THE ARAUCARIA PROJECT: ACCURATE DETERMINATION OF THE DYNAMICAL MASS OF THE CLASSICAL CEPHEID IN THE ECLIPSING SYSTEM OGLE-LMC-CEP-1812*

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ABSTRACT

We have analyzed the double-lined eclipsing binary system OGLE-LMC-CEP-1812 in the LMC and demonstrate that it contains a classical fundamental mode Cepheid pulsating with a period of 1.31 days. The secondary star is a stable giant. We derive the dynamical masses for both stars with an accuracy of 1.5%, making the Cepheid in this system the second classical Cepheid with a very accurate dynamical mass determination, following the OGLE-LMC-CEP-0227 system studied by Pietrzyński et al. The measured dynamical mass agrees very well with that predicted by pulsation models. We also derive the radii of both components and accurate orbital parameters for the binary system. This new, very accurate dynamical mass for a classical Cepheid will greatly contribute to the solution of the Cepheid mass discrepancy problem, and to our understanding of the structure and evolution of classical Cepheids.

Key words: binaries: eclipsing – distance scale – galaxies: distances and redshifts – galaxies: individual (LMC) – stars: variables: Cepheids

1. INTRODUCTION

Classical Cepheids have been key objects in the long-lasting efforts to measure the extragalactic distance scale and to probe the predictions of stellar evolution and stellar pulsation theory (e.g., Freedman & Madore 2010; Caputo et al. 2005). Given the enormous importance of Cepheids for the determination of the cosmic distance scale and cosmological parameters, it is of great importance to fully understand these stars astrophysically. One of the most nagging problems in Cepheid research has been the difficulty to reliably determine their masses. Christy (1968) and Stobie (1969) were the first to notice that Cepheid masses calculated from stellar pulsational theory were about 20% smaller than the corresponding masses estimated from their evolutionary tracks on the Hertzsprung–Russell diagram. In spite of the considerable progress in understanding the physics of Cepheid variable stars over the years, the “Cepheid mass discrepancy problem” has remained unsolved for more than 40 years (Keller & Wood 2002; Keller 2008; Evans et al. 2008; Caputo et al. 2005; Neilson et al. 2011 and references therein). The obvious solution to the problem comes from an independent and accurate measurement of the dynamical masses of a number of Cepheids with a range of pulsation periods, and there have been a number of efforts to find binary Cepheids allowing such a precise mass determination (Evans et al. 1997, 2006, 2008). However, the few Cepheids found in binary systems for which masses have been estimated all occur in single-lined, non-eclipsing systems. This has limited the accuracy of the best Cepheid dynamical mass measurements to less than 15%, which is not sufficiently accurate to resolve the mass discrepancy problem.

Recently, several eclipsing binary systems in the LMC have been discovered from OGLE Project data which contain candidates for classical Cepheid components (Udalski et al. 1999; Soszyński et al. 2008). Our group, as part of the Araucaria Project dedicated to the improvement of stellar distance indicators (Gieren et al. 2005), has been obtaining spectroscopic observations of these candidates to confirm the true binary nature of these systems and the Cepheid nature of the intrinsically variable components. Accurate high-resolution spectra collected by our group for OGLE-LMC-CEP-0227 (hereinafter CEP-0227) resulted in the first confirmed discovery of a classical Cepheid variable in an eclipsing system, perfectly suited for an accurate determination of its physical parameters (Pietrzyński et al. 2010). The analysis of our data led to the determination of the dynamical mass of this 3.8 day Cepheid with an unprecedented accuracy of 1%. This study provided strong constraints on theoretical pulsation and evolutionary models and favored the mass predictions for Cepheids from pulsation theory. Cassisi & Salaris (2011) have analyzed evolutionary models of this Cepheid finding good agreement between its evolutionary and dynamical mass when extra mixing is included. Neilson et al. (2011) find that the mass discrepancy can be accounted for if the evolutionary models include convective mass overshooting and pulsation-driven mass loss. The models also predict that the size of the Cepheid mass discrepancy depends on the Cepheid mass, with the size of the mass discrepancy expected to rise to lower periods (Caputo et al. 2005). On the other hand, Keller (2008) showed that the predicted behavior of the mass discrepancy depends on the assumed mass–luminosity relation. Therefore, it is clearly desirable to measure accurate dynamical masses for several additional Cepheids spanning a range in...
period in order to fully resolve this problem and to understand the structure, physics, and evolution of Cepheid variables.

In this Letter, we present the analysis of the second confirmed classical Cepheid in a double-lined eclipsing binary system, OGLE-LMC-CEP-1812 (hereinafter CEP-1812), and derive its dynamical mass with an accuracy of 1.5%. Our new binary Cepheid has a shorter pulsation period of 1.31 days compared to 3.80 days for CEP-0227, and its measured physical properties therefore present a valuable complement to those derived for CEP-0227.

