A&A 401, 271–279 (2003)
DOI: 10.1051/0004-6361:20030125

Astronomy & Astrophysics

# Outbursts in the Be star HR 2501[⋆,⋆⋆]

F. Carrier and G. Burki

Observatoire de Genève, 51 Chemin des Maillettes, 1290 Sauverny, Switzerland

Received 17 April 2002 / Accepted 15 January 2003

**Abstract.** The Be star HR 2501 was monitored in photometry, from 1978 to 1998 in the Geneva system and from 1990 to 1992 by the Hipparcos satellite, and in spectroscopy from 1998 to 2001 by using the Coralie spectrograph. Several mostly unrelated periods or time scales characterize the variability of HR 2501. First, the radial velocity data reveals that this is a new $\lambda$ Eri star, with a period of 0.79187 d due to non-radial pulsations or clouds close to the stellar photosphere. Second, both Geneva and Hipparcos photometries exhibit a mid- to long-term variability of characteristic time $\sim$500 d and peak-to-peak amplitude $\sim$0.4 mag, most probably a consequence of the recurrent outbursts of matter from the rapidly rotating Be star towards its disk. Third, a characteristic time of $\sim$300 d between the outbursts is shown by spectroscopy by looking at the variations of the equivalent width of H$\alpha$, H$\beta$ and HeI (5875.6 Å) emission lines (the outbursts studied in photometry and spectroscopy are unfortunately not the same due to the non-simultaneity of the monitorings). Fourth, the $V/R$ ratio of the double peaks in H$\alpha$ and H$\beta$ show a periodic-type variation during the second of the spectroscopic outbursts, with periods of respectively 16.7 and 15.1 d, in agreement with the prediction of the dynamical evolution of a blob of material ejected from the equator of the star into the Keplerian disk. Fifth, a short-term photometric period of 0.46 d is detected during an epoch of intensive monitoring; however, it must be noted that if this variability is confirmed, the value of this short-term period is unsure. The other main results are: i) During the 27 months of the spectroscopic survey, in addition to the mentioned outbursts, the emission in H$\alpha$ and H$\beta$ lines decreased progressively until it almost completely vanishes at the end. ii) The estimated radius of the circumstellar disk varies and reaches 5.5, 4 and 2 stellar radii at maximum for the H$\alpha$, H$\beta$ and HeI emission regions respectively; iii) The spectroscopic monitoring was particularly successful, and the series of observation of the line profiles, with the variation of the emission from day to day, is quite exceptional in the studies of Be stars.

**Key words.** stars: emission-line, Be – stars: individual: HR 2501 – stars: variables: general – techniques: photometric – techniques: radial velocities – line: profiles

## 1. Introduction

Be stars are variable early-type stars which, at least sometimes, exhibit emission lines in their spectra, produced by circumstellar envelopes (Struve 1931). Their variability, often present simultaneously in various aspects, are characterized by time scales between a few minutes and several years. The origin and connections of these variations remain an unsolved problem.

One of the most remarkable changes in Be star spectra is the emission line profile variation, monitored through the $V/R$ ratio, the relative intensity of the violet to red component of double emission lines ($V/R = [V - V_c]/[R - R_c]$). According to statistical studies of Be stars in northern, respectively southern, hemisphere, about 67%, respectively 76%, of them are $V/R$ variables and display quasi-periods mainly in the 2–13 years range with a mean of about 7 years, (Hirata & Hubert-Delplace 1981; Mennickent & Vogt 1991). The Be stars usually present $V/R$ variations with long time-scale.

Short-term periodic variations are also frequently present in Be stars. They can be explained either by non-radial pulsations or by clouds close to the stellar photosphere (Vogt & Penrod 1983). The short-term periodic Be stars, called $\lambda$ Eri stars, show strictly periodic variations with periods in the range 0.5–2.0 d. An intensive search for photometric periodic short-term variables among the Be stars has been undertaken according to the ease of determining the period with photometry. Stagg (1987) estimated that short-term variability seems to occur in about half of the Be stars. They usually show radial velocity variations and line profile changes with the same period.

In the framework of an extensive campaign of observational studies on Be stars (Burki 1999; Carrier et al. 1999, 2002), a monitoring was organized of HR 2501, an active Be star exhibiting various kinds of periodicities induced by its variable

---

*Send offprint requests to*: F. Carrier,
e-mail: `Fabien.Carrier@obs.unige.ch`

[⋆] Based on observations collected at the Swiss 40 cm, 70 cm and 120 cm telescopes at the European Southern Observatory (La Silla, Chile) and on data from the ESA Hipparcos satellite.

[⋆⋆] The photometric and radial velocity data 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/401/271` disk. HR 2501 (HD 49131, HP CMa, HIP 32385) is classified B2III in SIMBAD and B2Vn in the Michigan Catalogue (Houk & Cowley 1975) and is known as a close visual double. The separation between the two components has a value of nearly $5''$ and the companion has a visual magnitude of 8.24 (5.62 for the main component) (Worley & Douglass 1997). The Be characteristics were discovered by Corbally (1984) who detected emission in the hydrogen lines $H_\beta$, $H_\gamma$ and $H_\delta$. He estimated a large projected rotational velocity ($v \sin i \sim 350$ km s$^{-1}$). This star was first discovered to be light variable by Jerzykiewicz & Sterken (1977) with a time scale of a few days. Balona et al. (1992) also detected variations but no evidence of periodicity. In photometry, HR 2501 exhibited long-lived outbursts with a strong increase in brightness over 100 days followed by a slow decrease of about 400 d (Hubert & Floquet 1998).

This star, which exhibits variations according to the Hipparcos and Geneva photometric measurements (1978 to 1998), was monitored using the Coralie spectrometer mounted on the 120 cm Swiss telescope at La Silla (ESO, Chile). The results of this photometric and spectroscopic analysis are presented in this paper.

## 2. Observations

From November 1998 until January 2001, HR 2501 was measured with the Coralie high-resolution fiber-fed echelle spectrograph mounted on the Nasmyth focus on the 120 cm Swiss telescope at La Silla (ESO, Chile). Coralie is an improved version of the Elodie spectrograph (Baranne et al. 1996) with a resolving power of 50 000 ($\lambda/\Delta\lambda$). The Coralie spectra were extracted at the telescope, using a software package called INTER-TACOS (INTERpreter for the Treatment, the Analysis and the COrrelation of Spectra), developed by D. Queloz and L. Weber at the Geneva Observatory (Baranne et al. 1996). An amount of 71 echelle-spectra has been obtained during the 2 years of the survey. These observations cover 68 orders in the spectral range 3875–6820 Å. The $S/N$ ratios of spectra vary from 35 to 100 at 4500 Å and from 50 to 140 at 6000 Å.

