B-type stars in eclipsing binaries

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Several aspects of stellar evolution, such as determination of masses of β Cephei-type variable stars or finding tighter constraints on the value of the convective core overshooting parameter α, can be tested with B-type stars in eclipsing binary systems. Precise photometry and high-resolution spectroscopy with high signal-to-noise ratio (SNR) are required to achieve these goals, but since many of the targets are bright enough, the challenge is an acceptable one. The approach to examine both the aforementioned aspects of stellar evolution using observations of B-type stars obtained with a wide range of spectrographs, as well as BRITE-Constellation satellites, is presented in this paper.

1 Introduction

In many aspects, stellar astrophysics is based on the precisely determined fundamental parameters of stars, such as their masses and radii. With few exceptions, only detached eclipsing binaries (DEBs) of SB2-type enable direct determination of those parameters with the required precision of 3% (Clausen et al., 2008). Hence such objects allow us to test predictions of theoretical stellar evolution models. Recent review papers about DEBs (Torres et al., 2010) point out the lack of well-characterized massive stars.

Figure 1 illustrates the mass-radius (M-R) relation for stars with both parameters determined with an accuracy better than 2% (from DEBCat; Southworth, 2015). For massive stars the plot is poorly covered: there are only ∼40 main-sequence (MS) stars with $\log M > 0.4$ ($M > 2.5$ M$_\odot$), for which mass is accurately determined. Since our knowledge of massive-star evolution at MS is incomplete, there is a need to search for and characterize systems consisting of massive components for which precision of 3% in mass and radius determination can be achieved. More importantly, evolutionary codes adopt slightly different assumptions and thus quite often vary in their predictions. As an example, we compare Brott et al. (2011) and Ekström et al. (2012) evolutionary codes for massive stars. As shown in Fig. 2, the former code allows a much wider MS what is related to the main (but not the only) difference between the models – the treatment of convective core overshooting. In general, overshooting leads to larger stellar cores, higher luminosities and larger stellar radii, especially towards the end of the MS evolution. Its definition is related to the overshooting parameter α, which describes the extension of radiative zone affected by overshooting convective cells, in units of the local pressure scale height. Brott et al. (2011) models use the value of $\alpha = 0.335$, while Ekström et al. (2012) models assume $\alpha = 0.1$. The difference results in a much wider MS and larger radii predicted at MS by the first code. The significant differences in both models clearly show that the issue of convective core

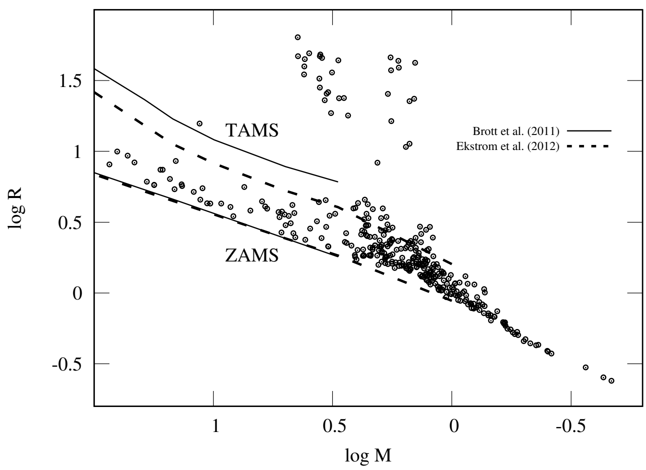

Fig. 1: Mass – radius relation of well characterised components of SB2-type eclipsing binary systems from DEBCat catalogue. ZAMS and TAMS from two stellar evolution codes – Brott et al. (solid line) and Ekström et al. (dashed line) – are plotted.

overshooting needs to be reexamined, and this can be done only by gathering more observational data and their comparison with the models.

As mentioned before, the larger is the value of convective core overshooting parameter, the larger radii in the MS phase. Figure 3 indicates that the Brott et al. (2011) code gives the radius growth of a 10 $M_{\odot}$ star during the MS phase (from ZAMS to TAMS) by a factor of three, while the Ekström et al. (2012) models – just by a factor of two. Another conclusion coming from the plot presented in Fig. 3 is that the MS phase lasts much longer than more advanced phases, e.g. the time of a secondary contraction phase for massive stars constitutes only 2% of the MS lifetime, while the post-MS phase (until reaching $T_{\rm eff} \sim 7\,000$ K), only about 1-2%. This means that chances of finding a massive star residing at the MS in a random set of selected targets are much higher than finding it in a more evolved phase. Since only for MS massive stars the differences between radii for different values of α are significant, the project objectives can be fully achieved.

