

The Be star α Cas is indeed the primary of a triple system $\star, \star \star$

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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 α Cas is indeed a close binary system composed of two B7 stars orbiting each other with a period of 11^d6604. 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: α Cas

1. Introduction

The B2V - B5III-IVe star α 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^m2 F8 star BD+47°183B at a distance of 33". Abt & Levy (1978) concluded that α 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^d55 ± 0^d71 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 Å 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 an-

alyze 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

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

Inspecting the Ondřejov (OND) and the Dominion Astrophysical Observatory (DAO) data archive, we actually found several pre-discovery blue spectra of α 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 coude spectra with the dispersion of 2.4 Å mm⁻¹ and three OND coude spectra with the dispersion of about 10 Å mm⁻¹ were obtained in Sept. 2003 and nine more DAO spectra with the dispersion of 10 Å 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, flat-fielding 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 different platforms (Linux, Windows, MacOS). It is being developed by Adam Harmanec. ¹ It can, among other things, import the spectra

¹ <https://astro.troja.mff.cuni.cz/projects/respefo>

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* Based on new spectroscopic observations from the Ondřejov echelle spectrograph attached to the 2.0 m reflector of the Astronomical Institute of Czech Academy of Sciences.

** Tables 3, 4, and 5 are available only in electronic form at the CDS via anonymous ftp to cdarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>

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, coude grating McKellar spectrograph, 9682M configuration, CCD SiTe4 detector; 3... OND 2.0 m reflector, coude spectrograph, CCD SiTe5 2030x800 pixel detector; 4... DAO 1.2 m reflector, coude grating McKellar spectrograph, 32121B configuration, CCD SiTe4 detector; 5... KPNO 0.9 m reflector, coude 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.

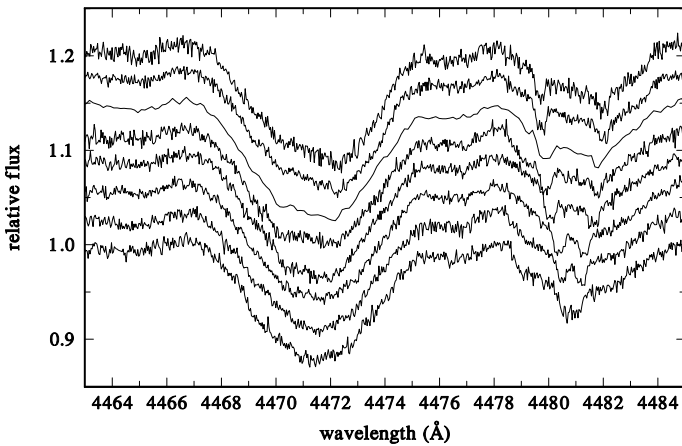


Fig. 1. A pre-discovery series of one OND and seven DAO spectra in the neighbourhood of the He I 4471.508 and Mg II 4481.228 Å from September 2003. From top to bottom the RJDs of the spectra are 52909.9993, 52910.0102, ...10.4959 (OND), ...10.6240, ...10.9934, 52911.6137, ...11.7928, and ...11.9786.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

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.