From 1978 to 1998, this star was measured in the Geneva photometric system (Golay 1980) with the photoelectric photometer P7 (Burnet & Rufener 1979) installed on the 40 cm and 70 cm Swiss telescopes in La Silla (ESO, Chile). 162 measurements were obtained. The photometric reduction procedure was described by Rufener (1964, 1985); the photometric data in the Geneva system are collected in the General Catalogue (Rufener 1988) and its up-to-date database (Burki et al. 2003). For a star of the brightness of HR 2501, the typical accuracy of the data is 0.005 in $V$ (see, e.g. Rufener 1988; Burki et al. 1991). In addition to these data, 150 photometric measurements have been obtained by the Hipparcos satellite (ESA 1997) in the range 7891–9052 (in HJD–2 440 000). To compare the magnitude $Hp$ from Hipparcos with $V$, the relation between $V - Hp$ and the Geneva colour index $[B - V]$ has been used (see Carrier et al. 1999).

**Table 1.** List of all absorption lines used to derive radial velocities. The line wavelength is given in Å.

| Line | Å | Line | Å | Line | Å |
|---|---|---|---|---|---|
| OII | 3911.962 | OII | 4275.529 | OII | 4602.059 |
| OII | 3919.270 | OII | 4294.871 | OII | 4609.373 |
| OII | 3945.033 | OII | 4303.833 | NII | 4630.543 |
| HeI | 4026.187 | OII | 4378.732 | NIII | 4634.122 |
| OII | 4054.219 | OII | 4395.935 | OII | 4676.231 |
| OII | 4075.859 | HeI | 4437.551 | HeII | 4685.698 |
| OII | 4132.804 | OII | 4452.380 | SiIII | 4813.333 |
| HeI | 4143.761 | MgII | 4481.126 | SiIII | 4819.712 |
| OII | 4156.528 | OII | 4488.193 | SiIII | 4828.951 |
| CIII | 4162.876 | SiIII | 4552.622 | OII | 4890.854 |
| OII | 4169.224 | SiIII | 4567.840 | OII | 4906.830 |
| OII | 4185.440 | SiIII | 4574.757 | SiIII | 5739.734 |
| OII | 4189.789 | OII | 4590.973 | OII | 6721.384 |
| SIII | 4253.589 | OII | 4596.172 | | |

## 3. Radial and rotational velocities determination

The main problem to determine radial velocities for Be stars is that their spectra contain only a few lines and, moreover, are often blended because of the rapid rotation of these stars, which ($v \sin i$) may reach 200–300 km s$^{-1}$. Other problems that can complicate the determination are emission in the line wings or the so-called transient periodic variations that can be present in the line wings for days to months after an outburst (Štefl et al. 1998). In order to compensate for the small number of lines and the poor definition of the line center, high $S/N$ spectra have been used to obtain the radial velocity, which was derived by cross-correlation, using the absorption lines listed in Table 1 (see Carrier et al. 2002). The cross-correlation method can be used with some assumptions: i) the line profile variations are the same in all analyzed lines (see Sect. 3) ii) no transient periods appear in line wings. First, the cross-correlation is carried out for each order independently. Next, all 68 cross-correlation functions (CCFs) are summed, and weighted by the flux in each order, to obtain the final CCF. Due to the problems discussed above, the radial velocities are obtained by fitting Gaussians only to the CCF center.

The correlation technique has the disavantage of producing a global average of the spectroscopic information contained in each of the studied lines. In particular, it does not allow us to study the eventual variations which could occur from line to line (e.g. 28 CMa, Baade 1984; Štefl et al. 2000). But this technique offers the great advantage of concentrating the information towards the studied parameter, i.e. the radial velocity. The consequence is a drastic reduction of the integration time of each measurement. This study required in only about 3 nights of cumulative observing time, thanks to the correlation technique.

The rotational velocity ($v \sin i$) was estimated by comparison between an artificially broadened synthetic spectrum and the spectrum of the star (Brown & Verschueren 1997), taking into account the broadening by instrumental effects. The synthetic spectrum was obtained from the SPECTRUM code (Gray & Corbally 1994). Only absorption lines, listed in Table 1, were

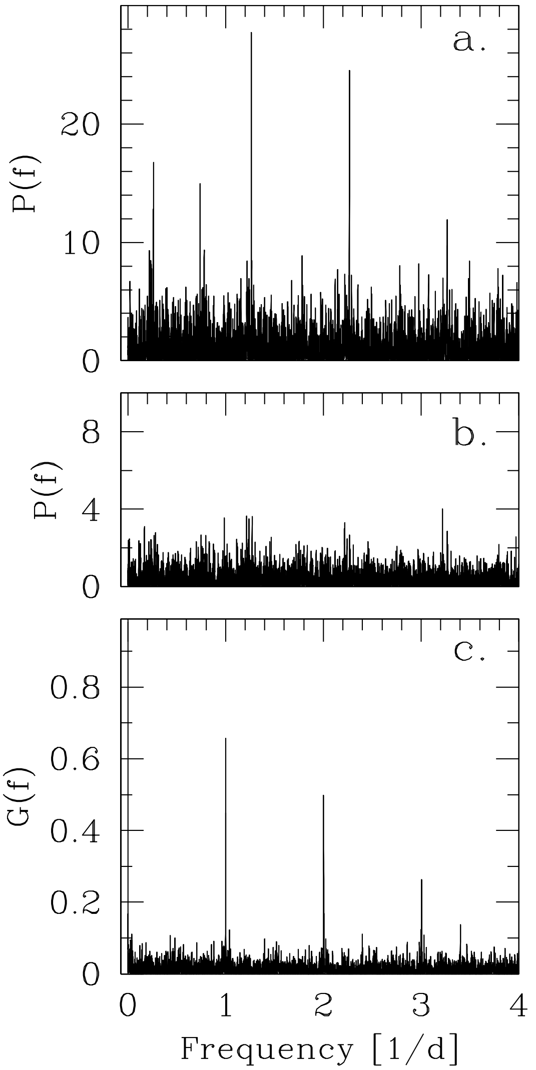

**Fig. 1.** Fourier analysis of the radial velocity data of HR 2501. **a)** Power in the Fourier transform; **b)** Power in the Fourier transform after subtraction of the main component at 1.2629 $d^{-1}$; **c)** General spectral window.

used for the rotational velocity determination. The rotational velocity ($\upsilon \sin i$) is estimated to be 165 ± 10 $\mathrm{km\,s^{-1}}$.