2. OBSERVATIONS

2.1. Optical Photometry

The optical photometry of CEP-1812 was obtained with the Warsaw 1.3 m telescope at Las Campanas Observatory in the course of the third phase of the OGLE project (e.g., Soszyński et al. 2008). A total of 883 I-band epochs spanning a period of 1076 days were secured. The data were reduced with the image-subtraction technique (Udalski 2003; Wozniak 2000). The instrumental data were calibrated onto the standard system using observations of several Landolt fields over several photometric nights. The estimated zero-point errors are about 0.01 mag (Udalski et al. 2008). For more details about the instrumental system, observing, reduction, and calibration procedures adopted in the course of the OGLE project the reader is referred to the references cited above.

2.2. High-resolution Spectroscopy

High-resolution spectra of the CEP-1812 system were collected with the Las Campanas Observatory Magellan Clay 6.5 m telescope and the Magellan Inamori Kyocera Echelle (MIKE) spectrograph (Bernstein et al. 2003), with the ESO Very Large Telescope Kueyen 8.2 m telescope and the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000), and with ESO 3.6 m telescope and the High Accuracy Radial velocity Planet Searcher (HARPS) fiber-fed echelle spectrograph (Mayor et al. 2003). In the case of the MIKE observations a 0.7 arcsec slit was used giving a resolution of about 40,000. The spectra were reduced with pipeline software developed by Kelson (2003). Exposure times ranged from 2400 s to 3200 s depending on observing conditions, and a typical resulting signal-to-noise ratio (S/N) was 10 at a wavelength of 4500 Å. The UVES observations were obtained with an exposure time of 2700 s and a 0.7 arcsec slit resulting in a spectral resolution of about 50,000 and an S/N at 4500 Å of better than 15. The UVES data were reduced with the ESO pipeline. The HARPS observations were obtained at a resolution of 60,000 and an S/N at 5000 Å of 4 for one hour integrations, and were reduced with the data reduction software developed by the Geneva observatory. A total of 88 high-quality spectra were collected with the three spectrographs.

CEP-1812 is located in a dense region in the LMC and even based on inspection of the OGLE template images with a spatial resolution of 0.8 arcsec (Soszyński et al. 2008) one can see several faint stars located very close to the star. Simple cross-correlation measurements showed the presence of a third velocity component. We therefore decided to measure velocities for CEP-1812 with the broadening function (BF) formalism (Rucinski 1992), which is widely recognized as an effective technique for radial velocity determination from complex spectra (Rucinski 2003). The BFs were calculated on the wavelength interval 4350–6100 Å using a template interpolated from the Coelho library of synthesized echelle resolution spectra (Coelho et al. 2005). The BFs revealed clear peaks for both components of CEP-1812 in all spectra. In addition, the third signal was detected in some 40% of our spectra at a constant radial velocity of 273 ± 5 km s−1. The BF signal of this star was used to calculate its light contribution to the total I-band brightness of the system to be about 10%. We found no significant offsets between the velocity systems of the three instruments.

3. SPECTROSCOPIC AND PHOTOMETRIC SOLUTIONS

Based on the photometric data the following ephemerides were derived:

\[
P_{\text{orb}} = 551.797 ± 0.010 \text{ days}
\]

\[
T_{0,\text{orb}} = 2,450,479.11 ± 0.07 \text{ days}
\]

\[
P_{\text{pul}} = 1.312904 ± 0.000003 \text{ days}
\]

\[
T_{0,\text{pul}} = 2,450,455.685 ± 0.006 \text{ days}
\]

Adopting these ephemerides the spectroscopic orbit (systemic velocity, velocity amplitudes, eccentricity, periastron passage, and mass ratio) plus a Fourier series of order six (which approximates the pulsations of the Cepheid primary component) were fitted to the radial velocity data. The orbit solution and the pulsational radial velocity curves of the Cepheid component are shown in Figure 1. Figure 2 shows the pulsational I-band light curve of the Cepheid. Adopting the obtained spectroscopic mass ratio of 0.705 ± 0.015, and an I-band third light contribution of 10%, we modeled the OGLE-LMC-CEP-1812 system with the Wilson–Devinney (WD) code (Wilson & Devinney 1971; Van Hamme & Wilson 2007) in an iterative way removing the intrinsic brightness variations of the Cepheid component. The parameters corresponding to our best model together with their uncertainties estimated from extensive Monte Carlo simulations are presented in Table 1. Unfortunately, at the present moment without near-infrared photometry, we are not in a position to derive \( T_{\text{eff}} \) of the components. Figure 3 presents the light curve of the eclipsing system with the intrinsic brightness variations of the Cepheid removed, together with our best-fit WD model for the system. Although the relative distance between components is very large, the eclipses are total, with the secondary transiting over the Cepheid disk during the primary eclipse. It is worth mentioning that the presence of the third component only

