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Properties and nature of Be stars⋆,⋆⋆,⋆⋆⋆

XXI. The long-term and the orbital variations of V832 Cyg = 59 Cyg

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⋆⋆ Also based on observations from Castanet-Tolosan, Hvar, Ondřejov, Pic-du-Midi, Rožen, San Pedro Mártir, Toronto and Xing-Long Observatories and on photoelectric photometry by AAVSO members.

⋆⋆⋆ Tables 3, 5–7 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/387/580

Abstract. An analysis of numerous homogenized *UBV* photoelectric observations and red spectra of the Be star V832 Cyg from several observatories led to the following principal findings:
1. Pronounced long-term light and colour variations of V832 Cyg result from a combination of two effects: from the gradual formation of a new Be envelope, and from an asymmetry and a slow revolution of the envelope (or its one-armed oscillation). The colour variations associated with the envelope formation are characterized by a positive correlation between brightness and emission strength, typical for stars which *are not* seen roughly equator-on.
2. The V magnitude observations prewhitened for the long-term changes follow a sinusoidal orbital light curve with a small amplitude and a period of $28\stackrel{d}{.}1971$ which is derived from observations spanning 43 years. This independently confirms a 12-year old suggestion that the star is a spectroscopic binary with a 29-d period. V832 Cyg thus becomes the fifth known Be star with cyclic long-term V/R variations, the duplicity of which has been proven, the four other cases being ζ Tau, V923 Aql, γ Cas and X Per. Therefore, the hypothesis that the long-term V/R variations may arise due to the attractive force of the binary companion at certain phases of the envelope formation is still worth considering as a viable alternative to the model of one-armed oscillation.
3. We have shown that the RV and V/R variations of the Hα and He I 6678 emission lines are all roughly in phase. In particular, the He I 6678 emission also moves with the Be primary which differs from what was found for another Be binary, φ Per.
4. We derived the orbital elements and found that in spite of the remaining uncertainties, the basic physical properties of the $28\stackrel{d}{.}2$ binary are well constrained.
5. The light minimum of the orbital light curve occurs at elongation when the Be star is approaching us and the object becomes bluest in $(B-V)$ and reddest in $(U-B)$ at the same time. This may indicate that a part of the optically thick regions of the envelope is eclipsed at these orbital phases.
Key words. stars: emission-line, Be – stars: binaries: close – stars: binaries: spectroscopic – stars: fundamental parameters – stars: individual: V832 Cyg

1. Introduction

The B1e star V832 Cyg (59 Cyg, HD 200120, BD+46°3133, HR 8047, f[1]Cyg, HIP 103632) is a well-known Be star thanks to its very pronounced spectral variations, studied by Curtiss (1916), Duval et al. (1975), Beeckmans (1976), Doazan et al. (1980), Marlborough & Snow (1980), Divan & Zorec (1982), Barker (1982, 1983), Doazan et al. (1985) and Doazan et al. (1989), among many others. Two short-lived shell phases were recorded in 1973 and in 1974–75. The second episode, which was well observed, lasted only 160 days.

The history of early investigation of V832 Cyg has been summarized by Barker (1982). A few sentences of the section "history" in his paper are worth quoting here: "in view of the large variations in the spectrum of 59 Cyg during the last several decades, it is extremely likely that the widely varying velocities (as well as an oft-repeated "SB1" annotation) are the result of different observers measuring different line features at different phases of activity. The present observations show large velocity changes but give no evidence that the star is a binary. Hence, it is assumed here that 59 Cyg is a single star with radial velocity -23 km s^{-1} as determined in this work." V832 Cyg is actually the brightest component A of a multiple visual system ADS 14526. Component B at a distance of $20\farcs1$ ($V = 9\stackrel{m}{.}38$, $B-V = 0\stackrel{m}{.}22$, $U-B = 0\stackrel{m}{.}04$) is an A8III star and forms a common-motion pair with V832 Cyg. Component C, at $26''$ is optical.

At about the same time when Barker was preparing his study, Harmanec (1982) speculated that the long-term spectral variations of V832 Cyg could be related to the presence of a companion with a long orbital period. Notably, McAlister et al. (1984) indeed reported the discovery of a speckle-interferometric companion to V832 Cyg (system Aa) at a distance of $0\farcs21$ but no proof of its possible relation to long-term spectral changes is available. Barker (1983) obtained a new series of electronic spectra of the star and, analyzing the Hα emission profiles,

Table 1. Journal of photometric observations of V832 Cyg with known times of observations.

File No.	Epoch HJD-2 400 000	No. of obs.	HD comp. /check	System
44	36377.9–36492.7	17	199890/ —	V
23	38204.9–38699.6	4	—	UBV
30	39045.6–43796.7	12	—	UBV
52	45241.3–46277.4	453	198639/199311	$(UB)V$
8	45876.2–48619.0	33	199311/199479	UBV
1	46258.6–51461.3	135	199311/199479	UBV
20	46584.8–47723.8	65	199311/199479	BV
43	47073.6–51168.2	149	199311/ —	V
61	47862.0–49022.5	92	—	V
52	48178.4–48487.5	32	199311/199479	UBV
1	51067.3–51715.4	136	203245/199311	UBV
1	51715.4–51715.4	2	199890/199311	UBV
30	51843.6–52072.9	38	203245/199311	UBV
1	51928.2–52211.3	107	203245/199311	UBV

Observing stations are identified by their file numbers used in the Ondřejov data archives (see column "File No.") as follows: 1... Hvar 0.65-m reflector, EMI6256 tube; 8... Xing-Long 0.60-m reflector; 20... University of Toronto 0.40-m reflector, Optec SSP-3 photometer; 23... Catalina, original UBV observations; 30... San Pedro Mártir: Older data set: $13C$ photometry transformed to UBV; Recent data set: UBV photometry with the 0.84-m reflector; 43... AAVSO observers with photoelectric photometers; 44... Mt Palomar 0.51-m reflector, EMI 6094 tube; 52... Rozhen 0.60-m reflector, EMI tube; 61... Hipparcos satellite, $H_{\rm p}$ magnitudes transformed to Johnson V.

he noted possible periodicity of the V/R ratio with either a 28-d or 14-d period. Tarasov & Tuominen (1987) obtained high-dispersion CCD Hα spectrograms of V832 Cyg and found periodic radial-velocity (RV hereafter) variations of the absorption core of Hα and its V/R variations with a $29^{\mathrm{d}}.14$ period, the phase of the RV maximum being JD 2 446 614.10. They concluded that V832 Cyg is a spectroscopic binary with a $29^{\mathrm{d}}.14$ orbital period. Soon thereafter, Tarasov & Tuominen (1988) analyzed the published spectroscopic data on V832 Cyg along with their additional CCD spectrograms. They improved the value of the orbital period to $27^{\mathrm{d}}.975$ and concluded that the orbital period could be detected in the V/R variations of the Balmer lines also in several published data sets. Very regrettably, their detailed study has never been published.

Recently, Rivinius & Štefl (2000) confirmed their result. Measuring the radial velocity of the He I 4471 line in 1990–1998 Heros spectra, they derived the velocity curve with a semiamplitude of 27 km s^{-1}. Using IUE spectra from 1978 to 1994, they refined the value of the orbital period to a value of $28^{\mathrm{d}}.1702$ which they kept fixed in their orbital solution for the He I 4471 line. They concluded that the orbit is eccentric ($e = 0.2$) and derived the epoch of periastron passage as JD 2 450 018.9 ± 2.5. They also discovered the presence of a weak emission component in the core of the He I 6678 line and suggested possible similarity of V832 Cyg to another Be binary, φ Per, studied recently by Gies et al. (1993) and Božić et al. (1995). They interpreted this emission as arising from a part of the Be disk around V832 Cyg illuminated by a hot (and as yet unseen) compact secondary to V832 Cyg in a $28^{\mathrm{d}}.17$ orbit.

The purpose of this paper is to investigate the character of the long-term light, colour and emission-line variations of V832 Cyg and to look for possible signatures of its *orbital* changes.

2. Observations and data reductions

2.1. Photometry

The observational data used in this study consist of numerous UBV, BV and V photometric measurements from 9 different observatories for which accurate dates of observations are known. They were secured between the years 1958 and 2000 and consist of both already published observations and new data obtained by us. Basic information is provided in Table 1. As seen there, most of the available data sets were secured differentially but relative to several different comparison stars, and there are also three data sets based on all-sky photometry.

Special effort was made to derive improved *all-sky* values for all comparison stars used, employing carefully standardized UBV observations secured at Hvar and San Pedro Mártir observatories. The new values are collected in Table 2, together with the number of all-sky observations and the rms errors. They were added to the respective magnitude differences to obtain directly comparable standard UBV magnitudes of V832 Cyg. For the convenience of future investigators, we publish all of our homogenized individual UBV observations together with their HJDs in Table 3.

