Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

DYNAMICAL MASS OF A TYPE II CEPHEID AND A DISK AROUND ITS BE STAR COMPANION

B. Pilecki[1]

Abstract. We present the main results of an analysis of a peculiar W Virginis (pWVir) type II Cepheid, OGLE-LMC-T2CEP-211 (P_{puls} = 9.393 d), in an SB2 binary system (P_{orb} = 242 d), which sheds light on the evolutionary status and structure of pWVir stars. We make the first-ever determination of the dynamical mass of a type-II Cepheid, M=0.64 ± 0.02 $M_{\odot}$, and its radius R=25.1 ± 0.3 $R_{\odot}$. The companion is a massive (5.67 $M_{\odot}$) main-sequence star that is partially obscured by a disk. Such a configuration suggests mass transfer in the system's history. We deduced that the system (P_{init}=12 d) was originally composed of stars of 3.5 $M_{\odot}$ and 2.8 $M_{\odot}$, the current Cepheid being the more massive. The system's age is now ∼200 Myr and the Cepheid is almost completely stripped of hydrogen, its helium mass being ∼92% of the total mass. The companion is most probably a Be main-sequence star with T=22000 K and R=2.5 $R_{\odot}$. The observations are consistent with our model of a three-ring disk (∼ 120 $R_{\odot}$) around the companion; however, a more complex structure of the disk, including a spiral formation, cannot be excluded. The disk probably originates from a combination of material from a past mass transfer, the mass being lost by the Cepheid through wind and pulsations, and a decretion disk around the rapidly-rotating secondary.

Keywords: Stars: variables: Cepheids, Stars: binaries: eclipsing, emission-line, Be, accretion, accretion disks

1 Introduction

Type II Cepheids are low-mass pulsating stars that belong to the disk and halo populations (Wallerstein 2002). They are a much older counterpart of the more massive classical Cepheids, which have periods and amplitudes in a similar range but are about 1.5–2 mag fainter. They exhibit a well-defined period–luminosity (P–L) relation (Leavitt 1908), enabling a measurement of distances both inside and outside our Galaxy (Groenewegen & Jurkovic 2017; Soszyński et al. 2018). Since the work of Gingold (1976, 1985), type II Cepheids have usually been divided into three subgroups (BL Her, W Vir and RV Tau); they are distinguished by different ranges of pulsation periods, observational properties and evolutionary status, but they obey a similar period–luminosity relation. However, Gingold did not explain either their occurrence rates or the values of their basic parameters, including their masses. The evolutionary status of W Vir stars is somewhat mysterious; some authors contradict the popular explanation (e.g. Pietrinferni et al. 2004).

It is clearly important to obtain direct measurements of the masses of a sample of type-II Cepheids in order to pinpoint their evolutionary status. The best sources of such measurements are observations of eclipsing binary systems in which one or both components are pulsating stars. We have applied this method to eclipsing binaries containing classical Cepheids, and obtained very precise masses (e.g. Pilecki et al. 2013, 2018b).

The OGLE project Soszyński et al. (2008, 2018) identified a group of W Virginis stars that had similar periods but different-looking light-curves, and called them "peculiar WVirginis stars" (hereafter pWVir). Since a significant fraction of pWVir stars shows eclipses and ellipsoidal modulations, it has been suggested that they are all members of binary systems.

The evolution of binary stars is also one of the most important channels for the formation of Be stars, as a lot of angular momentum has to be transferred to spin them up (Klement et al. 2019). The presence of a companion is also a crucial factor that shapes the disk around a Be star (Panoglou et al. 2019).

Up to now we have observed and analyzed two pWVir type II Cepheids that exhibit eclipses. OGLE-LMC-T2CEP-098 turned out to be an outlier that did not fit any known type of pulsating star, having a mass of 1.5 $M_{\odot}$ and a brightness in between those expected for classical and type II Cepheids (Pilecki et al. 2017). Below is a summary of the results published by Pilecki et al. (2018a) regarding a genuine type II Cepheid of a peculiar W Virginis type, OGLE-LMC-T2CEP-211. A complex disk structure (ringed or spiral) was also detected round it.

[1] Centrum Astronomiczne im. Mikołaja Kopernika, PAN, Bartycka 18, 00-716 Warsaw, Poland

