A&A 385, 488–502 (2002)
DOI: 10.1051/0004-6361:20020174

Astronomy & Astrophysics

Search for duplicity in periodic variable Be stars[⋆,⋆⋆,⋆⋆⋆]

F. Carrier, G. Burki, and M. Burnet

Observatoire de Genève, 1290 Sauverny, Switzerland

Received 9 August 2001 / Accepted 16 January 2002

Abstract. Four Be stars, HR 1960, HR 2968, HR 3237 and HR 3642, selected according to their periodic variations in HIPPARCOS and GENEVA photometries, were monitored from 1998 until 2001 with the CORALIE spectrograph. Among these stars, two are new spectroscopic binaries and one is a new λ Eri short period variable. HR 1960 is a low amplitude ($K = 3.4$ km s^{-1}) SB1 with a period of 395.48 d in agreement with the photometric prediction. HR 3237 is a short period SB1 ($P = 5.1526$ d). HR 3642 presents some interesting variations in photometry and spectroscopy: indeed, a mid- and a short-term variation is present with periods of 137.99 d (Hp magnitude) and 1.13028 d (radial velocity) respectively. The short-term variation, characteristic of the λ Eri stars, probably implies non-radial pulsations or inhomogeneities in the corotating disc. The last star, HR 2968, is an excellent photometric binary candidate, but no spectroscopic obviousness of a companion has been found.

Key words. stars: emission-line, Be – stars: binaries: spectroscopic – stars: individual: HR 1960, HR 2968, HR 3237, HR 3642

1. Introduction

Be stars are known to exhibit different types of variability, often present simultaneously, characterized by time scales between a few minutes and several years. Some of these variations are periodic, and this property is extremely important for the understanding of the Be phenomenon. Indeed, periodic changes in photometric and/or spectroscopic measurements can be induced by the presence of a companion, by the rotation, the pulsation or the evolution of the Be star, or by inhomogeneities in its rotating disc. The binarity is usually invoked to explain the mid-term periodic ($P \simeq 3$ to 500 d) variability of Be stars.

The four Be stars studied in this paper undergo photometric variations which can be linked to the presence of a companion. The essential role played by the multiplicity in the mid-term periodic variations and, thus, in the formation and evolution of Be-type stars was postulated by Carrier et al. (1999) and Burki (1999), who detected a periodicity of respectively 371 and 395.48 days in the GENEVA and HIPPARCOS photometric data of HR 2968 and HR 1960. In order to test this hypothesis, four Be stars, HR 1960, HR 2968, HR 3237 and HR 3642, which exhibit periodic variations according to the HIPPARCOS, TYCHO and/or GENEVA photometric measurements (1978 to 1998), have been monitored in radial velocity by using the CORALIE spectrometer mounted on the 120 cm Swiss telescope at La Silla (ESO, Chile). The results of the photometric and spectroscopic analysis are presented in this paper.

2. Periodic Be stars

Some typical examples of mid-term periodic Be stars are listed in Table 1 to illustrate the complexity of the variability phenomena in these stars. They show a variability in at least one of the parameters: the flux (photometry), the radial velocity, the relative intensity of the violet to red component of double-emission lines ($V/R = [V - V_c]/[R - R_c]$), the equivalent width (EW) of hydrogen lines.

2.1. Binary Be stars

Due to the difficulty in obtaining accurate radial velocities of hot stars, only a few tens of Be star orbits are known

---

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/385/488`

[⋆⋆⋆] Table 3 is only available in electronic form at `http://www.edpsciences.org`

Table 1. Mid-term periodic Be stars: some typical examples. This list is not exhaustive. The variability refers to the indicated period. The equivalent width is measured on the hydrogen lines, generally H_α or H_β. (1) This paper, (2) Katahira et al. (1996), (3) Koubský et al. (1989), (4) Koubský et al. (2000), (5) Harmanec (1984), (6) Božić et al. (1995), (7) Sterken et al. (1996), (8) Mennickent & Vogt (1988), (9) Božić et al. (1999), (10) Koubský et al. (1997), (11) Floquet et al. (1995), (12) Harmanec et al. (1996), (13) Hill et al. (1997), (14) Matthews et al. (1991), (15) Šimon (1996), (16) Pavlovski et al. (1997), (17) Peters (2001, (18) Štefl et al. 1990, (19) Božić & Pavlovski 1988), (20) Mennickent et al. (1998), (21) Andersen et al. (1988), (22) Andersen et al. (1989), (23) Doazan et al. (1982).