## 4. Short-term variation: Radial velocity variability

The results of the Fourier analysis of the 71 radial velocities are presented in Fig. 1. The power spectrum and the spectral window are classical for ground-based observations and a short-term periodic variation is very clearly shown, at frequency 1.2629 $\mathrm{d}^{-1}$, corresponding to the period 0.79187 ± 0.00038 d. A Fourier analysis done on several different shorter temporal intervals leads to the conclusion that this period is constant during the whole survey. Moreover, no other periodicity can be clearly deduced from our data. The corresponding velocity curve is shown in Fig. 2. The peak-to-peak amplitude of the variation reaches 20.5 $\mathrm{km\,s^{-1}}$. According to our measurements, HR 2501 is a new $\lambda$ Eridani star with a period of 0.79187 d. The rms scatter of the residuals, obtained by the subtraction of a sinusoidal curve, is 5.4 $\mathrm{km\,s^{-1}}$. This value, too large compared to other Be stars taken during the same survey (HR 1960 and HR 3237 have a rms scatter of 2.19 and 3.36 $\mathrm{km\,s^{-1}}$ respectively, see Carrier et al. 2002), should partly be due to the activity of the star.

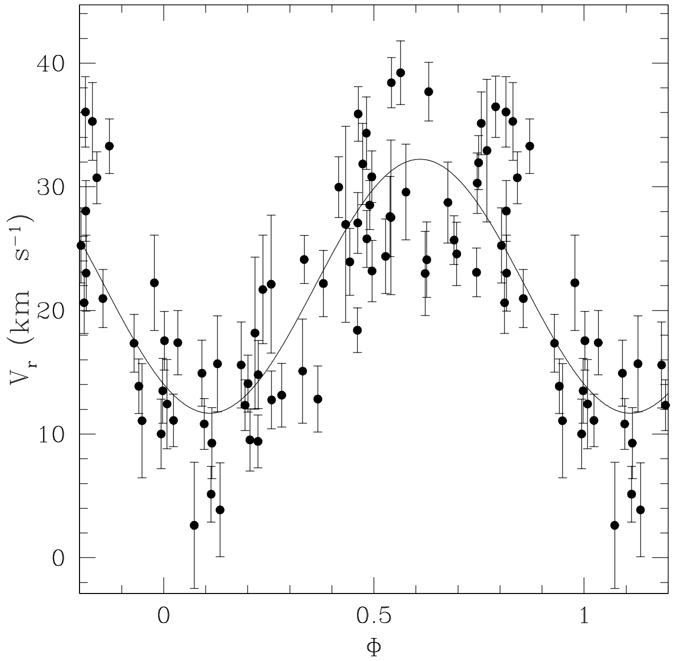

**Fig. 2.** Radial-velocity curve of HR 2501. The period is 0.79187 ± 0.00038 d. This star is a new $\lambda$ Eri. This curve represents the mean global variation of the radial velocity based on the correlation technique applied to the lines identified in Table 1.

In order to check the physical meaning of the cross-correlation technique in the case of this Be star, the main lines have been individually investigated. No line shows another significant periodicity other than the global value given above (0.79187 d, 1.2629 $\mathrm{d}^{-1}$) or its daily aliases. Four Fourier periodograms of individual lines are presented in Fig. 3. These figures are to be compared to the global Fourier analysis (Fig. 1a), based on all the lines listed in Table 1.

This relatively short period is not due to the duplicity of HR 2501. This is confirmed by the fact that the observed radial velocity variation is caused by the changing shape of the line profile, and not by a shift of the whole line as might be expected in a binary star (see Fig. 4). Thus, the line profile variation could be due to non-radial pulsations or clouds close to the stellar photosphere.

## 5. Outbursts

During outbursts, the changes in the disk imply equivalent width variations of emission lines. These changes can probably also be seen through the luminosity. However, a simultaneous campaign in photometry and spectroscopy is required to clearly describe this correlation. Moreover, the matter expelled into the disk can introduce $V/R$ variations. HR 2501 exhibits several outbursts analyzed from these three independent observations.

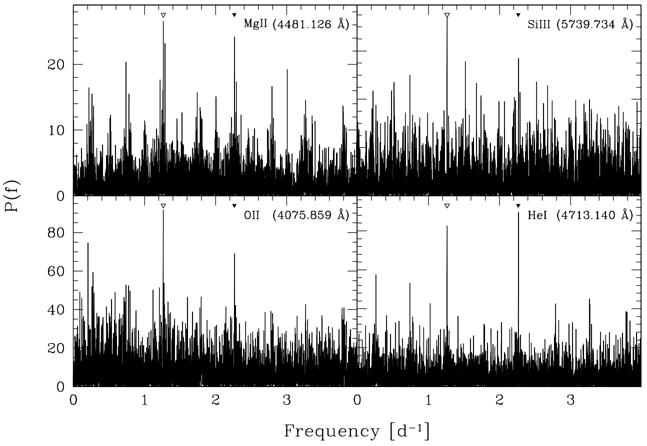

**Fig. 3.** Example of Fourier analyses of radial velocities deduced from four individual lines. The frequency 1.2629 d$^{-1}$ ($P$ = 0.79187 d) is present in the data of different chemical elements. The period of 0.79187 d is indicated with an open triangle, its daily alias with a black triangle.

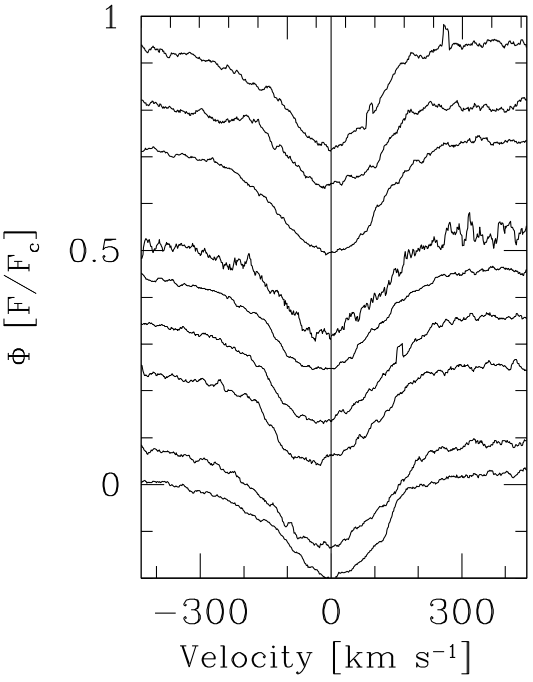

**Fig. 4.** Some observed line profiles HeI 4471.5 Å for HR 2501. The variation is weak. The profiles are sorted according to the phase and the flux is normalized. The period is 0.79187 d.