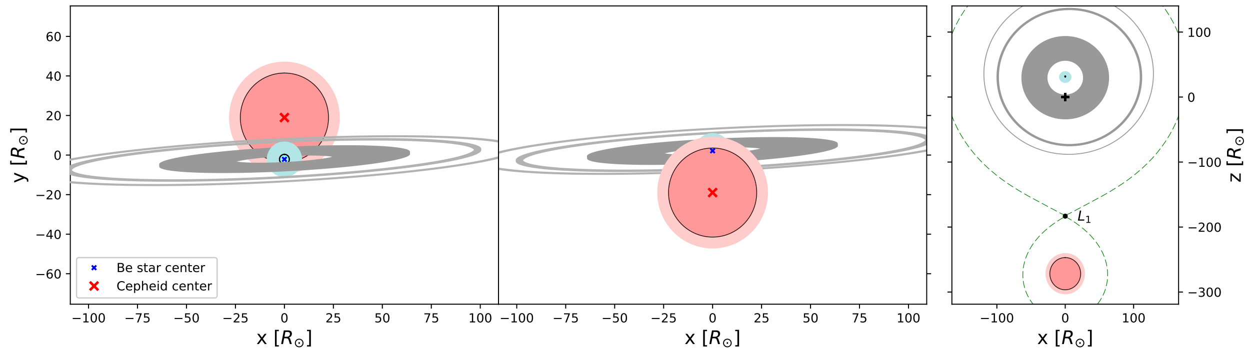

Fig. 1. Schematic model of the system. The Cepheid is in red, the companion in blue, and the rings of the disk in grey. The Roche lobe contours are plotted in the right panel.

2 Analysis of OGLE-LMC-T2CEP-098

2.1 *Detached binary: Cepheid + Be shell star with a disk.*

From the analysis of the light-curve and spectra of this Cepheid, we concluded that it is a giant (R=25.1 $R_\odot$) that undergoes a significant radius change during its pulsational cycle (light red area in Fig. 1), while its smaller companion is surrounded by a very extended (R $\sim$ 120 $R_\odot$) complex disk structure; our models suggest two or more rings, or a spiral structure. If we adopt the ring model, we find that the disk is tilted and slightly eccentric. The system is detached, so there is no fast mass transfer currently in the system, but accretion of the matter being lost through a wind from the companion is possible.

With the help of evolutionary theory, we also found that the companion is most probably a B-type dwarf (R=2.5 $R_\odot$) embedded in a bright shell ($\sim$9 $R_\odot$), suggesting a Be shell star and a decretion origin for the disk – or at least of its inner part.

2.2 *Hα and Hβ lines and the disk*

The broad Hα emission line clearly corresponds to the disk around the companion, and the absorption line to the companion itself, as can be seen in Fig. 2. The Cepheid seems relatively weak in Hα but stronger in Hβ, where both absorption and emission features of the disk are also seen.

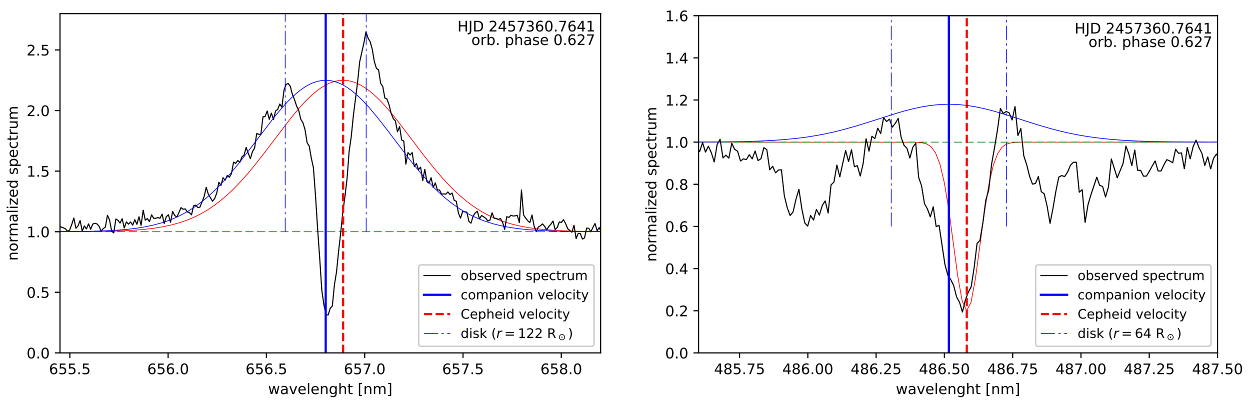

Fig. 2. The maxima of disk emission in Hα correspond roughly to the radius of the outer ring, while the maxima in Hβ correspond to the outer radius of the inner ring.

2.3 *The evolution*

The high mass ratio of the system indicates binary interaction (mass transfer) during its evolution. We performed a binary evolution analysis using the STARS code, with different initial conditions.

