

Properties and nature of Be stars[★]

27. Orbital and recent long-term variations of the Pleiades Be star Pleione = BU Tauri

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ABSTRACT

Radial-velocity variations of the H α emission measured on the steep wings of the H α line, prewhitened for the long-time changes, vary periodically with a period of $218^d.025 \pm 0^d.022$, confirming the suspected binary nature of the bright Be star BU Tau, a member of the Pleiades cluster. The orbit seems to have a high eccentricity over 0.7, but we also briefly discuss the possibility that the true orbit is circular and that the eccentricity is spurious owing to the phase-dependent effects of the circumstellar matter. The projected angular separation of the spectroscopic orbit is large enough to allow the detection of the binary with large optical interferometers, provided the magnitude difference primary – secondary is not too large. Since our data cover the onset of a new shell phase up to development of a metallic shell spectrum, we also briefly discuss the recent long-term changes. We confirm the formation of a new envelope, coexisting with the previous one, at the onset of the new shell phase. We find that the full width at half maximum of the H α profile has been decreasing with time for both envelopes. In this connection, we briefly discuss Hirata's hypothesis of precessing gaseous disk and possible alternative scenarios of the observed long-term changes.

Key words. stars: early-type – binaries: close – stars: emission-line, Be – stars: individual: BU Tau

1. Introduction

Pleione (BU Tau, 28 Tau, HD 23862) is a well-known Be star and a member of the Pleiades cluster. It underwent several phase transitions between B, Be, and Be shell phases, accompanied by pronounced light variations; see, e.g. Gulliver (1977), Sharov & Lyuty (1976), Iliev et al. (1988), Sharov & Lyutyj (1992), Hirata & Kogure (1976), Hirata & Kogure (1977), Hirata (1995), Doazan et al. (1988), Iliev et al. (2007), and Tanaka et al. (2007).

There is a rather complicated history of attempts to study the radial-velocity (RV hereafter) variations of this star. Struve & Swings (1943) measured RVs on the photographic spectra taken in the years 1938–1943 and tentatively concluded that the RV of BU Tau varies with a possible period of 142 days or – less likely – 106 days. Merrill (1952) studied RVs from 1941 to 1951 and found clear long-term variations with some overlapping changes on a shorter time scale. Gulliver (1977) analyzed a large collection of digitized photographic spectra from 1938–1954 and from 1969–1975 and concluded that there are no significant RV changes. Ballereau et al. (1988) carried out an analysis of a homogeneous series of Haute Provence high-dispersion

photographic spectra from 1978–1987 and once more concluded that the shell RVs vary with periods of 136.0 and 106.7 days. Katahira et al. (1996a,b) analyzed shell RVs from the two consecutive shell phases separated some 34 years, using published as well as new RVs and concluded that BU Tau is a spectroscopic binary with an orbital period of $218^d.0$, semi-amplitude of 5.9 km s^{-1} , and a large orbital eccentricity of 0.60. However, Rivinius et al. (2006) – analyzing a series of electronic spectra – were unable to confirm the 218-d period and concluded that BU Tau is not a spectroscopic binary. Hirata (2007) analyzed a long series of polarimetric observations and presented a model of a slowly precessing disk to explain the long-term B – Be – Be shell phase transition. He argued that the disk precession is caused by the attractive force of the secondary in the 218-d binary. Harmanec (1982) compiled the majority of at that time available RVs of BU Tau and averaged them over about 100 days. This resulted in a smooth RV curve with a period of about 13 000 days (35.6 years), in phase with the recorded shell episodes. Harmanec (1982) speculated that BU Tau could be a long-periodic binary with shell phases occurring always at the same orbital phases. A more distant companion with an angular distance of $0''.22$ was indeed discovered from speckle interferometry by McAlister et al. (1989). Gies et al. (1990) studied a sequence of low-dispersion H α spectra of BU Tau taken with a sampling rate of 7 ms during a lunar occultation on 1987 March 6. They detected an asymmetry of the envelope in

[★] Based on new spectral and photometric observations from the following observatories: Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, Haute Provence, IGeoE-Lisbon, Astronomical Institute AS CR Ondřejov, and Rozhen.

Table 1. Journal of new spectroscopic observations for BU Tau.

Station source	Time interval (HJD–2400000)	No. of obs.	Wavelength region (Å)
Ondřejov	49 581–54 872	101	6200–6800
DAO	49 786–54 912	26	6150–6700
OHP	51 569–52 664	21	6200–6700
Rozhen	52 710–54 108	23	6520–6610
Lisboa	54 874–54 881	4	6520–6600

agreement with the observed long-term V/R changes. They speculated that the speckle-interferometric component could have an eccentric orbit and that the recurrent shell phases could be caused by its periastron passages. Luthardt & Menchenkova (1994) compiled RVs from the years 1938–1990 and confirmed a period of 12 450–12 860 days. They advocated an eccentric orbit and mass transfer resulting in a release of a new shell during periastron passages, but the gaps in their RV curve do not allow one to conclude that the orbit has a high eccentricity. Finally, using the technique of adaptive optics photometry and astrometry, Roberts et al. (2007) report discovery of a new companion to BU Tau at a separation of $4''.66$ with a spectral type M5. They also confirm a companion at $0''.24$ and discuss other suggested companions.

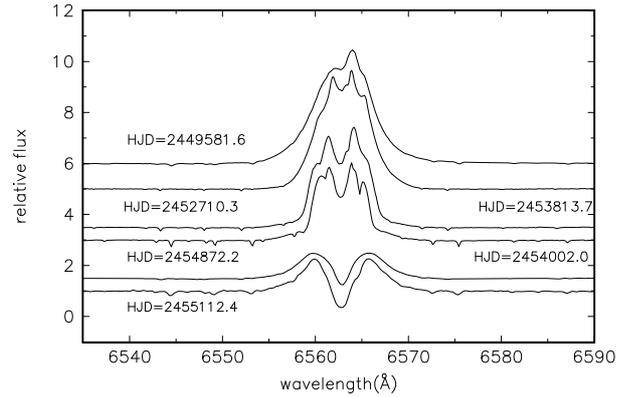
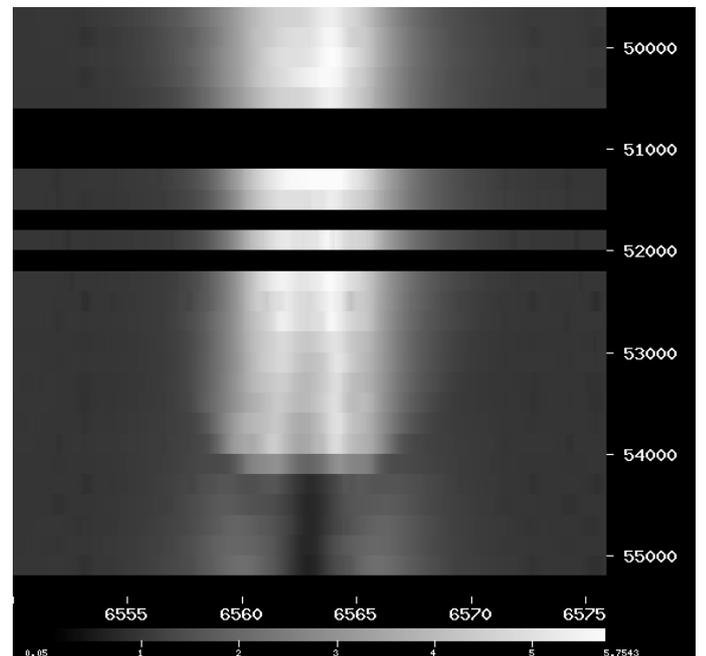
We succeeded in collecting a rich series of electronic spectra at several observatories, covering many cycles of the suspected 218-d period. The main goal of this study is, therefore, to resolve the issue of whether BU Tau is a spectroscopic binary. Katahira et al. (1996a,b) based their orbit on the RV measurements of shell lines that may be affected by possible asymmetries in the circumstellar matter. Moreover, their RV curve has a rather small amplitude and is based on a collection of heterogeneous data. It naturally shows a rather large scatter around the mean curve. The spectra at our disposal all cover the red spectral region near $H\alpha$. They were taken over the time interval when the star had fairly strong $H\alpha$ emission. Therefore, our study is based on the RV measurements of the steep wings of the emission, which is a procedure that turned out to be successful for detecting the duplicity of several other Be stars (Božić et al. 1995; Koubský et al. 2000; Harmanec et al. 2000; Miroshnichenko et al. 2001, 2002).