2 δ Pictoris

δ Pictoris (HD 42933, V = 4.8 mag) is a known binary system classified as B0.5 IV + B2 (Buscombe & Foster, 1995). Its initial analysis yielded orbital period $P \sim 1.67$ d and a mass ratio $q \sim 0.53$ (Thackeray, 1966). The system was observed by one of the BRITE-Constellation (Weiss et al., 2014; Pablo et al., 2016) satellites (BRITE Heweliusz) in 2015. Its detailed photometric and frequency analysis is described in this series by Pigulski et al., these proceedings, and reveals that the system has a β-Cephei-type component.

New spectra of the system were taken using BACHES echelle spectrograph (Kozłowski et al., 2016) installed on the 0.5-m robotic Solaris-1 telescope (Kozłowski et al., 2014; Sybilski et al., 2014) located at the SAAO. 36 spectra of SNR $\sim$ 80 were obtained between 27 October 2015 and 5 March 2016. The new data enabled an

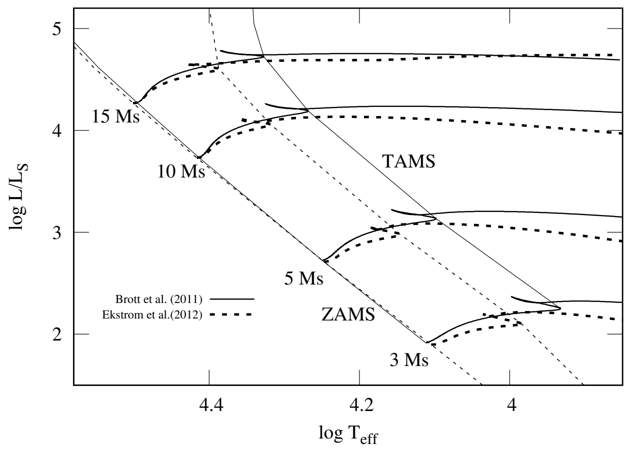

Fig. 2: Evolutionary tracks of 3, 5, 10, and 15 $M_\odot$ stars calculated with two codes – Brott et al. (solid line) and Ekström et al. (dashed line). ZAMS and TAMS are also marked on the plot.

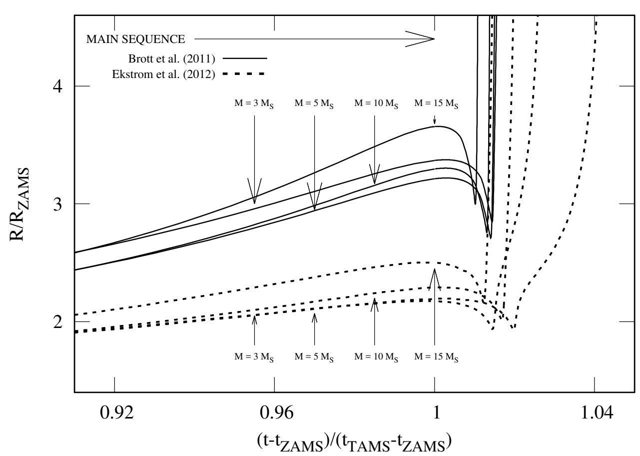

Fig. 3: Changes of a stellar radius in time for 3, 5, 10, 15 $M_\odot$ stars calculated with two codes – Brott et al. (solid line) and Ekström et al. (dashed line). The abscissae value of 1 indicates the end of a main sequence phase (TAMS).

