Cepheids in eclipsing binary systems

Bogumił Pilecki[1,2], Grzegorz Pietrzyński[1,2], Dariusz Graczyk[2] and Wolfgang Gieren[2]

1. Warsaw University Observatory, Aleje Ujazdowskie 4, 00-478 Warszawa, Poland
2. Universidad de Concepción, Departamento de Astronomía, Casilla 160-C, Concepción, Chile

We present the results of the analysis of eclipsing binary systems with pulsating components. As for now we have analyzed five systems with Classical Cepheids. For the first time we have measured the dynamical masses (together with other physical parameters) of Cepheids with an outstanding precision of less than 1 percent. These measurements served to solve the famous Cepheid mass discrepancy problem. For two of the stars it was also possible to determine directly the value of a projection factor, a very important parameter necessary to use the Baade-Wesselink method. One system was also confirmed to consist of two first-overtone Cepheids. Unfortunately due to high eccentricity only one eclipse is visible for this binary system.

1 Introduction

Classical Cepheids are radially pulsating giants and supergiants of population I. Thanks to their period-luminosity relation they are important distance indicators in the local Universe. They form a fundamental part of the cosmic distance ladder, 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 theory.

However there are many challenges to be faced. The metallicity dependence of the P-L relation (or the Leavitt Law) introduces systematic errors in the distance measurements. The relation needs to be calibrated. The projection factor (p-factor) which is crucial for the use of the Baade-Wesselink method is still quite a mystery, as the current results are somewhat contradictory, with the theory and observations yielding quite different results. There was a lack of direct measurements though.

For a long time there existed a Cepheid mass discrepancy problem – the calculated evolutionary mass was higher than the one obtained from the pulsation theory by about 20%. The dependence of this discrepancy on mass and metallicity is also unclear.

There is also a problem with apparent *fall* of Cepheids towards the Sun. Their measured velocities seem to be blueshifted by 1-2 km/s.

All these problems are hard to solve for single stars. On the other hand multiple and binary systems are very common and detached eclipsing double-lined spectroscopic binaries (SB2) provide us with the opportunity to directly and very accurately measure stellar parameters like mass, luminosity or radius. We can also measure the distance to such systems using almost purely geometrical methods.

Although Cepheids in binary systems were known, for many years it was hard to find one in an eclipsing system. The breakthrough came with the microlensing surveys like OGLE (Udalski et al., 2015) or MACHO (Alcock et al., 2002). Some candidates in the Large Magellanic Cloud (LMC) were proposed and later observed spectroscopically.

OGLE-LMC-CEP-0227 was the first to be confirmed (Pietrzyński et al., 2010). It was later reanalyzed by Pilecki et al. (2013) using a more advanced method and more data. Five other Cepheids were confirmed and their parameters measured until now: OGLE-LMC-CEP-1812 (Pietrzyński et al., 2011), OGLE-LMC-CEP-1718 A and B (Gieren et al., 2014), OGLE-LMC-CEP-2532 (Pilecki et al., 2015) and OGLE-LMC562.05-9009 (Gieren et al., 2015).

2 Method and analysis

For detailed description of the method and the analysis steps we refer the reader to Pilecki et al. (2013) and the papers on other Cepheids that follow. Here we will present just a short summary of the subject.

Radial velocities (RV) were measured using the Broadening Function method implemented in the RaveSpan code (Pilecki et al., 2012). Orbital solutions were then obtained using the same program and/or Wilson-Devinney code (Wilson & Devinney, 1971). In RaveSpan the pulsations are included and for the analysis with the Wilson-Devinney code they are first subtracted. As a result we have the masses and the system size (scaled by the inclination), the orbital parameters and the pulsational RV curve. The latter is used to measure the radius change after scaling it with the p-factor.

The photometric data were analyzed using a pulsation-enabled eclipsing modeling tool based on well-tested JKTEBOP code (Southworth et al., 2004) modified to allow the inclusion of pulsation variability. We generate a two-dimensional light curve that consist of purely eclipsing light-curves for different pulsating phases. Then a one-dimensional light curve is generated (interpolated from the grid) using a combination of pulsational and orbital phases calculated using a Cepheid and system ephemerides.

From the photometric solution we have the period, the time of the primary minimum, the inclination, the fractional radii, the eccentricity, the argument of periastron, the surface brightness ratios, the third light (if exists), and the p-factor value. Various limb darkening parameters are also tested.

To obtain an optimal solution and error estimation standard Monte Carlo and Markov Chain Monte Carlo (MCMC) samplings are used.

3 Results

As for now five systems were analyzed yielding physical parameters for three fundamental (FU) and three first-overtone (1O) Cepheids (see the list in Table 1). Using the obtained mass of the OGLE-LMC-CEP0227 Cepheid ($M_{cep} = 4.16 \pm 0.03 M_{\odot}$) we showed that the pulsation theory predicts it correctly and that the theory of evolution has to be adjusted. The parameters of all analyzed Cepheids can be found in the tables in their corresponding papers (see references in the Introduction).

