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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 $11^{\rm d}\!.6604$. 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 to derive the mass and perhaps even the radius of a Be star without too many model assumptions, mainly on the dynamical grounds.

Key words. Stars: 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 little or no signs of orbital motion. The component B is a $11^{\rm m}\!.2$ F8 star BD+47°183B at recorded separations ranging from $32''\!.8$ to $34''\!.4$. Abt & Levy (1978) concluded that *o* Cas is a single-line spectroscopic binary with a period of 1033 d 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 detailed references therein. The orbit is circular with a period of $1031^{\rm d}\!.55 \pm 0^{\rm d}\!.71$ and a remarkably large semi-amplitude of over 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 more massive of the two. Yet, 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 A line, which had been changing their positions on a time scale of days, perhaps with about a 4-d period.

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

2. Spectroscopic data and their reductions

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

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

Inspecting the Ondřejov (OND) and the Dominion Astrophysical Observatory (DAO) data archive, we actually found several pre-discovery blue spectra of *o* Cas: Two spectra taken on a single night in February 2003 with the Heros spectrograph attached to the Cassegrain focus of the Ondřejov 2 m reflector, seven DAO 1.2 m reflector coudé spectra with the dispersion of 2.4 A mm^{-1} and three OND coudé spectra with the dispersion of about 10 A mm^{-1} were obtained in Sept. 2003 and nine more DAO spectra with the dispersion of 10 A mm^{-1} in November 2003. 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 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, flatfielding and creation of 1-D frames) was carried out with the pipelines used in individual observatories. Further reduction (spectra normalization, cleaning from cosmics and flaws and radial-velocity (RV) and line intensity and equivalent width (EQW) measurements were carried out in the program `reSPEFO` 2. This program is written in JAVA and can run on

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⋆ Based on spectroscopic CCD observations obtained at the Dominion Astrophysical Observatory, Herzberg Astronomy and Astrophysics Research Centre, National Research Council of Canada, on new and archival spectroscopic observations obtained with the Heros echelle spectrograph, linear CCD coudé-focus spectrograph, and Ondřejov echelle spectrograph, all three attached to the 2.0 m reflector of the Astronomical Institute of Czech Academy of Sciences, on CCD spectra from the coudé feed spectrograph attached to the Kitt Peak 0.9 m reflector, on CCD spectra from Lisbon 0.356 m reflector, and on amateur echelle spectra from the BeSS database.

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

*) Four of the KPNO spectra cover the range from 4300 to 4650 Å.

Notes. 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 2030x800 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.

different platforms (Linux, Windows, MacOS). It is being developed by Adam Harmanec. [1] It can, among other things, import the 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 the wavelength calibration. The program is described in more detail in Appendix A.

Two examples of the blue spectra at our disposal are in Fig. 2. It is seen that many weak metallic lines in emission are present, which makes the task of proper spectra rectification quite challenging.

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 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 to misinterpret one for another is easy to do. 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 inevitable to obtain spectral series covering several consecutive days to see the relative motion of the two components in continuous time sequences. Three

[1] `https://astro.troja.mff.cuni.cz/projects/respefo`

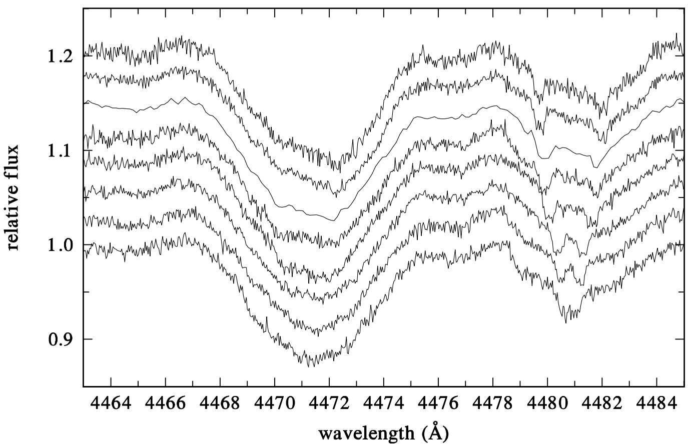

Fig. 1. A pre-discovery series of one OND and seven DAO spectra in the neighbourhood of the He I 4471.508 and Mg II 4481.228 Å from September 2003. From top to bottom the RJDs of the spectra are 52909.9993, 52910.0102, ...10.4959 (OND), ...10.6240, ...10.9934, 52911.6137, ...11.7928, and ...11.9786.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

