Evolutionary and Seismic Modeling of the δ Sct Pulsator in a Binary System AB Cassiopeia

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We present the analysis of the eclipsing binary system AB Cas, that consists of a δ Sct star and a low-mass companion. The Fourier transform of the *TESS* light curve, corrected for the orbital model, reveals 114 frequency peaks. The most prominent peak corresponds to the radial fundamental mode. We conduct simultaneous binary evolution and seismic modelling by fitting the masses, the radii, the orbital period of the system, and the dominant pulsational frequency in order to constrain the age and some free parameters of theory.

1 Introduction

AB Cas (A3V + K1V, Rodríguez & Breger, 2001) is a short-period, Algol type binary discovered as an eclipsing variable by Hoffmeister (1928). Over decades, this system was a subject of many photometric studies, e.g., by Tempesti (1971), Rodriguez et al. (1998), and Rodríguez et al. (2004a), along with the spectroscopic search for signatures of possible accretion disc (Kaitchuck et al., 1985). The main component is known to pulsate in a radial fundamental mode with a frequency $f_1 = 17.1564\,\mathrm{d}^{-1}$ (Rodriguez et al., 1998) and the amplitude of 0.05 mag in the V filter (Tempesti, 1971). Using the *uvby* photometry from Rodríguez et al. (2004a,b) and 27 high-resolution spectra, Hong et al. (2017) determined the absolute parameters of AB Cas components to be: $M_1 = 2.01 \pm 0.02$ M$_\odot$, $M_2 = 0.37 \pm 0.02$ M$_\odot$, $R_1 = 1.84 \pm 0.02$ R$_\odot$, $R_2 = 1.69 \pm 0.03$ R$_\odot$, $T_{\mathrm{eff},1} = 8080 \pm 170\,\mathrm{K}$, and $T_{\mathrm{eff},2} = 4925 \pm 150\,\mathrm{K}$.

2 Binary light curve modelling

The system was modelled with the `PHOEBE 2` code using the *TESS* and *uvby* Strömgren photometry.

2.1 Observations

AB Cas was observed by the *TESS* space mission in a 120 s cadence through nearly 81 days in three sectors: 18, 19, and 25. These data were obtained and processed from the Target Pixel Files by means of the `lightkurve` package (Lightkurve Collaboration et al., 2018). During the light curve extraction process, we included only the pixels, that showed a flux higher than three times the standard deviation above the overall median for each sector. Next, from the obtained light curves we removed the outliers that showed flux above 5σ. We also removed data with obvious nonphysical

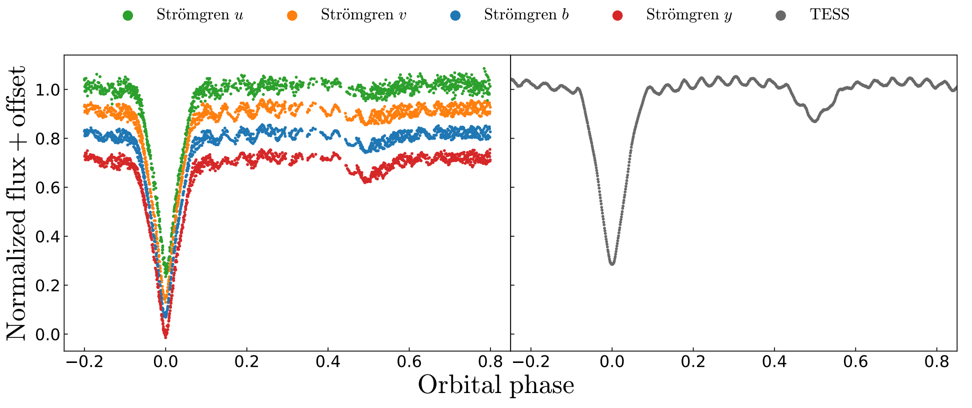

Fig. 1: Comparison of the *uvby* Strömgren observations (*left*) with the *TESS* light curve (*right*) for the binary system AB Cas.

trends, as sudden changes in brightness by several orders of magnitude. Each sector was then divided into two parts and, using out-of-eclipse data, normalised using a linear regression. Finally, we merged all the data back together, obtaining 51 300 observational points.

In addition, to get independent constraints on the absolute values of the components, we used Rodríguez et al. (2004a,b) photometry acquired using Sierra Nevada Observatory 90-cm telescope. These observations consist of 1 313 simultaneous photometric measurements in the *ubvy* filters spread through 20 photometric nights during years 1998 and 1999.