Some comments on the individual data sets and their reduction follow:

File 1: Hvar These observations were reduced to the standard UBV system via non-linear transformation formulæ using the HEC22 reduction program – see Harmanec et al. (1994) and Harmanec & Horn (1998). The first part of them was secured in the course of the international campaign on photometry of Be stars and has already been analyzed by Hadrava et al. (1989) and by Pavlovski et al. (1997) and published in detail by Harmanec et al. (1997).

During summer and autumn 1999, two of us (PH and HB) obtained dedicated series of observations of V832 Cyg aimed at detection of variations on the time scale of the orbital period and shorter. Since the comparison star originally recommended for the Be campaign, HD 199311, is rather faint for observations of V832 Cyg, we selected and used a brighter comparison star HR 8161 = HD 203245 after verifying its secular constancy. The first part of the 1999 Hvar observations was secured during a commissioning run with a new, computer controlled photometer, while the second part was obtained with the original one. Transformation coefficients were derived separately for these two parts of the data. A few observations were secured during one night in June 2000 with the original Hvar photometer by HB. Numerous observations with the new photometer were again secured during the summer and autumn of 2001. The 1999–2001 observations are published and analyzed for the first time here.

File 8: Xing-Long These observations were also secured as part of the international campaign on photometry of Be stars and reduced using the HEC22 program.

File 20 and 43: Toronto and AAVSO photoelectric program These observations come from the photometric archives of the AAVSO and of JRP. They were secured in support of the international program. The Toronto data were obtained by summer undergraduate research assistants, while the AAVSO V data were obtained by several different AAVSO observers equipped with photoelectric photometers (mostly SSP-3 from Optec). All the observations were reduced by AAVSO or by JRP via linear transformation equations and some results have already been published by Percy et al. (1988, 1996, 1997), Percy & Bakos (2001) and Landis et al. (1992).

File 23: Catalina These original UBV all-sky observations were published with dates of observations by Johnson et al. (1966). We converted their tabulated JDs into HJDs.

File 30: San Pedro Mártir The older part of these data is based on the all-sky 13C observations which were published by Johnson & Mitchell (1975). They were reduced to the standard UBV system via transformation formulæ, derived and published by Harmanec & Božić (2001). The formulæ are defined by those good standard stars observed at Hvar (see Harmanec et al. 1994) for

Table 2. Accurate Hvar and San Pedro Mártir *all-sky* mean UBV values for all comparison stars used.

Star	HD	No. of obs.	V (mag)	B (mag)	U (mag)	$(B-V)$ (mag)	$(U-B)$ (mag)
56 Cyg	198639	3	5.063 ± 0.004	5.251 ± 0.007	5.351 ± 0.009	0.187	0.101
HD 199311	199311	406	6.689 ± 0.010	6.767 ± 0.012	6.866 ± 0.015	0.079	0.099
HD 199479	199479	148	6.847 ± 0.012	6.807 ± 0.013	6.595 ± 0.016	−0.040	−0.212
HD 199890	199890	3	7.507 ± 0.002	7.409 ± 0.003	7.024 ± 0.007	−0.098	−0.385
HR 8161	203245	326	5.762 ± 0.010	5.635 ± 0.010	5.121 ± 0.013	−0.127	−0.514

Table 4. Published all-sky photometry of V832 Cyg without known accurate times of observations.

Date of obs.	Epoch (HJD-2 400 000)	V (mag)	$B-V$ (mag)	$U-B$ (mag)	N of obs.	Source
1955 – 1957 ??	35400::	4.49	−0.03	−0.93	3	Mendoza (1958)
?	?	4.61	−0.03	−0.92	?	Eggen (1963)
1956 – 1963	35655–38300:	4.88	−0.14	–	3	Ljungren & Oja (1964)
1962 – 1970	37850–40860:	4.79	−0.07	−0.92	1	Crawford et al. (1971)
Oct. 1969 to Sep. 1970	40495–40860	4.87	−0.07	−0.93	1	Lutz & Lutz (1972)
1970 – 1971	40800–41230:	4.57	−0.01	−0.99	2	Lutz & Lutz (1977)
Sep. 1973 to Aug. 1975	41930–42655	4.67	−0.03	−1.00	?	Warman & Echevaria (1977)*
Sep. 1973 to Aug. 1975	41930–42655	4.93	−0.14	−0.95	1	Echevaria et al. (1979)

*) According to Echevaria (2002, priv. com.), these values were preliminary and the values from the follow-up paper by Echevaria et al. (1979) should be preferred.

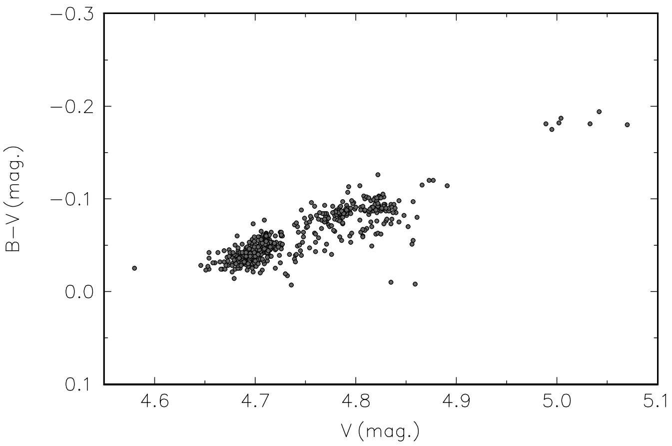

Fig. 1. A plot of the $B-V$ colour index vs. the V magnitude for all calibrated UBV observations of V832 Cyg.

which the 13C photometry was also available. The recent part of these observations was secured by PH, MW and PE with the 0.84-m reflector and Cuenta-pulsos photon-counting photometer equipped with an RCA 31034 photomultiplier and UBV filters. These data were also reduced with the HEC22 program, corrected for measured extinction and transformed to the standard Johnson system.

File 44: Mount Palomar These V observations were published by Lynds (1959). The new V value of HD 199890 from Table 2 was added to the magnitude differences V832 Cyg – HD 199890 to obtain V magnitudes of V832 Cyg comparable to the other data.

File 52: Rožen These UBV observations were secured by one of us, LI, and consist of two parts. The first one was shown in a preliminary graphical form in Kovatchev et al. (1986). These data are on an instrumental UBV system and the B and U magnitudes differ systematically from all other comparable data sets even after the new UBV values for the comparison star used, 56 Cyg = HD 198639, were added to the magnitude differences V832 Cyg – 56 Cyg. Observations secured during two nights in 1990 and 1991 were reduced with the help of the HEC22 program. It turned out that the available observations did not allow us to derive the dead-time of the instrument accurately enough from the available data. The B magnitude of V832 Cyg is bright enough to be sensitive to the exact value of the dead-time coefficient and the values of the $(B-V)$ and $(U-B)$ colours are affected by this uncertainty for both data sets. We, therefore, analyzed only the V observations from Rožen and – as a precaution – we use the earlier data set only for the study of long-term changes.

File 61: Hipparcos These observations were reduced to the standard V and B magnitudes via the transformation formulæ derived by Harmanec (1998). Since the star underwent long-term brightness and colour variations over the period 1989–93, covered by Hipparcos observations, we proceeded in such a way that we first found the mean relation between the V magnitude and the $(B-V)$ colour from all calibrated UBV observations and then we used proper values of $(B-V)$ in the $H_{\rm p}$ to BV transformation formulæ. As Fig. 1 shows, the $(B-V)$ vs. V relation is nearly linear for V832 Cyg.

2.2. Spectroscopy

To be able to study the relation between the long-term light and spectral changes, we collected all available records of the Hα profiles of V832 Cyg. New electronic spectra, covering the spectral region near Hα and available to us consist of the following five data sets:

1. 27 spectra were secured in 1994, 1997 and 1999 at the coudé focus of the 1.22-m reflector of the Dominion Astrophysical Observatory by SY. The detector was DAO UBC-1 CCD, which is a Loral 4096×200 thick device with 15 μm pixels. Using the 1200 grooves per mm grating, the reciprocal linear dispersion of 10 Å mm^{-1} translates to about 0.14 Å per pixel on the CCD;
2. 3 spectra were secured at the coudé focus of the Ondřejov 2-m telescope in 1999. The detector was a Reticon 1872RF/30, with 15 μm pixels. A 830.77 grooves per mm grating gave a dispersion of 17.2 Å mm^{-1} in the first order which translates into about 0.26 Å per pixel;
3. 1 Hα spectrum was obtained by LI with the 2-m telescope at Rožen. The detector was an ISTA camera with an Astro-552 CCD chip with 580×520 pixels, the pixel size being 23×18 μm. The reciprocal linear dispersion was 8.1 Å mm^{-1} or 0.2025 Å per pixel;
4. 4 CCD spectra were taken by members of Association T60 with the 0.6-m telescope at the Pic du Midi Observatory, at dispersions of 0.95 and 0.29 Å per pixel;
5. 14 CCD spectra were obtained by CB with 0.212-m and 0.190-m telescopes at Castanet-Tolosan. These spectra have dispersions of either 0.93 or 0.38 Å per pixel, the pixel size being 9 μm.