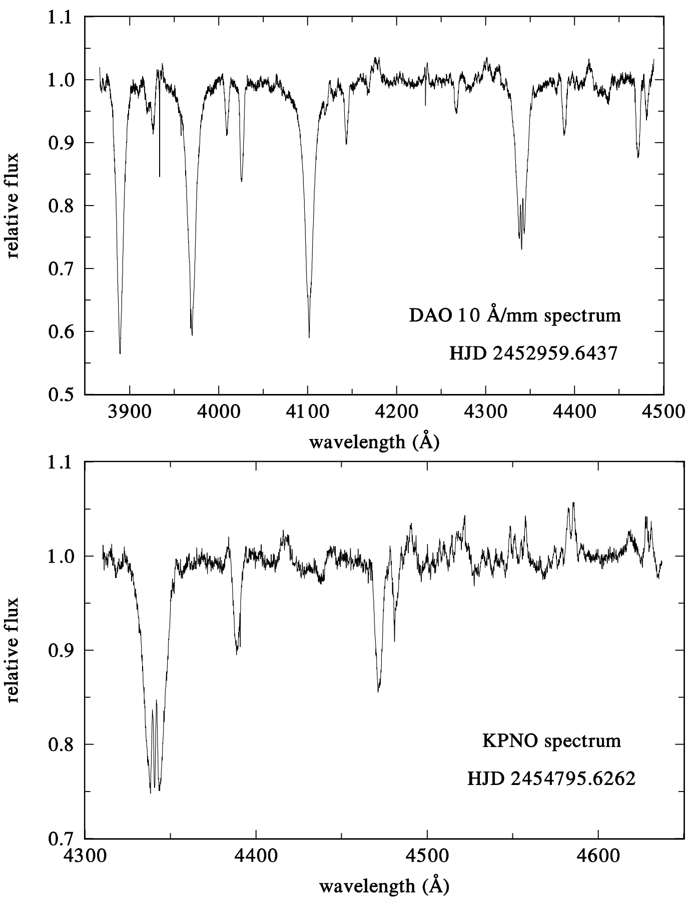

Fig. 2. Examples of some blue spectra at our disposal

limited series of spectra obtained within about a week of consecutive observations were obtained. Their RVs for (seemingly) stronger and weaker component of narrow Mg II lines are plotted vs. time in the three panels of Fig. 3. After a number of trials for period searches, separately for the RVs of the stronger, and the fainter component, using a program based on Deeming (1975) period search technique, we arrived at the conclusion that the most probable orbital period of the inner system is near

