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The Be star *o* Cas is indeed the primary of a triple system

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ABSTRACT

Analysis of radial velocities of two narrow absorption components in the Mg II 4481 Å line demonstrated that the secondary of the Be star *o* Cas is indeed a close binary system composed of two B7 stars orbiting each other with a period of $11\overset{\mathrm{d}}{.}6604$. Orbital solutions and spectral disentangling lead to consistent system properties. The system is extremely important for the research of Be stars since its future interferometric observations with a high spatial resolution could allow the mass and perhaps even the radius of a Be star to be derived without too many model assumptions, mainly on the dynamical grounds.

Key words. binaries: spectroscopic – stars: emission-line, Be – stars: fundamental parameters – stars: individual: *o* Cas

1. Introduction

The B2V – B5III-IVe star *o* Cas (22 Cas, HD 4180, BD+47°183, MWC 8, HIP 3504) is the brighter component of a wide visual system WDS J00447+4817, which exhibits few or no signs of orbital motion. Component B is an $11\overset{\mathrm{m}}{.}2$ F8 star BD+47°183B at recorded separations ranging from $32\overset{\prime\prime}{.}8$ to $34\overset{\prime\prime}{.}4$. Abt & Levy (1978) concluded that *o* Cas is a single-line spectroscopic binary with a period of 1033 days and a nearly circular orbit. Although this conclusion was questioned in some studies, the existence of such a pair was ultimately confirmed; see Koubský et al. (2010) and references therein. The orbit is circular with a period of $1031\overset{\mathrm{d}}{.}55 \pm 0\overset{\mathrm{d}}{.}71$ and a remarkably large semi-amplitude of more than 20 km s^{-1}. This represents a problem, since for the inclination of the orbit derived from interferometry, the companion to the Be primary should be the more massive of the two. However, there is no trace of it in the optical spectra. To explain this puzzle, Koubský et al. (2010) tentatively suggested that the companion could actually be a close binary composed of two A stars. Inspired by this suggestion, Grundstrom (2007) carefully inspected the Kitt Peak National Observatory (KPNO) blue spectra at her disposal and discovered two weak and narrow absorption lines in the core of the broad Mg II 4481 Å line, which had been changing their positions on a timescale of days, perhaps with about a four-day period.

Since no further studies of this possible binary appeared, this prompted us to combine our efforts, obtain new spectra, and analyse them in an effort to prove the existence of such a close binary and to derive its orbital elements.

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2. Spectroscopic data and their reductions

Throughout this paper, we shall use the dates of observations expressed in the 'reduced heliocentric Julian date' (RJD) defined as

$$\mathrm{RJD} = \mathrm{HJD} - 2400000.0.$$

Inspecting the Ondřejov (OND) and the Dominion Astrophysical Observatory (DAO) data archive, we actually found several pre-discovery blue spectra of *o* Cas. New electronic spectra were obtained at KPNO, DAO, OND, and Lisbon. We also used 22 amateur spectra from the BeSS database (Neiner et al. 2011) having a spectral resolution of 10000 or better. The journal of all spectroscopic observations used here is in Table 1.

The initial reduction of all spectra (bias subtraction, flat-fielding, and creation of 1D frames) was carried out with the pipelines used in individual observatories. Further reduction (spectra normalisation, cleaning from cosmics and flaws, and radial-velocity (RV) measurements) were carried out in the programme `reSPEFO` 2. This programme is written in JAVA and can run on different platforms (Linux, Windows, MacOS). It is being developed by Adam Harmanec. It can, among other things, import spectra that were originally reduced in `SPEFO` (Horn et al. 1996; Krpata 2008) and treat spectra stored as FITS files. For the DAO spectra, it also provides wavelength calibration. The programme is described in more detail in Appendix A.

A prediscovery series of Mg II line profiles is shown in Fig. 1 and two examples of the blue spectra that we have are in Fig. 2.

3. The inner orbit

In spite of the fact that we managed to accumulate 85 higher-resolution spectra with the Mg II 4481.228 Å sharp lines well

Table 1. Journal of blue electronic spectra of *o* Cas.