Since very pronounced long-term spectral variations occurred over the time interval covered by our spectra, we also briefly describe these changes and discuss them, especially in relation to the model put forward by Hirata (2007).

2. Spectroscopic observations and their reductions

The red spectra at our disposal were obtained at five observatories and their overview is in Table 1. Details about the instruments and data reduction can be found in Appendix A where also Table A.1 with our RV measurements of the steep wings of the $H\alpha$ emission and of the $H\alpha$ absorption core is provided. The latter was measured for comparison with the RVs collected and analyzed by Katahira et al. (1996b), but only for those spectra where the absorption was clearly visible.

Over the interval of the more than 5000 days covered by our observations, the strength of the $H\alpha$ emission gradually declined and the shape of the $H\alpha$ profile underwent notable changes.

**Fig. 1.** Comparison of $H\alpha$ profiles from different stages of the long-term changes.**Fig. 2.** A complete series of our $H\alpha$ profiles in a gray representation (only a few saturated or underexposed spectra were omitted). Abscissa shows the wavelength scale in Å, while the time on ordinate is shown in JD–2400000. Each horizontal strip represents an average of spectra secured within 200 days, and dark horizontal belts correspond to time intervals from which no spectra are available. At the bottom, there is a scale showing the correspondence between the flux level in the units of continuum and the gray scale.

Typical examples for several distinct stages are shown in Fig. 1, and the whole development of a new shell and metallic-shell phase is shown as a gray-scale representation of all usable $H\alpha$ profiles in Fig. 2.

The fading of the $H\alpha$ emission was accompanied by a light decrease in the J , H , K , and L IR photometric bands that started around JD 2451500 (Taranova et al. 2008). This clearly corresponds to the gradual development of the hydrogen shell spectrum according to our spectra – see also Tanaka et al. (2007). Emission has been slowly fading from JD 2453000 until now, when its peak intensity represents only about 30% of the intensity seen in our earliest spectra. During the transition from a single-peaked to double-peaked emission, there is some time interval when the $H\alpha$ profile has a characteristic wine-bottle shape. The occasional presence of additional absorption components

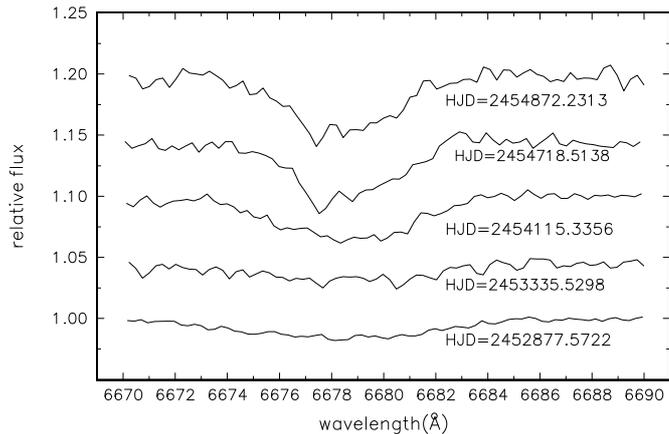


Fig. 3. Selected He I 6678 Å line profiles, ordered in time, with corresponding HJDs.

has been already noted by [Iliev et al. \(2007\)](#) or [Tanaka et al. \(2007\)](#) and is typical of all recorded shell phases of BU Tau. Besides the occasional presence of one or more additional absorptions, extended red emission wings are seen on some H α profiles. This makes the emission wings asymmetric and hard to measure for RV. We also note that all double-peaked profiles recorded prior to about JD 24540000 always have a red peak stronger than the violet one. Figure 2 shows that the *width* of the H α emission has remained more or less constant over the whole time interval covered by our observations. The same figure also shows that the metallic shell phase appeared rather abruptly.

Figure 3 shows the gradual development of the He I 6678 Å line profile. It illustrates well how shallow the line is at the beginning of a new shell phase. A very interesting finding is that, even for the B8 star, a presumably photospheric He I line can develop a shell component. The profile clearly gets stronger and narrower as the hydrogen shell line gets deeper. The additional absorption at the blue wing of the line seen on more recent spectra is the Fe II 6677.305 Å shell line.

3. Radial-velocity changes

Figures 4 and 5 are the time plots of the measured RVs vs. time for the H α emission wings and the absorption core. In the later, we also included all shell RVs used and published by [Katahira et al. \(1996b\)](#) and [Rivinius et al. \(2006\)](#). One can see systematic RV changes on at least two distinct time scales: a smooth change on a longer time scale and overlapping more rapid changes, especially the occasional steep decreases in RV.

Considering the uncertainties in accurate RV measurements combined with the fact that the full amplitude of the changes is low, it was deemed useful to convince readers that the RV changes are not only a result of changing asymmetry of the profiles, but they also represent a real shift of the whole line. To this end, we compare in Fig. 6 two pairs of the H α line profiles obtained near the local RV extrema. The upper pair comes from the beginning of a new shell phase and the bottom one from a more recent time when a weaker emission and deeper shell cores are present in the profiles (note a large difference in the flux scale of the two plots). The RV shift of the whole emission and absorption core is seen beyond any doubt. We, therefore, conclude that our RV measurements reflect *real RV variations* of BU Tau.

In accordance with [Katahira et al. \(1996b\)](#), we find that the evolution of the emission episode is accompanied by long-term

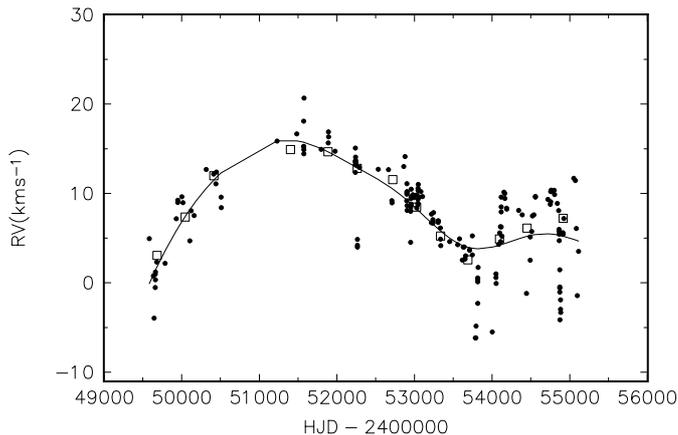


Fig. 4. Measured RVs of the H α emission wings plotted vs. time. Prewhitening for the long-term changes, carried out with the help of the program HEC13, is shown by a line. Empty squares show the alternate way to remove long-term RV changes via individual γ velocities for subsets spanning no more than a year. See the text for details.