First direct, distance-independent p-factor measurements were obtained for two of the stars. For OGLE-LMC-CEP0227 we obtained $p = 1.21 \pm 0.03$ and for OGLE-LMC562.05-9009 – $p = 1.37 \pm 0.09$. Such a difference between these Cepheids may be caused by an intrinsic dispersion, which may be not only period dependent. For these two stars the limb darkening was also estimated and the values resulted to be much lower and the phase dependence significantly different than expected.

Table 1: Analyzed Cepheids

ID	Type	Period [d]	Comment
OGLE-LMC-CEP-227	FU	3.797086	p-factor
OGLE-LMC562.05-9009	FU	2.987846	p-factor
OGLE-LMC-CEP-2532	1O	2.035349	single eclipse
OGLE-LMC-CEP-1718B	1O	2.480917	single eclipse
OGLE-LMC-CEP-1718A	1O	1.963663	single eclipse
OGLE-LMC-CEP-1812	FU	1.312903	

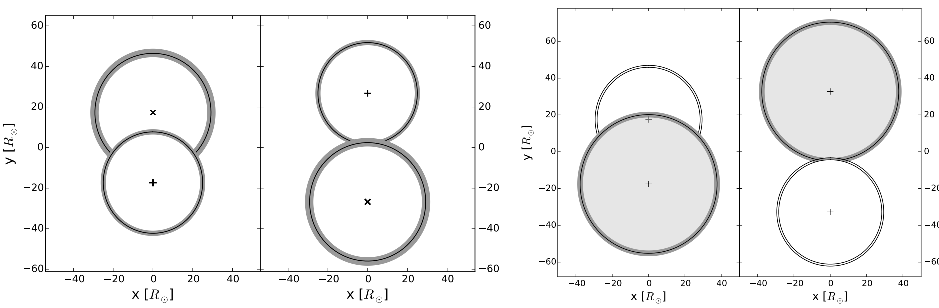

Fig. 1: Orbital configuration at the phases of primary and supposed secondary eclipse for OGLE LMC-CEP-1718 and LMC-CEP-2532.

The OGLE-LMC-CEP-1718 is especially interesting as both stars are pulsating. This lets us not only to constrain the models with the obtained parameters, but also with the difference or ratio of the parameters (their periods for example). The first-overtone Cepheids are however particularly unlucky as in both cases only one eclipse is present and it is much harder to precisely determine the parameters. The configuration for OGLE-LMC-CEP-1718 and OGLE-LMC-CEP-2532 is shown in Fig. 1.

The blueshift of the OGLE-LMC-CEP-227 Cepheid was observed with -1 km/s systemic velocity difference between the components. On the other hand no difference between velocities of the components for OGLE-LMC562.05-9009 was found within errors, meaning that it may actually be a differential value that depends on both stars in the system.

A sample model of the orbital radial velocity curve, the radius change and the light curve in V-vand at one of the eclipses are shown in Fig. 2, 3 and 4, respectively.

4 Summary

A discovery of a Cepheid in an eclipsing binary system gives us the opportunity to derive fundamental astrophysical parameters (like mass) of the Cepheid with few model assumptions. We have also very good means to independently calibrate distance determination methods. We can determine a distance to the same object using the Baade-Wesselink method, the period-luminosity relation and the eclipsing binary method. The projection factor may be also measured directly using almost purely geometrical methods. We have also the opportunity to measure the mean Cepheid velocity in respect to the companion.

After the analysis of five systems we have several high quality mass, radius and temperature measurements for classical Cepheids. These measurements served to

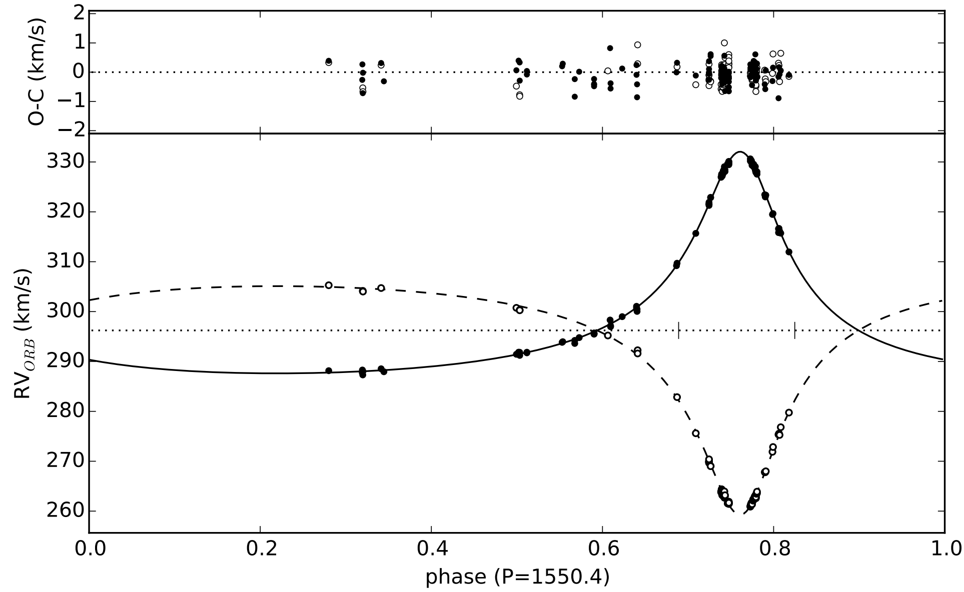

Fig. 2: Orbital radial velocity solution for OGLE-LMC562.05-9009.