The last two series of spectra have already been made available to the public[1]. All the spectra were properly reduced and the RV and spectrophotometric measurements were carried out with the help of the SPEFO program, written by Dr. J. Horn (see Horn et al. 1996).

All spectra at our disposal cover the region of the Hα profile. The DAO and Reticon spectra also contain the He I 6678 line profile. Samples of the Hα and He I 6678 profiles of V832 Cyg are shown in Figs. 2 and 3, respectively. One can see that the Hα profile is dominated by strong emission and exhibits V/R changes. The profile of He I 6678 is composed of a broad absorption and a double emission which exhibits variations in both the line intensity and the V/R ratio.

We obtained and investigated the following characteristics of the Hα profiles: the peak intensities I_V and I_R of the violet and red peaks of the double Hα emission expressed in units of the local continuum, their ratio I_V/I_R, the line intensity measured by the mean of the two, i.e.

[1] See http://www.astrosurf.com/buil/us/becat.htm

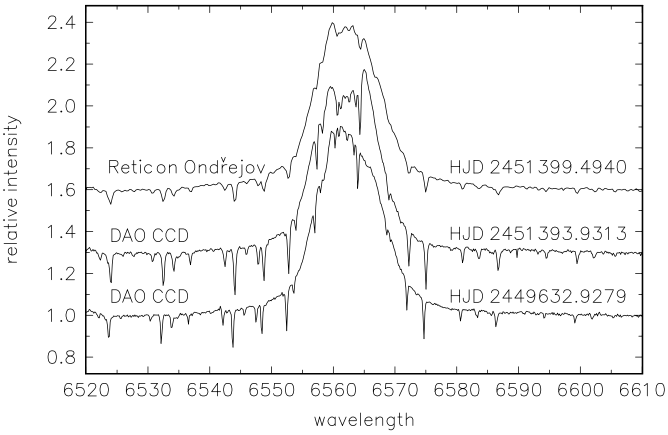

Fig. 2. A sample of three Hα profiles of V832 Cyg identified by the instrument and heliocentric Julian date. The profiles are on a heliocentric wavelength scale (in Å) and consecutive profiles were shifted for 0.3 in relative intensity.

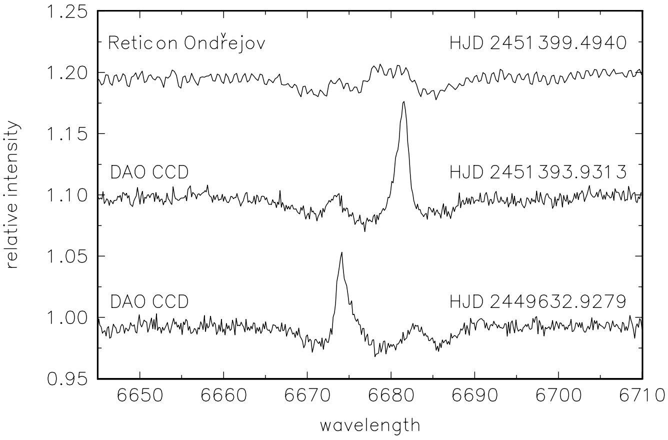

Fig. 3. A sample of the same three He I 6678 profiles of V832 Cyg as Hα profiles shown in Fig. 2, again identified by the instrument and heliocentric Julian date. The profiles are on a heliocentric wavelength scale (in Å) and consecutive profiles were shifted for 0.1 in relative intensity.

$(I_V+I_R)/2$ and the equivalent width of the emission profile EW (we omit the usual minus sign for the emission-line equivalent width). Note that our I_V/I_R ratio differs from the quantity denoted as V/R in the papers by Doazan et al. (1985, 1989) which was defined as $(I_V-1)/(I_R-1)$. It is necessary to warn that the Hα emission is so strong that in some profiles even a proper identification of the V and R peak of the emission is anything but easy. That is why we measured only the total peak intensity $(I_V+I_R)/2$ in such profiles when the separate V and R peaks could not be safely identified. The problem is also complicated by the presence of a number of strong telluric lines. For the He I 6678 profiles, we also measured the V and R peaks of the double emission and derived their mean and ratio but we did not measure the equivalent width of these complicated profiles.

For spectra with higher resolution we also derived the RV of the symmetric bottom parts of the steep wings of the Hα emission (up to about 1.3 in relative intensity) trying to take into account the distortion caused by the telluric lines. Whenever available, we also measured the RV of the emission wings and of the broad absorption wings of the He I 6678 profile. It turned out that although the Hα profile is quite complicated and the upper parts of the emission wings may become asymmetric, the settings on the bottom parts of the emission wings can be reproduced quite well as evidenced by the independent measurements in the series of DAO profiles.

Spectrophotometric quantities and heliocentric Julian dates which we directly derived ourselves from the published profiles are collected in Table 5. Note that we also re-measured the 17 scanner Hα profiles obtained by Barker (1983) which were later included in the detailed study by Doazan et al. (1985). Otherwise, we directly used the tabulated values from the papers by Doazan et al. (1985, 1989) which we do not reproduce here.

The spectrophotometric quantities derived by us from the new electronic spectra can be found in Table 6 while the RV measurements are collected in Table 7.

3. Long-term changes

One of the first systematic classifications of the variations of Be stars was devised by Harmanec (1983) who distinguished variations on three distinct time scales: long-term (years to decades), medium-term (several days to months) and rapid (about $0\overset{d}{.}1$ to a few days). Here, we use the terms "long-term" and "rapid" according to this scheme.

Figure 4 is a plot of the V/R ratio and peak intensity of the Hα emission, and of V, $B-V$ and $U-B$ individual observations of V832 Cyg vs. time. It shows how complicated and complex the long-term variations of the object are. Inspecting Fig. 4, one can only regret that the very interesting period of the two shell phases centred roughly on JDs 2 441 850 and 2 442 400, and the epoch of the near-absence of the Balmer emission around JD 2 443 200, are so poorly covered by photometric observations. The only existing occasional all-sky UBV observations of the star from that period, collected in Table 4 show that rather rapid and large brightness changes occurred at that time (see, however, a note to this table). It is also seen that the re-appearance of the Balmer emission after JD 2 443 200 was accompanied by a brightnening of the object. As seen in Fig. 5, the photometric spectral class of the object varied from a main-sequence B1 star to a B1 supergiant (after one takes the dereddening into account). All these are clear signatures of a positive correlation between the brightness and emission-line strength as defined by Harmanec (1983, 2000) (see also a detailed discussion in Koubský et al. 1997). In this interpretation, the optically dense inner parts of the envelope, *a pseudophotosphere*, seen under an intermediate angle, simulate an increase of the radius of the star which then appears larger and more luminous then in the period when it is without the envelope. (In contrast to it, for stars seen roughly equator-on, one observes an inverse correlation during which an increase of the emission strength is accompanied by a decrease of brightness of the object, which at the same time moves along the main-sequence towards a cooler spectral subclass in the colour-colour diagram.)

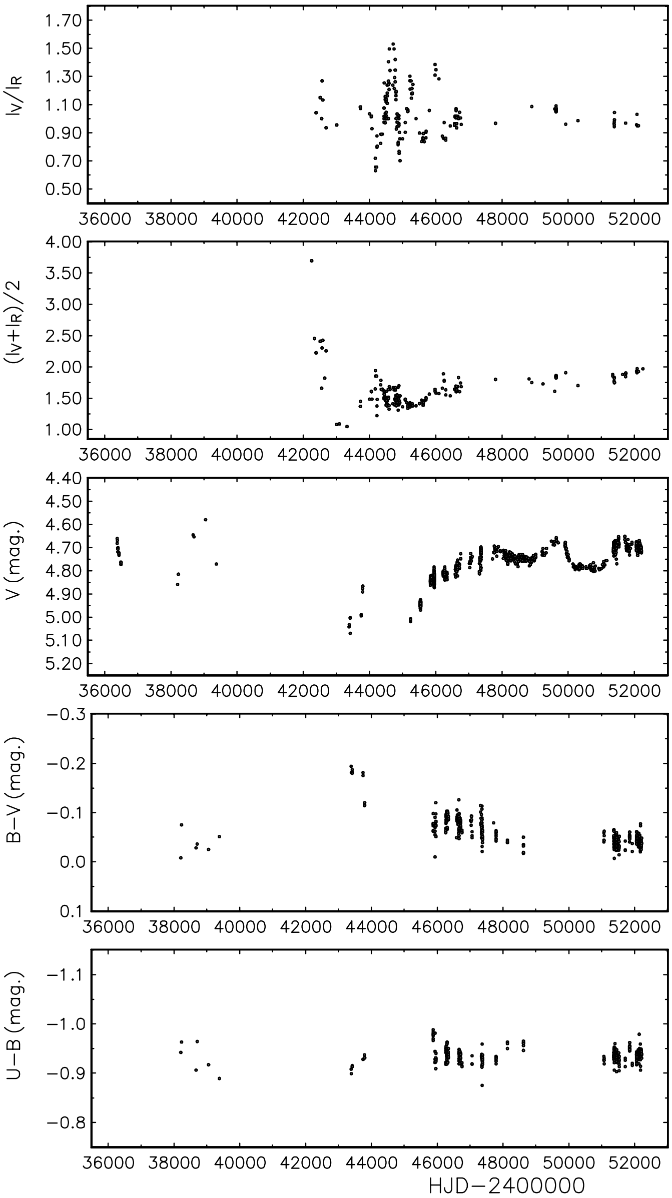

Fig. 4. Long-term Hα emission line strength, light and colour variations of V832 Cyg.

