A&A 416, 669–676 (2004)
DOI: 10.1051/0004-6361:20031732

Astronomy & Astrophysics

Properties and nature of Be stars⋆,⋆⋆

XXII. Long-term light and spectral variations of the new bright Be star HD 6226

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Received 14 May 2003 / Accepted 6 November 2003

Abstract. Photometric and spectroscopic monitoring of the B star HD 6226 resulted in the finding that this object is a new bright Be star with a clear positive correlation between the brightness and emission-line strength. The emission-line episodes are relatively short and seem to repeat frequently which makes this star an ideal target for studying the causes of the Be phenomenon. The general character of the light variations, the low $v \sin i = 70$ km s^{-1} and the very pronounced line asymmetries of the He I 6678 line, seen both outside and during emission-line episodes, are all attributes which make HD 6226 phenomenologically very similar to the well-known Be star ω CMa. Radial velocities of the deepest parts of the metallic and He I 6678 absorption lines vary with a strict period of $2\overset{\text{d}}{.}61507$ over the whole time interval covered by the observations, the velocities of the broad outer wings of the same lines varying in anti-phase and with a lower amplitude. This periodicity could not be found in the radial-velocity variations of the sharp core of Hα. There is some indication of variability on a time scale of 24–29 days but our data are insufficient to prove that conclusively. A comparison of the line spectrum obtained outside emission episodes with synthetic spectra, standard dereddening of *UBV* magnitudes and Hipparcos parallax all agree with the conclusion that HD 6226 is a star with the following basic properties: $T_{\rm eff} = 17\,000$ K, $\log g = 3.0$ [cgs], mass of 5 $M_{\odot}$ and radius of 11 $R_{\odot}$. The strong emission-line episodes may appear regularly, in a cycle of 630 days but with different durations of individual cycles. HD 6226 is probably one of the first B stars for which the Be nature was predicted on the basis of the character of its light and colour changes.

Key words. stars: binaries: spectroscopic – stars: emission-line, Be – stars: individual: HD 6226

1. Introduction

HD 6226 (BD+46°245, SAO 36891, HIP 4983) is a little studied bright B2IV-V (Guetter 1968) or B3III (Bidelman et al. 1988) star. Božić & Harmanec (1998) discovered light and colour variations of this star, having repetitive brightenings accompanied by a reddening of the $(B - V)$ index and a simultaneous blueing of $(U - B)$. From a period analysis of combined Hvar photometry and Hipparcos $H_{\rm p}$ magnitudes (Perryman et al. 1997), Božić & Harmanec concluded that if the brightenings occur regularly, the period of the phenomenon could be $481\overset{\text{d}}{.}3$. Without having any evidence from spectroscopy, they tentatively suggested that the light variations are reminiscent of a Be star with positive correlation between the optical brightness and the emission strength (cf., e.g., Gerasimovič 1928; Dachs 1982; Hirata 1982 or Harmanec 1983, 1994, 2000) and appealed to other observers to monitor the star both spectroscopically and photometrically.

McCollum et al. (2000) discovered a strong Hα emission line on a spectrum taken on November 11, 2000. However – to the best of our knowledge – a detailed account of their finding has not yet been published. Castelaz & McCollum (2003) presented another preliminary report based on their

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⋆ Based on spectral and photometric observations from the following observatories: Castanet-Tolosan, Dominion Astrophysical Observatory, Heidelberg, Hvar, Ondřejov, Skalnaté Pleso and Stará Lesná and also on photoelectric photometry by AAVSO members.

⋆⋆ Tables 2 and 4 are available only 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/416/669

Table 1. Journal of photoelectric observations; observing stations are identified by their running numbers they have in the Ondřejov/Praha photometric archives.

Station No.	Time interval (HJD-2 400 000)	No. of obs.	Passbands	Remark
1	45 212.6–52 847.6	483	*UBV*	
61	47 868.6–49 038.4	83	*V*	all-sky
18	50 660.4–52 696.3	66	*UBV*	
43	50 665.0–50 860.6	31	*V*	
3	50 684.5–51 602.3	274	*UBV*	

Observing stations and instruments:
1... Hvar 0.65-m reflector, a photometer with EMI 6256 tube; 3... Skalnaté Pleso 0.60-m reflector with a SSP5 photometer and Hamamatsu R4457 tube; 18... Stará Lesná 0.60-m reflector and a photometer with EMI 9789Q tube; 43... AAVSO photoelectric observing program coordinated by JRP; 61... Hipparcos satellite; H_p magnitude (Perryman et al. 1997) transformed to the standard Johnson V after Harmanec (1998).

spectroscopic observations secured between November 2002 and March 2003. The emission was not seen on spectra taken during November and December 2002 but reappeared on spectra taken between January 19 and March 15, 2003. They noted that this rules out the 481-d period suspected by Božić and Harmanec (1998) and claimed that "Hα emission changes generally do not follow the photometric variations of Be stars."

2. Observations and reductions

2.1. Photometry

Photoelectric observations of HD 6226 at our disposal consist of the following five data sets:

1. Systematic *UBV* observations from Hvar Observatory, Croatia; observations secured before 1991 have already been published by Pavlovski et al. (1997) and Harmanec et al. (1997).
2. Broad-band H_p magnitude observations secured by the Hipparcos satellite (Perryman et al. 1997) and transformed to the standard Johnson V with a transformation formula derived by Harmanec (1998).
3. *UBV* observations obtained with the 0.60-m reflector of the Stará Lesná Observatory, Slovakia.
4. *UBV* observations secured with a similar 0.60-m reflector of the Skalnaté Pleso Observatory, Slovakia.
5. V magnitude observations secured as a part of the AAVSO photoelectric program by Kenneth Luedeke and James Wood.