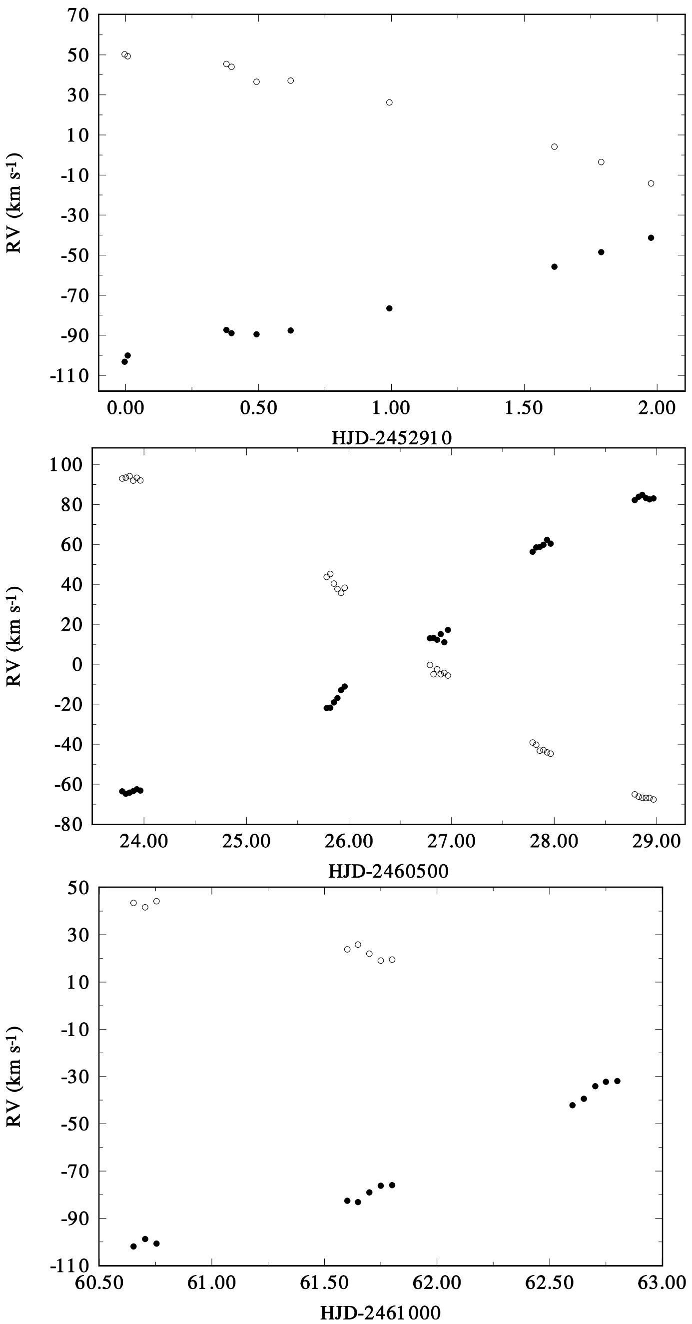

Fig. 3. A comparison of the RVs of the two narrow components of the Mg II 4481.228 Å line for three available time segments. The RVs of the primary and secondary are shown by black dots and open circles, repectively.

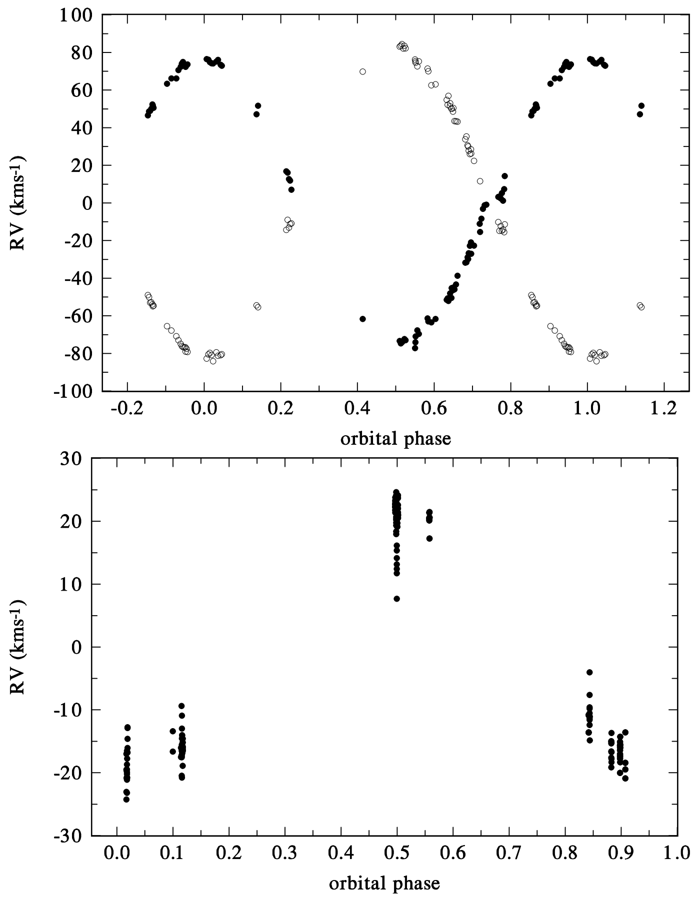

Fig. 4. Top: RV curves of the narrow Mg II lines for the period of $11^{\mathrm{d}}\!.066043(31)$ based on a `FOTEL` solution for RVs measured in `reSPEFO`. Bottom: RV curve of the short-period binary around the centre of mass of the $1031^{\mathrm{d}}\!.55$ binary based on the same RVs.

