A CLASSICAL CEPHEID IN A LARGE MAGELLANIC CLOUD ECLIPSING BINARY: EVIDENCE OF SHORTCOMINGS IN CURRENT STELLAR EVOLUTIONARY MODELS?

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ABSTRACT

The recent discovery and analysis of a classical Cepheid in the well-detached, double-lined, eclipsing binary OGLE-LMC-CEP0227 has provided the first determination of the dynamical mass of a classical Cepheid variable to an unprecedented 1\% accuracy. We show here that modern stellar evolution models, widely employed to study Galactic and extragalactic stellar systems, are able to match simultaneously the mass and radius (and effective temperature) of the two components with a single value for the age of the system, without any specific fine-tuning, assuming the typical metallicity of LMC Cepheids. Our conclusion is that there is no obvious discrepancy between dynamical and evolutionary masses for the Cepheid star in this system, contrary to previous claims of an overestimate of the Cepheid mass by stellar evolution theory.

Key words: binaries: eclipsing – stars: evolution – stars: fundamental parameters – stars: variables: Cepheids

Online-only material: color figures

1. INTRODUCTION

Classical Cepheid variables have been the subject of several theoretical and observational studies due to their fundamental role in establishing the extragalactic distance scale (see, e.g., Friedman et al. 2001; Sandage et al. 2006, and reference therein). The empirical determination of their pulsational properties also provides sets of observational benchmarks for testing both pulsational and stellar evolution models. One well-known problem related to the theory of classical Cepheids is the discrepancy between mass estimates obtained from pulsational and stellar evolution models. Specifically, by comparing results of theoretical pulsation calculations with the period, the estimated mean absolute magnitude and effective temperature of a Cepheid variable, a “pulsational mass,” can be derived. At the same time, a comparison of stellar evolution models with just the estimated mean absolute magnitude and effective temperature, a so-called evolutionary mass, can be assigned to the same object. Early investigations by Stobie (1969), Cogan (1970), and Rodgers (1970) discovered that these two independent mass estimates did not agree, the pulsational masses being smaller by 20\%–40\%. This disagreement has been named the “Cepheid mass discrepancy.”

The first fundamental step toward solving this problem was discussed by Andreasen (1988), who suggested that an increase of a factor of ~2.5 of the radiative opacities in the temperature regime $1.5 < (T/10^5 \text{ K}) < 8$ would be able to almost completely remove the discrepancy. This increase was nicely confirmed years later by accurate opacity computations performed by the OPAL group (Rogers & Iglesias 1992). Following the implementation of these new opacities in stellar model computations, there has been a large number of studies devoted to re-investigate the mass discrepancy problem (see, e.g., Keller & Wood 2002, 2006; Caputo et al. 2005; Evans et al. 2007, and references therein). These analyses concluded that the discrepancy was significantly reduced to about 10\%–15\% in mass.

Attempts to further reduce the disagreement from the point of view of stellar evolution modeling have invoked the inclusion of mass loss and an increase of the convective core mass during the core H-burning stage (see, e.g., Caputo et al. 2005; Bono et al. 2006; Keller 2008, and references therein) compared to the values determined from the Schwarzschild criterion. Keller (2008), and more recently Neilson et al. (2010), has shown that mass loss does not appear to be a viable solution because the required mass-loss efficiency would not only be extremely large, but also its dependence on the stellar mass would be at odds with independent empirical constraints. Neilson et al. (2010) have also presented compelling evidence to support the idea that a moderate increase of the convective core size during the main sequence would be able to completely eliminate the mass discrepancy. The proposed increase of the convective core mass may be achieved as a consequence of a change in the adopted physical inputs and/or the inclusion of additional physical processes like rotational mixing and mild convective core overshooting. Major modifications to the stellar model input physics do not seem realistic (see, e.g., Cassisi 2010), whereas a host of observational data—indeed of Cepheid stars—on, e.g., eclipsing binary systems with at least one component on the main sequence or near the turnoff, the turnoff morphology in color–magnitude diagrams of open clusters, and star counts along the main sequence and central He-burning sequences in star clusters (see, e.g., Andersen 1991; Pietrinferni et al. 2004, and references therein) demonstrate the need to extend the main-sequence convective cores beyond the formal Schwarzschild boundary. The added extension of the convective core size, $\Lambda_{\text{cco}}$, is often parameterized in terms of $\Lambda_{\text{cco}} = \lambda H_P$, where $H_P$ is the pressure scale height at the Schwarzschild boundary and $\lambda$ is a free parameter. The current, more widely used libraries of stellar models all include an extension of the convective core size beyond the Schwarzschild boundary (see, e.g., Pietrinferni et al. 2004; Bertelli et al. 2008; Dotter et al. 2008, and references therein).