With the exception of the all-sky Hipparcos observations, all data were obtained differentially. All observers used the standard comparison and check star, HR 189 = HD 4142 and HR 289 = HD 6114, recommended for the international Be-star photoelectric monitoring program.

The following accurate Hvar all-sky *UBV* values for HD 189

$$V = 5\overset{\text{m}}{.}674,\ B-V = -0\overset{\text{m}}{.}127,\ U-B = -0\overset{\text{m}}{.}566 \quad (1)$$

Table 3. Journal of electronic spectrograms of HD 6226.

Observatory	Time interval (HJD−2 400 000)	No. of spectra	Dispersion (Å mm^{-1})
1	50 653.98–52 875.90	12	10
2	50 659.58	1	3.9–6.8
3	52 658.28–52 679.31	2	3.9–6.8
4	52 677.26–52 679.26	2	38
5	52 832.45–52 877.51	18	17.2

Column "Observatory": 1... DAO CCD 4096; 2... Heidelberg, Heros; 3... Ondřejov, Heros; 4... Castanet Tolosan CCD; 5... Ondřejov, Coudé CCD700.

were added to the magnitude differences HD 6226 − HR 189 from all stations.

All observations were transformed to the standard Johnson system and corrections for differential extinction were applied. Hvar, Skalnaté Pleso and Stará Lesná observations were reduced with the HEC22 program (Harmanec et al. 1994; Harmanec & Horn 1998) via non-linear transformation formulæ (Hvar) or bilinear transformation (Skalnaté Pleso and Stará Lesná). AAVSO observations were reduced via a linear transformation. For convenience of future investigators, we publish all individual observations in Table 2.

2.2. Spectroscopy

Our new observational material consists of 35 electronic spectrograms, 3 from 1997 and 32 from 2003, secured at four observatories. After initial calibration and normalization, all spectrograms were rectified and their equivalent widths (EW), line intensities, and in most of them also radial velocities (RV hereafter) were measured, using the program SPEFO – see Horn et al. (1996) and Škoda (1996).

Journal of all observations is given in Table 3 and some details about the instrumentation and initial reductions are given below:

1. One echelle spectrogram was kindly obtained at our request by Dr. T. Rivinius on July 30, 1997 with the Heros spectrograph attached via optical fibre to the 0.7-m reflector of the Heidelberg Observatory. It covers the wavelength range from about 3600 to 8300 Å and has a linear dispersion ranging from 3.9 Å mm^{-1} at 4000 Å to 6.8 Å mm^{-1} at Hα. Initial wavelength and intensity calibrations of this spectrogram were carried out by Dr. T. Rivinius in Heidelberg.
2. Two more Heros echelle spectra were secured in January and February 2003 by PH with the Heros spectrograph, this time attached via optical fibre to the Cassegrain focus of the Ondřejov 2.0-m reflector. They cover the same wavelength region as the first spectrogram but their S/N ratio is lower due to rather poor weather conditions during exposures. Initial reductions of these spectra were carried out in MIDAS by MŠ and PŠ.
3. 12 CCD spectrograms (2 in 1997 and 10 in 2003) were secured by SY in the Cassegrain focus of the 1.8-m reflector (in 1997) and in the Coudé focus of the 1.2-m

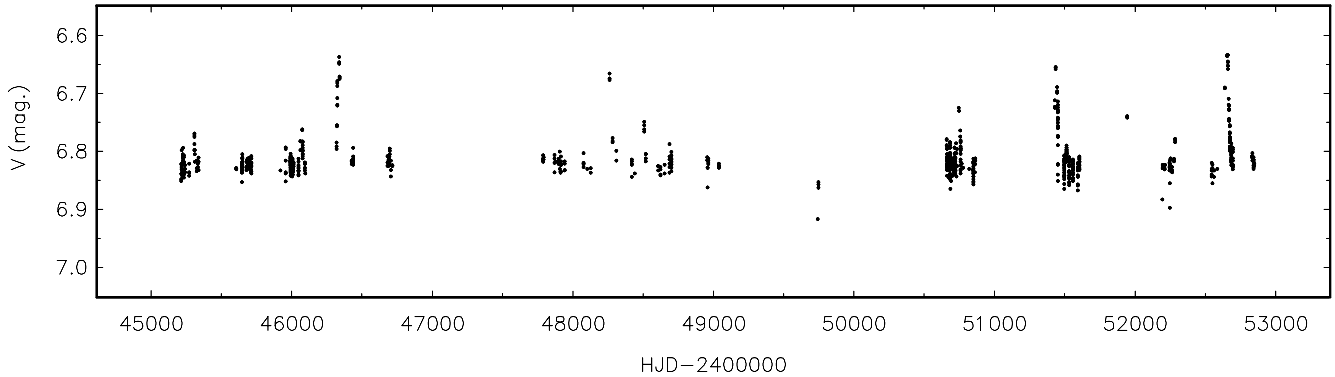

Fig. 1. Light variation of HD 6226 in the V passband plotted vs. time. Frequent light brightenings are clearly seen. All individual observations are shown.

reflector (in 2003) of the Dominion Astrophysical Observatory (DAO hereafter). They cover the wavelength region from 6200 to 6750 Å and have a linear dispersion 10 Å mm^{-1}. Their initial reductions (bias subtraction, flat-fielding and creation of 1-D spectra) were carried out by SY inside IRAF. Wavelength calibration was carried out inside SPEFO by PH.

