The impact of binary Cepheids on the distance determinations

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Due to the light of their companions, binary Cepheids might seem over-luminous and appear above the period-luminosity relation (PLR). This systematic effect introduces a shift in the PLR zero-point towards smaller magnitudes. We present quantitative results on the impact that companions to classical Cepheids have on the PLR zero-point. We use the binary population synthesis code StarTrack to evolve 200 000 binary systems for three metallicities Z=0.004, 0.008, 0.02, which correspond respectively to the metallicities of the Small and Large Magellanic Clouds and the Milky Way. We narrow these populations down to stars which pass the filtering criteria for classical Cepheids on their second and third crossing through the instability strip, and parametrize the impact of companions in form of the binarity fraction $f_{\rm bin} = 25, 50, 75, 100$. This yields a linear relation between the binarity fraction and the shift of the PLR zero-point, and find that it is steeper at shorter wavelengths.

1 Introduction

Classical Cepheids – famous for their period-luminosity relation (PLR) – are among most accurate and precise distance indicators. Our knowledge of the link between their luminosity and physical parameters – and by extension their performance as standard candles – constantly improves as more and more studies address different aspects of their nature, like metallicity (Gieren et al., 2018).

In the endeavor of refining the PLR, little attention has been devoted to the binarity of Cepheids. It is assumed that a companion has negligible effect on the cumulative light of a system and as such does not affect the zero-point of the PLR, even though $60 - 80\%$ of Milky Way (MW) Cepheids are binaries (Szabados, 2003; Mor et al., 2017). Furthermore, Evans et al. (2005) reported that at least 44% of all binary Cepheids are in fact triple systems; this discovery is crucial for mass determination of (assumed) binary components, as the presence of a tertiary leads to inaccurate estimations of the Cepheids' masses.

Only a fraction of Cepheids in binary systems can be thoroughly, when the inclination angle favors eclipses or the small contrast between the brightness of the Cepheid and its companion allows for spectroscopic analysis of both components. As a consequence, only 170 MW Cepheids in binary systems have been analyzed so far (a complete database was published by Szabados (2003) and updated since[1]) and among them only 32 have their orbital and physical parameters known (Kervella

[1] `https://konkoly.hu/CEP/intro.html`

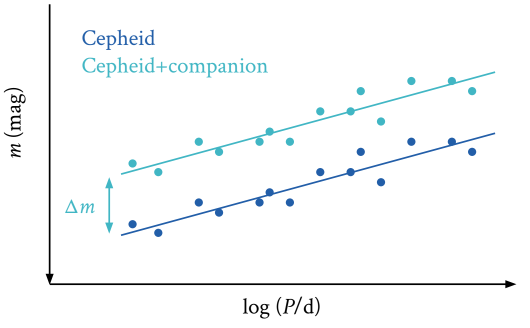

Fig. 1: A sketch of shift in the zero-point of period-luminosity relation (PLR), Δm, due to the presence of companions. Light blue dots represent Cepheids with binarity fraction of 100%, i.e. every Cepheid has a companion, while dark blue dots show the same Cepheids without companions. If PLRs are defined as $m_1 = \alpha \log(P) + \beta_1$, $m_2 = \alpha \log(P) + \beta_2$, then the difference of their zero points is $\Delta m = \beta_2 - \beta_1$.

et al., 2019a,b). In the Large Magellanic Cloud (LMC) the number of binary systems with Cepheids with known orbital and physical parameters is even smaller and equals seven (Pilecki et al., 2018). In the Small Magellanic Cloud (SMC) no binary Cepheids have been reported so far, but a handful of candidates awaits further attention (Udalski et al., 2015). All analyzed binary Cepheids in the LMC have giant evolved stars as companions, with radii and effective temperatures similar to the Cepheid's parameters[2], whereas companions to MW Cepheids are mostly hot main sequence stars which could only be detected in the ultraviolet domain (Evans, 1992).