One can also note that after the formation of a new Be envelope, large cyclic V/R variations with about 2-year-long cycles were observed until about JD 2 447 000 when the brightness of the star also reached its contemporary value (between about $4\overset{m}{.}7$ and $4\overset{m}{.}8$ in V). The brightening of the object was accompanied by reddening of the $(B-V)$ index. In contrast to this, the $(U-B)$ index showed only rather mild cyclic variations over the whole interval covered by the observations.

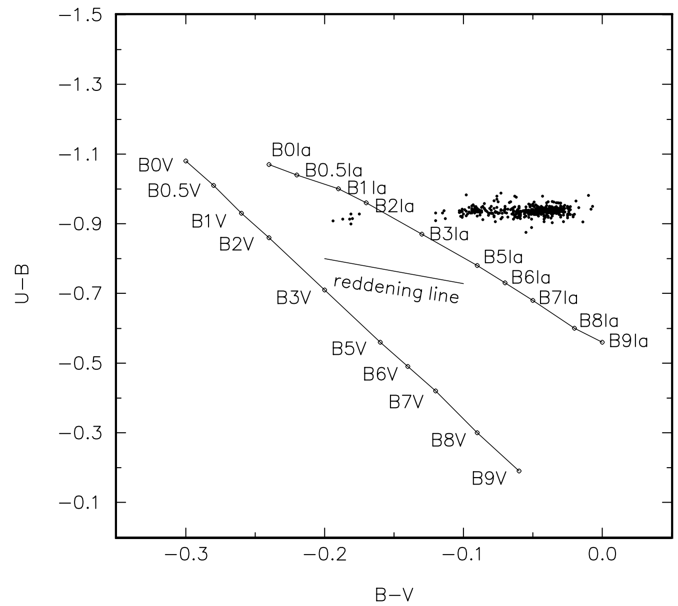

Fig. 5. $(U-B)$ vs. $(B-V)$ colour diagram with the main-sequence and supergiant sequence shown. It is seen that the observations of V832 Cyg correspond to a positive correlation between the brightness and emission-line strength. After dereddening the object moves between B1V and B1Ia in the diagram.

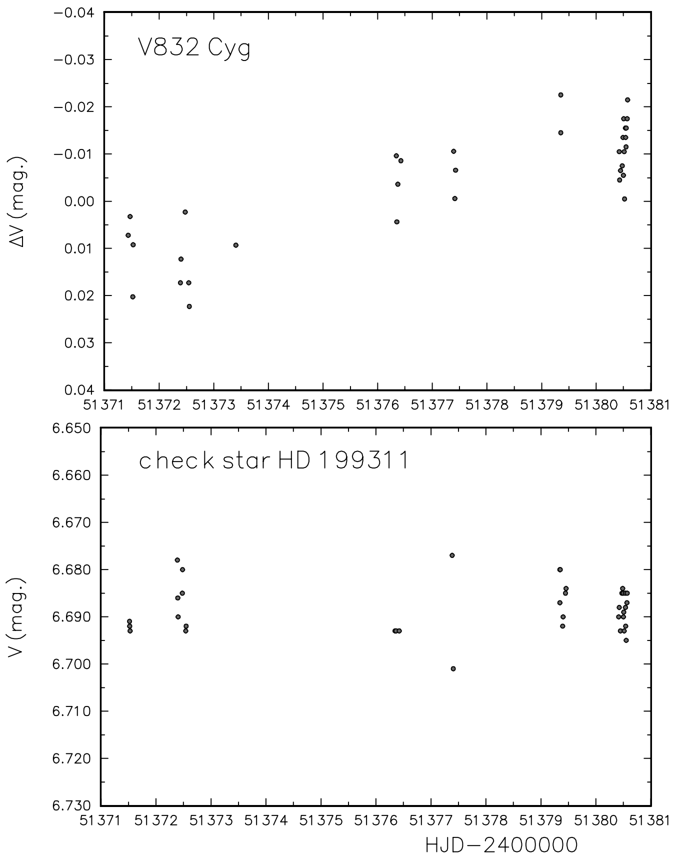

Fig. 6. A time plot of a longer series of 1999 Hvar V observations, prewhitened for long-term changes. The only significant variations occur on a time scale of days, not on a time scale of hours.

4. Rapid changes

While the long-term light variations of V832 Cyg have been discussed in the past, there are only a few reports of the light changes on shorter time scales. Lynds (1959) observed a steady decline in brightness between June and October 1958. Tarasov & Shcherbakov (1985) analyzed a series of 38 Å mm^{-1} Hα spectra obtained with the Crimean 1.22-m reflector equipped with an image intensifier. They reported periodic variations of the V/R ratio with a possible period of $0\overset{\mathrm{d}}{.}263$, in addition to night-to-night changes. Hadrava et al. (1989) reported the presence of variations on a time scale of days. They did not analyze the data for periodicity but inspecting the time plots they published, one could suspect the presence of mild periodic variations with a period close to one month. In a study which has never been published, Yang analyzed a series of Hγ and He I 4471 line profiles obtained during 3 nights in August 1988. He detected moving sub-features with a mean time separation of $0\overset{\mathrm{d}}{.}0678$ and an average acceleration of 4570 km s^{-1} per day. Hubert & Floquet (1998) analyzed Hipparcos photometry of Be stars for periodicity. For V832 Cyg, they reported a short period of $0\overset{\mathrm{d}}{.}28$ which was recently also detected by an autocorrelation technique by Percy et al. (2002a, 2002b).

We began our analysis by prewhitening the most numerous set of V observations for the pronounced and – at some epochs also quite fast – long-term light changes, using Vondrák's (1969, 1977) smoothing technique. After some trial we found that the best removal of the long-term changes is obtained when one uses the smoothing parameter ε equal to 1×10^{-12}.

It is necessary to say that our photometric observations were not aimed at studies of possible rapid light changes and were not obtained in really long whole-night series. They are, therefore, less ideal for any search for rapid changes. In July 1999, we obtained a series of observations at Hvar in very good weather conditions. This series spans one week in about $0\overset{\mathrm{d}}{.}2$ long series. From it, we see no evidence of significant variations on a time scale of hours exceeding the usual scatter of $0\overset{\mathrm{m}}{.}02$, illustrated by observations of a check star – see Fig. 6. Only gradual changes on a time scale of days are observed.

In the next step, we searched the more recent and reasonably homogeneous prewhitened V observations for periodicity over the whole range of periods from 3000 days down to $0\overset{\mathrm{d}}{.}2$ using Stellingwerf's (1978) PDM method. In particular, we analyzed 344 individual V observations after HJD 2 451 000 secured at Hvar, San Pedro Mártir and by AAVSO observers. Thanks to a large difference in local time between North America and Mexico on one side, and Hvar on the other, this data set is suitable for a test on the presence of rapid changes. Figure 7 shows the PDM periodogram. It is clearly seen that the light of V832 Cyg varies with a frequency of about 0.035 $\mathrm{c\,d}^{-1}$, i.e. with a period close to $28\overset{\mathrm{d}}{.}2$. The same conclusion

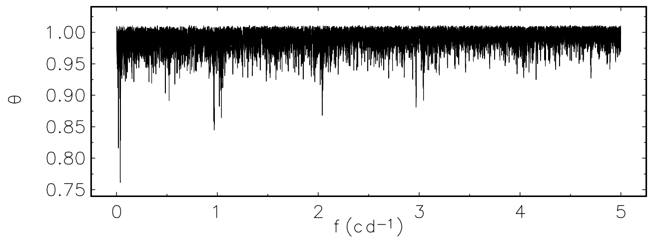

Fig. 7. Stelligwerf's PDM periodogram of V photometry prewhitened for long-term changes.