4. 2 CCD spectrograms were secured in February 2003 by CB at the Castanet Tolosan Observatory. They cover the wavelength region from 6350 to 6890 Å and have a linear dispersion of 38 Å mm^{-1}. Their initial reduction was carried out by CB.
5. 18 CCD spectrograms were secured during summer 2003 in the Coudé focus of the Ondřejov 2-m reflector. These spectrograms have a linear dispersion of 17 Å mm^{-1} and cover the wavelength region from 6280 to 6720 Å. They were obtained (weather permitting) on several consecutive nights or even twice during a night to provide information on possible rapid variability of the line spectrum of the star.

For the red parts of all spectra (with the exception of the Castanet Tolosan spectrum which has a less accurate wavelength calibration and a very weak DAO spectrum obtained for HJD 2 452 771.9930) we measured RVs of Hα (broad absorption wings, emission wings (when seen) and a central sharp absorption core), broad absorption wings and absorption cores for the He I 6678 line, Si II doublet at 6347 and 6371 Å and Ne I 6402 line, using SPEFO and comparing the direct and reverse images of the profiles. For the Hα profile, we set on the symmetric steep portions of the emission profile, taking care to avoid disturbances due to telluric lines. We originally also tried to measure the C II doublet at 6578 and 6582 Å but these lines are badly affected by the neighbouring telluric lines and their accurate measurement was impossible.

All measurements were carried repeatedly (by JK, PH and HB), to increase the accuracy of the results. In all cases, the zero point of the RV scale was corrected through the use of reliable telluric lines, as described in Horn et al. (1996). We can, therefore, assume that all RVs from the red region have the same zero point and can be combined directly.

For the Hα profiles, we also measured its equivalent width EW, central intensity I_c and/or the peak intensities I_V and I_R of the V and R peaks of the double emission. For He I 6678,

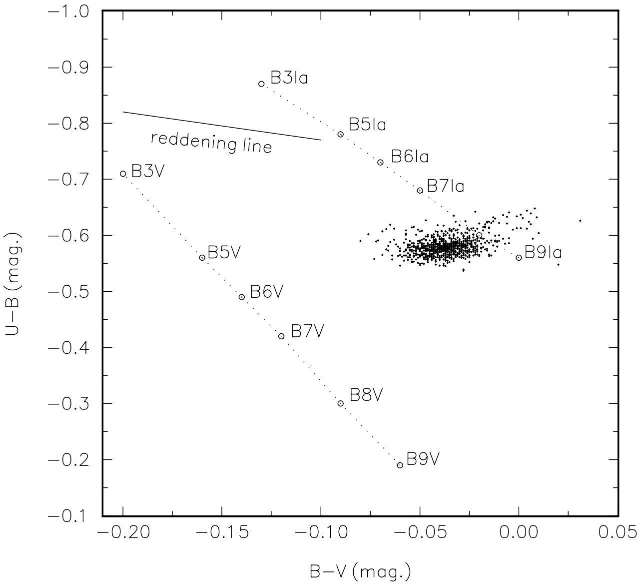

Fig. 2. The $(U-B)$ vs. $(B-V)$ diagram with all individual UBV observations of HD 6226 shown by black dots. Also shown are standard sequences for normal dwarfs and bright supergiants. It is clearly seen that HD 6226 is a reddened star and exhibits colour behaviour typical of a positive correlation between light and emission strength as defined by Harmanec (1983).

we measured the equivalent width and central intensity. These quantitative measurements are summarized in Table 4.

3. Long-term variations of HD 6226

Figure 1 is the time plot of the V magnitude of HD 6226 over the interval covered by our observations. One can see that major brightenings were observed around JD 2 446 330, ..48 250, ..51 440, and ..52 655 and milder or incompletely covered ones on JD 2 446 070, ..48 500, ..50 745, ..51 940::, and ..52 290.

Figure 2 is colour-colour diagram and all individual observations are shown. The object is reddened and the character of the colour changes corresponds to a positive correlation between the brightness and emission strength. The object moves from main sequence towards supergiant sequence and back in the colour-colour diagram.

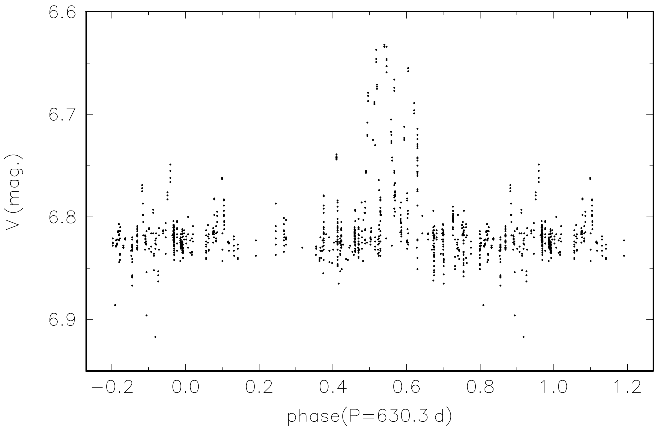

Fig. 3. Light variation of HD 6226 in the *V* passband plotted vs. phase of the 630$^{d}_{.}$3 period. One can see that the major light brightenings clearly occur on that time scale but their strength varies from one cycle to another.

