Contrib. Astron. Obs. Skalnaté Pleso **49**, 252 – 257, (2019)

Tracking massive pairs

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Received: October 18, 2018; Accepted: January 22, 2019

Abstract. The analysis of eclipsing binaries with massive components enables to test stellar evolution models and track selected aspects of the structure of early-type stars. Stellar pairs with B-type components may serve to find tighter constraints on the mechanisms of convective core overshooting or masses of β Cephei-type stars. We present the results of an analysis of several eclipsing binaries – N Sco, LS CMa, and δ Vel – observed by BRITE-Constellation satellites and followed by a wide range of ground-based telescopes.

Key words: binaries: spectroscopic – binaries: eclipsing – stars: oscillations

1. Introduction

Stellar astrophysics is based on the precise determination of fundamental stellar parameters, like masses, radii, and effective temperatures. Detached eclipsing binaries (DEBs) of SB2-type enable determination of these parameters with the required precision of 3% (Torres et al., 2010), and thus allow us to test the predictions of stellar evolution models.

2. Finding constrains on convective core overshooting

Inspection of the catalogue of the detached eclipsing binaries (Southworth, 2015, DEBCat) indicates the lack of massive stars with precise masses and radii. There is only a dozen of systems with well-characterised B-type components. Considering that our knowledge of the evolution of early-type stars on the main sequence (MS) is incomplete, there is a need to find and study binary systems with massive components.

Even if modern evolutionary codes are very advanced, there are still some uncertainties that affect the modelling of stellar structure and evolution. One of the major issues under debate in models of high-mass stars is the convective boundary mixing, called overshooting. It affects the size of convective stellar cores, the size of MS stellar radii, and the MS lifetime. The greater the effect of convective core overshooting is assumed in the models, the wider the MS, and so the more the TAMS is shifted towards higher luminosity (see Ratajczak et al., 2017, Fig. 1). Finding observational constrains on the convective core overshooting parameters may be possible by tracking DEBs with B-type stars located close to TAMS. By determining the masses and radii of massive components of these systems and comparing them with the models, we aim at limiting the parameters of convective core overshooting.

The analysed sample consists of bright DEBs with B-type components mostly observed by BRITE (Weiss et al., 2014; Pablo et al., 2016), for which spectroscopy was carried out using a wide range of spectrographs. The outcome of the survey resulted in a dozen of systems, many of which turned out to be less evolved than expected, residing closer to ZAMS than thought. A few promising systems are still under analysis. We have also performed analysis of fainter targets not observed by BRITE, namely HD 161160, HD 153387, HD 93004, HD 82422, HD 326440, HD 145614, and V743 Cep.

3. Selected BRITE targets – N Sco and LS CMa

One of the peculiar objects from the BRITE sample is N Sco (HD 148703, $V = 4.23$ mag), which was not classified as an eclipsing binary to date, just considered as a variable star.

BRITE photometry revealed eclipses in the data, which were confirmed by the Solar Mass Ejection Imager (Jackson et al., 2004, SMEI) data taken between 2003 and 2011. The orbital period of N Sco is $P \sim 223.88$ d. and the system is highly eccentric with $e = 0.93$. Spectroscopic data were obtained using the following spectrographs: BACHES (Kozłowski et al., 2014), PUCHEROS (Vanzi et al., 2012), FIDEOS (Vanzi et al., 2018), and HRS/SALT (Bramall et al., 2010). High-resolution HRS spectra were used to detect the spectral lines of the secondary component at the highest radial velocity (RV) separation. The preliminary analysis of the system was presented by Ratajczak & Pigulski (2018).

N Sco turned out to be the most eccentric eclipsing binary with massive components. Its high eccentricity is a puzzle possibly giving a new perspective on the formation and evolution of such systems.

Another intriguing system from BRITE is LS CMa (HD 52670, $V = 5.63$ mag), which was already classified as an eclipsing binary, but with an unknown orbital period. The object was observed by the BRITE-Toronto satellite and the data enabled to determine the orbital period of $P \sim 70.048$ d. We have also detected an additional periodic signal with frequency $f = 0.624$ c/d, confirmed by the SMEI observations. The BRITE light curve of LS CMa is presented in Fig. 1.