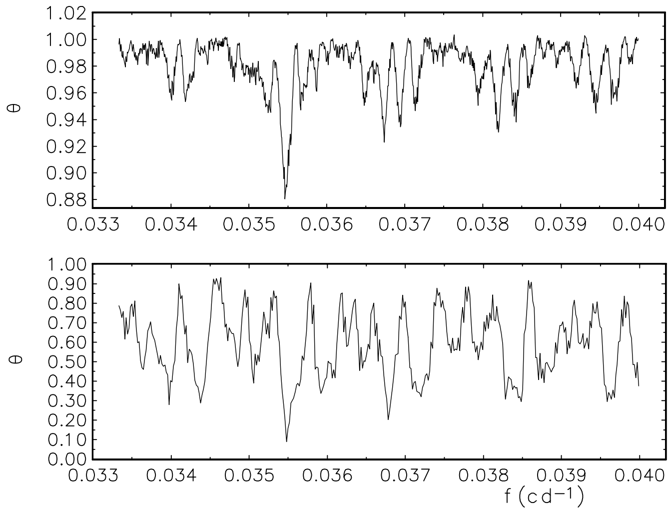

Fig. 8. Stelligwerf's PDM periodogram of V photometry prewhitened for long-term changes (upper panel) and of the I_V/I_R ratio of the double Hα emission (bottom panel).

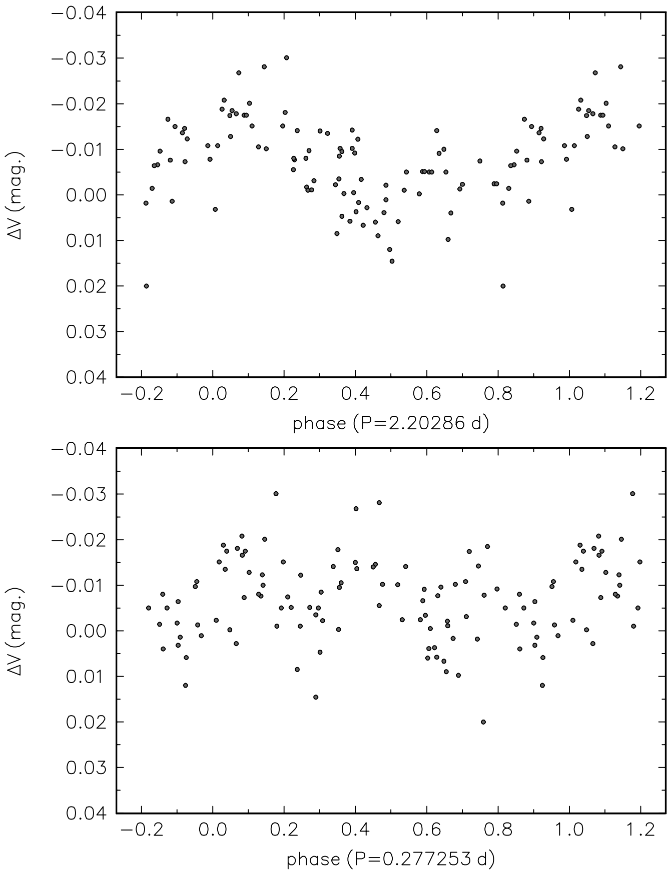

Fig. 9. Phase diagrams for the best-fit "period" of $2^{\mathrm{d}}.20286$, and for the best "period" near $0^{\mathrm{d}}.280$, for the Hipparcos photometry alone (again prewhitened for the long-term changes).

follows also from the analysis of the V/R variations of the Hα profile from the quiet epoch (after JD 2 446 500).

In Fig. 8 we compare the periodograms of the V residuals and the V/R ratio in the neighbourhood of the orbital period. The deepest minima in both periodograms correspond to the same value of the orbital period of about $28^{\mathrm{d}}.19$.

At this stage, it seems appropriate to say a few words about Hipparcos photometry. It appears to us that this precious data set seems to be overinterpreted by some investigators. While the set is basically free from the usual one-day aliases occurring for observations from the Earth, it has its own, very selective time distribution as was pointed out by Štefl et al. (1998) and recently discussed by Percy et al. (2002a, 2002b) and Jerzykiewicz & Pamyatnykh (2000). Besides, it usually represents something like 100 data points per one object. For completeness, we also ran a PDM period search on Hipparcos data prewhitened for the long-term changes, again over the interval of periods down to $0^{\mathrm{d}}.2$. Notably, we did not detect any significant period near $0^{\mathrm{d}}.280$ but a rather well defined periodicity of $2^{\mathrm{d}}.20286$ – see Fig. 9. This shows how dangerous it is to search for periodicity in a limited data set which displays only mild variations. We cannot confirm the $2^{\mathrm{d}}.2$ period from other data and believe it to be an accidental, formal fit for one limited data set, not a real periodicity.

For completeness, we also show a phase diagram for the best "period" near $0^{\mathrm{d}}.280$, namely $0^{\mathrm{d}}.277253$. It is seen that the phase curve for this period does not look very convincing but it shows certain organized structure, not just a white noise. We also note that all the reports of possible rapid changes cluster around a similar value of $0^{\mathrm{d}}.26$–$0^{\mathrm{d}}.28$, the sub-feature separation detected by Yang being about 1/4 of that value. Since V832 Cyg lies in the region of the HR diagram where β Cep pulsational instability occurs, it is conceivable that it is a pulsating star. In the light of what was said above, however, we postpone the investigation of possible rapid changes until new, dedicated series of observations are available.

5. Orbital light, colour and V/R changes

As already mentioned, the PDM search carried out for the whole data set of 865 individual V observations prewhitened for the long-term changes (note that we used the earlier set of 453 Rožen observations in the process of prewhitening but not in the period analyses for orbital period for the reasons mentioned earlier) identified the presence of a $28^{\mathrm{d}}.2$ period in the photometric data.

Table 8. Sinusoidal fits to 865 individual V observations of V832 Cyg prewhitened for long-term variations. Individual zero points of the magnitude scale were allowed for each data set used in solution 1 while solution 2 was derived for one joint zero point for all data. All epochs are in HJD-2 400 000, A is the semiamplitude of the light curve and the rms error is the error per 1 observation of unit weight.

Element	solution 1	solution 2
P (d)	28.1971 ± 0.0038	28.1918 ± 0.0035
$T_{\rm min.light}$	50013.71 ± 0.35	50013.61 ± 0.39
A (mag)	0.00807 ± 0.00060	0.00751 ± 0.00063
rms (mag)	0.0122	0.0129

We therefore take for granted that – apart from the long-term changes – the brightness of V832 Cyg varies slightly with the orbital period. We formally used the program FOTEL (Hadrava 1990), designed for orbital solutions of spectroscopic binaries, to derive a quantitative description of the light curve and an improved value of the orbital period. The results are summarized in Table 8 for two different solutions, based on individual and common zero points of the magnitude scale for individual data sets. We deliberately used a reference epoch of minimum light close to the epoch of periastron passage derived by Rivinius & Štefl (2000) to allow a direct comparison with their RV curve. Note that we obtained a slightly different – and presumably also a more accurate – value of the orbital period since our data span a longer period of time than theirs: from 1958 to 2001. We verified that the light minimum occurs at the same phase for our improved value of the orbital period for the early, intermediate and new V data subsets. In the following discussion we shall adopt the linear ephemeris from solution 1.

Figure 10 shows the light curve based on all V observations and also the light curve based on 1-d normal points derived from the same data.

To study also the colour variations, we extracted 1-d normal points from prewhitened Hvar and San Pedro Mártir observations and show their phase diagrams in Fig. 11. One can see that the object gets slightly bluer in $(B-V)$, and redder in $(U-B)$ near the light mininum.

In Fig. 12 we show the orbital variations of the I_R/I_V ratio of the Hα and He I 6678 emission lines from all spectra taken after JD 2 446 650, i.e. in the epoch without large cyclic I_R/I_V changes. One can see that the curve for the Hα line has a more complicated phase dependence than the almost perfectly sinusoidal He I 6678 I_R/I_V curve. The minima of both curves occur somewhat earlier than the light minimum.

Finally, we also analyzed the RV curves. Figure 13 shows the velocity curves based on the RV measurements of the bottom part of the Hα emission wings and on the wings of the double He I 6678 emission. One can see a clear sinusoidal variation of the Hα emission RVs with the orbital phase. It is also significant that the epoch of the RV minimum of the Hα emission, HJD 2 450 013.81 ± 0.62, is identical to the epoch of minimum light.