If such binaries remain unrecognized they might cause a systematic shift to the PLR zero-point because of the excess light from a companion. In extreme cases, when a companion is a red giant or a Cepheid itself, the light of the system can even be doubled (Pilecki et al., 2018). This can introduce a systematic shift in PLR towards smaller magnitudes, Δm, as sketched in Fig. 1, and in turn add up to the error budget of distance determination. To date the most precise distance determinations from the Cepheid PLR have uncertainties of 0.014 mag in the visual domain, and 0.006 mag in the near-infrared (Wielgórski et al., 2017). Such small uncertainties suggest binarity should be factored into the analysis because the impact of the companion's light might not be negligible anymore.

2 Binary population synthesis

Regarding the fact that 60−80% of Cepheids are binaries (Szabados, 2003; Mor et al., 2017) and only a fraction has been detected so far, we resort to the population synthesis method, which is bias-free and allows control over the binarity fraction. Binary population synthesis codes run stellar and binary evolution fast end efficiently, but this advantage is balanced by an abridged set of stellar parameters that describe binary systems and approximate formulas that govern their evolution. For this study we used the binary population synthesis code StarTrack (Belczynski et al., 2002,

[2]This is most likely a selection effect: in the LMC the companions were detected thanks to eclipses, and giant stars are more prone to cause eclipses on Cepheids than MS stars.

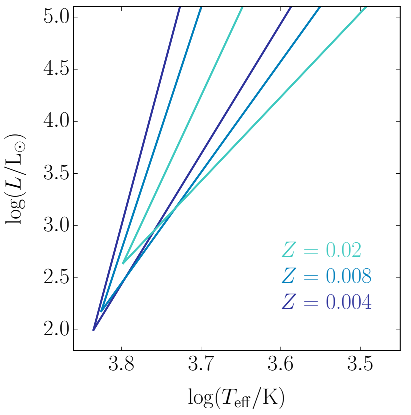

Fig. 2: Width and shape of the instability strip for different metallicities, as determined from Bono et al. (2000).

2008) to generate three distinct populations for metallicities $Z = 0.004, 0.008, 0.02$, which correspond to the SMC, LMC, and MW, respectively. Each population consists of 200 000 binaries created by randomly assigning four initial parameters from distributions: (i) broken power-law initial mass function (IMF, Kroupa & Weidner, 2003) for the mass of the primary M_{A} in range $3 - 150\,\mathrm{M}_{\odot}$; (ii) flat distribution of mass ratio of secondary to primary $q = M_{\mathrm{B}}/M_{\mathrm{A}}$ (Kobulnicky & Fryer, 2007) in range $q_{\mathrm{min}} - 1$, where q_{min} is the mass ratio that determines the lower mass limit of the secondary $M_{\mathrm{B}} = 0.08\,\mathrm{M}_{\odot}$; (iii) flat distribution of the logarithm of binary separation (Abt, 1983) in range $a_{\mathrm{min}} - 10^5\,\mathrm{R}_{\odot}$, where a_{min} is the doubled sum of components' radii at periastron; (iv) thermal-equilibrium distribution of eccentricities (Heggie, 1975) $\Xi(e) = 2e$ in range $0 - 0.99$.

All synthetic populations were subjected to a filtering algorithm in order to exclude systems with stars that do not resemble Cepheids. The algorithm adds a star to the final sample if all requirements are fulfilled: (i) star's effective temperature and luminosity places it inside the instability strip (IS) of fundamental mode classical Cepheids (Bono et al., 2000), that is shown in Fig. 2; (ii) star is in the evolutionary stage of core helium burning; (iii) star experienced none or little mass transfer (less than 5% of initial mass) prior to the IS; (iv) star's mass loss due to stellar wind inside the IS is smaller than $10^{-6}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ (Deasy, 1988). As a consequence, the final sample consists of systems with classical Cepheids on their blue loop (second and third IS crossing) and allows for the possibility that both components are Cepheids simultaneously. The final samples were then scaled according to the Star Formation History in the LMC (Harris & Zaritsky, 2009), SMC (Rubele et al., 2018), and MW (e.g. Klencki et al., 2017), which rendered a reliable combination of Cepheids on the second and third IS crossing.