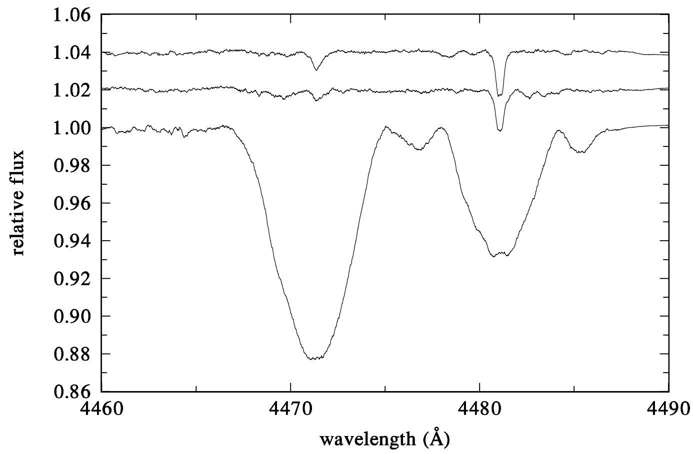

Fig. 5. The disentangled line profiles of the He I 4471 Å, and Mg II 4481 Å line for the three components of the triple system. All profiles are normalised to the joint continuum of the whole system and the profiles of the primary and secondary of the $11^{\mathrm{d}}\!.66$ subsystem were shifted for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

$11^{\mathrm{d}}\!.7$. Then we used the program `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 $1031^{\mathrm{d}}\!.55$ orbit fixed at values obtained by Koubský et al. (2010) from very long series of observations. After identifying the primary and secondary components properly, we finally arrived at a very satisfactory solution presented in Table 2. The phase plots of all well-resolved RVs measured in `reSPEFO` via a comparison of direct and flipped line-profile images is in Fig. 4.

To confirm the result, we then used all 137 available spectra to disentangle them with the program `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 Figure 5.

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	–

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 o Cas 1031$^{\mathrm{d}}$55 binary system using Bayesian inference. Videla et al. (2022) estimated the mass of the Be primary as (5.62 ± 1.19) M$_\odot$ while Anguita-Aguero et al. (2023) derived masses as 5.77 and 4.66 M$_\odot$, however with huge errors.

Our study allow us to provide more realistic estimates of the basic physical properties of the system and its components. Based on 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 inner binary 3.37 M$_\odot$, and 3.26 M$_\odot$, therefore the total mass of the inner binary comes as 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 a very satisfactory 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 accord with available spectral classifications. We wish to point out that o Cas is an astrophysically unique and a very important system. Its future interferometric observations with a high spatial resolution should permit the first determination of the 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. It is true that estimates of dynamically determined masses of several Be stars in binaries and/or multiple systems have already been published – see, e.g., Klement et al. (2022) and references therein. However, some of these estimates depend either on distance estimates or on less certain radial-velocity curves of compact companions detected in the far-UV spectra. We are aware of only two triple-star systems somewhat similar to o Cas: ν Gem (Klement et al. 2021) and V1371 Tau (Rocha et al. 2026). However, in both these cases, there are some problems. The Hα emission in both systems is rather weak and the RV curve of the Be star of ν Gem was thus derived from the RV of the shell absorption line in Hα, which need not return the true RV amplitude. Both systems also have much longer outer periods than o Cas (7160 d for ν Gem, and unsure ∼ 11 yr for V1371 Tau).

In passing we note that there are several systems, which represent an interesting challenge to the theory of the evolutionary history of such multiple systems. Besides o Cas, one can mention ξ Tau (Nemravová et al. 2016), o And (Božić et al. submitted to A& A), and already mentioned ν Gem (Klement et al. 2021), and V1371 Tau (Rocha et al. 2026). ξ Tau (HD 21364) consists of two B9V sharp-lined stars in a 7$^{\mathrm{d}}$1466 orbit, which revolve in a 145$^{\mathrm{d}}$15 orbit with a rapidly rotating absorption-line B star. o And (HD 217675) consists of two sharp-lined stars in a 33$^{\mathrm{d}}$0 orbit which probably revolve in a 2500 d orbit with a rapidly rotating B6e star. ν Gem = HD 45542 consists of two B stars in a 53$^{\mathrm{d}}$76 orbit, which revolve in a 7160 d orbit with a Be star. Finally, V1371 Tau = HD 36665 is a 33$^{\mathrm{d}}$62 eclipsing binary in an eccentric orbit which revolves in a wide orbit, possibly 11 yr long, with a less luminous Be star, having only weak Hα emission, absent in some epochs.

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Appendix A: Program `reSPEFO` for the reductions and measurements of 1-D 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 1-D spectra produced by standard observatory pipelines. For the majority of observatories, the spectra in 1-D 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.