Pietrzyński et al. (2010) have very recently provided the first accurate determination of the dynamical mass of a classical Cepheid variable in a well-detached, double-lined, eclipsing binary in the Large Magellanic Cloud (OGLE-LMC-CEP0227). Thanks to the availability of a high-quality photometric data set,
the spectroscopic follow-up, and the near-perfect characteristics of the system to derive accurate masses for both components, Pietrzyński et al. (2010) were able to estimate the mass of the pulsator to an unprecedented 1% precision. The discovery and analysis of this binary system is a pivotal step forward in testing the accuracy of both pulsation and stellar evolution theory. Pietrzyński et al. (2010) emphasize that their dynamical estimate of the Cepheid mass is in good agreement with the estimated pulsational mass, while they suggest the existence of a discrepancy with the mass predicted by stellar evolution models. In view of the high precision of the parameters of this binary system, and the huge effort devoted in this last decade toward improving stellar evolution models, we consider that the estimate of the Cepheid evolutionary mass for this system deserves a more specific investigation. The accurate determination of masses and radii for both components allows us to test for the first time in a more direct way the accuracy of theoretical evolutionary masses of Cepheid stars. Following a standard and powerful methodology of eclipsing binary studies (i.e., Andersen 1991), we will test whether in the age–radius diagram evolutionary models calculated for the empirical values of the mass of the two components and a typical LMC composition can match the observed radii for a common value of the age. With this procedure we want to address the following question: is it possible to reproduce the mass/radius constraints of both components of OGLE-LMC-CEP0227 by employing a set of widely used off-the-shelf modern stellar evolution models, without any fine-tuning for this specific object?

The next section briefly describes the models employed in our analysis and presents a comparison with the results for OGLE-LMC-CEP0227. A final discussion closes the Letter.

2. THE COMPARISON BETWEEN STELLAR EVOLUTION THEORY AND OBSERVATIONS

We have employed the same state-of-the-art input physics and stellar evolution code adopted for building the widely used BaSTI stellar model archive3 (see Pietrinferni et al. 2004, for details), to compute a series of models with masses between \( \sim 4.1 \) and \( \sim 4.2 \, M_\odot \), appropriate for the OGLE-LMC-CEP0227 components. The BaSTI archive has been extensively tested against observations of local stellar populations and eclipsing binary systems (see, e.g., Tomasella et al. 2008, and references therein), and is widely employed in studies of Galactic and extragalactic resolved star clusters (see, e.g., De Angeli et al. 2005; Mackey & Broby Nielsen 2007; Marín-Franch et al. 2009, for just a few examples), in the determination of star formation history and chemical enrichment history of resolved Local Group galaxies (see, e.g., Carrera et al. 2008) and also in studies of integrated properties of extragalactic stellar populations (see, e.g., Carter et al. 2009).

We adopted in our calculations the typical initial chemical composition of LMC stars, \( Z = 0.008 \) and \( Y = 0.256 \)—that corresponds to \([\text{Fe/H}] = -0.35\) for the solar \((Z/X)\) ratio by Grevesse & Noels (1993)—e.g., the same composition used by Pietrzyński et al. (2010) to determine the pulsational mass of the Cepheid variable. The convective cores along the main sequence have been extended by an amount \( \Lambda_{\text{evo}} = 0.2 \, H_p \), as in the BaSTI models for this mass range. As discussed in Pietrinferni et al. (2004), the calibration of \( \Lambda_{\text{evo}} \) in the BaSTI models is based on

| Physical Parameter | Primary (A) | Secondary (B) |
|-------------------|-------------|---------------|
| Mass \((M/M_\odot)\) | 4.14 ± 0.05 | 4.14 ± 0.07  |
| Radius \((R/R_\odot)\) | 32.4 ± 1.5  | 44.9 ± 1.5   |
| \(T_{\text{eff}}(K)\) | 5900 ± 250  | 5080 ± 270   |

3 The BaSTI stellar evolutionary model archive is available at the following URL address: http://www.oa-teramo.inaf.it/BASTI.
for the same combinations of $M_i$ values that satisfies the $R$–age diagram. We have also plotted the fundamental blue edge (FBE) and fundamental red edge (FRE) of the Cepheid instability strip as provided by Fiorentino et al. (2007) pulsational models, for a metallicity of $Z = 0.008$, and a mixing length equal to $1.5 H_p$, their reference choice for the treatment of the superadiabatic layers. The two components appear to have been captured—as also remarked by Pietrzyński et al. (2010)—in a very short-lived evolutionary stage, i.e., when they move along the brighter branch of the blue loop during the core He-burning stage. By examining Figure 2, we can add that the A component is located at the boundary between the fundamental and the first overtone region within the instability strip, whereas the B component appears to have left the instability strip since a short time. The fact that the B component is not a variable star, and its location with respect to the FRE, poses an important constraint on the efficiency of superadiabatic convection in the pulsational models: any substantial decrease of the mixing length adopted in the pulsational models would shift the FRE toward lower $T_{\text{eff}}$ (e.g., Fiorentino et al. 2007), moving the B component within the instability strip, at odds with the observations.