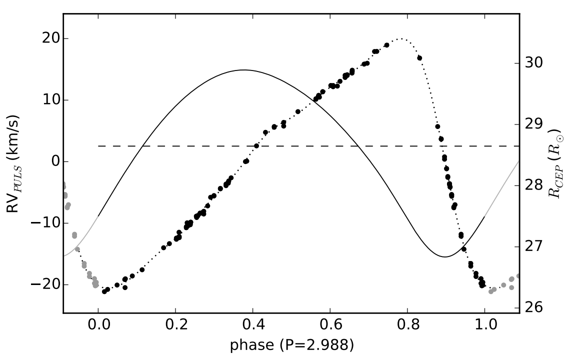

Fig. 3: Pulsational RV curve and radius variation of OGLE-LMC562.05-9009.

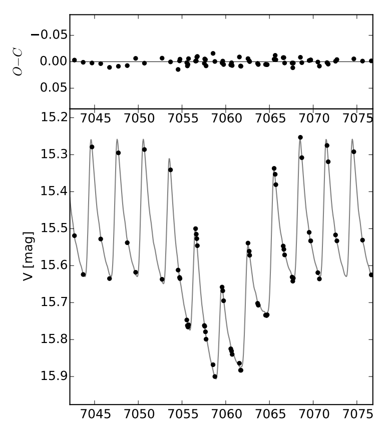

Fig. 4: V-band light curve of OGLE-LMC562.05-9009 at one of the eclipses.

solve the famous Cepheid mass discrepancy problem with the pulsation theory as a winner. For the first time we have measured directly and in a distance-independent manner the p-factor value of a Cepheid. The second measurement shown that it may not only depend on the period, but also that there may exist some intrinsic dispersion dependent on other physical parameters of the star.

We have found that the limb darkening dependence on phase and its value is different than expected and that the Cepheids in eclipsing systems are ideal targets for a detailed study of this quantity. We are going to analyze this parameter soon using the high quality data obtained recently.

According to the orbital solutions it seems that the Cepheid velocities may be slightly blueshifted by about -1 km/s (as in case of OGLE-LMC-CEP0227) in respect to the companion, but the measurement may depend of the intrinsic blueshift of the companion which may compensate it (as in case of OGLE-LMC562.05-9009).

Acknowledgements. We gratefully acknowledge financial support for this work from the Polish National Science Center grant MAESTRO 2012/06/A/ST9/00269.

References

Alcock, C., et al., *The MACHO Project Large Magellanic Cloud Variable Star Inventory. XII. Three Cepheid Variables in Eclipsing Binaries*, ApJ **573**, 338 (2002), astro-ph/0201481

Gieren, W., et al., *The Araucaria Project. OGLE-LMC-CEP-1718: An Exotic Eclipsing Binary System Composed of Two Classical Overtone Cepheids in a 413 Day Orbit*, ApJ **786**, 80 (2014), 1403.3617

Gieren, W., et al., *The Araucaria Project: A Study of the Classical Cepheid in the Eclipsing Binary System OGLE LMC562.05.9009 in the Large Magellanic Cloud*, ApJ **815**, 28 (2015), 1511.02826

Pietrzyński, G., et al., *The dynamical mass of a classical Cepheid variable star in an eclipsing binary system*, Nature **468**, 542 (2010)

Pietrzyński, G., et al., *The Araucaria Project: Accurate Determination of the Dynamical Mass of the Classical Cepheid in the Eclipsing System OGLE-LMC-CEP-1812*, ApJ **742**, L20 (2011), 1109.5414

Pilecki, B., Konorski, P., Gorski, M., *RaveSpan - Radial Velocity and Spectrum Analyzer*, in M. T. Richards, I. Hubeny (eds.) IAU Symposium, *IAU Symposium*, volume 282, 301–302 (2012)

Pilecki, B., et al., *Physical parameters and the projection factor of the classical Cepheid in the binary system OGLE-LMC-CEP-0227*, MNRAS **436**, 953 (2013), 1308.5023

Pilecki, B., et al., *The Araucaria Project: the First-overtone Classical Cepheid in the Eclipsing System OGLE-LMC-CEP-2532*, ApJ **806**, 29 (2015), 1504.04611

Southworth, J., Maxted, P. F. L., Smalley, B., *Eclipsing binaries in open clusters - II. V453 Cyg in NGC 6871*, MNRAS **351**, 1277 (2004), astro-ph/0403572

Udalski, A., Szymański, M. K., Szymański, G., *OGLE-IV: Fourth Phase of the Optical Gravitational Lensing Experiment*, Acta Astron. **65**, 1 (2015), 1504.05966

Wilson, R. E., Devinney, E. J., *Realization of Accurate Close-Binary Light Curves: Application to MR Cygni*, ApJ **166**, 605 (1971)