Spg. No.	Time interval (RJD)	No. of RVs	Wavelength range (Å)	Spectral res.
1	52695.29–52695.34	2	4200–4750	40000
2	52910.00–52911.98	7	4460–4600	42600
3	52910.38–52910.50	3	4380–4630	11700
4	52959.59–52981.97	9	3870–4500	14200
5	53233.92–55163.73	14	4230–4585(*)	13000
6	55801.57–59179.34	22	4750–6990	10000
7	60114.55–60132.54	6	4410–4540	51600
8	60270.32–60344.33	7	4380–4635	10600
2	60523.79–60528.97	30	4380–4520	42600
2	60586.67–60587.02	4	4380–4520	42600
2	60879.82–60881.97	7	4380–4520	42600
2	60921.77–60922.00	6	4380–4520	42600
2	60937.70–60938.04	7	4380–4520	42600
2	61060.65–61062.80	13	4380–4520	42600

Notes. (*)Four of the KPNO spectra cover the range from 4300 to 4650 Å. Column "Spg. No.": 1…OND 2.0 m reflector, Cassegrain Heros spectrograph (Kaufer 1988); 2…DAO 1.2 m reflector, coudé grating McKellar spectrograph, 9682M configuration, CCD SITe4 detector; 3…OND 2.0 m reflector, coudé spectrograph, CCD SITe5 2030 × 800 pixel detector; 4…DAO 1.2 m reflector, coudé grating McKellar spectrograph, 32121B configuration, CCD SITe4 detector; 5…KPNO 0.9 m reflector, coudé feed spectrograph; 6…BeSS amateur echelle spectra (Neiner et al. 2011; `http://basebe.obspm.fr/basebe`); 7…OND 2.0 m reflector, OES echelle spectrograph, CCD EEV 42-40-1-368 detector; 8…Lisbon Celestron C14 0.356 m reflector, LhiresIII spectrograph.

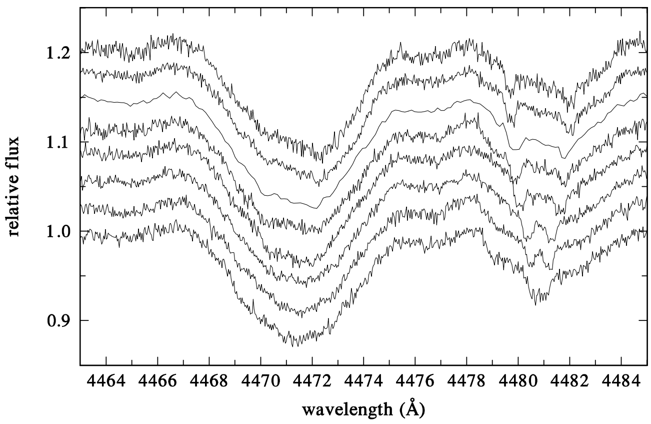

Fig. 1. A pre-discovery series of one OND and seven DAO spectra in the neighbourhood of the He I 4471.508 and Mg II 4481.228 Å from September 2003. From top to bottom the RJDs of the spectra are 52909.9993, 52910.0102, …10.4959 (OND), …10.6240, …10.9934, 52911.6137, …11.7928, and …11.9786. A smooth change in the position of the two narrow Mg II lines in time is clearly seen.