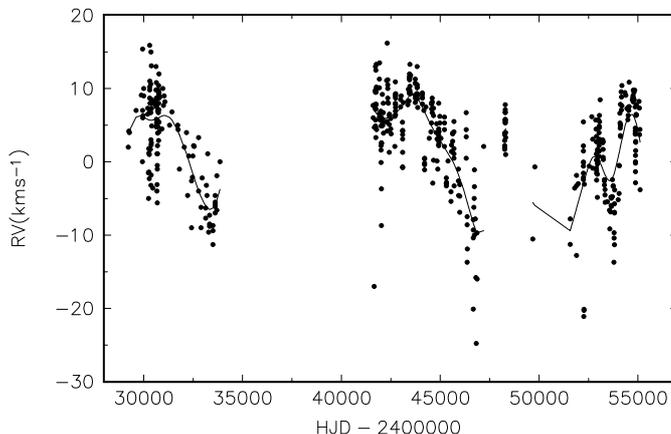


Fig. 5. Measured H α absorption core plotted vs. time. We also included the RV measurements of shell lines by [Katahira et al. \(1996b\)](#) and [Rivinius et al. \(2006\)](#) to this plot. Prewhitening for the long-term changes, carried out with the help of the program HEC13, is shown by a line. See the text for details.

RV changes that need to be removed prior to a search for possible periodic RV changes. To also make this step as objective as possible, we used two different procedures.

One is that we smoothed the long-term changes using the program HEC13, written by PH and based on a smoothing technique developed by [Vondrák \(1969, 1977\)](#)¹. For both emission and absorption RVs, optimal smoothings were obtained for the smoothing parameter $\varepsilon = 10^{-16}$ fitted through 200-d normals. (Inspecting the time plots of RVs, we identified ~ 200 days as a time scale on which more rapid changes were observed, and this was the reason for the choice of 200-d normals. We have verified, however, that the result of smoothing is not sensitive to the particular choice of the averaging interval for the smoothing within reasonable limits). The RV residuals from the smoothing were subjected to a period search based on the [Stellingwerf \(1978\)](#) PDM technique over a period range from 5000 down to 0.05 d. The dominant frequency found in both searches was

¹ The program HEC13 with brief instructions how to use it is available to interested users at <http://astro.troja.mff.cuni.cz/ftp/hec/HEC13>

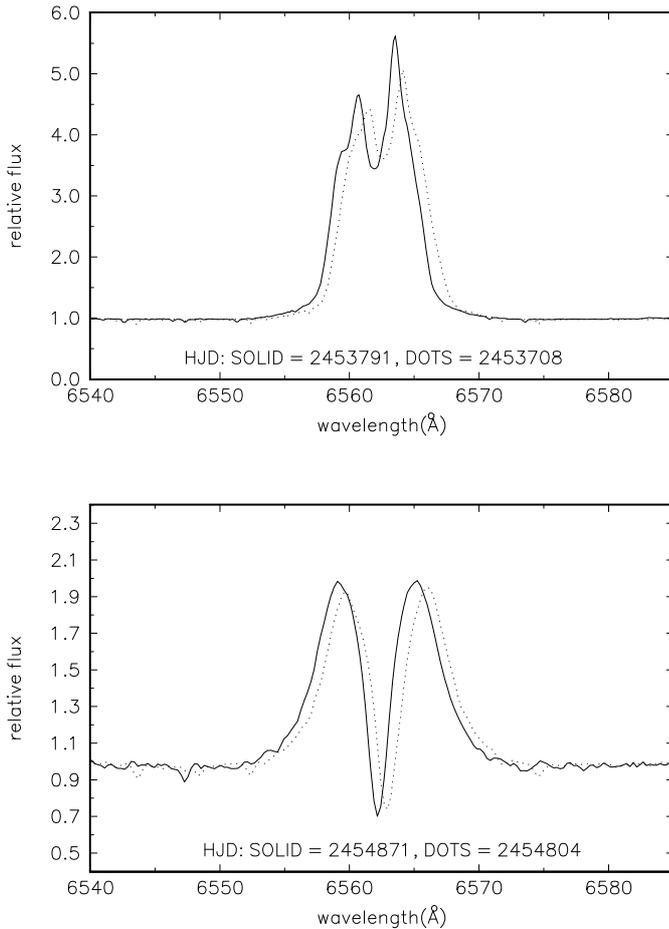


Fig. 6. A comparison of two pairs of the $H\alpha$ line profiles from the locally recorded velocity extrema (HJDs of the profiles are indicated).

$0.004587 \text{ c d}^{-1}$ and its integer submultiples. The one-day aliases were largely suppressed thanks to having data from observatories, that have a large difference in their local time, producing much shallower minima in the θ statistics ($\sim 0.75\text{--}0.82$) and scattered phase diagrams. To make the diagrams readable, we show the corresponding θ statistics in Fig. 7 for the emission (top) and absorption (bottom) RVs only for a limited frequency interval down to 0.1 c d^{-1} . The result seems to confirm the 218-d periodicity discovered by [Katahira et al. \(1996b\)](#).

As another demonstration that the 218-d period is real, we show phase plots in Fig. 8 for the original RVs (without prewhitening for the long-term changes) for several subsets of data covering time intervals no longer than one year. Clearly similar RV curves, with sharp minima, rather flat maxima, and a mutual phase coherence, are seen in all cases. The first subset is based solely on the RVs from the Ondřejov spectra secured with Reticon detector, which were already investigated by [Rivinius et al. \(2006\)](#).

4. BU Tau as a spectroscopic binary

Our findings, and especially the fact that the $H\alpha$ Balmer emission line moves in RV as a whole in spite of very large secular changes of its strength, indicate that BU Tau is indeed a single-line spectroscopic binary that moves in a highly eccentric orbit. We therefore used the program SPEL (written by the late Dr. Jiří Horn and never published) to derive the orbital elements. For comparison with [Katahira et al. \(1996b\)](#), we first

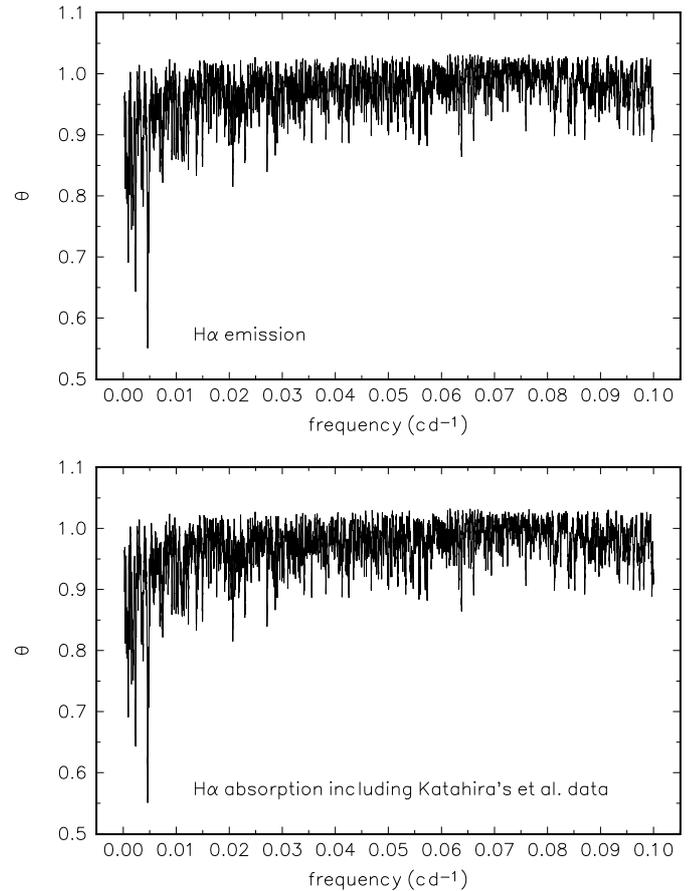


Fig. 7. [Stellingwerf \(1978\)](#) PDM θ statistics for all emission-wing RVs (top) and shell absorption-core RVs including [Katahira et al. \(1996b\)](#). The dominant frequency of $0.004587 \text{ c d}^{-1}$ corresponds to the 218-d period.