Before closing this section, we wish to comment briefly about the effect of our assumptions about metallicity and mass loss, for there are no spectroscopic estimates of the chemical composition of OGLE-LMC-CEP0227 components, and no strong constraints on the mass-loss rate of Cepheids and their progenitors. Our analysis, as well as the value determined by Pietrzyński et al. (2010) for the pulsational mass of the Cepheid component, is based on the assumption of a “typical” iron abundance $[\text{Fe/H}] = -0.35$, that is consistent with the mean value determined spectroscopically by Romaniello et al. (2008) for a sample of 22 LMC Cepheids. These authors also find a spread of $[\text{Fe/H}]$ values for their sample, with $[\text{Fe/H}]$ ranging between $-0.62$ and $-0.10$ dex. Given the lack of $[\text{Fe/H}]$ estimates for OGLE-LMC-CEP0227 components, we have tested to what extent assumptions on their metallicity are critical for the outcome of this analysis. We found that varying $[\text{Fe/H}]$ by $\pm 0.10$ dex (i.e., varying $Z$ between 0.006 and 0.01, and $Y$ using the He-enrichment ratio $\Delta Y/\Delta Z = 1.4$, as in the BaSTI archive) around the reference value still ensures consistency between theory and observations in the age–radius diagram. Values of $[\text{Fe/H}]$ outside this range prevent models—with mass consistent with the empirical values—from crossing the Cepheid instability strip during the central He-burning phase. As a consequence, one would need in this case to fine-tune the evolutionary calculations to match this system, for example, by including overshooting from the bottom of the convective envelopes, that favors the development of loops in the Hertzsprung–Russell diagram during the central He-burning phase.

As for the mass-loss assumptions, we have already remarked that neglecting mass loss or employing the Reimers prescription with $\eta = 0.4$ (a standard choice for the value of this free parameter) does provide consistency between evolutionary and empirical masses. Observations have not determined yet conclusive and stringent bounds on mass-loss rates for Cepheids and their progenitors. Very recently, Marengo et al. (2010) have found some indications that the Cepheid prototype $\delta$ Cephei may be currently losing mass, at a rate in the range of $\approx 5 \times 10^{-9}$ to $6 \times 10^{-8} M_\odot$ yr$^{-1}$. As an extreme test, we have calculated models employing the upper limit of this mass-loss rate during the central He-burning phase and our standard assumptions on the binary metallicity. The models lose $\approx 2 M_\odot$ during the He-burning phase, and the mass-loss efficiency is so large that the stellar models show a very anomalous path in the...
H-R diagram. Such a high mass-loss rate—if conclusively established and, moreover, if typical of Cepheids also in the LMC—would be compatible with standard stellar evolution models only in the case of episodic mass-loss events that do not change the total mass of the star by more than a few hundredths of solar masses.

3. CONCLUSIONS

The recent study by Pietrzyński et al. (2010) of a classical Cepheid in the well-detached, double-lined, eclipsing binary OGLE-LMC-CEP0227 has provided the first very accurate determination of the dynamical mass of a classical Cepheid variable and its radius. Our analysis has shown that stellar evolutionary models widely employed to study Galactic and extragalactic stellar populations are able to match—assuming the typical metallicity of LMC Cepheids—the derived mass and radius of both components with a single value for the age of the system, without any specific fine-tuning. Our result implies that there is no discrepancy between dynamical and evolutionary masses for the Cepheid star in this system, when current stellar models—calculated with up-to-date stellar physics and extensively tested against independent empirical benchmarks—are used in conjunction with the method employed in this analysis.

It is also worth noticing that the agreement between evolutionary masses and high-precision dynamical masses of Cepheids discussed in this Letter is based on just a single eclipsing binary system. The discovery and analysis of more systems similar to OGLE-LMC-CEP0227—in conjunction with direct measurements of their chemical composition—will be enormously beneficial to the fields of stellar evolution and pulsation theory.

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