Ground-based spectroscopic observations of the target resulted in 44 spectra in total (using CHIRON, PUCHEROS, BACHES, and FIDEOS spectrographs) taken in order to determine the RVs of the components and their masses.

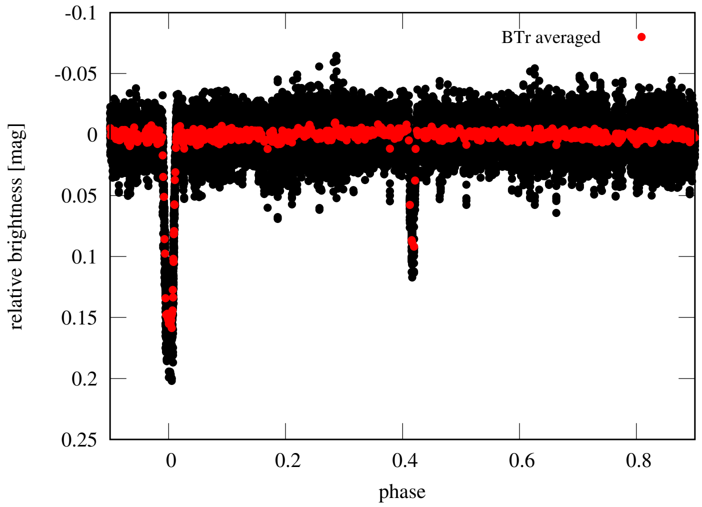

Figure 1. The BRITE light curve of LS CMa. Red points indicate averaged data from the BRITE-Toronto satellite.

4. Mass determination of β Cephei-type stars

β Cephei-type stars are important test-beds of massive stars asteroseismology. The mass estimation of a given β Cephei-type star sets constrains on several aspects of stellar structure modelling.

There are a few examples of β Cephei-type stars in eclipsing binary systems of SB1 type (eg. EN Lac, V381 Car, λ Sco, V916 Cen). Since a direct dynamical mass determination of these stars is not possible, it is crucial to detect spectral lines of secondary (fainter) components and thus estimate the masses of both stars – including a β Cephei-type one.

We have investigated the possibility of detection the secondary's spectrum if its contribution to the total flux of the system is about 2% when we consider B- and A-type stars in a system and about 0.1% when the system consists of B- and F-type stars (Ratajczak et al., 2017). All this under assumption that the spectral observations are obtained when the stars are in quadrature phases, because the chance to detect the secondary's lines is the highest at these phases.

Tests on the synthetic spectra yielded that a signal-to-noise ratio (SNR) of 500 is required in the first case (B- and A-type components) and 8 000 in the other (B- and F-type components). Such high SNR can be achieved only by adding many high-SNR spectra. The power of this method is also proven in the spectral disentangling technique described by Kolbas et al. (2015), where the authors show that it is possible to resolve a stellar component that contributes only 1% to the total light of the triple system.

To test their method of spectral disentangling on our data we have studied δ Vel (HD 74956, $V = 1.95$ mag), the brightest known DEB. The system is well described in the literature by eg. Kervella et al. (2009) and was a subject of photometric, spectroscopic, and astrometric studies.

We have analysed the δ Vel photometric data obtained by BRITE (see Fig. 2), as well as by the SMEI satellite. Our analysis confirmed the estimated orbital period of the system ($P = 45.15$ d.) and the lack of detectable additional periodic signal in both components.

The spectra of the system were obtained with the BESO spectrograph on the Bochum 1.5-m Hexapod Telescope at the Cerro Armazones Observatory. The spectra of the individual components were extracted with the method of spectral disentangling using a time series of 65 spectra. Atmospheric parameters of each individual component (disentangled spectra) were derived from an optimal fit using a precalculated grid of synthetic spectra and a genetic optimisation algorithm. The fitting was performed in the 4400 − 4650 Å spectral region, for the fixed surface gravity values and the light ratio estimated by Mérand et al. (2011). The analysis reveals effective temperatures of the components of $T_1 = 10\,250$ K, $T_2 = 9\,450$ K, and a projected rotational velocity of $v \sin i_1 = 130$ km s^{-1}, $v \sin i_2 = 138$ km s^{-1}, for the primary and secondary, respectively. These values are in agreement with the estimations presented by Mérand et al. (2011). The best fits to the spectra are presented in Fig. 3.