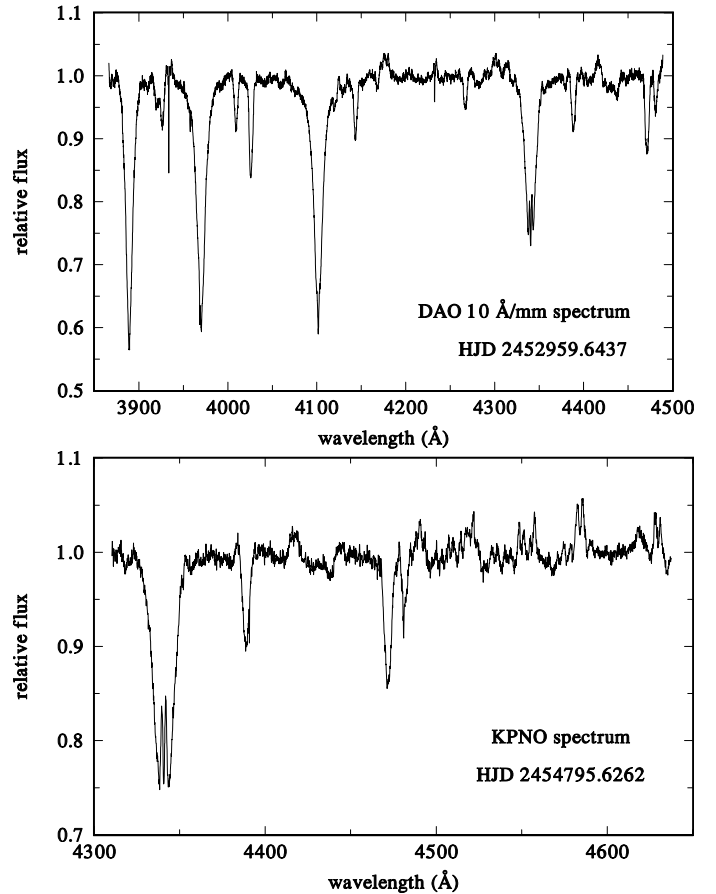


Fig. 2. Examples of some blue spectra at our disposal

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 mis-interpret 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 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 11^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^d.55 orbit fixed at values obtained by Koubský et al. (2010) from very

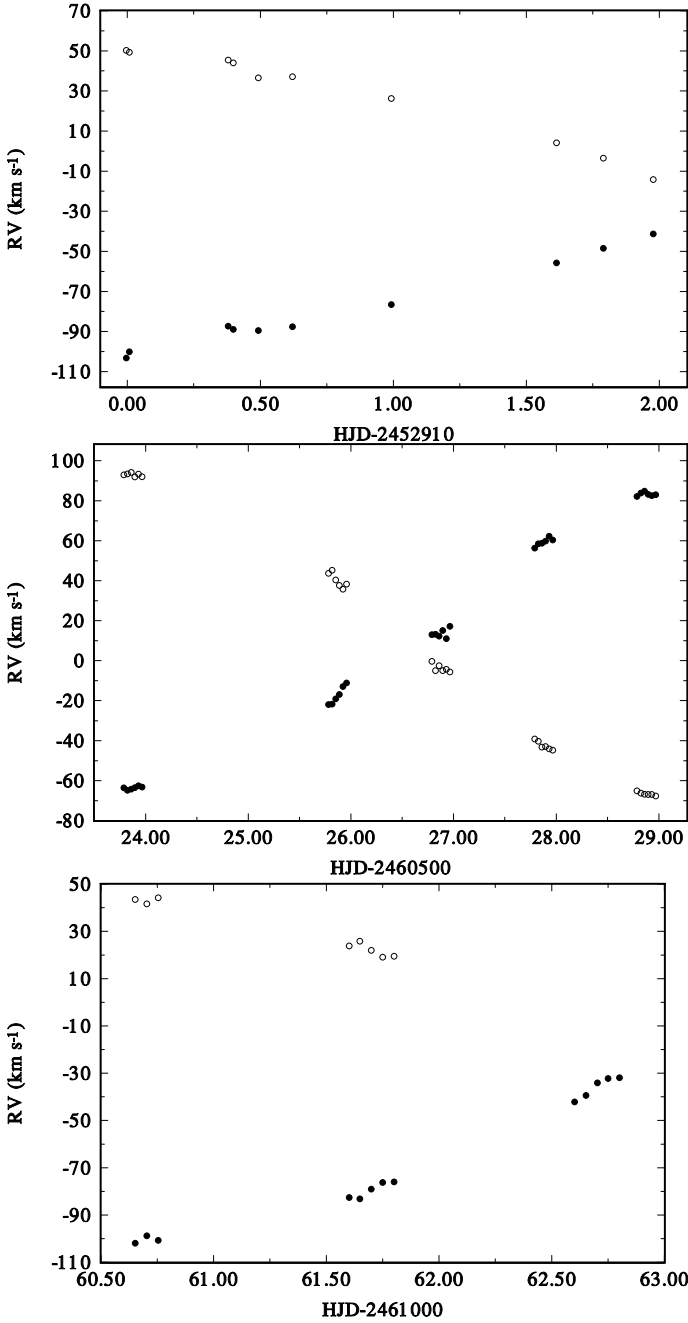


Fig. 3. A comparison of the RVs of the two narrow components of the Mg II 4481.228 Å line for three available time segments. The RVs of the primary and secondary are shown by black dots and open circles, respectively.