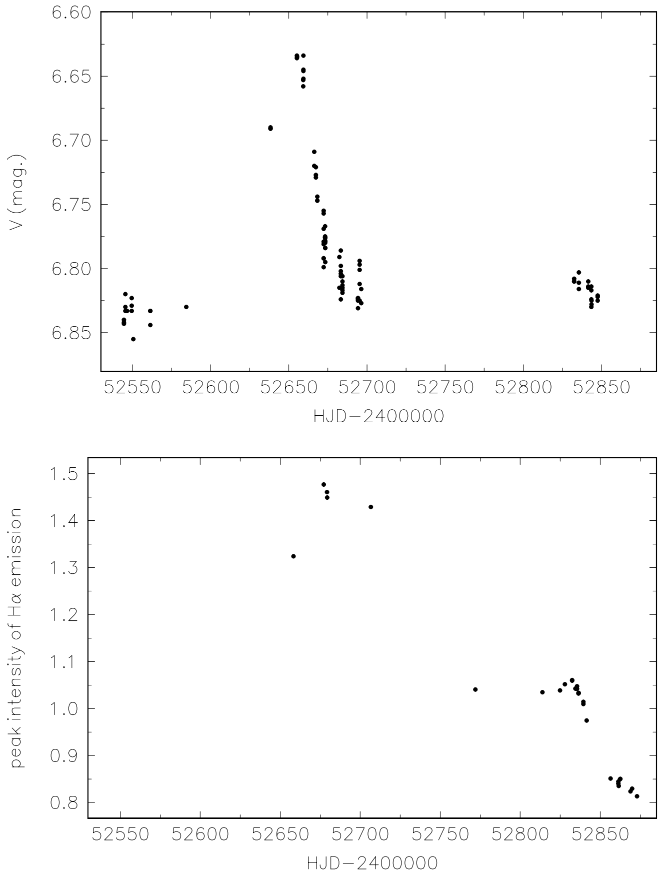

Fig. 4. The 2003 emission-line episode of HD 6226: *Upper panel: V* magnitude vs. time. *Bottom panel:* Peak intensity $(V + R)/2$ of the Hα emission vs. time.

Long-term variations of Be stars are known to be cyclic but usually not strictly periodic. However – since Božić and Harmanec (1998) suspected the presence of a periodicity and since the brightenings of HD 6226 occur quite often and could be related to possible binary nature of the object, we carried out a period search in the *V*-band observations down to 50 days. We found that there is only one period of 630$^{d}_{.}$3 for which all the major brightenings fall into a similar narrow phase interval – see the phase diagram in Fig. 3. One can see, however, that each brightening is characterized by a somewhat different strength and duration and that some of the milder brightenings occur at phases other than the major ones. Only continuing observations can help to decide whether there is indeed some regular clock controlling the occurrence of major brightenings.

In Fig. 4 we compare the *V* magnitude and the strength of the Hα emission observed during the 2003 episode in detail. In addition to our spectra, secured on only four different nights, one can also use *qualitative information* from spectra reported by Castelaz & McCollum (2003)[1]. They observed Hα absorption between JD 2 452 595 and ..651 and Hα emission between JD 2 452 659 and .. 713, in a good agreement with our findings.

We note that the observed sequence of events is typical of the positive correlation between brightness and emission strength, as defined by Harmanec (1983, 2000) and discussed semi-quantitatively for another Be star, V839 Her = 4 Her by Koubský et al. (1997). Our interpretation is the following: The initial formation of the envelope manifests itself as *a pseudophotosphere*, a region above the stellar photosphere which is optically thick in the continuum. Since we probably observe HD 6226 more pole-on than equator-on (considering its low $v \sin i$ – see below), this pseudophotosphere acts to increase the observed radius of the star which naturally leads to brightening of the object and its apparent evolution from the main sequence towards the supergiant sequence in the colour-colour diagram. As the envelope grows, it gradually gets optically thin in the continuum but opaque in the Balmer lines and this leads to the development of Balmer emission lines and a gradual decrease of the brightness of the object to its undisturbed level. Figure 4 indeed shows that the increase of the strength of Hα emission follows with some lag after the brightness increase.

A representative selection of Hα and He I 6678 line profiles is displayed in Figs. 7 and 8. It is seen that a central absorption reversal developed gradually in the Hα emission profile as the strength of the emission grew. We tried to subtract one 1997 Hα profile without emission from the 2003 ones. We found that while for the profile obtained at JD 2 452 658 this subtraction led to a net emission profile without a central reversal, all consecutive profiles have a central reversal even after the subtraction.

No trace of emission was observed in any of 1997 spectra (HJDs from 2 450 653.98 to 2 450 713.05). Figure 5 is a detailed plot of *V* magnitude vs. time over the period of these spectroscopic observations. All the 1997 spectra were obtained during a time interval when the brightness of the star was in its normal low state, although another brightening occurred shortly after the last 1997 spectrogram was obtained.

Regrettably, we do not have photometric data close enough to the first, November 11, 2000 observation of the Balmer emission in the spectrum of HD 6226 by McCollum et al. (2000). Nevertheless – as one can see in Fig. 6 – there is at least partial evidence that this emission episode was also accompanied by a brightening of the object.

[1] Their preliminary report is based on extracted echelle spectra near Hα without flux or wavelength calibration.

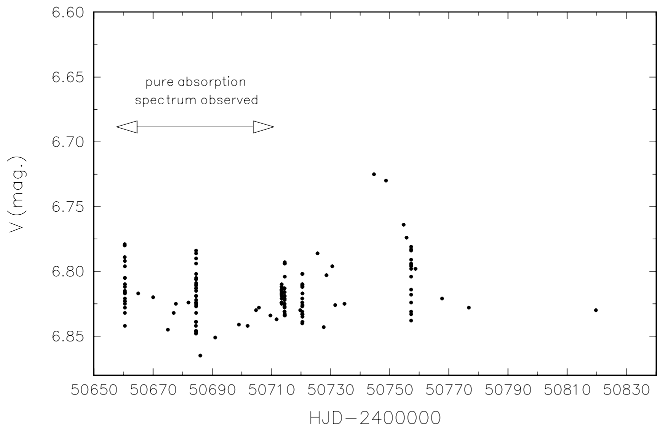

Fig. 5. A plot of the *V* magnitude vs. time for the period covered by the 1997 spectral observations.