Name	HR	Period	Variability in				SB?	Remark	Reference
		[d]	*Photom.*	$V_{\rm r}$	V/R	EW			
29 Dor	1960	395.48	x	x	–	–	SB1		(1)
V468 Pup	2968	371	x	–	–	–		Also long-period variation	(1)
Pleione	1180	218		x			SB1	Also long-period variation	(2)
V923 Aql	7415	214.756		x			SB1		(3)
60 Cyg	8053	146.6	–	x			SB1	Also short-period	(4)
V345 Car	3642	137.99	x	–	–	x		Also short-period	(1)
ζ Tau	1910	132.9735	x?	x			SB1		(5) (19)
φ Per	496	126.6731	x	x			SB2		(6)
FY CMa	2855	92.7	x	–					(7)
10 CMa	2492	87.9	x	–					(7)
V696 Mon	2142	80.860		x	x			light variation	(8) (17) (20)
OT Gem	2817	71.89	x					During active Be phase	(9)
4 Her	5938	46.1921		x	x	x	SB1		(10)
KX And	HD218393	38.919	x	x			SB2	Changes in the light curve shape	(11) (18)
β Lyr	7106	12.935	x	x			SB2	Also photometric period 282 d	(12)
V360 Lac	8690	10.085408	x	x			SB2		(13)
LQ And	9070	7.41324		x		x	SB1	Also a shorter period 0.619 d	(14)
CX Dra	7084	6.696	x	x	x?	x?	SB2		(15) (16)
MX Pup	3237	5.1526	–	x	–	–	SB1	Quasi-period 11.546 d	(1)
J Vel	4074	4.656	x	–					(7)
SX Cas	HD232121	36.561	x	x			SB2	P decreasing	(21)
RX Cas	BD+67 244	32.3301	x	x			SB2	P increasing	(22)
88 Her	6664	86.7221	–	x			SB1	Also long-term variation	(23)

and only some of them are SB2. A list of these objects can be found in Harmanec (2001). In Table 1, the symbol x in the column $V_{\rm r}$ refers to the Be stars whose binarity is confirmed by radial velocity observations (SB2 or SB1 in the column SB), and the symbol – indicates that periodic variations of the radial velocity have not yet been found. It can be seen that:

- HR 1960, φ Per, V360 Lac, CX Dra, KX And, ζ Tau, SX Cas, RX Cas and β Lyr show a photometric variability having the same period as the orbital one, however, the causes of such light variations are different. HR 1960 and φ Per have a roughly sinusoidal variation. V360 Lac shows a fairly well defined double-wave light curve indicative of ellipsoidal variability and cyclic long-term changes. The light curves of CX Dra and KX And vary strongly from one cycle to another. The same applies to ζ Tau which shows disk eclipses in some cycles. β Lyr, SX Cas and RX Cas are eclipsing binaries.
- HR 2968, HR 3642, HR 2492, HR 2855 and HR 4074 present periodic photometric variations, probably due to a companion, while this period has not been detected in the radial velocity data.
- Pleione, V923 Aql, 60 Cyg, 4 Her, 88 Her, LQ And and HD 3237 do not exhibit photometric variations with the same period as the orbital one.
- OT Gem and HR 2968 show periodic photometric variations during the active Be phase only.
- In the case of CX Dra, all variations have been observed, with a period corresponding to the orbital one.
- HR 2142 displays shell phases and V/R variations with a period (80.860 d) which is probably the orbital one.

It is thus evident that the binarity is often not detected simultaneously in photometry and spectroscopy. Once more, the complexity of the Be phenomenon appears clearly, even in the restricted and a priori more simple case of the periodic variables. Simultaneous photometric and spectroscopic monitorings are necessary to try to achieve a complete understanding of the variability of these stars.

Table 2. Variability of λ Eri stars: some typical examples. The variability refers to the indicated period. The equivalent width is measured on the hydrogen lines, generally H_α or H_β. (1) This paper, (4) Koubský et al. (2000), (24) Harmanec (1998), (25) Balona et al. (1999), (26) Štefl et al. (1999), (27) Balona & Kaye (1999), (28) Balona (1999), (29) Balona & Kambe (1999), (30) Carrier et al. (2002).