derived orbital elements for Balmer *absorption* RVs, using the data from their study, RVs published by [Rivinius et al. \(2006\)](#), and our own $H\alpha$ absorption RVs, prewhitened with HEC13 as shown in Fig. 5. The resulting orbital elements are given as solution 1 in Table 2 and the corresponding phase plots are shown in Fig. 9. For more clarity, we plot there the photographic RVs, Heros RVs from [Rivinius et al. \(2006\)](#), and our $H\alpha$ absorption RVs in three separate panels. Although [Rivinius et al. \(2006\)](#) write that the suspected binary nature of BU Tau could not be confirmed on the basis of their data, their RVs also nicely follow the 218-d period. This constitutes yet another support for the reality of this period. Our solution 1 agrees well with the result of [Katahira et al. \(1996b\)](#).

Next, we analyzed the emission RVs that we consider as most realistically describing the true orbital motion. To see how sensitive the result is to the manner of prewhitening the data we derived the elements not only for the RVs prewhitened with the help of HEC13 (see above) but also from the original data. To this end, we divided the data into subsets spanning no more than one year and allowed SPEL to derive separate γ velocities for individual data subsets. The results are summarized in Table 2, and the corresponding RV curves compared in Fig. 10.

The inspection of Fig. 10 shows that even the $H\alpha$ emission-wing RVs are indeed indicative of an orbit with high eccentricity but that there is also an alternative possibility that the observed deep RV minimum could be a consequence of some unspecified effect of circumstellar matter, reminiscent of “an inverse

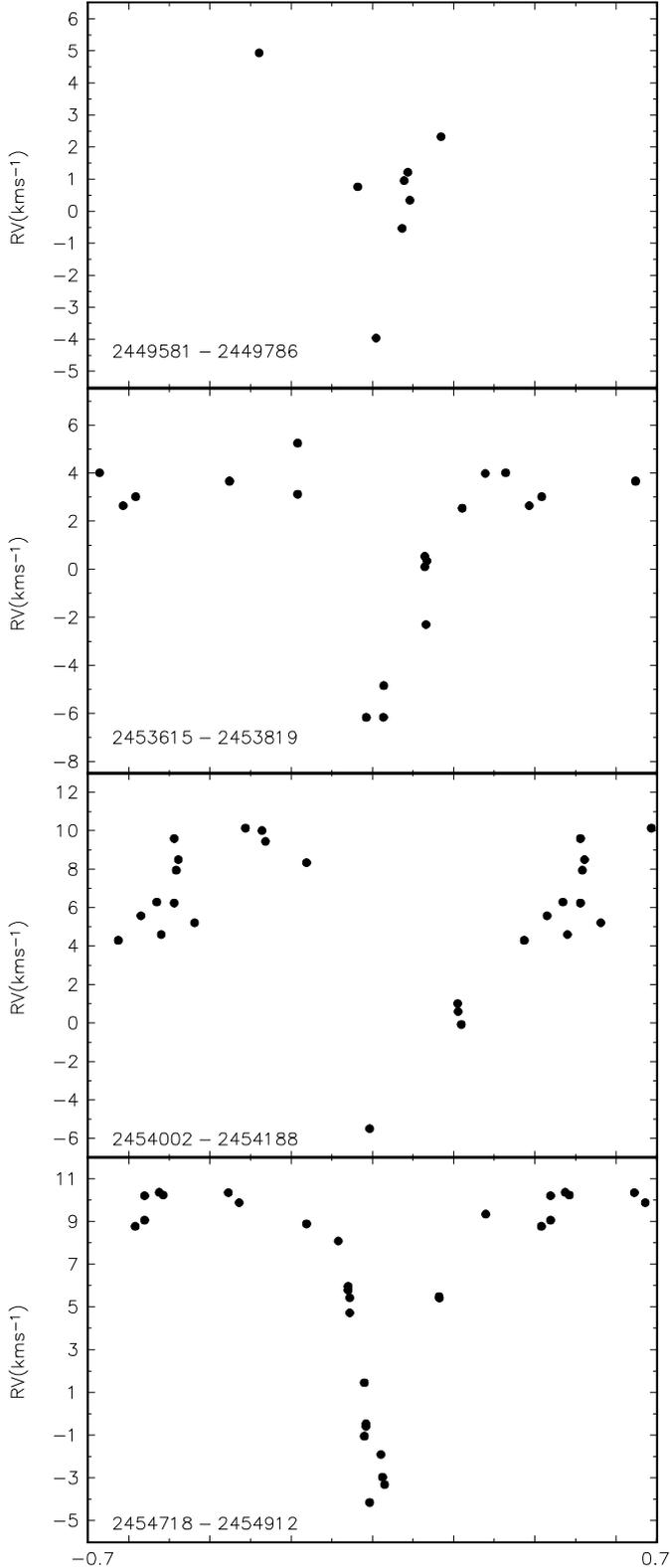


Fig. 8. Orbital RV curves of the $H\alpha$ emission shown for subsets of data spanning less than a year. For all plots, period $218^{\text{d}}.053$ was used, with phase zero at HJD 2452041.11, which corresponds to the RV minimum (see Table 2).

rotational or Rossiter effect”. In this case, the true orbit could essentially be circular. To this end, we derived yet another, a circular-orbit solution for the $H\alpha$ emission RVs prewhitened for long-term changes via HEC13, omitting all RVs from the phase interval around phase zero with the most negative RVs.