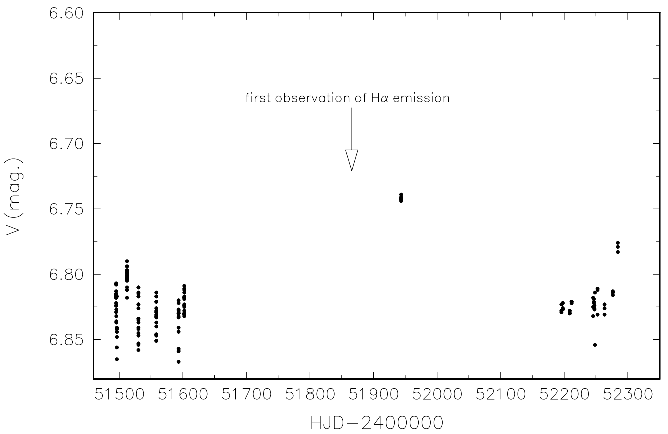

Fig. 6. A plot of the *V* magnitude vs. time for the period covered when the emission of HD 6226 was first observed on JD 2 451 860.

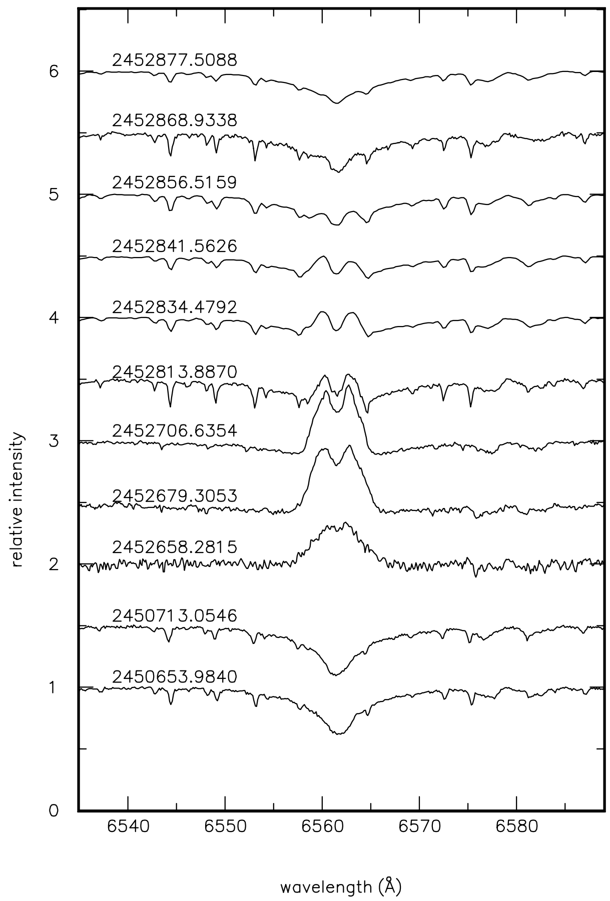

Fig. 7. A representative selection of the 1997 and 2003 Hα and C II 6578 & 6582 line profiles of HD 6226.

4. Search for periodic variations

Both Figs. 7 and 8 and Table 4 indicate that HD 6226 exhibits very pronounced line-profile as well as RV variations on a time scale of days. The series of He I 6678 line profiles shows variations reminiscent of those of ω CMa (HD 56139), another Be star with a low $v \sin i$ value – see Baade (1981).

Using several period searching techniques, we therefore analyzed all RV data as well as spectrophotometric quantities for the presence of possible periodic changes over the range of periods from long ones down to $0\overset{\rm d}{.}3$.

4.1. *Periodic changes on a time scale comparable to stellar rotation*

The RV of the narrow deepest part and of the outer wings of the He I 6678 line profile vary with a strict periodicity of $2\overset{\rm d}{.}615$ or its 1-year alias of $2\overset{\rm d}{.}618$ and in antiphase to each other. Since the sharp lowest part of the line is best defined, we calculated sinusoidal fits of its RV leading to the following linear ephemeris

$$T_{\rm max.RV} = \text{HJD } 2\,452\,834.836(36) + 2\overset{\rm d}{.}61507(13) \cdot E, \qquad (2)$$

the errors of the two last digits being given in the brackets. A similar fit for the $2\overset{\rm d}{.}618$ alias gave a worse rms error of the fit. Note that the ephemeris can reconcile data separated by 6 years.

Keeping the period from ephemeris (2) fixed, we derived similar fits also for the broad wings of the line. The same periodicity was found in the RVs of the deepest parts and wings of the mean RV of the Si II doublet and Ne I line. We also derived such a fit to the RV of the broad outer wings of Hα absorption, though its RV suffers from large measuring errors and shows no very clear evidence of the $2\overset{\rm d}{.}615$ period. These sinusoidal fits are summarized in Table 4 and the corresponding phase diagrams are plotted in Fig. 9.