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Table 1

| Parameter               | Value                  |
|-------------------------|------------------------|
| \( P_{\text{orb}} \)   | \( 551.797 ± 0.010 \)  |
| \( T_{0,\text{orb}} \)| \( 2,450,479.11 ± 0.07 \) |
| \( P_{\text{pul}} \)   | \( 1.312904 ± 0.000003 \) |
| \( T_{0,\text{pul}} \)| \( 2,450,455.685 ± 0.006 \) |

Note: The quoted uncertainties were estimated from extensive Monte Carlo simulations.
Figure 1. Disentangled spectroscopic orbit of the CEP-1812 system, folded on the orbital period of 551.8 days (upper panel), and the pulsational radial velocity curve of the Cepheid, folded on its pulsation period of 1.31 days (lower panel). The Cepheid is the higher-mass star in the system (filled circles in the upper panel). The measured (constant) velocities of the faint third star in the light are not shown for clarity.

Figure 2. Disentangled photometric $I$-band light curve of the Cepheid component in CEP-1812 from 883 individual measurements.
Figure 3. Observed orbital I-band light curve together with the photometric solution as obtained from the analysis with the WD code.

marginally affects the mass determination. Neglecting the third light leads to an inclination of 89.5.

4. DISCUSSION AND CONCLUSIONS

The Cepheid in OGLE-LMC-CEP-1812 is a classical Cepheid, and not a Type II low-mass Cepheid. The evidence comes from its mass of 3.74 ± 0.06 M⊙ which agrees well with the predicted pulsational mass for a classical Cepheid of this short period (Bono et al. 2001), and from its radius (17.4 ± 0.9 R⊙) which again is in good agreement with the radius of a classical Cepheid predicted from period–radius relations (e.g., Gieren et al. 1998). The position of the Cepheid in the period–mean-magnitude plane for LMC Cepheids shown in Figure 4 also proves beyond any doubt that CEP-1812 is a classical Cepheid. Based on the analysis of the Fourier parameters Soszynski et al. (2008) firmly classified this star as a fundamental mode pulsator. The system OGLE-LMC-CEP-1812 is thus the second known double-lined eclipsing binary system with a classical fundamental mode Cepheid component. The secondary component is a less massive, smaller, and cooler stable giant star, a configuration that is significantly different from the OGLE-LMC-CEP-0227 system whose stable secondary giant star has the same mass, and a slightly larger diameter than the Cepheid in that system. The configuration is also quite unusual from an evolutionary point of view because the system consists of two well-separated stars in a relatively short stage of common giant phase evolution in spite of the large mass difference. According to the BaSTI evolutionary tracks (Pietrinferni et al. 2004) a star with mass 3.74 M/M⊙ will enter the instability strip from the giant branch after approximately 190 Myr of evolution, whereas a star of mass 2.64 M/M⊙ will reach a radius of 12.1 R/R⊙ on the subgiant branch after approximately 369 Myr of evolution. While detailed evolutionary models of the two stars in the binary will be needed, these estimates call into question the assumption that the stars are members of a coeval binary system.

In order to calculate the pulsational mass of CEP-1812 we adopted a period–mass relation based on nonlinear, convective Cepheid models constructed for the typical chemical composition of LMC Cepheids ([Z(metals)] = 0.008, [Y(helium)] = 0.256; Bono et al. 2000; Luck et al. 1998). We note that the calculation of the pulsation mass depends neither on the assumed distance nor on the reddening. The resulting pulsation mass (3.27 ± 0.64 M⊙) agrees very well with the dynamical mass of the star. Pietrzyński et al. (2010) came to the same conclusion for
Figure 4. I-band period–luminosity relation \( P \) in days for classical fundamental mode Cepheids as defined by the catalog of OGLE III Cepheids in the LMC (Soszynski et al. 2008). The position of our binary system is marked by the upper filled circle (out-of-eclipse total brightness of the system, including the faint third star in the light), and the position of CEP-1812 (its mean brightness, freed from the contributions coming from the binary companion and the faint third star) is indicated by the lower circle. The Cepheid falls almost exactly on the ridge line of the period–magnitude relation indicating that CEP-1812 is a classical Cepheid.

CEP-227. Therefore, we now have strong observational evidence that the pulsation mass of a Cepheid variable is indeed correctly measuring its true, current mass.

The dynamical mass determinations for both stars in OGLE-LMC-CEP-1812 are accurate to about 1.5%, adding them to the very short list of evolved massive stars with very accurate mass determinations. In a forthcoming study, we will discuss evolutionary models for the Cepheid in the system which will further add to the solution of the Cepheid mass discrepancy problem, and to a deeper understanding of the physics and evolution of classical Cepheid variable stars.

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