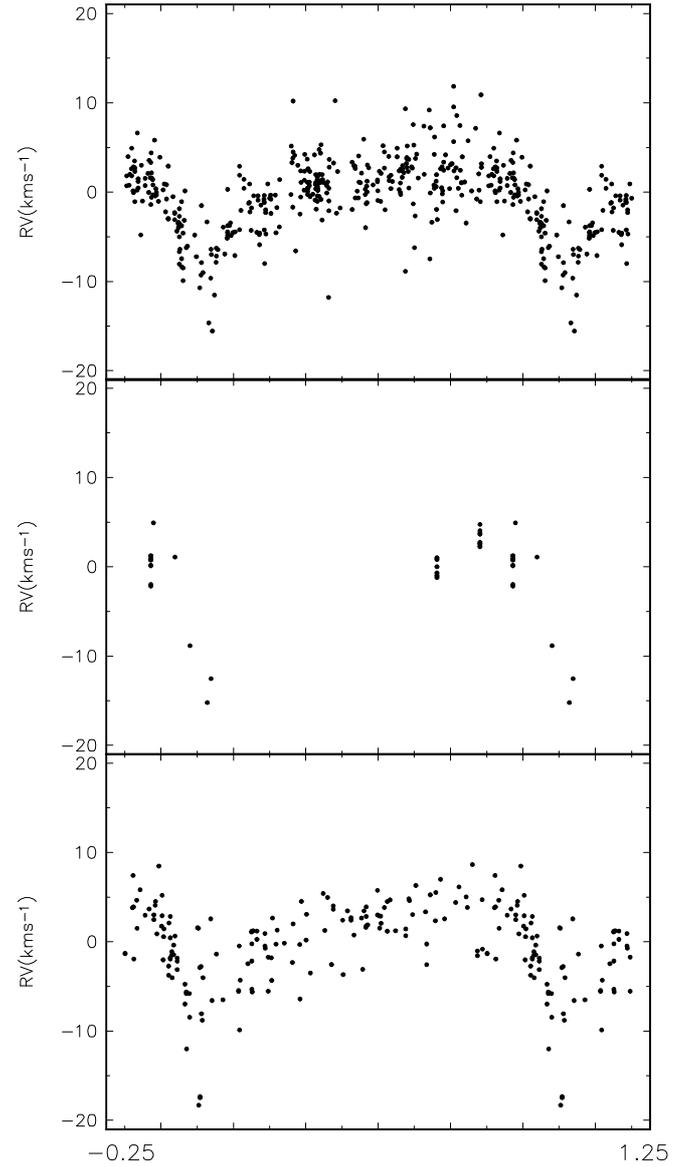


Fig. 9. *Top:* the phase plots of all available Balmer absorption RVs, prewhitened for the long-term RV variations with HEC13 (as shown in Fig. 5). Elements from solution 1 of Table 2 were used, with phase zero at minimum RV. For clarity, we show three different data subsets separately: *Top panel:* photographic RVs from [Katahira et al. \(1996b\)](#); *Central panel:* RVs from electronic Heros spectra published by [Rivinius et al. \(2006\)](#); *Bottom panel:* RVs from electronic spectra used in this paper.

This resulted in the following elements: $P = 218^{\text{d}}.34 \pm 0.62$, $T_{\text{super.c.}} = \text{HJD } 2452009.9 \pm 4.8$, $K_1 = 1.72 \pm 0.21 \text{ km s}^{-1}$.

Using the elliptical-orbit elements for the $H\alpha$ emission RVs from Table 2, we estimated the basic properties of the binary from the mass function $f(m) = 0.00165 M_{\odot}$ for several plausible orbital inclinations, assuming a normal mass of the primary corresponding to its spectral type after [Harmanec \(1988\)](#) to be $M_1 = 2.9 M_{\odot}$.

The results of Table 3 show that the binary properties, especially the low mass ratio, are quite similar to other binaries discovered so far with Be primaries. For the estimates, we only considered higher orbital inclinations since BU Tau is one of the cases of an inverse correlation between the brightness and

Table 2. Several sets of orbital elements.

Solution:	1	2	3
orbital element	Old & new H α abs.	H α emis. wings	H α emis. wings
P (d)	218.023 \pm 0.023	218.099 \pm 0.050	218.053 \pm 0.053
$T_{\text{periastr.}}$ (d)	40040.4 \pm 1.6	52039.34 \pm 0.69	52039.73 \pm 0.73
$T_{\text{super.c.}}$ (d)	40032.3	52035.50	52034.79
$T_{\text{min. RV}}$ (d)	40044.5	52040.64	52041.11
e	0.596 \pm 0.035	0.774 \pm 0.028	0.745 \pm 0.026
ω ($^{\circ}$)	147.7 \pm 4.5	154.2 \pm 4.0	157.3 \pm 3.5
K_1 (km s $^{-1}$)	5.41 \pm 0.35	6.30 \pm 0.63	6.39 \pm 0.46
γ (km s $^{-1}$)	-0.15 \pm 0.1	0.35 \pm 0.15	-
rms (km s $^{-1}$)	3.21	1.93	1.58

Notes. Solution 1... Katahira, Rivinius and this paper, prewhitened with HEC13; Solution 2... New emission-line RVs prewhitened with HEC13; Solution 3... New emission-line RVs with allowance for locally derived γ velocities.

Table 3. Basic physical properties of BU Tau as a single-line binary based on elliptical-orbit solution for the H α emission RVs – (cf. Table 2).

i ($^{\circ}$)	M_2/M_1	M_2 (M_{\odot})	A (R_{\odot})	$A_{\text{peri.}}$ (R_{\odot})
90	0.0876	0.254	223.5	53.0
70	0.0936	0.272	223.9	53.1
50	0.1164	0.338	225.5	53.4

Notes. The estimates are derived assuming the primary mass of $M_1 = 2.9 M_{\odot}$, A and $A_{\text{peri.}}$ denote the semi-major axis and the binary separation at periastron, respectively.

emission-line strength, which indicates that we see the system roughly equator-on – cf, e.g., Harmanec (1983).

If we adopt the distance to Pleiades $d = 138$ pc after Groenewegen et al. (2007), we estimate that the projected angular distance of the binary components should be $\theta = 0''.0075$, dropping down to $0''.0018$ at periastron. This angular separation is certainly within reach of existing large optical interferometers. The only problem is the luminosity ratio primary/secondary. If the secondary would be a normal late M dwarf corresponding to its mass, it would be fainter in the visual region by more than 10 mag and the only chance to search for it would be in the far IR region, where, however, the IR excess from the Be envelope can complicate the detection. However – if it were a hot subdwarf, similar to the one found for another Be binary φ Per by Gies et al. (1998) – it might be observable in the optical region since the absolute visual magnitude of BU Tau is fainter for some 2 mag than for the φ Per B0.5e primary. Finally, a cool Roche-lobe filling secondary seems improbable since it would probably produce binary eclipses.

In any case, attempts to resolve the 218-d binary system with some large interferometer are very desirable since a visual orbit would help not only to estimate the true orbital inclination but also to clarify whether the orbit has a high eccentricity or is nearly circular.