The amplitude of the variations is larger for lines with a smaller intrinsic width. The two most negative RVs of metallic line cores come from Heros spectra which have about twice better resolution than either Ondřejov Coudé or DAO spectra. Such behaviour is typical of apparent RV variations due to velocity fields in the stellar atmospheres or envelopes. We therefore tentatively conclude that the $2\overset{\rm d}{.}615$ period is a signature of such variations, and that it roughly measures the stellar rotation since the horizontal amplitudes of velocity fields are usually small in comparison to linear velocity of rotation.

The velocity measured on the wings of the emission line does not follow the $2\overset{\rm d}{.}615$ period but can be reconciled with a longer period of $2\overset{\rm d}{.}719$. The number of our measurements is very limited, however.

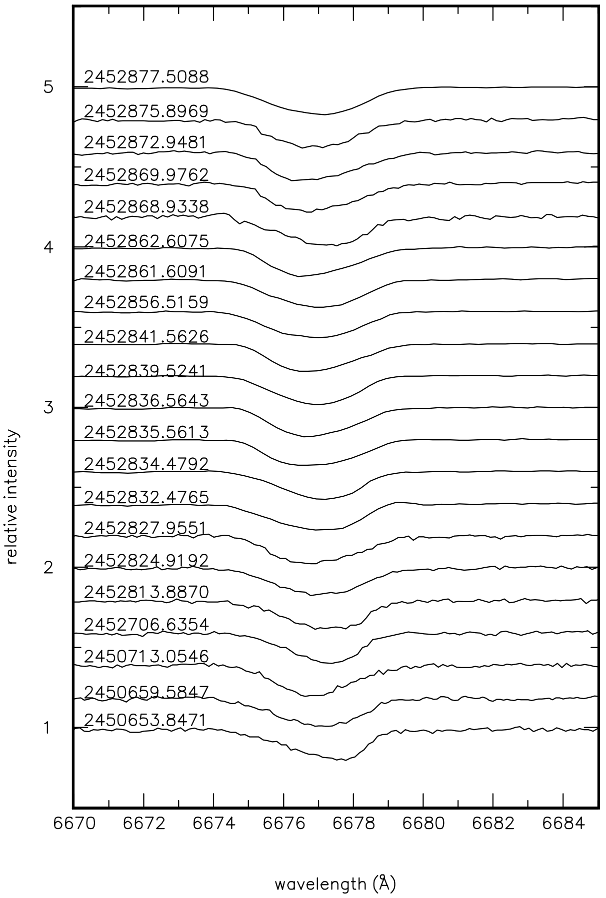

Fig. 8. A representative selection of the 1997 and 2003 He I 6678 line profiles of HD 6226. Note the pronounced and variable line asymmetry.

4.2. Rapid variations on a time scale of hours?

An inspection of Fig. 5 asks the question of whether at least a part of the light variations of HD 6226 is not related to variability on a time scale of hours. This cannot be excluded completely – especially since the position of the star in the HR diagram is at the edge of the β Cep instability strip. However, no really compelling evidence of rapid *light* changes is currently available. We use and show here individual observations, integrated over only 10 seconds, and that the increased scatter in Fig. 5 comes from two less than ideal nights of Skalnaté Pleso observations during which transparency variations were obvious also from the observations of the check star. Otherwise, the evidence for rapid variations exceeding the usual scatter belt of some 0^{m}.02–0^{m}.03 is lacking, as also seen in the time plot of the variable along with the check-star observations shown by Božić and Harmanec (1998). Using the self-correlation technique by Percy et al. (2002), we find no evidence of variations on a time scale shorter than 0.4 days and amplitudes larger than 0^{m}.01 also in the Hipparcos photometry of the star.

On the other hand, our recent Ondřejov spectra, obtained during the same night, do provide some evidence of moving sub-features travelling accross the He I 6678 line profile – see Fig. 10. This seems to support our previous conclusion that the object is a line-profile variable.