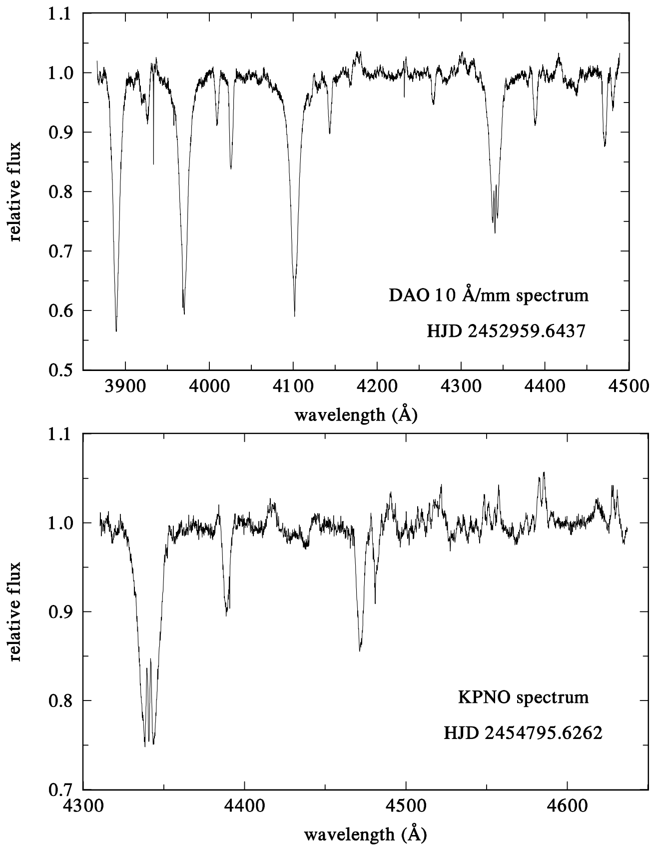

Fig. 2. Examples of some blue spectra at our disposal.

visible (out of the total number of 137 spectra listed in Table 1), finding the true orbital period of the inner orbit was all but easy. The two weak and narrow lines are rather similar to each other and it is easy to misinterpret one for another. Another complication arises from the fact that the whole binary moves with the Be tertiary in the 1032 d orbit with a non-negligible semi-amplitude of about 20 km s^{-1}. It was necessary to obtain spectral series covering several consecutive days to see the relative motion of the two components in continuous time sequences. Three limited series of spectra obtained within about a week of consecutive observations were obtained. Their RVs for (seemingly) stronger and weaker components of narrow Mg II lines were plotted versus time in the three panels of Fig. 3. After a number of trials for period searches, separately for the RVs of the stronger and fainter components, using a programme based on the Deeming (1975) period search technique, we concluded that the most probable orbital period of the inner system is close to $11\overset{d}{.}7$. Then we used the programme `FOTEL` (Hadrava 1990, 2004a), which is able to derive orbital solutions for triple systems. In our case, we kept the orbital elements of the outer $1031\overset{d}{.}55$ orbit fixed at values obtained by Koubský et al. (2010) from a very long series of observations. After properly identifying the primary and secondary components, we finally arrived at a very satisfactory solution presented in Table 2. The phase plots of all well-resolved RVs measured in `reSPEFO` through a comparison of direct and flipped line-profile images are in Fig. 4.

To confirm the result, we then used all 137 available spectra to disentangle them with the programme `KOREL` (Hadrava 1995, 1997, 2004b). The resulting orbital elements are also listed in Table 2 and the disentangled line profiles of all three stars are shown in Fig. 5. The referee called our attention to the fact that the disentangled Mg II line profile of the Be primary seems to have a small central peak, reminiscent of central quasi-emission peaks found for several Be stars seen roughly equator-on (see Rivinius et al. 1999, and references therein). Although we agree that this possibility deserves further investigation with high-quality spectra, for the moment we conclude that the effect is only an artefact of the disentangling process. The same feature is not seen in the neighbouring stronger He I line, and we have