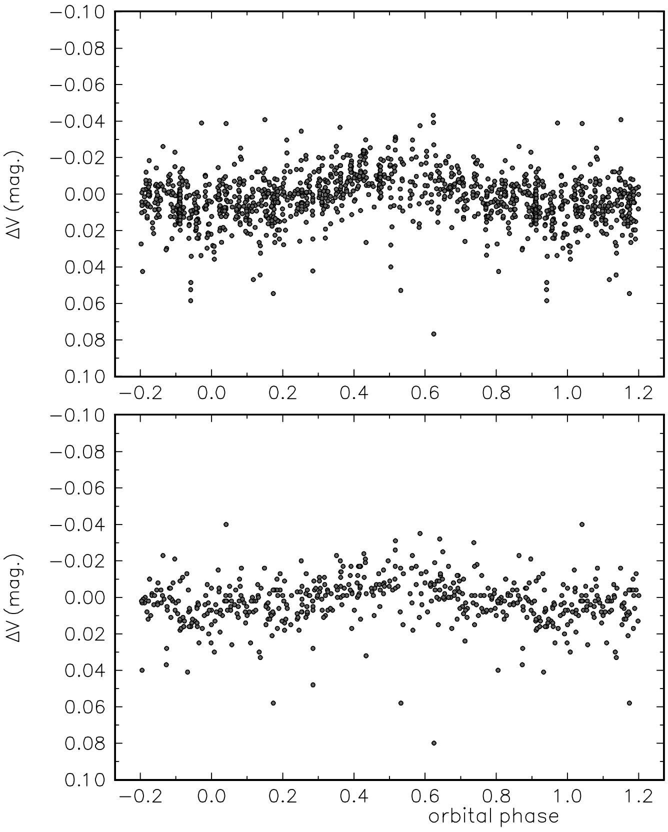

Fig. 10. The orbital V magnitude light curve of V832 Cyg plotted for the ephemeris of solution 1: $T_{\rm min.light}$ = HJD 2 450 013.71+28$^{\rm d}\!.$1971×E. Individual observations are shown in the upper panel while the bottom panel shows the 1-d normal points.

A notable thing is that the He I 6678 emission also roughly follows the RV curve of the V832 Cyg primary, though with a larger amplitude and some shift in phase, and *does not define* a RV curve with a large amplitude *in antiphase* to the RV curve of the Hα emission as was found by Gies et al. (1993) and Božić et al. (1995) for φ Per. The larger scatter along the RV curve is understandable since the He I 6678 emission line is very weak and the measurements can also partly be affected by possible weak subfeatures moving across the He I 6678 line profile. Besides, one can suspect that some additional emission is affecting the RV of the He I 6678 emission near RV maximum. A closer inspection of Fig. 13 reveals that it is still conceivable that in all phases outside the RV maximum the He I 6678 emission closely follows the RV curve of the Hα emission. This has to be verified with a more numerous data set.

6. Towards interpretation

6.1. Basic physical properties of the Be primary

Let us first try to estimate the basic physical properties of the primary component of the 28$^{\rm d}\!.$2 binary. One can obtain

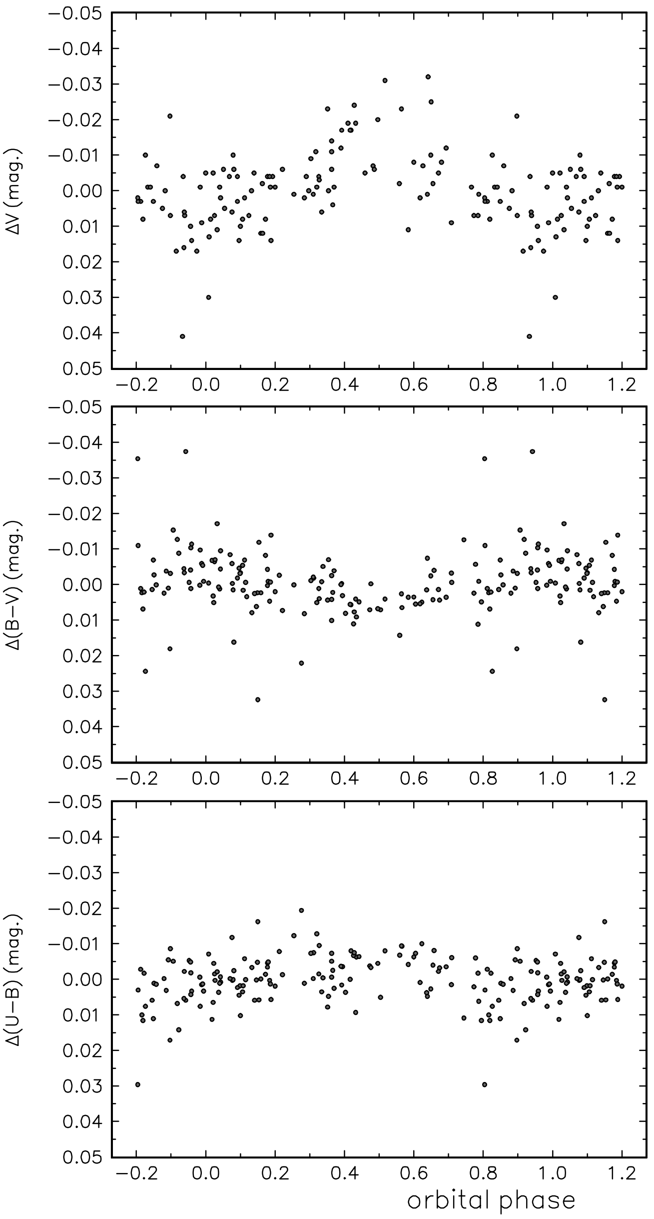

Fig. 11. The orbital light and colour curves based on Hvar and San Pedro Mártir observations prewhitened for long-term changes. The ephemeris of solution 1 was used: $T_{\rm min.light}$ = HJD 2 450 013.71+$28.^{\rm d}1971 \times E$.

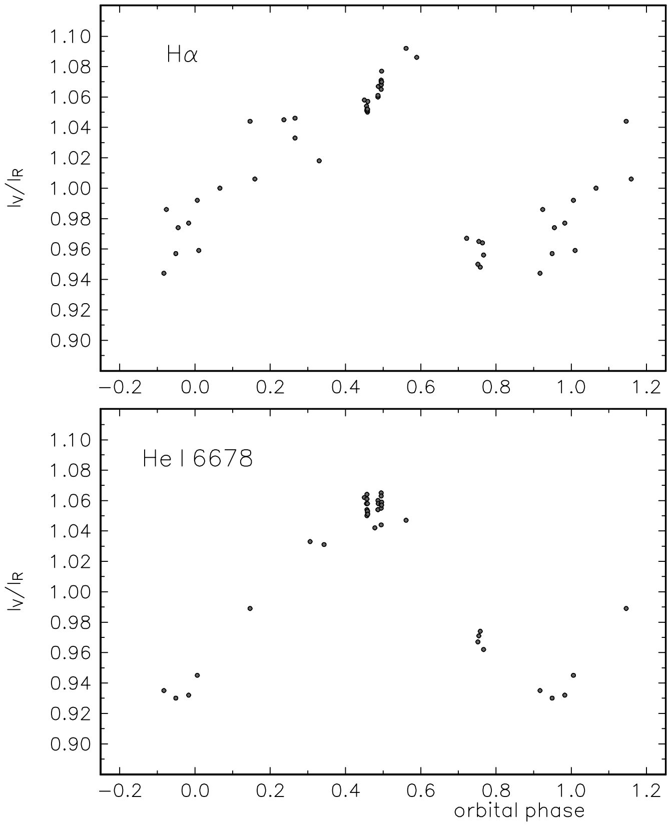

Fig. 12. The orbital I_R/I_V curve of Hα and He I 6678 lines plotted for the ephemeris of solution 1: $T_{\rm min.light}$ = HJD 2 450 013.71+$28.^{\rm d}1971 \times E$.

an estimate of the radius of the primary using dereddened V_0 magnitude, effective temperature and the Hipparcos parallax of $0.''00290 \pm 0.''00064$ (Perryman et al. 1997). The best estimate of the properties of the underlying star comes from the epoch near JD 2 443 000 when the star was almost without emission. The mean value of 5 UBV observations available to us from that epoch (year 1977) is

$V = 5.^{\rm m}030$, $(B-V) = -0.^{\rm m}185$, $(U-B) = -0.^{\rm m}910$.

A standard dereddening leads to

$V_0 = 4.^{\rm m}797$, $(B-V)_0 = -0.^{\rm m}258$, $(U-B)_0 = -0.^{\rm m}963$.

It agrees very well with the value of $E(B-V) = 0.^{\rm m}07$ derived for V832 Cyg from the magnitude of the 2200 Å interstellar bump by Beeckmans & Hubert-Delplace (1980). According to Hartkopf et al. (2001), the magnitude difference between V832 Cyg and its closer visual companion Aa is $2.^{\rm m}85$ which means that one has to add $0.^{\rm m}076$ to the dereddened V_0 magnitude to obtain the brightness of the V832 Cyg primary of $4.^{\rm m}873$. The above dereddened colours correspond well to a B1 main sequence star and the corresponding

$\log T_{\rm eff.} = 4.413$

if one interpolates in Popper's (1980) calibration. Together with the Hipparcos parallax this gives the following estimate of the radius of the primary

$R = 5.31\ R_\odot\ (4.35\,R_\odot\ - 6.81\,R_\odot)$

where the range given in brackets in based on the quoted error in the Hipparcos parallax only. Note that the radius and mass of a normal star of the given effective temperature are

$R = 4.85\ R_\odot$ and $M = 10.78\ M_\odot$

after Harmanec's (1988) calibration. Our independent estimate of the radius agrees well with it. The same is also true if one estimates the radius using the acceleration of sub-features detected by Yang in 1988, $v \sin i$ values quoted below and the assumption of an intermediate inclination.