### 5.1. Equivalent width observations

HR 2501 presents some interesting spectroscopic behaviors. An analysis of the disk variations can be investigated through the line equivalent widths ($EW$). Almost all line profiles are affected by emission, but often very faintly. Therefore, the more appropriate lines are H$_\alpha$ and H$_\beta$ hydrogen lines or some strong helium lines, in particular the HeI 5875.6 Å line. All observed line profiles consist of two contributions: the stellar photospheric absorption and the circumstellar emission. The $EW$ of the photospheric profile of the lines is assumed to be constant with time, thus all the variations of $EW$ are supposed to come from the disk. Figure 5 shows the variation of $EW$ with time for H$_\alpha$, H$_\beta$ and HeI (5875.6 Å). The main points to be noted are:

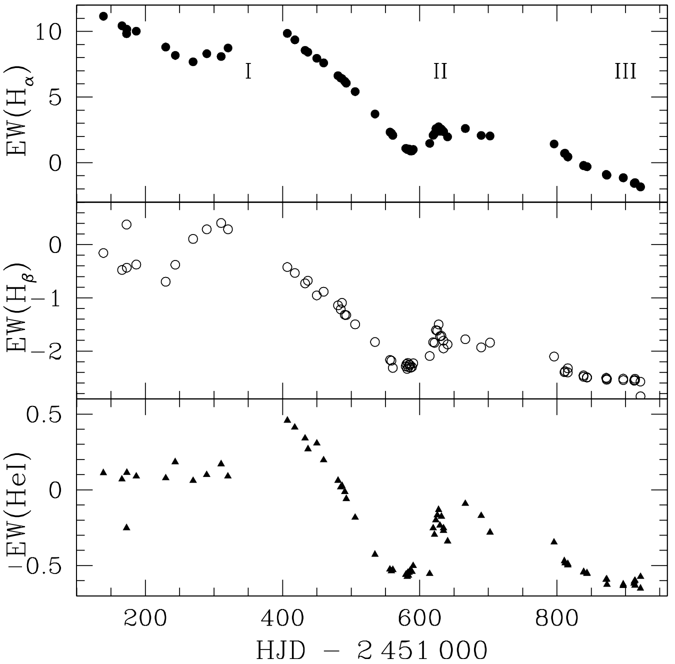

**Fig. 5.** The equivalent width of the H$_\alpha$, H$_\beta$ and HeI (5875.6 Å) lines versus time. HR 2501 undergoes episodic outbursts with a time scale of several hundred days. The location of the three outbursts is indicated (see Sect. 5.1). The $EW$ value is positive when the line is in emission.

- The three lines showed the same behavior, i.e. a global decrease of $EW$ from the beginning of the survey. In 1998 (HJD ~ 2 451 150) the intensity of the emission lines was strong, thus the circumstellar disk was important. Then it started to decrease and in January 2001 (HJD ~ 2 451 920), the emission had almost disappeared.
- In addition, this Be star underwent variations with a timescale of several hundred days. Figure 5 presents small increases of the $EW$ due to episodic ejections of matter. Three outbursts can be identified, denoted I, II and III, at epochs 350, 630 and 900 (in HJD–2 451 000). The first two outbursts were important and lasted about 100 d. The third outburst, at the end of the survey, is very faint in $EW$ but is clearly present in $V/R$ (see Sect. 5.4).
- The amplitude of the variations does not remain constant from one outburst to another, as is also the case in the photometric data (see Sect. 5.2).

Note that a similar behavior was observed in $\mu$ Cen by Hanuschik et al. (1993).

### 5.2. Photometric variability

HR 2501 exhibited several outbursts between 1978 and 1993 (see Figs. 6 and 7), monitored with Geneva and Hipparcos photometries. As noted by Hubert & Floquet (1998), the characteristic time between two outbursts is roughly 500 d. The $V$ light curve obtained during the period HJD 2 443 600–5500 (April 1978 to June 1985) is shown in Fig. 6. The value of the period

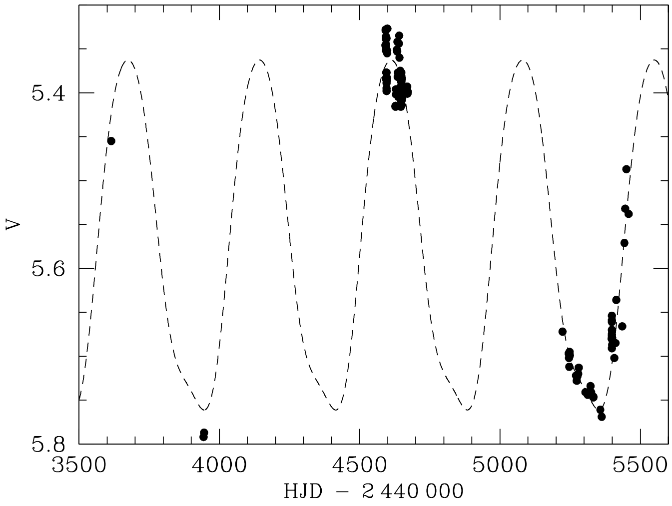

**Fig. 6.** *V* light variations (Geneva photometry) of HR 2501 in the interval April 1978 to June 1985. A curve with a period of 469 d and $T_0$ = HJD 2 443 675 is drawn.

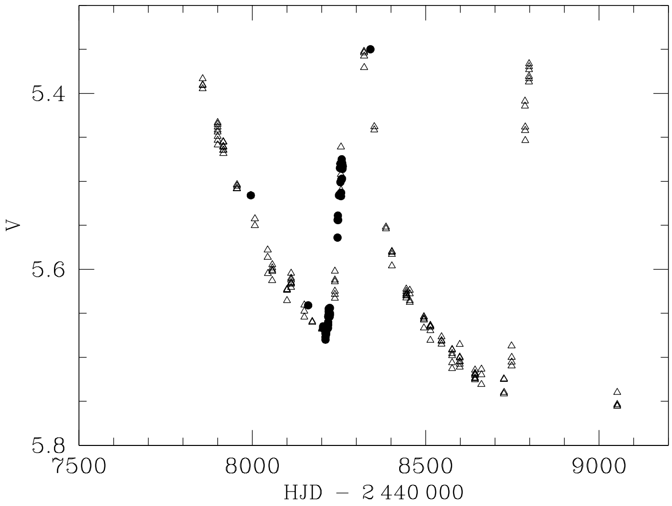

**Fig. 7.** *V* light variations, Geneva (filled dots) and Hipparcos (open triangles) photometries, of HR 2501 in the interval December 1989 to May 1993. The two maxima are separated by about 530 d.