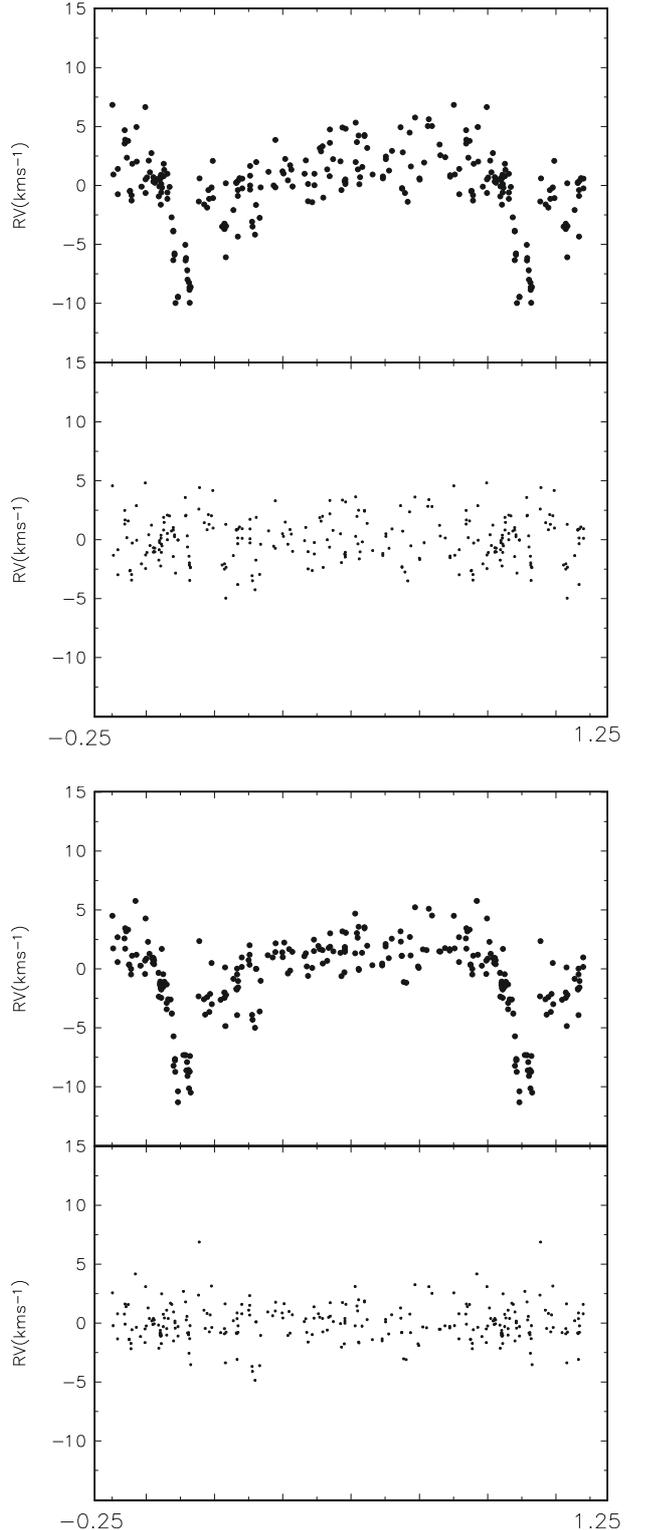


Fig. 10. The orbital RV curves of BU Tau based on the H α emission RVs plotted for the solutions 2 and 3 of Table 2. Phase zero corresponds to the respective epoch of minimum RV and the O-C deviations from the solutions are shown by small circles in separate panels. *Top two panels:* RVs prewhitened via HEC13 (solution 2). *Two bottom panels:* original RVs minus locally derived systemic γ RVs (solution 3). See the text for details.

5. Comments on Hirata's model

We have postponed a detailed study of the long-term changes for a later work (Iliev et al. in prep.), but we wish to comment

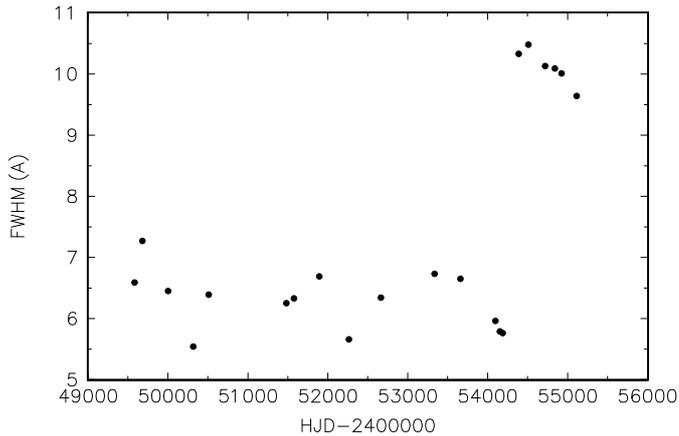


Fig. 11. A time development of the FWHM (in Å) of the H α emission. The rapid increase is caused by the formation and a fast strengthening of another double emission due to a newly formed envelope.

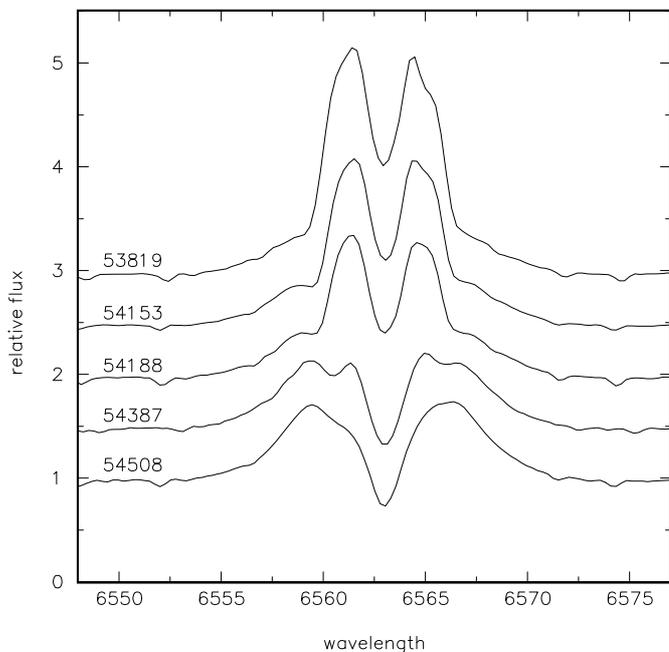


Fig. 12. A series of the H α profiles over the time interval of the formation of a new shell. The HJDs-2400000 of individual spectra are shown and the time runs *from the top to the bottom*. One can see how the new broad emission gradually rises in intensity and how its blending with the decaying previous double (but narrower) emission creates a profile with four emission peaks for some time. Then the new emission gets so strong that it merges with the original one.

briefly on the hypothesis put forward recently by Hirata (2007). He obtained systematic spectroscopy and polarimetry of BU Tau from 1974 to 2003 and finds a change in the polarization angle from about 60° to 130° over that time interval. He interprets this change as evidence of the precession of the circumstellar disk that is responsible for the observed H α emission. He further argues that also the change in the H α profiles from a weak double emission with a strong central absorption core to a strong

emission with a wine-bottle shape indicates that the disk was first seen more or less edge-on and later more face-on. Tanaka et al. (2007) studied the spectra of BU Tau from Nov. 2005 until April 2007, which cover the period of a formation of the new shell phase. They argue that a new disk was formed in the equatorial plane of the B star while the old disk was decaying but still present. According to their interpretation, the old disk was precessing in space as suggested by Hirata (2007). Our spectra cover a much longer time interval, including the one studied by Tanaka et al. (2007), and as Fig. 2 shows, the change of the H α profile was smooth. We thus measured the full width at half maximum (FWHM) of a representative selection of our H α emission-line profiles and the variation in FWHM with time is shown in Fig. 11. It was already demonstrated by Struve (1931) in his first model of Be stars as rapidly rotating objects that there is a clear correlation between the width of presumably photospheric He I lines and the width of the Balmer emission lines, which is preserved during the long-term changes. This correlation has been confirmed by a number of later studies – see, e.g., Fig. 5 of Slettebak (1979). One would therefore expect that, if the appearance of a new shell phase of BU Tau is primarily a consequence of a geometrical effect, namely a gradual precession of a flat disk that becomes to be seen equator-on, the FWHM should gradually grow as the new shell phase is approaching. In contrast, Fig. 11 shows that the FWHM of H α was *slowly decreasing* during the last 15 years. Its dramatic increase is related to the formation of a new envelope, which our spectra clearly confirm – see Fig. 12. The apparent discontinuous increase in the FWHM occurs at the moment when the strength of the broader emission from the new envelope rises to a half of the peak intensity of the original emission. All this indicates that the observed variations are primarily due to physical changes in the circumstellar matter and cannot be reduced to a simple geometrical cause – a precession of the original gaseous disk. There has been a rather widespread tendency in recent years to interpret the presence of shell absorption lines as evidence of an equator-on view, since many investigators are picturing the Be star disk as a flat structure located at the stellar equator with a (rather small) opening angle (Waters 1986; Bjorkman & Cassinelli 1993; Hanuschik 1995, 1996). It is true that this model can lead to theoretical Balmer profiles similar to the observed ones, see, e.g., the 3D radiative line transfer models by Hummel (1994). One should be aware, however, that there is no unique proof of a specific geometry on the level of various simplifications of current models. For instance, Höflich (1987, 1988) succeeded in modeling several Balmer emission-line profiles of particular Be stars with his model consisting of an NLTE atmosphere and a *spherical* envelope. It is then conceivable that strong shell lines could also develop in the spectrum of a Be star seen more or less pole-on in situations where a very extended *spheroidal envelope* forms around it. Similarly, it might be worth considering whether the asymmetry detected by the gradual change in the polarimetric angle is indeed caused by the precession of a flat disk or by some other effect, e.g. by a slowly revolving elongated (non-axisymmetric) disk.