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.

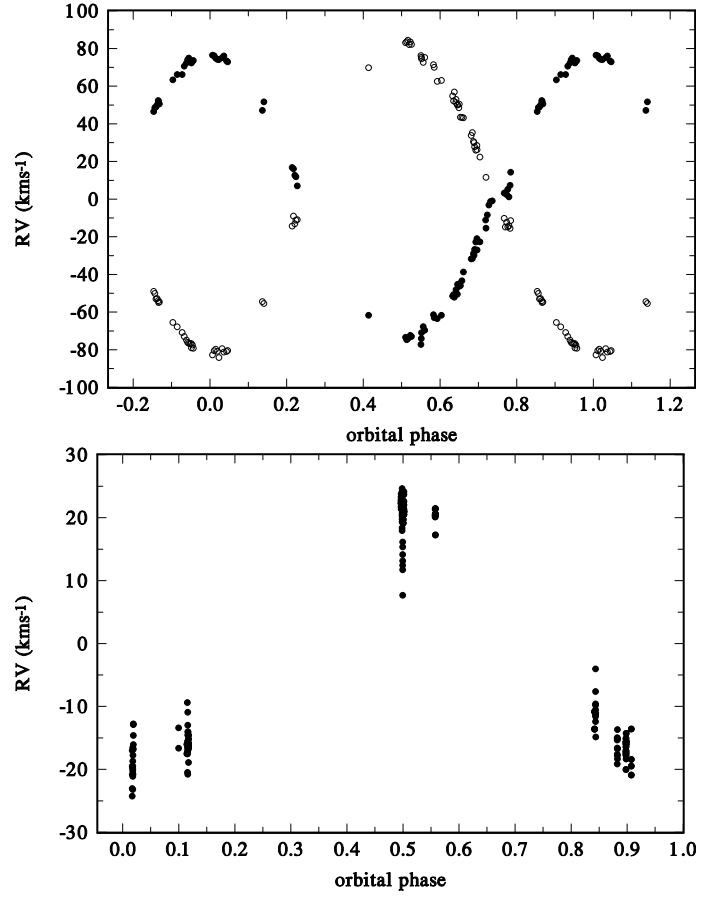


Fig. 4. Top: RV curves of the narrow Mg II lines for the period of 11ᵒ066043(31) based on a *FOTEL* solution for RVs measured in *reSPEFO*. Bottom: RV curve of the short-period binary around the centre of mass of the 1031ᵒ55 binary based on the same RVs.

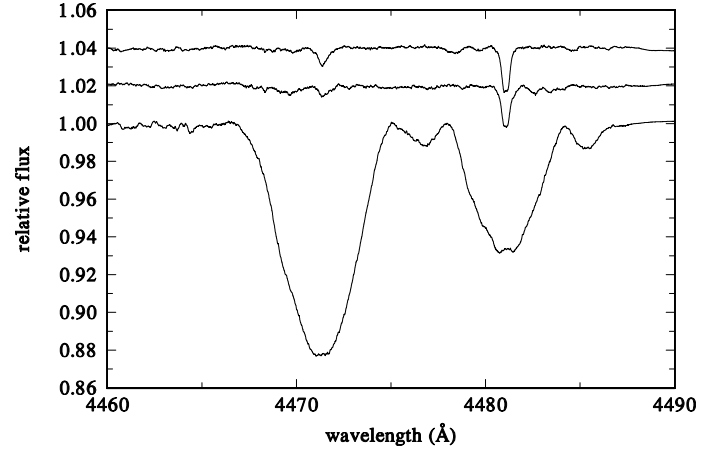


Fig. 5. The disentangled line profiles of the He I 4471 Å, and Mg II 4481 Å line for the three components of the triple system. All profiles are normalised to the joint continuum of the whole system and the profiles of the primary and secondary of the 11ᵒ66 subsystem were shifted for 0.04, and 0.02, respectively, in relative flux.