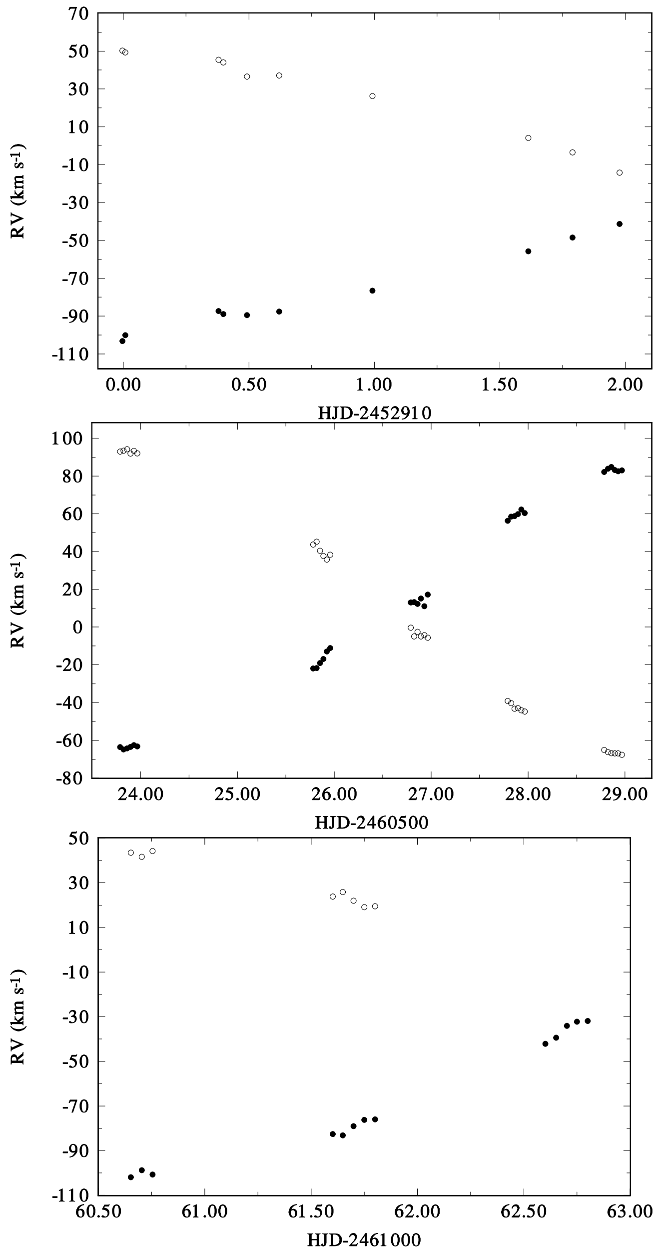

Fig. 3. Comparison of the RVs of the two narrow components of the Mg II 4481.228 Å line for three available time segments. The RVs of the primary and secondary are shown by black dots and open circles, respectively.

verified that it is absent if we disentangle only the high-resolution spectra.

4. Probable properties of the triple system

Obviously unaware of the Koubský et al. (2010) study, Videla et al. (2022) and Anguita-Aguero et al. (2023) attempted to estimate the masses of the wide $1031\overset{d}{.}55$ binary system *o* Cas using Bayesian inference. Videla et al. (2022) estimated the mass of the Be primary as $(5.62 \pm 1.19)\,M_\odot$ while Anguita-Aguero et al. (2023) derived masses as 5.77 and $4.66\,M_\odot$, however with huge errors.

Our study allows us to provide more realistic estimates of the basic physical properties of the system and its components. Based on the KOREL solution of Table 2 and assuming that the inner system is observed under the same orbital inclination of 65° as that estimated from interferometry for the outer system, we obtain the masses of the components of the inner binary, $3.37\,M_\odot$ and $3.26\,M_\odot$, therefore the total mass of the inner binary is $6.63\,M_\odot$. From the solution for the outer system, we obtain the total mass of the inner binary as $6.73\,M_\odot$, the mass of the distant Be component being $6.07\,M_\odot$. These two results are in very good