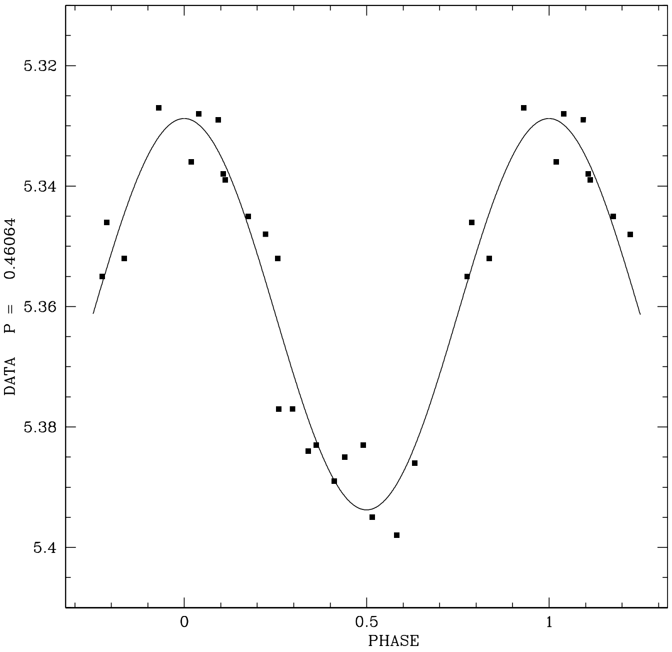

**Fig. 8.** Probable short period (0.46064 d) and small amplitude light change in *V* (Geneva photometry), during the interval of maximum luminosity HJD 2 444 591–599 (December 1981). The variability is unquestionable, but the value of the period, if any, is unsure. The residual standard deviation around the fitted curve is 0.006.

of 469 ± 20 d is in global agreement with the data. The uncertainty on the period corresponds to an increase of the residual standard deviation by a factor of 1.5, which is a quite large value. As already noted, the increase in brightness is more rapid than the decrease.

During the interval HJD 2 447 800–9 100 (October 1989 to May 1993), the light curve was not stable (see Fig. 7); the time spent between the observed outbursts is about 530 ± 10 d, and the luminosity of the minima are decreasing. Thanks to the complementarity of the Geneva and Hipparcos photometric data, and to the sharpness of the *V* light increases, clearly apparent in Fig. 7, the evaluation of the time between the two successive outbursts is quite easy and reliable.

Thus, the mid-term light variation in HR 2501 is recurrent but not periodic, and moreover the amplitude (about 0.4 mag) of this light modulation is not constant. These variations should be due to the activity of the star (ejection of matter or disk formation), and not to a strictly periodic process such as the orbital motion of a companion or the rotation. This highlights the same phenomenon as the equivalent width variations (see Sect. 5.1 and Fig. 5). However, it is important to note that periods of the same order of magnitude as this characteristic time have been found for the photometric variability of two other Be stars of our program: 371 d for HR 2968 (Carrier et al. 1999) and 395 d for HR 1960 (Burki 1999).

Sixty-eight measurements have been obtained in the interval HJD 2 444 590–4 680 (December 1980 to March 1981), corresponding to a brightness maximum. As shown by Fig. 6, the dispersion of the values is very large, $\sigma(V) = 0.0205$, i.e. 4 times larger than the precision of the measurements. The analysis of these data reveals that a short-term variation could be present in the first part of the data (HJD 2 444 591–599). Figure 8 shows that a light curve with a period of 0.4606 d and a peak-to-peak amplitude of 0.065 mag is in agreement with the observations (superimposed on the large amplitude mid-term variation). However, we have to be careful because: i) two other periods are also in agreement with the data (0.8635 d and 6.516 d), without any possibility of choosing which is the correct one, due to aliasing problems; ii) these 3 possible periods are no longer present in the subsequent data (HJD 2 444 600–4 680 January to March 1981); iii) these periods do not correspond to the value of the short spectroscopic period of 0.79187 d. We have identified the period of 0.4606 d as the most probable on the basis of the residual standard deviation which takes the values 0.0064, 0.0070 and 0.0120 respectively for the periods 0.4606, 0.8635 and 6.516 d.