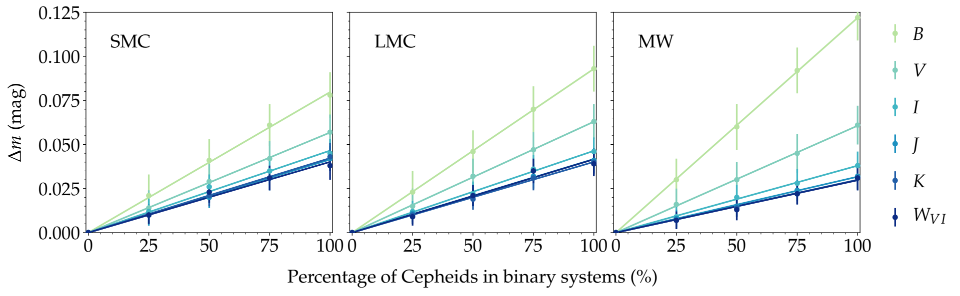

Fig. 3: Excess of brightness in the period-luminosity relation as a function of percentage of Cepheids in binary systems with respect to the reference point, i.e. Cepheids without companions.

3 Shift in the period-luminosity relation

The total brightness of a system (Cepheid + companion) is calculated as follows (e.g. Ridpath, 2012):

$$m_{\rm tot} = m_{\rm cep} - 2.5 \log(1 + 10^{-0.4(m_{\rm com} - m_{\rm cep})}),$$

where individual brightnesses $m_{\rm cep}$ and $m_{\rm com}$ are expressed in most common pass-bands: B, V, I, J, K, and Wesenheit index $W_{\rm VI}$, based on ALTAS9 model atmospheres of Castelli & Kurucz (2003), and distance modulus to the LMC, $(m-M) = 18.476$ mag (Pietrzyński et al., 2019). The distance for SMC, LMC, and MW synthetic populations was assumed the same, because the analysis presented here requires calculations of only differential brightnesses, not absolute ones. The effect of reddening was omitted for the same reason.

Because we work on synthetic data, we can control the effect of binarity by setting a *binarity parameter* $f_{\rm bin} = 0, 25, 50, 75, 100\%$, i.e. the percentage of Cepheids with companions with respect to the entire sample. For example, $f_{\rm bin} = 0\%$ means that all companions are ignored and the total light comes entirely from Cepheids themselves, while $f_{\rm bin} = 100\%$ means that all Cepheids have companions that contribute their light to the total light of the systems. Any value in between these extremes was set by ignoring companions to Cepheids at random. The shift in the zero-point of PLR, Δm, is expressed as a difference in zero-points at fixed slopes for a pure population of single Cepheids and a mixed population of Cepheids + companions, as sketched in Fig. 1. If $\Delta m = 0$ mag the binary population does not shift the zero-point of PLR, but if $\Delta m > 0$ mag, the excess light from Cepheids' companions introduces the shift in the zero-point of the PLR. Our analysis was performed for binary synthetic populations of different metallicities (SMC, LMC and MW), different filters (B, V, I, J, K, $W_{\rm VI}$) and different binarity fractions ($f_{\rm bin} = 25, 50, 75, 100\%$), and is plotted in Fig. 3.

The results in Fig. 3 show a linear dependence of the shift in the zero-point, Δm, as a function of binarity fraction, $f_{\rm bin}$. This dependence has a steeper slope for shorter wavelengths. The exception is $W_{\rm VI}$, which seems to depend equally little on binary fraction as J- and K-band. Moreover, Δm depends on metallicity, but in a complex way – the dispersion of $f_{\rm bin}$-Δm relations in different pass-bands is

