tightest system among all the BIND Cepheids, with an orbital period of 413 days.

3.8. Period–luminosity relations

Most of the Cepheids are expected to exist in binary systems, with the great majority of them having early-type main sequence companions that are much fainter and are hardly seen in the spectra (Bohm-Vitense & Proffitt 1985; Kervella et al. 2019). As the systems we analyzed here are known to be composed of two Cepheids, there is a tempting possibility to investigate the effect of binarity on the average brightening of period–luminosity (P–L) relations.

The presence of two Cepheids allows us to determine the luminosity ratio from the known period ratios (see Table 1). This in turn allows us to split the total observed flux between the two components. We did this for their V- and I-band magnitudes and calculated corresponding Wesenheit magnitudes, $W(V,I)_i = I - 1.55(V - I)$, for individual Cepheids. With the same approach as in P21, we prepared the P–L relations for all Cepheids in their host galaxies, fundamentalizing periods of 1O Cepheids. We then compared the $W(V,I)_i$ values with these relations and found that almost all the individual components lie significantly below them, sometimes on them, and never significantly above. For the LMC systems the average difference is 0.016 ± 0.012 mag, while for the SMC it is 0.053 ± 0.022 mag. A weighted mean of both is 0.024 ± 0.010 mag. Although this detection is not particularly firm, the sign is what we expect and the value appears reasonable. This is also the first empirical determination of a P–L relation shift due to binarity.

One may note that this is only a shift due to the presence of a secondary component, while there may exist higher-order multiple systems with Cepheids. However, we can expect the influence of higher-order components to be much weaker because: (1) they are more rare, (2) they are on average less massive and luminous, and (3) they would have a less significant relative effect on the total brightness.

4. Conclusions and perspectives

Alcock et al. (1995) identified the first three double Cepheids in the LMC galaxy (identified LMC-CEP-0571,0835,1718 in this work). Although these authors speculated they could be binaries, the conclusion was that the physical connection between them could not be determined without long-time-scale spectroscopic monitoring. Alcock et al. (1995) expected periods of longer than 1.5 years. In 2014, we performed a spectroscopic study of one of these systems (LMC-CEP-1718; Gieren et al. 2014), revealing an orbital period of 1.13 yr. This was the first – and for a long time the only – double Cepheid spectroscopically confirmed as a binary system (i.e., a BIND Cepheid).

In the present study, we confirmed nine more double Cepheids from the MW, LMC, and the SMC galaxies to be components of binary systems, increasing the total number of BIND Cepheids from 1 to 10. With this discovery, we also tripled the number of all spectroscopically confirmed Cepheids in double-lined binary systems. The SMC and MW BIND Cepheids are the first found in double-lined systems in their host galaxies. The MW Cepheids are also the closest to us of this type. Located at a distance of around 11 and 26 kpc, they are five and two times closer than the previously known SB2 Cepheids in the LMC. As there are no known unresolved double Cepheids other than those presented here, these ten BIND Cepheids will probably be the only ones we know for quite a long time.

As expected from the O–C analysis, the orbital periods of seven systems (or eight if counting LMC-CEP-0571 with a lower limit of 3.6 yr) are indeed long, longer than 5 years. This makes the probability that any of these systems will exhibit an eclipse very low. In this sense, we are very lucky that the shortest-period BIND Cepheid (LMC-CEP-1718; Pilecki et al. 2018) was found to be eclipsing, even if the eclipse is grazing, as there was only about 8% chance of that, and the chance for eclipses in other

BIND Cepheids is much lower still – about 3% on average. In our current sample, there is only one system with a relatively short period, SMC-CEP-2893, but as mentioned before, it is probably positioned almost face on. The long-period end cannot be easily probed with the spectroscopic observations spanning less than 4 years. Therefore, the longest orbital period of about 18 years was found for LMC-CEP-0835 based on the O−C analysis. This makes it the longest-period binary discovered to date in another galaxy. We note, however, that such long periods, or even longer, are quite common in the MW, also among binary Cepheids (see e.g. a recent work of Cseh et al. 2023).

Our study shows that the O−C analysis provides quite reliable results regarding detection of binarity and orbital periods whenever more than one cycle of the orbital motion is covered. In case of BIND Cepheids, the anticorrelated O−C behavior may also indicate binarity even when the cycle is not completely covered.

For the first time, we empirically estimate the effect of binarity on the period–luminosity relation. The sign of the shift is as expected and the value ($\Delta W(V, I) = 0.024 \pm 0.010$ mag) appears reasonable. However, a further, more detailed study is needed to improve and confirm this value.

Perspectives

This is a long-term project and with this paper we come to the end of its first phase, the goal of which was to spectroscopically confirm binarity of all known double Cepheids and to obtain first estimates of basic parameters, such as orbital period. Moving forward, the next phase of the project is designed to obtain the final physical properties of the components and precise orbital parameters of the systems. To this end, we plan to continue monitoring all the objects until we have sufficient data for a reliable solution, publishing final results for a given system or systems as soon as they are ready.

Unless we detect eclipses for any of these systems, a direct measurement of masses will not be possible. From the orbital solution, it is only possible to measure mass ratios and $M \sin(i)^3$ because of our lack of knowledge about the inclination (i), and so we will only be able to obtain lower limits. However, from the directly measured mass ratios and the extremely precise period ratios readily available from the photometric data, radius ratios can also be calculated using, for example, the period–mass–radius relation (Bono et al. 2001; Pilecki et al. 2018) or basic pulsation theory models (Pilecki et al. 2017; Smolec & Moskalik 2008). Using additional data, such as known distances (individual or to the host galaxy in the case of the LMC and SMC objects), observed brightness, and temperature measured from spectra, absolute radii and masses can also be determined. This means that, potentially, we may be able to obtain new accurate mass estimates from SB2 systems for up to 18 Cepheids, which will be a huge improvement on our current knowledge (6 direct measurements and 5 uncertain estimates from SB1 systems; Pilecki et al. 2018; Evans et al. 2018). We estimate the precision of masses obtained in this way to be better than 10%. Together with already published LMC-CEP-1718, this set of nine new BIND Cepheids (10 systems, 20 Cepheids in total) will form as an important basis for various follow-up studies (e.g., statistical analyses and evolutionary and pulsation modeling).

A very tempting possibility to open up with the presented BIND Cepheids is to try to resolve them interferometrically and measure the angular separation (ϕ). From there, it is possible to directly calculate a geometrical distance using a simple formula: $d[\mathrm{pc}] = 9.2984 \times L[R_\odot]/\phi[\mathrm{mas}]$, where L is the linear projected separation from the spectroscopic solution. As mentioned above, we can start with the closest system GD-CEP-0291, but eventually move to the Magellanic Clouds, using the advantages that BIND Cepheids are luminous and display a large orbital separation of the components, which is necessary to resolve them. Normally, systems with such properties are hard to identify in other galaxies. Some were detected through eclipses during sometimes decades-long microlensing surveys (OGLE, MACHO) but in addition to its inefficiency, this method favors tighter orbits. The longest orbital period measured so far for an extragalactic system is $P = 1550$ days (~4 yr; Gieren et al. 2015), which translates to a separation of 0.16 mas. Therefore, BIND Cepheids are currently our best candidates for a direct and accurate geometric distance determination to the LMC and SMC galaxies; this would eventually lead to the ultimate calibration of the first rung of the cosmic distance ladder.

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