In Fig. 1, we compare the *uvby* (the left panel) and *TESS* (the right panel) light curves phased with the orbital period. In the case of the *uvby* data, all observations were phased, whereas, in the case of the *TESS* data we depicted the light curve covering only one orbital period.

2.2 *PHOEBE 2 analysis*

In order to derive physical and orbital parameters of AB Cas we performed a fit using simultaneously five phased and binned *uvby* and *TESS* light curves. For this purpose, we used the PHOEBE 2 software[1] (version 2.3, Prša & Zwitter, 2005; Prša et al., 2016) with the trust-region reflective algorithm (Branch et al., 1999) for least-squares optimisation.

By means of the Fourier analysis applied to the whole *TESS* light curve, we determined the orbital period of AB Cas to be $P_{\mathrm{orb}} = 1.3668810(6)$ d and we fixed this value in the further modelling. During the fit, we assumed masses of both components from Hong et al. (2017). Moreover, we assumed the circular orbit, the synchronous rotation of both components, and the spin-orbit alignment in the system. The fluxes and the limb-darkening coefficients for the primary were obtained from ATLAS 9 models (Castelli & Kurucz, 2003) with the solar metallicity. In the case of the secondary component, the solar-metallicity PHOENIX models (Hauschildt

[1] http://phoebe-project.org/

Tab. 1: Absolute parameters of AB Cas system.

Component	Mass	Radius	$\log T_{\rm eff}$	$\log L/L_\odot$
Primary	$2.01 \pm 0.02^\star$	1.862 ± 0.017	3.922 ± 0.006	$1.183 \pm 0.019^\dagger$
Secondary	$0.37 \pm 0.02^\star$	1.695 ± 0.027	3.677 ± 0.005	$0.122 \pm 0.026^\dagger$

Notes: * Fixed during the fitting procedure, after Hong et al. (2017)
† From $\log L/L_\odot = 4\log(T_{\rm eff}/T_{\rm eff\odot}) + 2\log(R/R_\odot)$

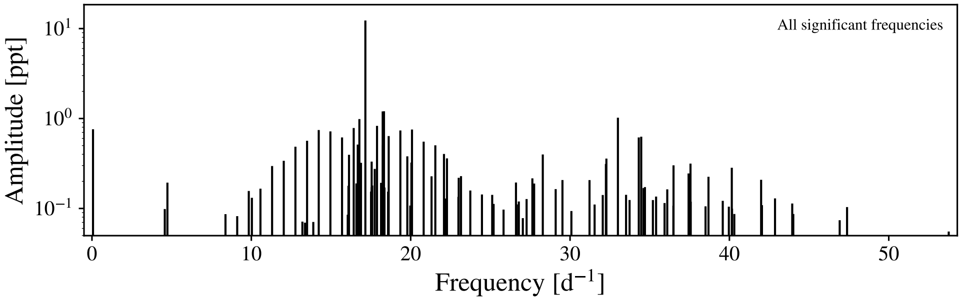

Fig. 2: Oscillation spectrum of all significant frequencies that were found in the *TESS* data after removing the binary light curve.

et al., 1997; Husser et al., 2013) were used. The absolute parameters of the system from the above described analysis are presented in Tab. 1.

3 Frequency analysis

The discrete Fourier transform (Deeming, 1975; Kurtz, 1985) with iterative prewhitening procedure for the *TESS* data revealed 114 frequencies with $S/N \geq 4$. These frequencies occupy the region up to $\sim 54\,{\rm d}^{-1}$, with the dominant peak at $f = 17.156430\,{\rm d}^{-1}$. The schematic oscillation spectrum of the system is shown in Fig. 2.

Given, that the dominant frequency f_1 was identified as a radial fundamental mode (Rodriguez et al., 1998) we checked the frequency ratios as an attempt to identify possible radial overtones, but we found no signs of them in the data.

4 Binary evolution and seismic analysis

In order to obtain fundamental parameters that described the AB Cas at the time of settling on the ZAMS, we constructed and calculated an extensive grid of evolutionary models utilising the `MESA-binary` code of Paxton et al. (2011). As a result, we found several dozen models that reproduce the exact value of the observed orbital period as well as the masses and radii of both components within the 3σ errors.

These models have the following initial orbital period and the masses for donor and acceptor: $P_{\rm ini} = 3.388 \pm 0.766\,{\rm d}$, $M_{\rm don,ini} = 1.714 \pm 0.328\ {\rm M}_\odot$, $M_{\rm acc,ini} = 0.843 \pm 0.272\ {\rm M}_\odot$. The best chemical composition was found to be $X_0 = 0.71 \pm 0.03$, $Z = 0.02 \pm 0.006$ with the overshooting parameter $f_{\rm ov} = 0.015 \pm 0.014$ and the mixing parameter $\alpha_{\rm MLT} = 1.3 \pm 0.5$.