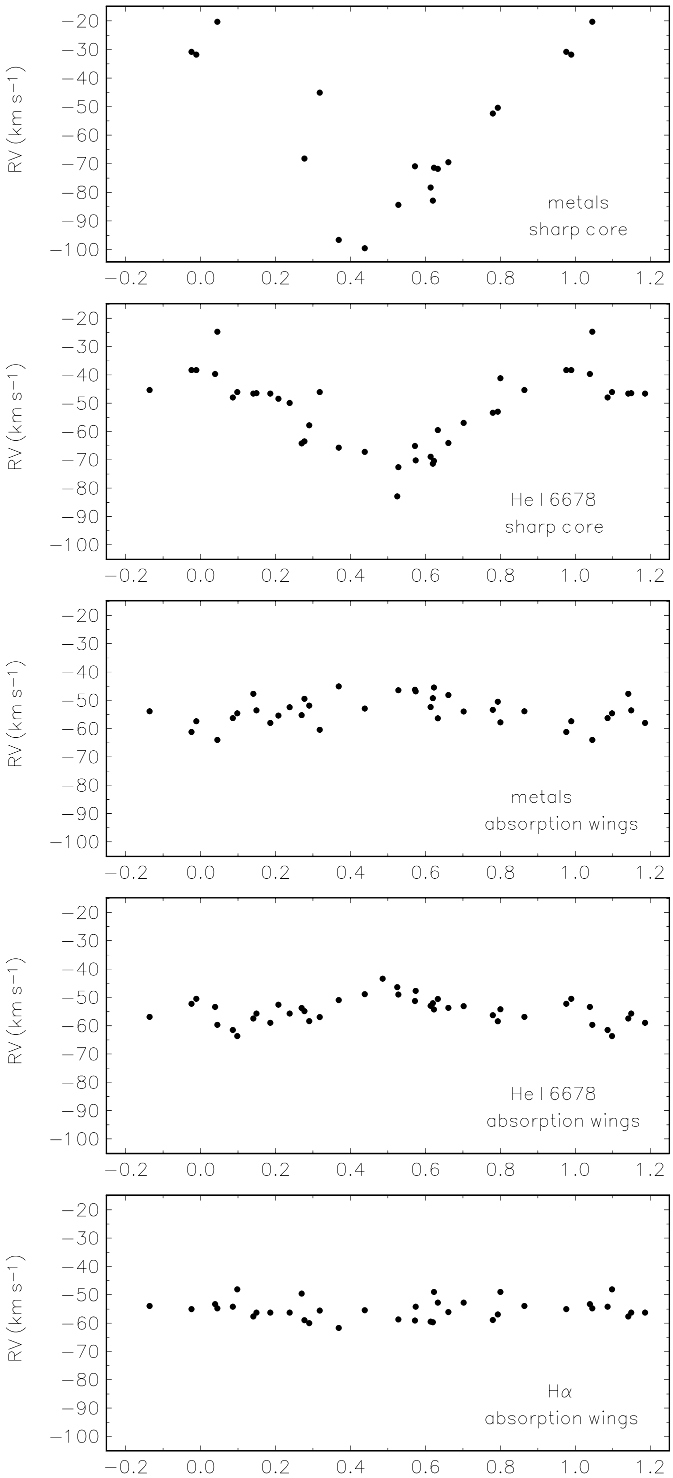

Fig. 9. Radial-velocity variations of different measured features plotted vs. phase of the 2^{d}.61507 period for ephemeris (2).

4.3. A longer period?

The very accurate RV measurements of the Hα sharp absorption core cannot be reconciled with the 2^{d}.615 period (although they also clearly exhibit some rapid changes undoubtedly exceeding the measuring error of some 1–2 km s^{-1}) but with a much longer period of 24^{d}.920 ± 0^{d}.025 and a semi-amplitude of 6 km s^{-1}. A period analysis of the RV residuals from the 2^{d}.615

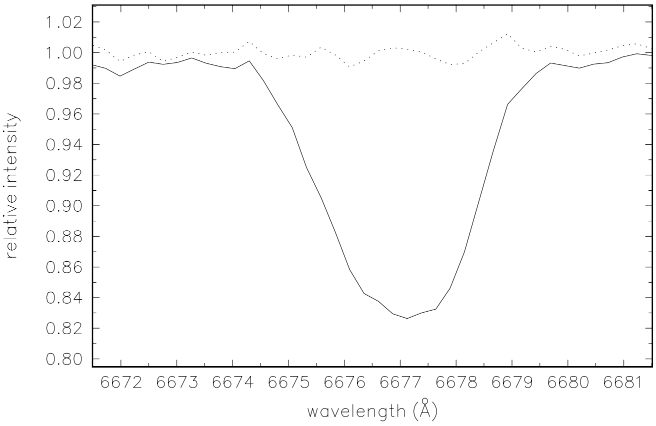

Fig. 10. The Ondřejov He I 6678 line profile obtained on HJD 2 452 861.3761 (solid line) and a difference between this profile and a profile obtained $0^{\mathrm{d}}.233$ later (dotted line). A typical signature of moving sub-features is seen.

period for the sharp He I 6678 absorption core gives a similar period of $29^{\mathrm{d}}.686$. It is easy to verify that such a periodicity could be reconciled with orbital motion in a binary system seen under a low inclination and leads to a reasonable mass of the primary (assuming a low mass ratio, as usually observed for Be binaries) but we do not want to over-interpret our limited series of observations.

5. Probable basic physical properties of HD 6226

We used the well-exposed 1997 Heros spectrogram obtained when the star was without emission for comparison with a synthetic spectrum. Synthetic spectra for our analysis were calculated from Kurucz's (1993b) grid of solar composition LTE line-blanketed model atmospheres with the help of the computer code SYNSPEC (Hubeny et al. 1994). Oscillator strengths, wavelengths and damping parameters for all lines contributing to the resulting spectrum in the neighbourhood of the line profiles in question were taken from the list of Kurucz (1993a). The synthetic spectra resulting from SYNSPEC were rotationally broadened with the SPEFO program.

After several trials, we found that the whole optical spectrum is best fitted by a model spectrum with the following properties:
T_{eff} = 17000 K, log g = 3.0 [cgs] and $v \sin i$ = 70 km s^{-1}. Figure 11 shows that the fit of the model spectrum to the observed one is very satisfactory. The only larger discrepancy concerns the He I 6678 line but this line is known to be prone to NLTE effects.

One can carry out several independent checks. First, the standard dereddening of the *UBV* values characteristic for the non-emission stage of the star
$V = 6^{\mathrm{m}}.835$, $(B-V) = -0^{\mathrm{m}}.042$, $(U-B) = -0^{\mathrm{m}}.565$
leads to
$V_0 = 6^{\mathrm{m}}.402$, $(B-V)_0 = -0^{\mathrm{m}}.177$, $(U-B)_0 = -0^{\mathrm{m}}.663$.
According to the calibration given by Popper (1980), this corresponds to T_{eff} = 16940 K, in excellent agreement with our spectral fit.