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Appendix A: Overview of available spectroscopic observations

Here, we provide some details on the spectra used in this study and listed in Table 1 and on their reduction:

1. *Ondřejov spectra*: All 101 electronic spectrograms were obtained in the coudé focus of the 2.0-m reflector and have a linear dispersion of 17.2 \AA mm^{-1} and a 2-pixel resolution $12600 (11\text{--}12 \text{ km s}^{-1} \text{ per pixel})$. The first 35 spectra were taken with a Reticon 1872RF linear detector and cover a spectral region from 6300 to 6730 \AA . Complete reductions of these spectrograms were carried out by JN with the program SPEFO, written by the late Dr. J. Horn and further developed by Dr. P. Škoda and more recently by Mr. J. Krpata – see Horn et al. (1996) and Škoda (1996). The remaining spectra were secured with an SITE-5 800×2000 CCD detector and cover a slightly longer wavelength interval $6260\text{--}6760 \text{ \AA}$. Their initial reductions (bias subtraction, flatfielding, creation of 1-D images, and wavelength calibration) were carried out by MŠ in IRAF.
2. *DAO spectra*: These spectrograms were obtained in the coudé focus of the 1.22-m reflector of the Dominion Astrophysical Observatory by SY, who also carried out their initial reductions (bias subtraction, flatfielding, and creation of 1-D images). Their wavelength calibration was carried out by JN in SPEFO. The spectra were obtained with the 32121H spectrograph with the IS32R image slicer. The detectors were UBC-1 4096×200 CCD for data before May 2005 and SITE-4 4096×2048 CCD for data after May 2005. They cover a wavelength region from 6150 to 6750 \AA , have a linear dispersion of 10 \AA mm^{-1} and 2-pixel resolution of $21700 (\sim 7 \text{ km s}^{-1} \text{ per pixel})$.
3. *OHP spectra*: The public ELODIE archive of the Haute Provence Observatory (Moultaka et al. 2004) contains 30 spectra listed as BU Tau, but some of them are actually spectra of 27 Tau. We were able to recover 21 usable spectra. For the purpose of this study, we extracted, rectified, and measured only the red parts of these spectrograms.
4. *Rozhen spectra*: All 23 spectra from Rozhen observatory were obtained in the coudé spectrograph of the 2-m RCC telescope. A CCD camera Photometrics AT200 with SITE SI003AB 1024×1024 chip was used. The spectrograph was used in a configuration providing high-resolution spectra suitable for revealing fine details and the structure of the spectral lines. A Bausch & Lomb 632/22.3 grating was used in its 2nd order, giving a linear dispersion of 4.2 \AA/mm with 2-pixel resolution of $33\,000 (\sim 4.5 \text{ km s}^{-1} \text{ per pixel})$. Wavelength coverage is about 100 \AA around $H\alpha$. The initial reduction (bias subtraction, flatfielding, creation of 1-D images and wavelength calibration) was carried out by LI in MIDAS.
5. *Lisboa spectra*: these 4 CCD spectra were obtained with the IGeoE 0.356-m SC telescope working at F/11. The spectrograph is a Littrow LHIRESI with a 2400 grooves per mm grating and a spectral resolution of about 14,000. The initial

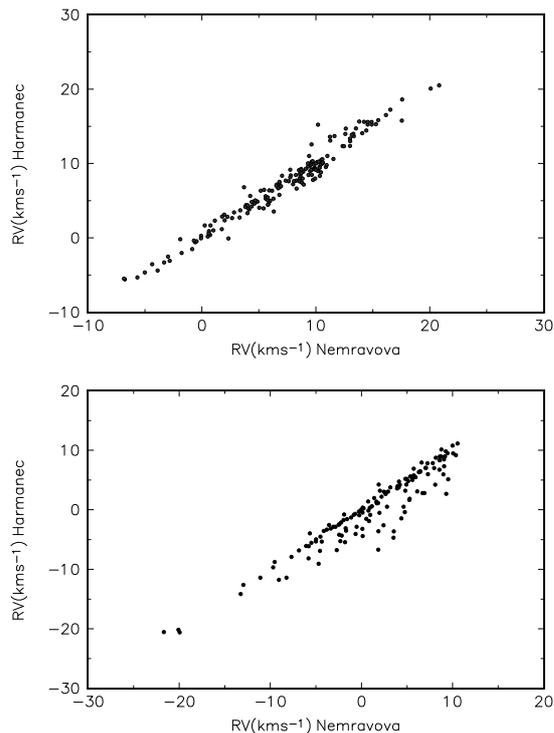


Fig. A.1. A comparison of independent RV measurements of the steep $H\alpha$ emission wings (*upper panel*) and shell core absorption (*bottom panel*).

reduction (bias subtraction, flatfielding, creation of 1-D images, and wavelength calibration) of the spectra was made by JR.

The rectification and removal of cospics and flaws of *all spectrograms* were carried out in a uniform way by JN in SPEFO. The program SPEFO was also used to RV measurements, based on a comparison of direct and flipped images of the spectral line profiles. Since we were searching for small RV variations and since the setting on the steep wings of the emission-line profiles was not always straightforward (see below), these RV measurements were carried out independently by JN and PH. Besides the settings on the steep wings of the $H\alpha$ emission, we also measured the $H\alpha$ absorption core on all spectra where such absorption was present to have a comparison with the results of Katahira et al. (1996b). We also tried to measure RV of the He I 6678 \AA absorption wings but due to weakness of this line and its possible structure, these measurements turned out to be useless so we did not use them. Following Horn et al. (1996), we also measured selected stronger and unblended telluric lines in all spectra and used them to a correction of the RV zero point. Thanks to that, the spectra from all observatories can be treated as coming from one instrument for all practical purposes.

A comparison of the two sets of independent RV measurements is shown in Fig. A.1. In general, the agreement is good. A formal regression between the measurements of PH and JN was derived. Its slope is 0.98 ± 0.01 for the emission and 0.94 ± 0.01 for the absorption. For the absorption line, it is conceivable that in specific cases one or the other measurer was confused by a telluric line blended with the stellar absorption core. For analysis, we used the mean RVs of the two independent measurements. All our RVs with the corresponding HJDs of their mid-exposures are provided in Table A.1.

Table A.1. Radial velocities of the H α emission wings and shell absorption core obtained via averaging the independent measurements by J. Nemravová and P. Harmanec; DAO = Dominion Astrophysical Observatory, Victoria; ROZ = Rozhen National Observatory; OND = Ondřejov Observatory; LIS = IGeoE-Lisbon; OHP = Haute Provence Observatory.