Table 5
Results from Binary Evolution Analysis

Parameter	Initial	Current	Measured
System			
Mass ratio	0.8 ± 0.03	7.87 ± 0.05	8.92 ± 0.05
Orbital period (days)	12.0 ± 0.7	180.8 ± 1.7	242.14 ± 0.04
β	···	0.0 ± 0.04	···
Primary Component/Currently Cepheid			
Spectral type	B5V	GIII	GIII
M_1 ($M_\odot$)	3.52 ± 0.12	0.715 ± 0.004	0.643 ± 0.015
R_1 ($R_\odot$)	1.91 ± 0.13	25.12 ± 0.12	25.1 ± 0.3
$\log g$ (cgs)	4.42 ± 0.06	1.491 ± 0.005	1.446 ± 0.015
T1 (K)	15700 ± 450	5410 ± 370	5400 ± 200
$\log L_1/L_\odot$	2.30 ± 0.05	2.65 ± 0.06	2.68 ± 0.07
Secondary Component			
Spectral type	B7V	B2V	···
M_2 ($M_\odot$)	2.82 ± 0.19	5.625 ± 0.005	5.67 ± 0.06
R_2 ($R_\odot$)	1.68 ± 0.12	2.51 ± 0.17	9 ± 2
$\log g$ (cgs)	4.44 ± 0.07	4.39 ± 0.06	···
T2 (K)	13700 ± 530	22000 ± 450	7000 ± 1000
$\log L_2/L_\odot$	1.95 ± 0.10	3.117 ± 0.011	···

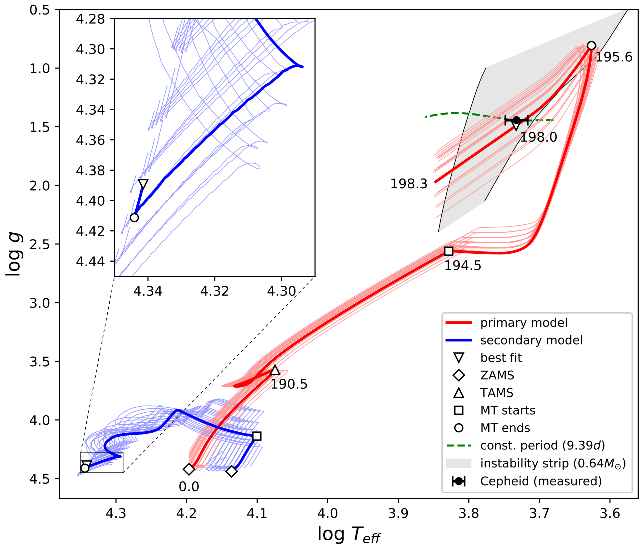

Fig. 3. Left: Table with the model, initial and current, and measured parameters. **Right:** Temperature *vs.* $\log g$ diagram, showing the evolutionary tracks of the primary (the current Cepheid) in red and the secondary (now probably a Be star) in blue. The Cepheid is now crossing the instability strip (grey area).

The analysis suggested that the system was initially composed of stars with masses of 3.5 $M_\odot$ and 2.8 $M_\odot$ and an orbital period of ~12 days. Mass transfer started about 4 Myr after the Cepheid progenitor completed its main-sequence evolution. Mass transfer ceased about 2.5 Myr ago, and the Cepheid is now evolving towards lower temperatures and passing through the instability strip. In losing most of its mass, it has become almost completely depleted of hydrogen.

The companion never evolved from the main sequence, and should now be a B2 star with a radius of 2.5 $R_\odot$. According to the light-curve analysis, the bright component of the companion is much larger (~9 $R_\odot$), which – together with the observed spectral features – indicates that the companion is a Be shell star.

Our evolutionary model suggests that this may be typical of the early stages of existence of Be stars, not long after the accretion from the previously more massive star has finished.

More information about this work is available at `https://users.camk.edu.pl/pilecki/`, where the data are also provided. See also the original publication, Pilecki et al. (2018a).

We gratefully acknowledge financial support for this work from the Polish National Science Center grant SONATA 2014/15/D/ST9/02248.

References

Gingold, R. A. 1976, ApJ, 204, 116
Gingold, R. A. 1985, Mem. Soc. Astron. Italiana, 56, 169
Groenewegen, M. A. T. & Jurkovic, M. I. 2017, A&A, 604, A29
Klement, R., Carciofi, A. C., Rivinius, T., et al. 2019, arXiv e-prints, arXiv:1909.12413
Leavitt, H. S. 1908, Annals of HCO, 60, 87
Panoglou, D., Borges Fernandes, M., Baade, D., et al. 2019, MNRAS, 486, 5139
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Pilecki, B., Dervişoğlu, A., Gieren, W., et al. 2018a, ApJ, 868, 30
Pilecki, B., Gieren, W., Pietrzyński, G., et al. 2018b, ApJ, 862, 43
Pilecki, B., Gieren, W., Smolec, R., et al. 2017, ApJ, 842, 110
Pilecki, B., Graczyk, D., Pietrzyński, G., et al. 2013, MNRAS, 436, 953
Soszyński, I., Udalski, A., Szymański, M. K., et al. 2008, Acta Astron., 58, 293
Soszyński, I., Udalski, A., Szymański, M. K., et al. 2018, Acta Astron., 68, 89
Wallerstein, G. 2002, PASP, 114, 689