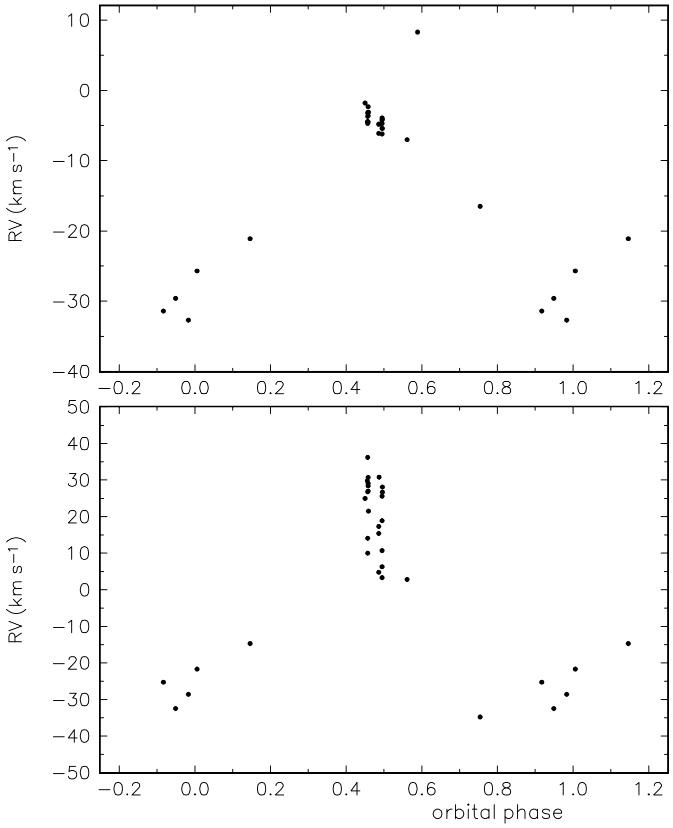

Fig. 13. The RV curves based on RV measurements of the bottom part of the Hα emission wings (top) and wings of the double He I 6678 emission in DAO, Ondřejov and Rožen spectra. The ephemeris of solution 1 was used: $T_{\rm min.light} = $ HJD 2 450 013.71+28$^{\rm d}_{.}$1971 × E.

The primary of V832 Cyg is a rapid rotator. Hutchings & Stoeckley (1977) derived $v \sin i = 450$ km s^{-1} and this value agrees well with our He I line profiles. Chauville et al. (2001) derived $v \sin i = 379 \pm 22$ km s^{-1} from high-dispersion spectra obtained in 1992. The often quoted value of 260 km s^{-1}, published by Slettebak (1982), is too low. For our estimate of the radius and mass of the primary, the Keplerian velocity at the equator of the primary is 620 km s^{-1}. For instance for $v \sin i = 450$ km s^{-1} this implies that the inclination of the rotational axis must be higher than 46°. One also gets a lower estimate of the corotation period near the primary as 0$^{\rm d}_{.}$43.

6.2. Basic physical properties of the 28$^{\rm d}_{.}$2 spectroscopic binary

A reliable determination of the orbital elements of an emission-line object is always a difficult task. At first sight, one could argue that the RV curve obtained by Rivinius & Štefl (2000) which is based on the RVs of a presumably photospheric He I 4471 absorption line should be trusted. This need not be true, however. In Table 9 we collected several available orbital solutions, based on earlier as well as our new RVs. We note that the longitude of periastron of the eccentric orbit derived by Rivinius & Štefl is about 270°. Already Sterne (1941) has shown that a spurious eccentricity due to tidal distortion of a binary component must lead to an eccentric orbit solution with ω close to 270° or 90° if the observed RVs are formally subjected to a program for orbital solution. Harmanec (2001) recently pointed out that *any* disturbance of the true orbital RV curve which *is symmetric with respect to the line joining the binary components* will lead to such an effect. This is indeed observed, for instance for stars nearly filling their Roche lobes (see, e.g., Kenyon & Garcia 1986). Therefore – although there must certainly exist binaries with truly eccentric orbits and values of the longitude of periastron close to either 90° or 270° – one should always investigate such cases carefully against possibly spurious eccentricity. Also the semiamplitude of the orbital solution obtained by Rivinius & Štefl may in fact be larger than the true one. As one would expect for such an early-Be star, and as Rivinius and Štefl themselves mentioned in the more extended version of their paper, posted during the Alicante IAU Col. 175 meeting, even the He I 4471 line profiles *are partly filled by emission.* Since the orbital V/R variations are essentially in phase with the RV curves as we have demonstrated above, it is clear that the determination of RVs from the absoption parts of the profiles will lead to a RV curve with an amplitude *higher than the true orbital amplitude.* This is because when, for instance, the V/R ratio and orbital RV are at maximum, the V wing of the seemingly absorption line is a bit more filled by emission, therefore the whole absorption part of the profile corresponds to a RV higher than the true orbital RV. This conjecture seems to be supported by an inspection of Table 9. The amplitude of the RV curve of the central Hα absorption line derived by Tarasov & Tuominen (1987) is much higher than the amplitude of the He I 4471 absorption. This is to be expected since the Hα emission is much stronger than that of He I 4471, therefore the effect of the V/R changes must also be larger.

We therefore believe that the determination of the true orbital RV curve can best be obtained from the RV measurements of the wings of Hα emission as we did here and as Božić et al. (1995) did earlier for φ Per. Note that it is very probable that the rotational velocity of the circumstellar disk decreases with increasing distance from the star. One can, therefore, assume that any possible asymmetries in the distribution of the circumstellar matter will affect the central parts of the emission profiles more than the outer wings of the emission which reflect the motion of the inner and probably more axially symmetric parts of the disk. If the disk is centred on the primary, the outer wings of the Balmer emission should reflect the true orbital motion of the primary. Indeed, the RV curve of the emission wings is circular and has an amplitude of only 13 km s^{-1} – see Table 9. Consequently, we base our estimate of the properties of the binary system on this RV curve. In Table 10 we give them for the two extremes of possible orbital inclination, making a reasonable assumption that the equatorial plane of the primary and the orbital plane of the binary coincide. One can see that

Table 9. A comparison of various orbital solutions for V832 Cyg derived with FOTEL program. Solution denoted TT is a solution derived by us from the RVs of the central absorption core of Hα profile published by Tarasov & Tuominen (1987). Solution RS is based on He I 4471 absorption RVs and is reproduced here from the paper by Rivinius & Štefl (2000) (note that they cross-correlated the profiles to derive the RVs and were not able to obtain the systemic velocity γ). The remaining solutions are based on our RVs from Table 7. All epochs are in HJD-2 400 000 and the rms error is error per 1 observation of unit weight.

Element	TT	RS	Hα emis.	He I 6678 emis.	He I 6678 abs.
P (d)	28.1971fixed	28.1702 ± 0.0014	28.1971fixed	28.1971fixed	28.1971fixed
$T_{\rm min.RV}$	46627.98 ± 0.34	50013.6	50013.81 ± 0.62	50010.23 ± 0.66	50010.1 ± 1.2
$T_{\rm periastr.}$	–	50018.9 ± 2.5	–	–	–
e	0 fixed	0.20 ± 0.08	0 fixed	0 fixed	0 fixed
ω (deg.)	–	271 ± 35	–	–	–
K (km s^{-1})	52.6 ± 1.3	27.2 ± 8.5	13.0 ± 1.0	31.3 ± 1.6	25.4 ± 3.0
γ (km s^{-1})	21.4 ± 2.3	–	−16.49 ± 0.76	−4.7 ± 2.1	−14.1 ± 3.2
No. of RVs	13	46	30	29	29
rms (km s^{-1})	7.98	?	3.08	8.43	13.0

Table 10. Possible basic properties of the $28^{\rm d}\!.2$ binary system, derived for the two extremes of orbital inclination and adopting the primary mass of 10.78 $M_\odot$ and the semiamplitude of 13 km s^{-1} from the orbital solution for Hα emission – cf. Table 9. Tabulated are the mass ratio, mass of secondary and the expected semiamplitude of its orbital RV curve K_2, binary separation A and the radii of the Roche lobes around both stars $R_1^{\rm R}$ and $R_2^{\rm R}$.

i (°)	M_2/M_1	M_2 ($M_\odot$)	K_2 (km s^{-1})	A ($R_\odot$)	$R_1^{\rm R}$ ($R_\odot$)	$R_2^{\rm R}$ ($R_\odot$)
90	0.089	0.96	146	88.6	53.8	16.9
45	0.129	1.39	101	89.7	51.3	19.1

Table 11. Sinusoidal fits to the I_V/I_R variations of the Hα and He I 6678 emission profiles of V832 Cyg from the epoch without long-term V/R changes after HJD 2 446 650. All epochs are in HJD-2 400 000, A is the semiamplitude of the I_V/I_R curve and the rms error is the error per 1 observation of unit weight.