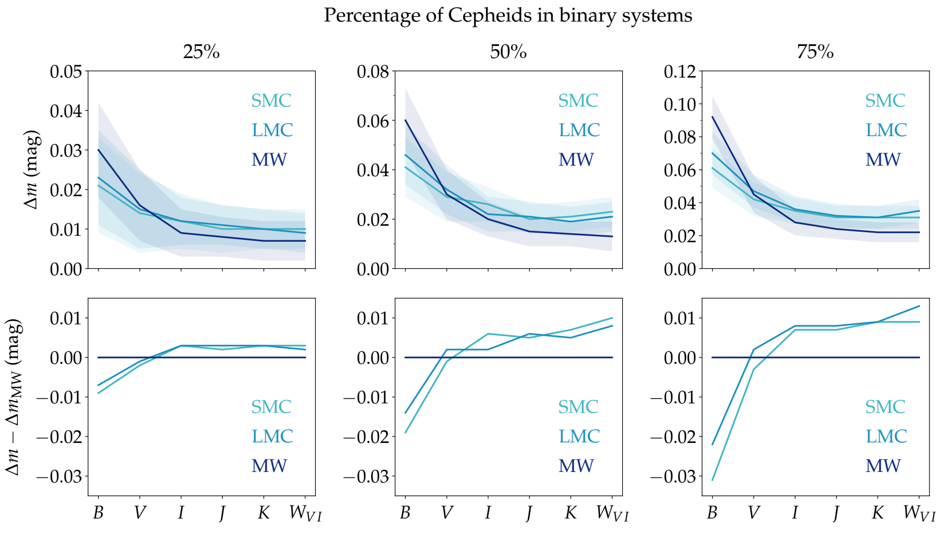

Fig. 4: Differences in the zero-point of period-luminosity relations, Δm, as a function of the pass-bands. Results depend on metallicity and the percentage of binary systems in the sample (25, 50, 75%). Top panels show absolute Δm, bottom panels show $\Delta m - \Delta m_{\rm MW}$, i.e. zero-point shifts relative to the zero-point shift of the Milky way.

smaller for SMC than for the LMC, and is the largest for the MW. For example, the dispersion of the shift in the zero-point between B and K-band, given a binarity fraction of 50%, is 0.02 mag in SMC and 0.045 mag in the MW. This result is caused by different contributions of light from Cepheid and its companion, and requires further investigation in order to pinpoint those stellar properties most affected by the metallicity which cause the effect.

In Fig. 4 the shift in the zero-point is presented as a function of wavelength. Top panels show that Δm in the smallest in J-, K-bands, and $W_{\rm VI}$. Bottom panels show the *relative* shift in the zero-point, with respect to the zero-point shift of the MW (plotted as horizontal line). The reason to include the relative shift is that the PLR for classical Cepheids has long been considered universal, i.e. independent of population effects (like metallicity) and the same for all galaxies, and as such would have the values of slope and zero-point fixed for a given pass-band. Together with metallicity effects (Gieren et al., 2018), binarity challenges this view. Bottom panels of Fig. 4 show that, for a given pass-band, values of zero-point vary depending on galaxy's metal content. The relative zero-point shifts for the SMC and LMC are positive (larger than the zero-point shift for the MW) for longer wavelengths and negative (smaller than the zero-point shift for the MW) for shorter wavelengths. At the wavelength corresponding to the V-band, relative zero-point shift is zero for all galaxies, meaning that in the V-band the effect of binarity on Δm cancels out.

4 Conclusions

Our study provides the first quantitative description of contamination of the PLR by binary Cepheids for three different environments: SMC, LMC, MW. Quantification was made possible thanks to an introduced parameter – the zero-point shift, Δm – which reflects how much the PLR is shifted due to the excess light from the Cepheids' companions. We report that the zero-point shift, Δm, depends on binarity fraction, wavelength of observations, and metallicity. Although the binarity fraction is beyond our control outside the population synthesis method, we can minimize the effect of Δm on distance determination by utilizing data collected in the near-infrared domain or expressed as Wesenheit index. Furthermore, for a fixed binary fraction, the shifts in the zero-points caused by binarity cancel out in V-band in all considered galaxies.

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