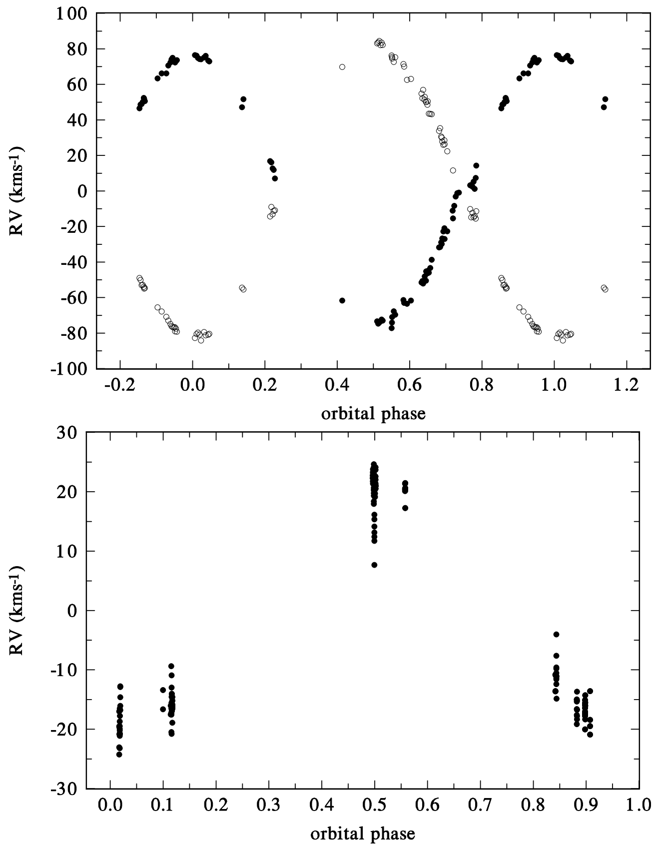

Fig. 4. Top: RV curves of the narrow Mg II lines for the period of $11\overset{d}{.}066043(31)$ based on a FOTEL solution for RVs measured in reSPEFO. Bottom: RV curve of the short-period binary around the centre of mass of the $1031\overset{d}{.}55$ binary based on the same RVs.

Table 2. Orbital elements based on reSPEFO RVs of the two narrow Mg II 4481 Å lines and a FOTEL triple-star solution.

Element	FOTEL	KOREL
P (d)	11.66043 ± 0.000031	11.66045
$T_{\mathrm{RVmax.1}}$ (RJD)	60529.5023 ± 0.0078	60529.5332
e	0.0 fixed	0.0 fixed
γ (km s^{-1})	−10.65 ± 0.22	−10.5
K_1 (km s^{-1})	75.79 ± 0.45	78.58
K_1/K_2	0.9303 ± 0.0073	0.9675
K_2 (km s^{-1})	81.47	81.22
K_3/K_1	0.2703 ± 0.0038	0.2695
K_{1+2} (km s^{-1})	20.487	21.18
K_3 (km s^{-1})	21.000	23.05
$m_1 \sin^3 i$ ($M_\odot$)	2.434	2.506
$m_2 \sin^3 i$ ($M_\odot$)	2.264	2.425
$a \sin i$ ($R_\odot$)	36.24	36.83
No. of RVs (prim./sec.)	85/80	137
rms (km s^{-1})	2.76	–

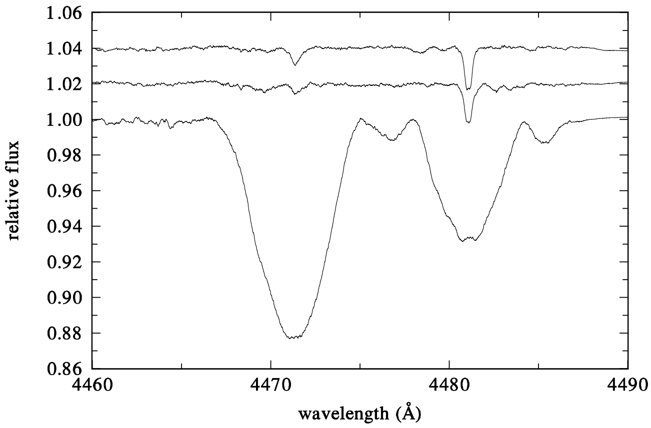

Fig. 5. The disentangled line profiles of the He I 4471 Å, and Mg II 4481 Å line for the three components of the triple system. All profiles are normalised to the joint continuum of the whole system and the profiles of the primary and secondary of the 11.^{d}66 subsystem were shifted for 0.04, and 0.02, respectively, in relative flux.

agreement. We note that according to the tabulation of normal masses by Harmanec (1988) the two components of the inner binary are probably B7 stars, while the Be component would correspond to a normal star of spectral type B3, in accordance with available spectral classifications. We wish to point out that o Cas is an astrophysically unique and very important system. Its future interferometric observations with a high spatial resolution should permit the first determination of the precise mass of a Be star based solely on the dynamical considerations, without the use of any statistical relations between the spectral type and stellar properties. A very favourable circumstance is also the relatively short outer orbit, with semi-amplitudes of the orbital motion of about 20 km s^{-1}, which guarantee good accuracy of mass determination.