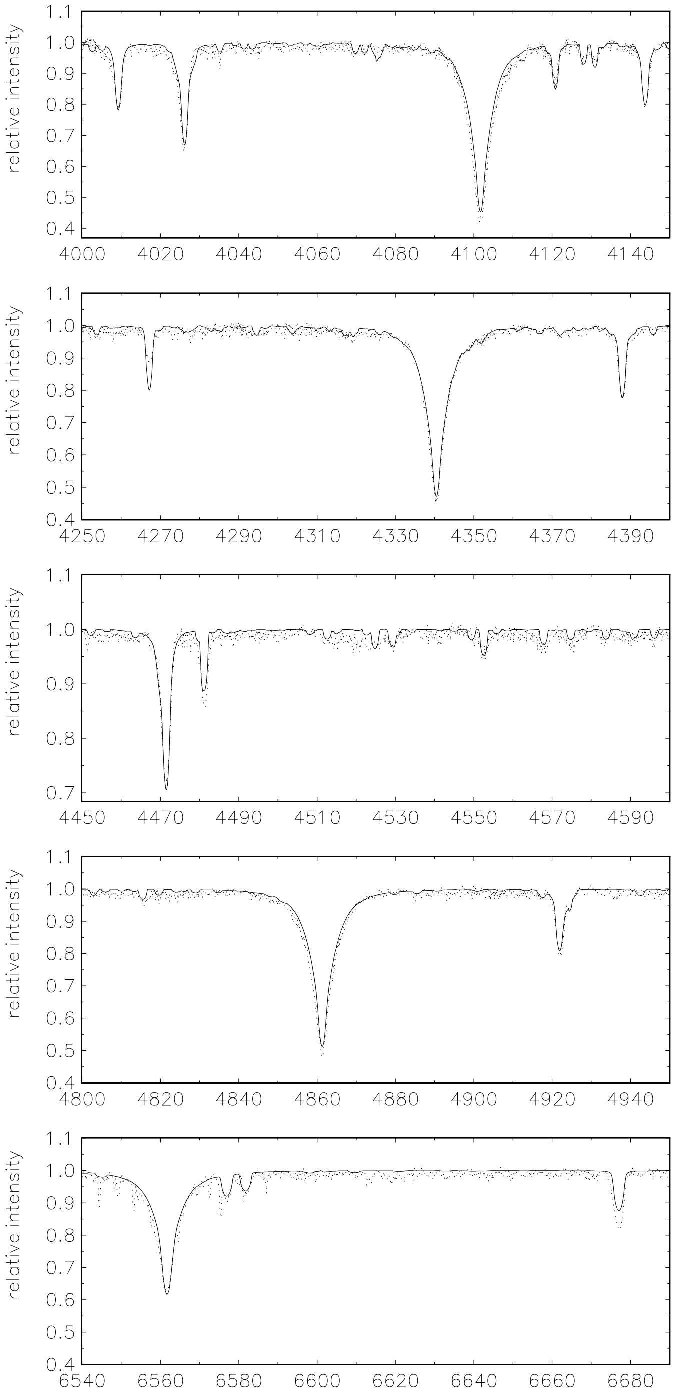

Fig. 11. A comparison of the 1997 Heros spectrogram of HD 6226 with a synthetic spectrum for 17000 K and log g = 3.0 [cgs] broadened to $v \sin i$ = 70 km s^{-1}. Al wavelengths are in Å. Apart from the He I 6678 line, prone to NLTE effects, the agreement is generally very satisfactory.

One can also use the dereddened V magnitude and the parallax observed by the Hipparcos satellite (Perryman et al. 1997), p = 0.″00113 ± 0.″00079, to estimate the probable radius of HD 6226 as 10.3 (6.1–34.3) $R_{\odot}$. This can be compared to the radius of R = 11.7 $R_{\odot}$, corresponding to a star having log g = 3.0 and a normal mass of 5.0 $M_{\odot}$ for its T_{eff} = 17 000 K according to Harmanec's (1988) calibration based on accurate masses and radii of detached binaries.

Assuming a radius of, say, 11 $R_{\odot}$, and adopting $2\overset{d}{.}615$ as a measure of the stellar rotational period, one arrives at equatorial velocity of 213 km s^{-1} and $i = 19°$. For the same radius and a mass of 5 $M_{\odot}$, the break-up velocity at the equator (adopting the Roche-model approximation) would be 240 km s^{-1} – a comparable number, considering all uncertainties.

One can see that above estimates agree well within the limits of their accuracy. However, they could change significantly if the object was a binary with two components, each of them contributing non-negligibly to the total luminosity of the object in the optical passbands.

It is clear that the inclination under which we observe the star must be low. This, of course, raises the question of the presence of a sharp central absorption seen during the emission episode in the Hα emission line. One possible interpretation is to assume that the Be envelope is sufficiently spheroidal to produce absorption effects even above the poles of the star. Another one would be to assume that the narrow absorption comes from a secondary in a putative binary system. It seems clear, however, that it *cannot* originate in a stellar wind from polar regions of the star since its RV blueshift with respect to the stellar photosphere – if any – is smaller than 5 km s^{-1}.

Clearly, HD 6226 is a very interesting Be star which deserves further intensive study.

Acknowledgements. We thank Drs. T. Rivinius, D. Baade and S. Štefl who kindly put their 1997 Heros spectrum of HD 6226 at our disposal, and the AAVSO and its photoelectric observers K. Luedeke and J. Wood for providing their observations. We acknowledge the use of the recent version of program FOTEL written by Dr. P. Hadrava. Research of P. Harmanec was supported from the research plan J13/98: 113200004 of Ministry of Education, Youth and Sports. He, P. Škoda and M. Šlechta were also supported from the research plan AV 0Z1 003909 and project K2043105 of the Academy of Sciences of the Czech Republic. At final stages, this research was supported from the grant GA ČR 205/2002/0788 of the Granting Agency of the Czech Republic. J. Žižňovský acknowledges support from the VEGA grant No. 2-3014/23.

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