Element	Hα	Hα "eccentric"	He I 6678
P (d)	28.1971 fixed	28.1965 ± 0.0049	28.1971 fixed
$T_{{\rm min.}I_V/I_R}$	50010.77 ± 0.43	50007.62 ±0.70	50012.09 ± 0.18
e	0.0 fixed	0.524 ± 0.096	0.0 fixed
ω (deg)	–	86.5 ± 8.9	–
A (mag)	0.0548 ± 0.0041	0.0664 ± 0.0083	0.0618 ± 0.0016
No. of obs.	44	44	36
rms (mag)	0.0193	0.0117	0.0060

the dimensions of the binary system are quite well constrained. No matter whether one adopts our circular orbit and $K_1 = 13$ km s^{-1} based on the broad wings of the Hα emission or the eccentric orbit with $K_1 = 27.2$ km s^{-1} advocated by Rivinius & Štefl (2000), the separation of the components must be about 90 $R_\odot$ and the mass ratio between about 0.1 and 0.2. For the mass of the primary appropriate for its effective temperature the expected mass of the secondary should be between 1 and 2 $M_\odot$. This implies an expected semi-amplitude of the secondary between about 60 and 150 km s^{-1}.

The I_V/I_R orbital variations, detectable after HJD 2 446 650 when the slowly revolving elongation of the envelope vanished, which are depicted in Fig. 12, deserve a few comments.

1. In Table 11 we present several fits to these changes, calculated with the help of the FOTEL program. We derived sinusoidal fits for both lines but we also derived "an eccentric orbit" solution for the Hα emission to allow an empirical modelling of its non-sinusoidal shape. We allowed for a free convergence of all elements, including the orbital period in this particular solution. This resulted in the determination of the orbital period which is in perfect agreement with the value derived from photometry. Note also that the formal "longitude of periastron" is roughly 90°, i.e. again a value indicating that the asymmetry of the I_V/I_R curve is symmetrically distributed with respect to the line joining the two stars. The solutions also confirm that the minima of the curves somewhat precede the minima of the brightness and of the RV curve of the Hα emission. Note that Koubský et al. (1997) also found a non-sinusoidal I_V/I_R change of the Hα emission for V839 Her = 4 Her, another Be binary with a circular orbit. For a Be envelope inside the critical Roche lobe in a binary system one would expect that given the shape of the lobe, more material and presumably more emission power should be in the parts of the disk facing the secondary. This naturally explains why the V/R and RV curves are roughly in phase. However, for both V839 Her and V832 Cyg it seems that the asymmetry of the emission region must be slighly tilted with respect to the line joining the two stars. Since no evidence of gas streams between the components in either of the two binaries is available, the origin of this asymmetry remains unexplained;

2. Rivinius & Štefl (2000) seem to imply that there is an additional emission in the He I 6678 line of V832 Cyg, varying in antiphase with the RV curve of the primary. They also recall similarity to φ Per and interpret the He I 6678 emission as arising in a segment of the disk around the primary, which is facing the secondary and which is illuminated by its presumably very hot radiation. An interesting fact about the fits of Table 11 is that the amplitudes of the changes *are comparable* for both lines. We therefore suggest that a more natural interpretation of the He I 6678 emission is that it originates in all the inner parts of the disk around the primary.

The mutual phase relationship of the RV and light variation of V832 Cyg is quite unusual and hard to explain. While for several other known Be binaries the light minimum occurs at elongation when the Be star is *receding from us* (as already pointed out by Kříž & Harmanec 1975), we observe just the opposite situation for V832 Cyg. We do not have any convincing interpretation of this behaviour. Only very tentatively we suggest that considering also the colour variation one can say that the mild light minimum near orbital phase zero when the Be component is approaching seems to indicate a mild decrease in the dimensions of the area responsible for the continuum radiation (the object moves towards the main sequence in the $(U-B)$ vs. $(B-V)$ diagram). Perhaps, a part of the optically thick regions of the envelope is being eclipsed at these orbital phases.

In passing, we also note that there is no unambiguous direct evidence of the secondary spectrum at the moment. The origin of the weak He II 4686 emission line (amounting to 0.5 per cent of the continuum radiation), detected in the mean Heros spectrum by Rivinius & Štefl (2000), is not quite clear. The authors say only that the spectra were "RV corrected" but they do not say how. Should the He II emission line be associated with the secondary, its RV curve should have an amplitude of about 100 km s^{-1} which should be tested with future high-resolution and high-S/N spectra.

6.3. Approximate properties of the speckle-interferometric pair Aa

Figure 14 is a plot of the position angle and separation of the closer visual component to V832 Cyg, ADS 14526Aa, based on data published by Hartkopf et al. (2001). Evidence of the orbital motion is obvious. It is interesting to attempt rough estimates of the orbital period of this closer visual pair. Using the observed parallax, the largest recorded angular separation of $0\farcs22$ and Kepler's Third Law (assuming a total mass of 13 $M_{\odot}$), one arrives at an orbital period of 183 years. Assuming a uniform change of the position angle with time, one gets 193 years to complete one full 360° cycle. No matter how rough both these estimates are, it seems that the orbital period of the Aa system may be about 200 years.

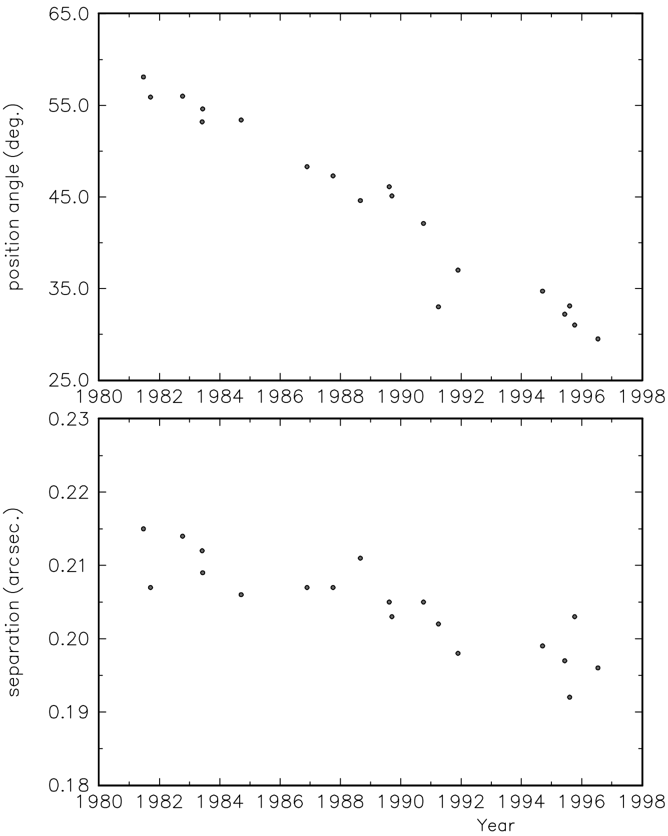

Fig. 14. Recorded orbital motion of the closer visual component ADS Aa.

6.4. Long-term changes

The observed long-term variations depicted in Fig. 4 can be qualitatively understood as follows:

1. The observed positive correlation between the emission strength and brightness of the object indicates, according to Harmanec (1983), that the star is not observed equator-on (as suggested by Hutchings & Stoeckley 1977) but under some intermediate angle. Note that Rivinius et al. (2000) also argue in favour of an intermediate inclination. The newly formed envelope was elongated and its gradual revolution in space caused the V/R variations with the 2-year cycles. The envelope gradually became axially symmetric and the long-term V/R changes ceased after about JD 2 446 650.
2. The reason why the envelope became elongated remains unclear. In recent years, most researchers adopt the model of the so-called one-arm oscillation by Kato (1983) and Okazaki (1991). We note, however, that the original idea by Kříž & Harmanec (1975) that the elongated disk can somehow be formed via interaction of components in a binary system still represents a viable alternative hypothesis since the number of confirmed binaries among long-term V/R Be variables is growing steadily – as recently discussed by Harmanec (2001).

3. We have no clear explanation for either the cyclic changes of the $(U - B)$ index or similar (but somewhat shorter) cyclic changes of the brightness in V observed since about JD 2 447 000. Their origin must probably be sought in physical variations in the Be envelope during the process of its gradual evolution.

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