It is true that dynamically determined masses of several Be stars in binaries and/or multiple systems have already been published; see, for example Klement et al. (2022) and references therein. However, some of these estimates depend either on distance estimates or on less certain RV curves of compact companions detected in the far-UV spectra.

We are aware of only the following few triple systems containing a Be star; all are much less favourable for accurate mass determination than o Cas. For V2048 Oph = 66 Oph, an inner binary rather similar to o Cas, composed of two late B or early A stars orbiting each other with a period of 10.^{d}78, was found by Štefl et al. (2004). However, the outer orbit of this binary with the Be primary is very long, 23421.^{d}1 ± 4.^{d}1 according to Hutter et al. (2021), and not very favourable for mass determination. Another triple system, ν Gem = HD 45542 (Klement et al. 2021) consists of two stars orbiting with a period of 53.^{d}8 and a distant Be star with a long outer orbit of about 7000 d. The Hα emission of the Be star is rather weak, and the RV curve of the Be star was thus derived from the RV of the Hα shell absorption line, which does not need to return the true RV amplitude. V1371 Tau = HD 36665 (Rocha et al. 2026) consists of three early B stars. Two of them form a peculiar eccentric-orbit eclipsing binary with a period of 33.^{d}62 and the third body is a Be star in uncertain ~11 yr period. There is a suspicion of secular change of the orbital inclination of the inner eclipsing binary, and there are also rapid light changes present in the system. A well-known B6e star o And = HD 217675 is in a wide orbit of a still uncertain period of several years with two sharp-lined stars, which revolve around each other with a 33.^{d}0 period (Hill et al. 1988; Zhuchkov et al. 2010).

In passing, we note that similar triple or even multiple systems represent an interesting challenge to the theory of their evolutionary history. In addition to o Cas and the systems discussed above, one can also mention the compact triple system ξ Tau (Nemravová et al. 2016), with a rapidly rotating B star, not known to have Balmer emission.

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Appendix A: Program reSPEFO for the reductions and measurements of 1D electronic spectra

Program reSPEFO, written in Java by Adam Harmanec, is a modern replacement for the original SPEFO program developed in Pascal by the late Jiří Horn (Horn et al. 1996). It runs on different platforms (Unix, Windows, macOS) and provides a comprehensive environment for one-dimensional spectral analysis. reSPEFO operates primarily on 1D spectra produced by standard observatory pipelines. For the majority of observatories, the spectra in 1D frames are already stored as pairs of wavelength and relative flux, typically in FITS format. The program converts imported data into an internal .spf format, which preserves raw data, metadata, preprocessing steps, and measurement results, allowing workflows to be revisited without repeating earlier steps. Besides spectra recorded in the standard FITS format, the current version 2 of reSPEFO can process spectra from the CHIRON echelle spectrograph from CTIO, spectra from the BeSS database, FEROS echelle spectra, spectra from the Hercules echelle spectrograph, and also spectra from the DAO, for which it can also derive the wavelength scale from measurements of comparison ThAr or FeAr spectra. It is also able to import spectra reduced earlier with the original SPEFO as well as plain ASCII files recorded as wavelength - relative flux pairs.

The usual sequence of reduction steps is to define the project, import the spectra, rectify them, clean them of cosmics and residual flaws not removed by standard observatory pipelines, and measure RVs and spectrophotometric quantities of selected spectral lines. The tracing paper method of RV measurement allows flexible settings on different parts of more complicated line profiles in spectra from several components of a multiple stellar system. For red and infrared spectra, it is also possible to measure a selection of telluric lines to apply small additional corrections to the zero point to bring spectra from different instruments onto a common wavelength scale. The tracing paper method is illustrated in Appendix C of the paper by Harmanec et al. (2020) and its practical realisation in the program reSPEFO is described in detail in Sect. 3.1 of the paper by Wolf et al. (2021).

Version 2 of the program, together with a detailed documentation and user manual can be downloaded at https://astro.troja.mff.cuni.cz/projects/respefo, separately for Unix, Windows, and macOS operating systems.

The software is distributed under the EPL 2.0 license and remains under active development.