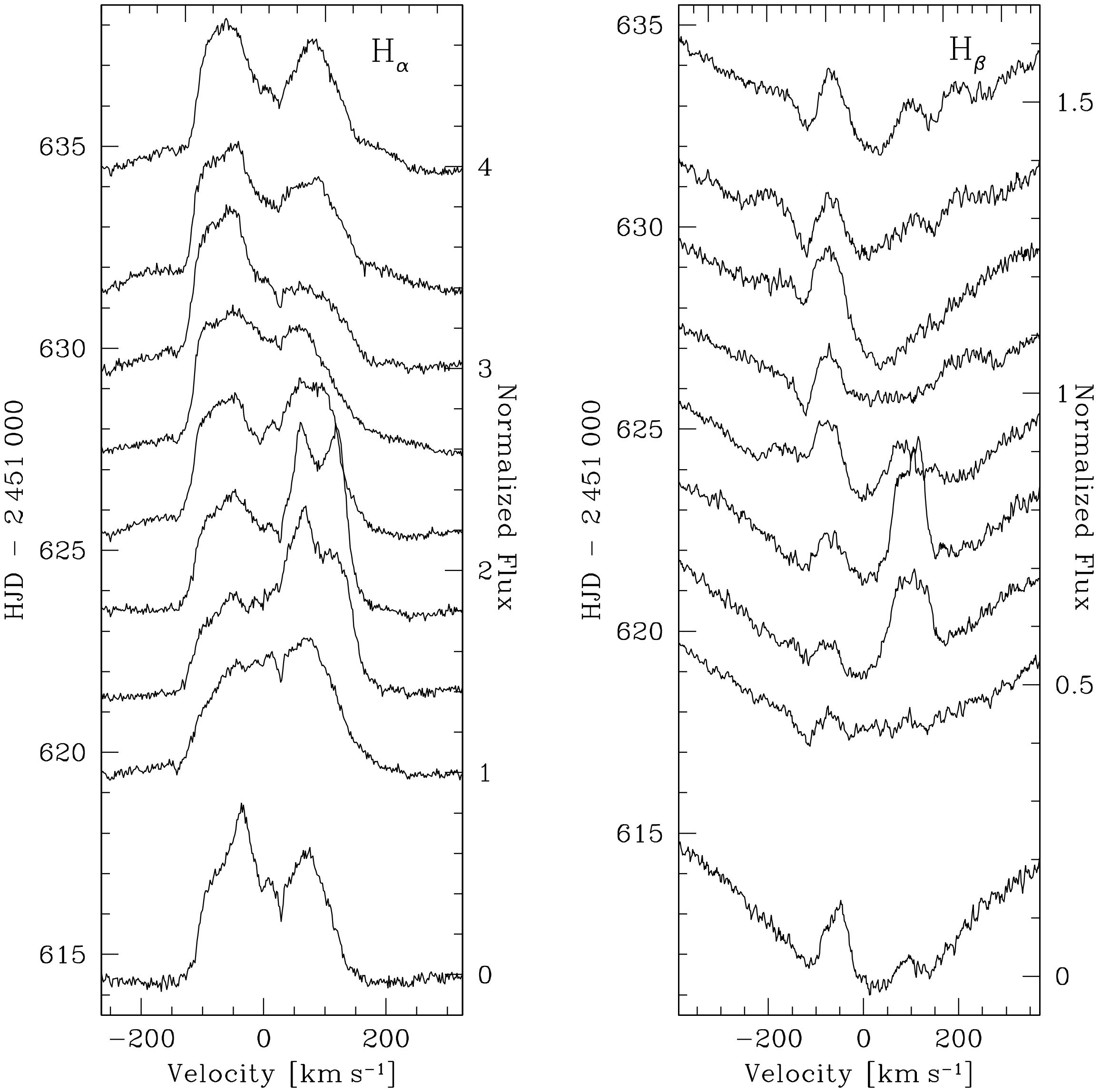

**Fig. 9.** Evolution of the $H_\alpha$ (left) and $H_\beta$ (right) line profiles of HR 2501 in the range 613.5–638.5 (in HJD–2 451 000). The flux is normalized. After a long stability, line profile variations suddenly occur during that period and then the star becomes stable again.

### 5.3. Circumstellar disk

Optical emission lines of Be stars originate in disk-like circumstellar envelopes. A quite exceptional series of line profiles results from our spectroscopic monitoring. Indeed, a complete description of the evolution of the main optical lines, in particular H$_\alpha$ and H$_\beta$ (see Fig. 9), was obtained during the second outburst. To our knowledge, such a high resolution (in wavelength and time) spectroscopic monitoring was never before obtained, or at least not published, for Be stars. These observations allow a very detailed analysis of the evolution of the global characteristics of the circumstellar disk during an outburst (this section) and of the progression of the blobs of ejected matter through this disk (see Sect. 5.4).

For an optically thin rotating disk, peak emission occurs at a radial velocity which corresponds to the projected velocity of the material at the outer disk boundary $V_\mathrm{p}$, because this region contains the largest number of emitting particles. Thus, in the hypothesis of a Keplerian disk, the projected equatorial rotational velocity $v \sin i$ is related to the peak separation $\Delta V_\mathrm{p}$ by (Hummel & Vrancken 1995):

$$\frac{R_\mathrm{d}}{R_*} = \left(\frac{2v \sin i}{\Delta V_\mathrm{p}}\right)^2 , \tag{1}$$

where $R_*$ is the stellar radius and $R_\mathrm{d}$ the characteristic emission radius. The size of the helium emission region can be determined from the relation (1), because HeI emission lines are optically thin (Hanuschik 1987) and intrinsic broadening ($\Delta V_\mathrm{th} \sim 3$ km s$^{-1}$) is much smaller than the typical kinematical broadening of a few hundred km s$^{-1}$.

However, for the H$\alpha$ and H$\beta$ lines, a non-coherent scattering broadening, caused by the thickness of these lines (Hummel 1994), appears in the direction perpendicular to the disk plane (small $i$ values) and generates the so-called winebottle-type profiles. Then, the profiles can be understood as the convolution of the kinematical broadening distribution (usually a

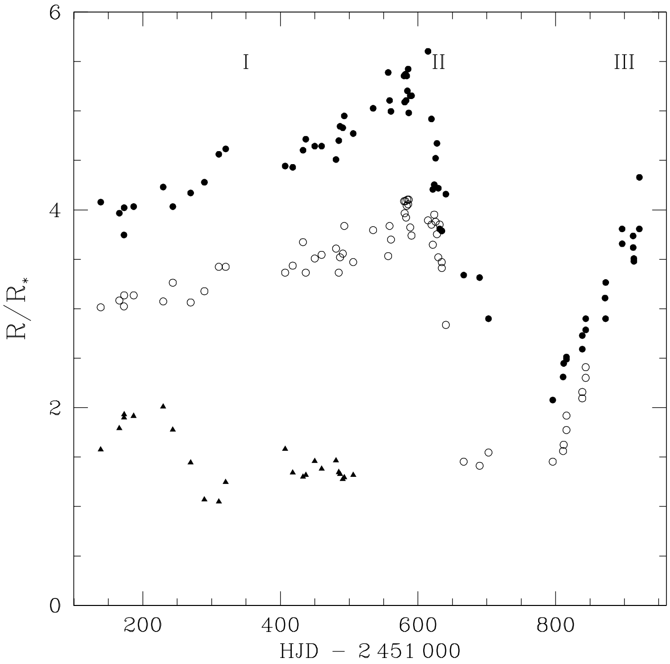

**Fig. 10.** Evolution of the radius of the H$\alpha$, H$\beta$ and HeI region, identified respectively by filled dots, open dots and filled triangles. The emission of He lines are weak and it is difficult to obtain accurate measurements on the disk after HJD 2 451 500. Time of the three outbursts is indicated (see Sect. 5.1).