Name	HR	Period [d]	Variability in				Remark	Reference
			Photom.	V_r and/or line profile	V/R	*EW*		
28 (ω) CMa	2749	1.37		x	x		Transient period of 1.48 d or slow variation of the period	(25) (26) (24)
V345 Car	3642	1.13028	–	x	x	–	Also a mid-term variation	(1)
60 Cyg	8053	1.0647	–	x			Also a mid-term variation	(4)
HP CMa	2501	0.79187	–	x	–	–	Non-periodic mid-term variation	(30)
ζ Tau	1910	0.777		x		x	Also a mid-term variation	(27)
η Cen	5440	0.64	x	x			Additional period of 0.57 d	(28)
ζ Oph	6175	0.084 & 0.139	–	x			Photom. period of 0.193 d	(29)

2.2. λ *Eridani stars*

Short-term variations are also frequently present in Be stars. They can be explained either by the non-radial pulsation or by an inhomogeneity of the disc around the rotating Be star. It is difficult to choose between these two alternatives (see Balona 1995; Balona et al. 1999). The short-term periodic Be stars, called λ Eri stars, show strictly periodic light variations with periods in the range 0.5–2.0 d. An intensive search of photometric periodic short-term variables among the Be stars has been undertaken according to the facility in 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 (see Table 2 for some examples). As a consequence of the line profile variation, the equivalent width (*EW*) of some lines (as ζ Tauri) or the V/R ratio of emission line can follow the same period too. But the *EW* and the V/R ratio usually vary with a longer time scale, related to the phase changes (Hanuschik et al. 1995).

3. Observations

Since September 1998, HR 1960, HR 2968, HR 3237 and HR 3642 have been measured with the CORALIE high-resolution fiber-fed echelle spectrograph mounted on the Nasmyth focus on the 120 cm New Swiss telescope at La Silla (ESO, Chile). CORALIE is an improved version of the ELODIE spectrograph (Baranne et al. 1996). Thanks to a slightly different optical combination at the entrance of the spectrograph and the use of a 2 k by 2 k CCD camera with smaller pixels (15 μm), CORALIE has a larger resolution than ELODIE. A resolving power of 50 000 ($\lambda/\Delta\lambda$) is observed with a 3 pixel sampling. The CORALIE data were reduced 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 159 echelle-spectra was 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 25 to 70 at 4500 Å and from 50 to 140 at 6000 Å.

From 1978 to 1998, these stars were 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). The photometric reduction procedure is 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 1998). In addition to these data, several photometric measurements have been obtained by the HIPPARCOS satellite (ESA 1997) in the range of 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).

4. Radial velocity determinations

The main problem to determine radial velocities for Be stars is that the spectra of these stars contain only a few lines. Moreover as the Be stars are often rapid rotators ($v \sin i$ can reach 200–300 km s^{-1}), most of the lines are unusable because they are blended. In order to compensate for the small number of lines and the poor definition of the line center, high S/N spectra are used to obtain the radial velocity. The applied method consists of the correlation between the considered spectrum and a reference spectrum. Synthetic spectra are used as templates (Morse et al. 1991). Since early-type star spectra present significant feature changes from one spectral type to another, it is important to dispose of a template as similar as possible to the real spectrum. Therefore the T_eff, the $\log g$ and the $v \sin i$ have to be determined for each star. Thus synthetic spectra could be calculated in a grid as dense as necessary

Table 4. Physical characteristics of the Be stars analyzed in this paper. The spectral type gets out of SIMBAD. The values of $v\sin i$ are calculated in this paper (see Sect. 5). The primary mass is calculated by photometric calibrations for HR 1960 and HR 2968, the estimate of Schmidt-Kaler (1982) is used for the others. The equivalent width is negative for an absorption line. This sample is varied in regard of the spectral type and the emission intensity.

Name HR	ST	$v\sin i$ [km s^{-1}]	$EW(\mathrm{H}_\alpha)$ [Å]	$\mathcal{M}_1$ [$\mathcal{M}_\odot$]	$\mathcal{M}_2$ [$\mathcal{M}_\odot$]
1960	B9.5Ve	175	$-2.6 - -2.2$	3	0.5–3
2968	B6IVe	150	$2.6 - 5.8$	5.9	≤ 1.2
3237	B1.5IIIe	120	$27.5 - 53.3$	15	0.6–6.6
3642	B2IVe	110	$3.8 - 6.5$	13	≤ 1.7

to closely match the observed stellar spectrum for any combinations of the above quoted parameters (Nordström et al. 1994).