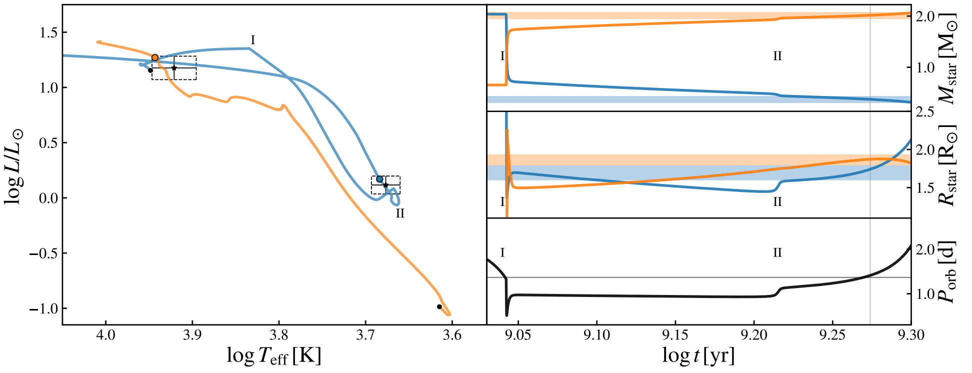

Fig. 3: HR diagram (*left*) and the evolution of masses, radii, and orbital period (*right* panels), for one of the models reproducing observed parameters of the components. See text in Sec. 4 for more details.

The parameter describing the mass transfer conservativeness rate was found to be $(1-\beta) = 1-(0.145\pm0.135) = 0.855\pm0.135$. This gives the fraction of mass $\beta = 0.145\pm0.135$ lost from vicinity of the acceptor in the form of a fast wind during the mass transfer (Tauris & van den Heuvel, 2006).

One of the best models that reproduces the observed absolute parameters of the components is presented in Fig. 3. This model has the parameters: $P_{\rm ini} = 3.21879\,{\rm d}$, $M_{\rm don,ini} = 2.042\ {\rm M}_\odot$, $M_{\rm acc,ini} = 0.653\ {\rm M}_\odot$, $X_0 = 0.737$, $Z = 0.016$, $f_{\rm ov} = 0.009$, $\alpha_{\rm MLT} = 1.3$, and $\beta = 0.18$, and its position on the HR diagram with the corresponding evolutionary tracks is depicted in the left panel of Fig. 3. There are shown also the 3σ observational error boxes for both components. The location of the best model is marked with the colour dots (blue for donor, orange for acceptor). This model has 1.86 Gyr and is marked with vertical grey lines on the right panel of Fig. 3. In this panel we plotted the evolution of masses, radii, and orbital period. The allowed ranges of these parameters are marked with colour stripes. Moreover, we also mark two moments in the evolution: `I` presents the onset of the mass transfer and `II` corresponds roughly to the minimum of the effective temperature and luminosity of the donor. The moment `II` marks the core conversion to fully helium and the beginning of the shell H-burning for the donor star.

For all models that reproduce the masses and radii of both components, we computed radial pulsations using the code of Dziembowski (1977). The closest frequency of the radial fundamental mode in our models has the value of $f = 17.1874\,{\rm d}^{-1}$, however it is far beyond the Rayleigh limit ($\sim 0.0046\,{\rm d}^{-1}$) from the observed frequency, $f_{\rm obs} = 17.1564\,{\rm d}^{-1}$. Thus, more in-depth evolutionary analysis is indispensable in order to get a model that is able to reproduce the observed pulsation frequency.

5 Conclusions

We presented a comprehensive analysis of the AB Cas system, that consists of a pulsating δ Sct star and a low-mass component. Using the Strömgren observations collected from the literature along with the high-precision space *TESS* photometry, we modelled the eclipsing light curve of the system using the `PHOEBE 2` code. Next, the binary model was subtracted from the data and the Fourier analysis was performed on the residuals. This analysis revealed 114 oscillating signals, with the most prominent peak at $f = 17.156430\,\mathrm{d}^{-1}$. The fact that the dominant frequency is the radial fundamental mode gives a high potential to obtain strong constraints on the more massive component of the system.

Using the `MESA-binary` code we modelled the AB Cas and successfully reproduced the orbital period, masses, and radii for both components. However, we were unable to find a model whose radial fundamental mode would have a frequency close to the observed value within the Rayleigh limit. Thus, more detailed modeling is needed to explain all observed properties of the AB Cas binary.

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