Time of obs. (HJD-2400000)	RV(H α em.) [km s $^{-1}$]	RV(H α abs.) [km s $^{-1}$]	Source	Time of obs. (HJD-2400000)	RV(H α em.) [km s $^{-1}$]	RV(H α abs.) [km s $^{-1}$]	Source
49581.5875	4.94	–	OND	52957.5296	8.80	–0.28	OND
49634.6281	0.76	–	OND	52978.2960	9.86	0.06	ROZ
49644.5439	–3.96	–	OND	52992.4704	9.53	5.72	OND
49658.4732	–0.54	–	OND	53027.3770	8.36	2.20	OND
49659.4898	0.95	–	OND	53029.2971	9.82	3.96	OND
49661.4455	1.21	–	OND	53042.2717	8.90	1.48	ROZ
49662.5208	0.34	–	OND	53042.2776	8.73	0.74	ROZ
49679.3450	2.32	–10.53	OND	53044.2905	10.57	4.86	ROZ
49786.7179	2.17	–0.69	DAO	53044.3017	10.35	4.64	ROZ
49930.5573	7.16	–	OND	53046.3601	9.36	3.09	ROZ
49948.5677	9.24	–	OND	53048.3209	11.01	6.33	OND
49949.6057	8.98	–	OND	53060.2802	9.59	5.48	OND
50001.5337	9.63	–	OND	53082.2765	10.21	8.46	OND
50015.4509	8.96	–	OND	53103.2588	9.65	2.68	ROZ
50104.4137	4.68	–	OND	53216.5807	7.69	2.99	OND
50122.3298	8.05	–	OND	53216.5841	6.72	2.61	OND
50159.3244	7.52	–	OND	53236.5388	7.07	0.62	OND
50316.5313	12.67	–	OND	53236.5418	6.67	1.69	OND
50410.5517	12.17	–	OND	53236.5444	6.85	2.75	OND
50439.3454	11.07	–	OND	53244.5837	7.85	0.32	ROZ
50448.4556	12.39	–	OND	53303.4677	6.89	–3.16	ROZ
50508.3366	9.58	–	OND	53303.4734	6.76	–2.61	ROZ
50509.3213	8.40	–	OND	53306.4628	6.94	–2.43	ROZ
51227.6834	15.86	–	DAO	53332.2934	6.14	–3.80	ROZ
51481.5805	16.66	–	OND	53335.5298	4.87	–4.51	OND
51570.2954	18.09	–11.26	OHP	53335.5058	4.15	–5.53	OND
51572.2713	15.23	–	OHP	53452.2425	4.60	–5.45	ROZ
51572.2823	15.27	–7.80	OHP	53555.5651	4.25	–6.60	OND
51573.3101	14.43	–	OHP	53579.5663	4.92	–9.15	OND
51573.3184	14.89	–	OHP	53615.5628	2.54	–6.85	OND
51576.2801	20.66	–	OND	53628.0077	3.98	–4.82	DAO
51797.5902	14.92	–3.58	OND	53638.9848	4.01	–5.96	DAO
51888.4738	15.65	–12.79	OHP	53651.5938	2.64	–4.98	OND
51889.4120	16.89	–1.85	OHP	53658.5135	3.02	–6.07	OND
51892.4705	16.33	–3.26	OHP	53708.8482	3.65	–2.43	DAO
51975.3321	14.73	–2.98	OND	53708.8552	3.68	–4.75	DAO
52236.4148	12.34	–0.05	OHP	53745.4308	3.12	–3.33	OND
52236.4313	13.49	–0.60	OHP	53745.4444	5.25	–3.26	OND
52237.4193	13.64	1.47	OHP	53782.3483	–6.17	–13.71	ROZ
52238.4212	15.07	–2.16	OHP	53791.3420	–6.16	–9.69	OND
52239.4098	14.07	5.44	OHP	53791.6955	–4.84	–10.42	DAO
52241.4048	13.66	2.18	OHP	53813.6682	0.54	–6.90	DAO
52241.4168	13.28	–0.09	OHP	53813.6731	0.10	–7.00	DAO
52242.3968	13.50	–2.44	OHP	53814.3319	–2.30	–11.32	ROZ
52242.4088	13.17	–1.56	OHP	53814.7058	0.35	–5.74	DAO
52263.3571	4.86	–21.12	OHP	53819.2800	1.72	–3.85	OND
52264.3598	3.99	–20.28	OHP	54002.0002	–5.50	–5.17	DAO
52264.3759	4.19	–20.14	OHP	54049.4053	1.00	–0.49	ROZ
52287.7753	12.91	–3.06	DAO	54049.5688	0.59	–4.32	ROZ
52533.0560	12.70	–0.59	DAO	54051.3857	–0.08	–0.54	ROZ
52664.2587	12.66	6.15	OHP	54085.1936	4.30	6.64	OND
52706.7375	9.20	3.07	DAO	54097.3352	5.58	5.29	OND
52710.2434	8.94	–0.88	ROZ	54105.7532	6.28	4.59	DAO
52860.5294	13.01	5.71	ROZ	54108.3564	4.60	3.58	ROZ
52877.5835	14.12	4.46	OND	54115.3230	9.59	7.83	OND
52899.5953	9.18	2.73	OND	54115.3365	6.24	5.07	OND
52900.5672	10.16	1.06	OND	54116.3092	7.94	5.01	OND
52900.5694	9.91	3.46	OND	54117.3291	8.49	4.97	OND
52902.4322	11.08	0.23	OND	54126.2227	5.21	3.45	OND
52902.4376	10.01	–0.84	OND				

Table A.1. continued.

Time of obs. (HJD-2400000)	RV(H α em.) [km s ⁻¹]	RV(H α abs.) [km s ⁻¹]	Source	Time of obs. (HJD-2400000)	RV(H α em.) [km s ⁻¹]	RV(H α abs.) [km s ⁻¹]	Source
54153.2844	10.13	9.55	OND				
52904.6492	10.21	-1.22	OND	54162.3401	10.00	7.07	OND
52904.6537	8.10	-1.58	OND	54164.2850	9.44	8.85	OND
52904.6581	8.64	-2.50	OND	54186.2921	8.34	10.40	OND
52949.6009	4.53	-4.85	OND	54188.3212	8.24	7.65	OND
52949.6044	7.99	-1.69	OND	54341.0107	8.10	9.45	DAO
52949.6091	8.48	0.25	OND	54387.5177	7.60	9.07	OND
52952.5541	9.42	1.66	ROZ	54442.9976	-1.19	7.27	DAO
52952.5619	8.61	0.73	ROZ	54490.2613	2.53	5.75	OND
52957.5042	10.46	1.38	OND	54490.9272	5.12	7.32	DAO
52957.5113	9.64	-0.03	OND	54508.3482	5.75	6.33	OND
54519.6647	7.47	7.46	DAO	54871.4085	1.45	0.87	OND
54537.3145	7.61	7.02	OND	54871.4347	-1.05	-1.35	OND
54557.3011	9.58	7.53	OND	54872.2313	-0.59	0.00	OND
54557.3179	9.66	10.86	OND	54872.2523	-0.47	-0.18	OND
54718.5138	9.34	8.46	OND	54874.3436	-4.15	-2.85	LIS
54748.4616	8.77	8.77	OND	54880.3360	-1.91	2.66	LIS
54753.4457	10.20	9.03	OND	54881.3230	-2.97	2.77	LIS
54753.4540	9.06	8.76	OND	54882.3222	-3.32	1.51	LIS
54761.4009	10.36	9.77	OND	54911.6519	5.48	6.32	DAO
54763.4827	10.24	8.19	OND	54911.6904	5.42	6.43	DAO
54798.4322	10.35	9.47	OND	54912.6793	5.60	6.45	DAO
54804.2374	9.88	8.46	OND	54924.3033	7.18	7.77	OND
54840.4814	8.89	9.77	OND	55050.5248	11.68	8.25	OND
54857.4154	8.08	7.49	OND	55071.5298	11.44	7.33	OND
54862.6448	5.96	3.92	DAO	55083.6501	6.07	3.72	OND
54862.6812	5.78	3.76	DAO	55097.4911	-1.45	4.41	OND
54863.6276	5.43	4.58	DAO	55112.4081	3.52	-3.81	OND
54863.6627	4.72	4.21	DAO				

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