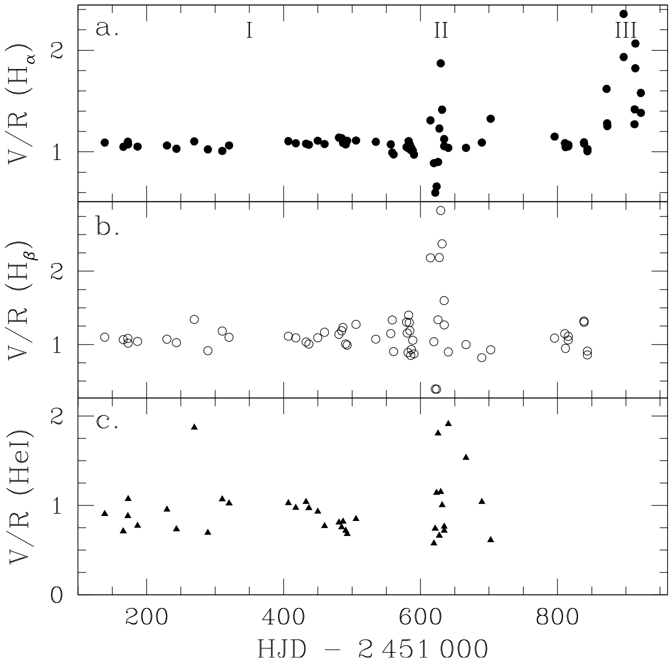

**Fig. 11.** $V/R$ ratio variations of $H_\alpha$ **a)**, $H_\beta$ **b)** and HeI **c)** lines. The $V/R$ ratios are quasi-constant except near 620 and 900 (in HJD–2 451 000). The $V/R$ ratio of $H_\beta$ and HeI lines are not determined after 850 (in HJD–2 451 000), because the intensity of the emission is too weak. Time of the three outbursts is indicated (see Sect. 5.1).

double-peak profile) with the scattering broadening function (also a double-peak profile). The peak at $V_k$, due to kinematics of the disk, will be split symmetrically by the scattering process into a shoulder at $V_s$ and a peak at $V_p$ (Hummel & Vrancken 1995). Thus:

$$V_k = \frac{V_s + V_p}{2}. \tag{2}$$

Therefore, for the hydrogen lines, the separation of these reconstructed peaks $\Delta V_k$ is directly related to the radius of the circumstellar disk, and the following relation is obtained:

$$\frac{R_d}{R_*} = \left(\frac{2v \sin i}{\Delta V_k}\right)^2. \tag{3}$$

The evolution of the normalized disk radius $\frac{R_d}{R_*}$ is presented in Fig. 10, which shows that:

- the behavior is the same for H$\alpha$ and H$\beta$ regions. The HeI region is smaller and thus very sensible to multiple phenomena;
- until HJD 2 451 600, the radius of the circumstellar disk slowly increases;
- then, the disk almost completely disappears and after HJD 2 451 750 increases again;
- outside the outbursts, the envelope radius increases, whereas the emission strength decreases (see Sect. 5.1);
- the matter of the circumstellar envelope is ejected by the star and is finally blown away;
- before the second large outburst (II), the disk had nearly disappeared. The expelled matter allows the disk radius to increase again;
- the circumstellar envelope is rather small compared to other stars (Mennickent & Vogt 1991; Hummel & Vrancken 1995).

### 5.4. V/R variations

The $V/R$ ratio is an excellent indicator of the homogeneity of the disk. Figure 11 shows its evolution calculated for $H_\alpha$, $H_\beta$ and HeI.

- The $V/R$ ratios are quasi-constant until HJD ~ 2 451 620. They only present some very weak short-term variations but not periodic ones.
- Large variations happen near HJD ~ 2 451 620. First the $V/R$ ratio suddenly decreases, then increases and finally stabilizes itself again (see Fig. 9).
- This kind of variations appear again near HJD ~ 2 451 900.

Such variations are rarely described among Be stars. However, they are similar to those of PP Car (Mennickent & Vogt 1991), which showed, during late 1984 and early 1985, rapid $V/R$ changes from $V > R$ to $V < R$ in time-scales of 20 d, superimposed on a 10 yr quasi-period.

The large variations happening during the second outburst, shown in Fig. 12, can be explained with a simple model:

- there is a gradual input of material from the stellar surface into the disk and the rotation of these blobs of matter produces the observed short-term variations;
- the period of these variations is shorter for HeI than H lines, because of the size of the emitting regions which is smaller for the helium (see Sect. 5.3);

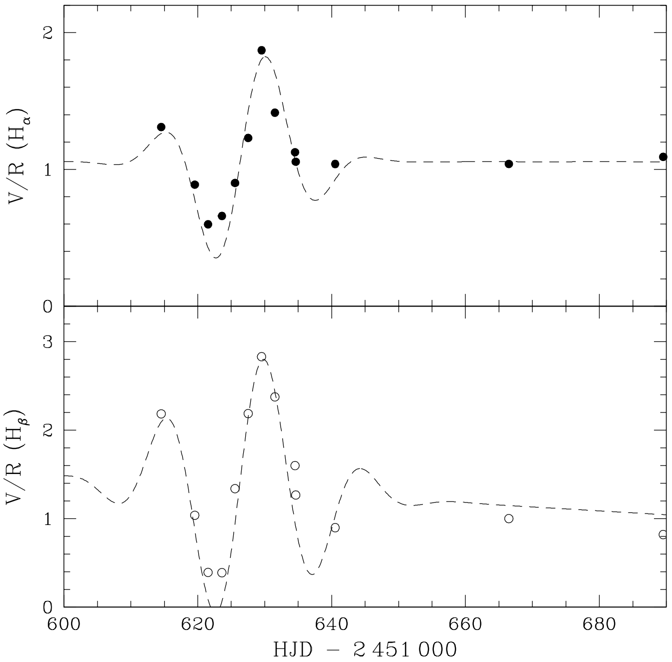

**Fig. 12.** $V/R$ ratio variations of H$_\alpha$, H$_\beta$ lines during the second outburst at HJD ~ 2 451 620. The dashed curves only illustrate the observed variations and are composed of a sinusoidal curve, which can be interpreted by the rotation of a material point, and an exponential decrease; they are not derived from theoretical models. The periods of these curves in the interval HJD ~ 2 451 610–640 are 16.7 and 15.1 d for the H$_\alpha$ and H$_\beta$ lines respectively. Outside this interval, we have postulated that $V/R$ is almost constant, as suggested by Fig. 11 before HJD 2 451 600.

- such variations are not observed during the first outburst, but are present again during the third outburst. This can be due to the size of the disk. Indeed, as noted by Mennickent & Vogt (1991), such short-term $V/R$ variability occurs only in small circumstellar envelopes which are more sensitive to building up inhomogeneities and blobs. In this context, note that the disk size of HR 2501 is similar to the smallest ones determined by Quirrenbach et al. (1997) with interferometric observations; the disk sizes of the seven Be stars in that paper vary between 3.6 and 11.6 stellar radii.