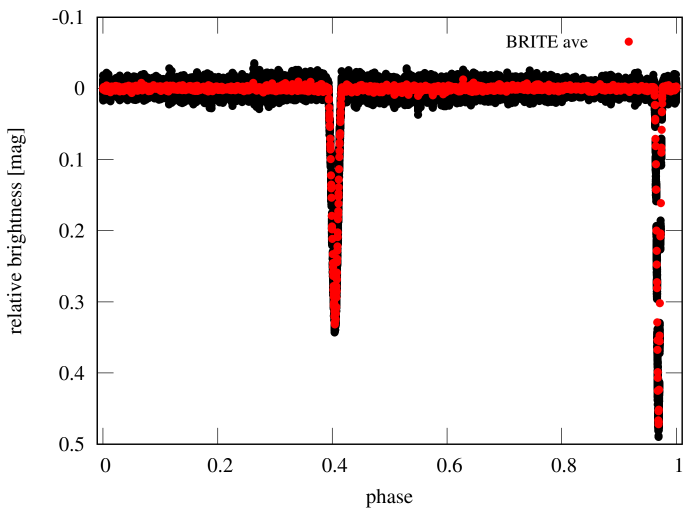

Figure 2. BRITE light curve of δ Vel. Red points indicate averaged data.

We have also studied the following SB1 systems with β Cephei components: EN Lac, V381 Car, and the β Cephei binary pair itself. The analysis of about

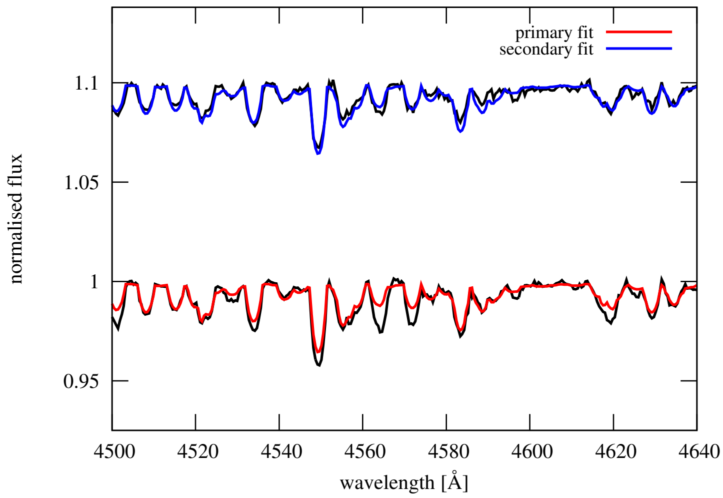

Figure 3. The most optimal fits to disentangled spectra of δ Vel components. The spectra of the secondary are shifted for clarity of the plot.

1 000 spectra of EN Lac was carried out in order to disentangle the system components, but due to pulsations it is a challenging task, so the target needs further investigation. We have also performed the simulations of the β Cephei binary system, which reveals that the secondary component contributes about 2% to the total flux of the system (at $\lambda = 5\,500$ Å). More than a thousand spectra were obtained for the target and the technique of adding spectra in quadrature phases is being implemented. We have also performed spectral disentangling for the V381 Car system, which reveals a weak secondary spectrum. The detailed analysis of that object will be described elsewhere.

Acknowledgements. MR acknowledges support by the National Science Center through the grant 2015/16/S/ST9/00461, AP through the grant 2016/21/B/ST9/01126, KP was supported by the Croatian Science Foundation under the grant 2014-09-8656. The authors thank prof. R. Chini for putting spectra of δ Vel at their disposal. The analysis was based on data collected by the BRITE Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science and Technology (FNiTP MNiSW), and the National Science Centre (NCN). This work is supported by the ERC through a Starting Grant. Some of the observations reported here were obtained with the Southern African Large Telescope (SALT).

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