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 1031ᵒ55 binary system using Bayesian inference. Videla et al. (2022) estimated the mass of the Be pri-

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
$T_{RVmax,1}$ (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 _⊙)	2.434	2.506
$m_2 \sin^3 i$ (M _⊙)	2.264	2.425
$a \sin i$ (R _⊙)	36.24	36.83
No. of RVs (prim./sec.)	85/80	137
rms (km s ⁻¹)	2.76	–

mary as (5.62 ± 1.19) M_⊙ while Anguita-Aguero et al. (2023) derived masses as 5.77 and 4.66 M_⊙, 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_⊙, and 3.26 ms, therefore the total mass of the inner binary comes as 6.63 M_⊙. From the solution for the outer system, we obtain the total mass of the inner binary as 6.73 M_⊙, the mass of the distant Be component being 6.07 M_⊙. 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 classification. 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 H α 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 H α , 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 men-

tion 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^d1466 orbit, which revolve in a 145^d15 orbit with a rapidly rotating absorption-line B star. *o* And (HD 217675) consists of two sharp-lined stars in a 33^d0 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^d76 orbit, which revolve in a 7160 d orbit with a Be star. Finally, V1371 Tau = HD 36665 is a 33^d62 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 H α emission, absent in some epochs.

Acknowledgements. We gratefully acknowledge the use of the latest publicly available versions of the programs `FOTEL` and `KOREL` written by P. Hadrava. We thank Marek Skarka who obtained two of the OND OES spectra in service mode for us. Collection of the spectra was supported by the grants 205/06/0304, 205/08/H005, P209/10/0715, and GA15-02112S of the Czech Science Foundation. This work has made use of data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC; <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. We also used some echelle spectra of the BeSS database, operated at LESIA, Observatoire de Meudon, France: <http://basebe.obspm.fr>. Finally, we acknowledge the use of the electronic database from the CDS, Strasbourg, and the electronic bibliography maintained by the NASA/ADS system.

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

Program `reSPEFO`, written by Adam Harmanec in Java, is a replacement of the program `SPEFO`, written in Pascal by the late Jiří Horn (Horn et al. 1996). The program can run under different platforms (Unix, Windows, MacOS) and provides a wide range of operations. In principle, it uses 1-D spectra created by standard pipelines of individual observatories. For the majority of observatories, the spectra in 1-D frames are already pairs of wavelength and relative flux. The current version 2 of `reSPEFO` has several distinct regimes to treat the spectra. Besides the spectra recorded in the standard FITS format, it can treat spectra from the CHIRON echelle spectrograph from CTIO, spectra from the BeSS database, FEROS echelle spectra, spectra from the Hercules echelle spectrograph, and also the spectra from the DAO, for which it can also derive the wavelength scale from the measurements of the comparison ThAr or FeAr spectra. It is also able to import the spectra reduced earlier with the original `SPEFO` program. Normally, the spectra are imported to `reSPEFO` from standard FITS files but the program can also read plain ASCII files recorded as pairs wavelength - relative flux.

The usual flow of consecutive steps of the reduction is to define the project, import the spectra, rectify them, clean them from cosmics and flaws that were not removed by standard observatory pipelines, and measure RVs and spectrophotometric quantities of selected spectral lines. The tracing paper method of RV measurement allows settings on different parts of more complicated line profiles on the 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 ensure additional small corrections of the zero point of the wavelength scale and bringing the spectra from different instruments into one joint wavelength scale. The tracing paper method is illustrated in the 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).

The version 2 of the program, together with a detailed documentation and manual to its use can be downloaded at <https://astro.troja.mff.cuni.cz/projects/respefo>, separately for Unix, Windows, and MacOS operating systems.