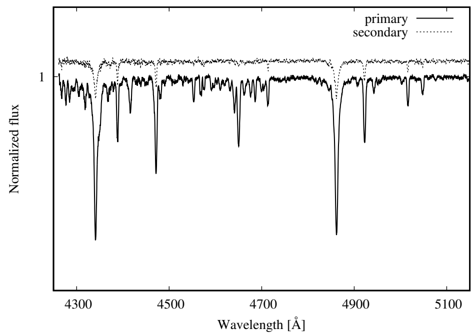

Fig. 4: Normalized and shifted disentangled spectra of both components of δ Pictoris.

improvement of the spectroscopic solution and permitted spectral disentangling with the FDBINARY code (see Fig. 4; Ilijic et al., 2004). The initial analysis resulted in the radial velocity amplitudes of $K_1 = 169.3 \pm 1.7$ km s^{-1} and $K_2 = 288.3 \pm 4.2$ km s^{-1}, which correspond to the components masses of $M_1 = 14.86 \pm 0.15$ M$_\odot$ and $M_2 = 8.29 \pm 0.06$ M$_\odot$. Further spectroscopic analysis of the disentangled spectra was carried out with the STARFIT code (Kolbas et al., 2014) leading to: $T_{\rm eff1} \sim 26\,000$ K, $T_{\rm eff2} \sim 22\,500$ K, $v \sin i_1 \sim 209$ km s^{-1}, $v \sin i_2 \sim 116$ km s^{-1}, while the light ratio of the components is ~ 0.18. The SNR of the disentangled spectra are ~ 360 and 65 for the primary and secondary, respectively.

3 β Cephei-type stars mass determination

Among massive stars, β Cephei-type stars play an important role in many aspects of asteroseismology. Although asteroseismology of such stars has been carried out for a long time permitting determination of restrictions on the rotation or opacity issues, the state of our knowledge about the internal structure of B-type pulsating stars is still insufficient. The main aspects requiring deeper investigation are issues of rotation (Maeder et al., 2009), distribution of angular momentum, opacity (Walczak & Daszyńska-Daszkiewicz, 2010), internal mixing, and the MS lifetime related to the value α parameter (Mowlavi & Forestini, 1994). Knowing a mass of a given β Cephei-type star, makes all of the above-mentioned issues of stellar structure easier to treat.

Studies on β Cephei-type stars show also non-negligible differences between dynamical masses and masses derived from evolutionary model calculations (Herrero et al., 1992; Mokiem et al., 2007). This issue, described as a mass discrepancy problem, points out how important for seismic modelling is determination of dynamical masses for at least several β Cephei-type stars. Therefore investigation of eclipsing binaries containing stars of such type is of great value.

There are several examples of β Cephei-type stars in eclipsing binary systems, e.g.: EN Lac (Pigulski & Jerzykiewicz, 1988), V381 Car (Freyhammer et al., 2005), λ Sco (Tango et al., 2006), and V916 Cen (Pigulski & Pojmański, 2008). All of those systems are SB1 type, therefore direct mass determination of these stars is not possible. The key to success is the detection of spectral lines of secondary components and thus determination the masses of both stars – including the β Cephei-type component. Dynamical mass determination of β Cephei-type stars is crucial for understanding of the details of stellar-interior modelling of these objects. Worth mentioning here are also non-eclipsing SB2 systems with β Cephei-type components: σ Sco (Tkachenko et al., 2014) and α Vir (Tkachenko et al., 2016), for which quite solid values of dynamical masses were derived.

Using synthetic spectra, we investigated the influence of adding a fainter component to a spectrum of a primary (i.e. brighter, β Cephei-type) star. The tests revealed that the contribution of a secondary to the total flux of the system amounts about 2% in the case when we deal with B- and A-type components and about 0.1% in the case when the system consists of B- and F-type stars. The influence of a fainter component is higher when rotational velocities are slower and when radial velocity difference between components is higher. Thus it is important to carry out spectral observations in phases when the stars are in quadratures (i.e. not eclipsing each other). Another test we run on synthetic spectra indicates that in order to detect lines of a secondary, one needs a SNR of 500 for the first case and 8 000 for the latter. This can be achieved by adding many high-SNR spectra taken during quadratures. The strength of this method is also presented in spectral disentangling technique (for a resolved Algol component that contributes only 1% to the total light; Kolbas et al., 2015).

δ Pictoris, which turned out to be a SB2 binary system with a β Cephei-type component is thus an example of a great value. Detailed studies of this target and of another promising system – EN Lac – are ongoing, but all of the systems mentioned above deserve further investigation.

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