The $V/R$ ratio modulation is due to a perturbation orbiting in the disk and moving away from the star. The observed modulation period corresponds thus to the period of rotation of the observed material (hydrogen or helium) at a distance fixed by the size of the corresponding envelope. In the case of a Keplerian disk and assuming that the material orbits with the critical velocity near the stellar surface, the period of a material point rotating around the star at distance $R$ is:

$$P = \frac{2\pi R}{V} = \frac{2\pi}{V_*}\left(\frac{R}{R_*}\right)^{\frac{3}{2}} R_*\,, \tag{4}$$

where $V_*$ and $R_*$ are the velocity at the stellar surface and the stellar radius. The result of these calculations is:

- In the case of H$\alpha$, by assuming a stellar radius of 10 $R_\odot$ (Schmidt-Kaler 1982), a size of the disk $\frac{R_\mathrm{d}}{R_*}$ of 4.5 (see Chap. 5.3) and a rotational velocity at the stellar surface of 290 km s$^{-1}$ (a typical value for Be stars), a period of 16.7 d is obtained, which is in perfect agreement with the period deduced from the observations (16.7 d, see Fig. 12).
- For the H$\beta$ line, assuming a size of the disk $\frac{R_\mathrm{d}}{R_*}$ of 3.7, the period is 12.4 d, which is smaller than the observed one (15.1 d), but remains within the errors.
- With a radius of 1.5 $R_*$ for the HeI region, a period of 3.2 d should be observed, but the sampling of our data does not allow to check this point. Indeed, this variation could be observed during several periods, but with sudden phase shifts due to the passage of another blob of matter in the HeI zone. Taking into account the uncertainties on $V/R$ (HeI), these data can only confirm the presence of variations with a time scale of a few days (see Fig. 11c)

## 6. Conclusion

The various variabilities, periodic or not, revealed by our photometric and spectroscopic monitorings bring a lot of fundamental information which would not have been obtained in the case of non-variable Be star. HR 2501 is transiently developing and losing its disk in a discontinuous process revealed by the observation of blobs. Its progression from the star through the disk has been followed thanks to the large number of high resolution spectra recorded during the spectroscopic survey.

From the photosphere of HR 2501 to its disk, these observations are:

- A periodicity of 0.79187 d revealed by the radial velocity: HR 2501 is a new $\lambda$ Eri star.
- A time-scale of about 16 d for the variation of the $V/R$ ratio of H$\alpha$ and H$\beta$ emission lines during one of the monitored outbursts, in agreement with a simple model of discontinuous matter ejection in a Keplerian disk.
- A characteristic time of about 500 d for the photometric variations, characterizing the global processes of mid-term photospheric evolution of HR 2501 and disk formation.
- The radius of the disk varies with time; the maximum values are 5.5, 4 and 2 stellar radii for the H$\alpha$, H$\beta$ and HeI (5875.6 Å) emission regions respectively.

Such short, mid and long-term monitorings are needed to improve our knowledge on Be stars. Of course, it would be very important to obtain simultaneously the photometric and spectroscopic data.

*Acknowledgements.* We would like to express our warm thanks to the observers who obtained the measurements at the 40 cm, 70 cm and 120 cm Swiss telescopes at La Silla. These photometric and spectroscopic monitorings have been successful thanks to their assiduity. We also thank Dr Zorec for his helpful remarks. This work has been partly supported by the Swiss National Science Foundation.

## References

Baade, D. 1984, A&A, 134, 105
Balona, L. A., Cuypers, J., & Marang, F. 1992, A&AS, 92, 533
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 1
Brown, A. G. A, & Verschueren, W. 1997, A&A, 319, 811

Burki, G. 1999, A&A, 346, 134
Burki, G., Cramer, N., & Nicolet, B. 1991, A&AS, 87, 163
Burki, G., Cramer, N., Nicolet, B., et al. 2003, `http://obswww.unige.ch/gcpd/ph13.html`
Burnet, M., & Rufener, F. 1979, A&A, 74, 54
Carrier, F., Burki, G., & Richard, C. 1999, A&A, 341, 469
Carrier, F., Burki, G., & Burnet, M. 2002, A&A, 385, 488
Corbally, C. J. 1984, ApJS, 55, 657
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Golay, M. 1980, Vistas Astron., 24, 141
Gray, R. O., & Corbally, C. J. 1994, AJ, 107, 742
Hanuschik, R. W. 1987, A&A, 173, 299
Hanuschik, R. W., Dachs, J., Baudzus, M., & Thimm, G. 1993, A&A, 274, 356
Hirata, R., & Hubert-Delplace, A. 1981, Workshop on Pulsating B Stars, ed. G. E. V. O. N., C. Sterken, Nice Observatory, 217
Houk, N., & Cowley, A. P. 1975, Catalogue of two-dimensional spectral types for the HD stars, Vol. I, Univ. of Michigan, Ann Arbor
Hubert, A. M., & Floquet, M. 1998, A&A, 335, 565
Hummel, W. 1994, A&A, 289, 458
Hummel, W., & Vrancken, M. 1995, A&A, 302, 751
Jerzykiewicz, M., & Sterken, C. 1977, Acta Astron., 27, 365
Mennickent, R. E., & Vogt, N. 1991, A&A, 241, 159
Quirrenbach, A., Bjorkman, K. S., Bjorkman, J. E., et al. 1997, ApJ, 479, 477
Rufener, F. 1964, Publ. Obs. Genève, A, 66, 413
Rufener, F. 1985, in Calibration of Fundamental Stellar Quantities, ed. D. S. Hayes et al. (Dordrecht: Reidel Publ. Co.), IAU Symp. 111, 253
Rufener, F. 1988, Geneva Photometric Catalogue, 4th edn. (Obs. Genève)
Schmidt-Kaler, Th. 1982, in Landolt-Bornstein, ed. K.-H. Hellwege (Springer, Group VI), Subvolume 2b, p. 31
Stagg, C. 1987, MNRAS, 227, 213
Štefl, S., Baade, D., Rivinius, T., et al. 1998, ASP Conf. Ser., 135, 348
Štefl, S., Budovicová, A., Baade, D., et al. 2000, IAU Coll. 175, ASP Conf. Proc., 214, 240
Struve, O. 1931, ApJ, 73, 94
Vogt, S. S., & Penrod, G. D. 1983, ApJ, 275, 661
Worley, C. E., & Douglass, G. G. 1997, A&AS, 125, 523