The spectrum synthesis of the spectral region 3875–6820 Å was accomplished using the SYNSPEC (Hubeny et al. 1994) code with the model atmospheres interpolated from Kurucz ATLAS9 (1994) grid. Vienna Atomic Line Database (VALD-2) was used to create a line list for the spectrum synthesis (Kupka et al. 1999). This program uses a LTE-model, which is not appropriate in determining abundances of early B-stars, but is efficient enough for the calculation of radial velocities. First the synthetic spectrum is computed without rotation, with a solar composition and with a microturbulent velocity of 2 km s^{-1}. Next the obtained spectrum is broadened with profiles to take the rotation and the resolving power of the observed spectra into account. Many tests were conducted employing several templates to discover which yielded the strongest and sharpest cross-correlation function. Only the absorption lines listed in Table 3 were used to derive the radial velocities. The radial velocities were finally obtained from the cross-correlation function by fitting a function obtained by the convolution between a Gaussian and a rotation profile given by Gray (1976).

The main sources of the radial velocity error are the spectrum noise and the stellar parameter mismatch between the real spectrum and the template (T_{eff}, $\log g$, $v\sin i$ and metallicity). Raboud (1996) estimated radial velocity errors for B stars according to their $v\sin i$ and the S/N of their spectrum. This leed to a typical error of 1.4 km s^{-1} with $S/N = 60$ and $v\sin i = 200$. However, in our case, a more realistic error determination is given by the O−C of the two detected binaries (see Table 5).

5. Rotational velocity determinations

Rotational velocity ($v\sin i$) was estimated by comparison between an artificially broadened synthetic spectrum and the spectrum of the star (Brown & Verschueren 1997) (see Table 4). A grid of synthetic spectra was built with the SPECTRUM code (Gray & Corbally 1994). Only spectral lines presenting any sign of emission were used for the rotational velocity determination. The broadening by instrumental effects was taken into account. Estimating the accuracy of the $v\sin i$'s is difficult because of the subjective nature of the rotational velocity determination. The values should be accurate to within ~10%.

6. HR 1960

6.1. Description

HR 1960 (HD 37935, HIP 26368) is a late B-type star classified B9.5Ve in SIMBAD (Centre de Données Astronomiques de Strasbourg, CDS). In the Michigan Catalogue (Houk & Cowley 1975), the spectral type is B9.5V. The observed rotational velocity is quite high and has a value determined from CORALIE spectra of 175 km s^{-1} which is in agreement with the value of Andersen & Nordström (1983) who found 175–250 km s^{-1}. The star was declared constant by Balona et al. (1992) and was used as a comparison star to analyze the photometric variability of HD 269858 (Sterken et al. 1993) and SN 1987A (Burki et al. 1989, 1991). The star was also found constant in the HIPPARCOS Catalogue (ESA 1997). In radial velocity, HR 1960 was declared stable by Andersen & Nordström (1983). However, Burki (1999) detected a very small periodic photometric variation of 395.48 d.

6.2. Photometric and radial velocity variability

The reality of this photometric variation was analyzed by Burki (1999). The main points are: i) the independent samples from GENEVA and HIPPARCOS photometries show the same period; ii) the star HR 1744 measured with HR 1960 during the monitoring of SN 1987A does not exhibit this period of 395.48 d. It results from these photometric surveys that HR 1960 is probably the long-period variable star with the smallest amplitude yet known, i.e. 3 mmag in V and 2 mmag in $[B-V]$. This detection was possible due to the periodic character of the variability, to the accuracy of the photometric data and to the equipment being maintained very stable for several years.

HR 1960 was monitored in spectroscopy with CORALIE for two cycles during which 44 radial velocity measurements were obtained. Figures 2 and 3 show the result of the Fourier analysis of the photometric (GENEVA and HIPPARCOS) and radial velocity data. The main points are:

- The global structure of the spectral windows (Figs. 2d and 3d) is quite typical, i.e. the main peaks are at about 1 d^{-1}.
- The detailed structure of the spectral windows (Figs. 2c and 3c) show several peaks around 1 d^{-1}, indicating that the spurious aliasing peaks must be numerous in the Fourier Transform diagrams.

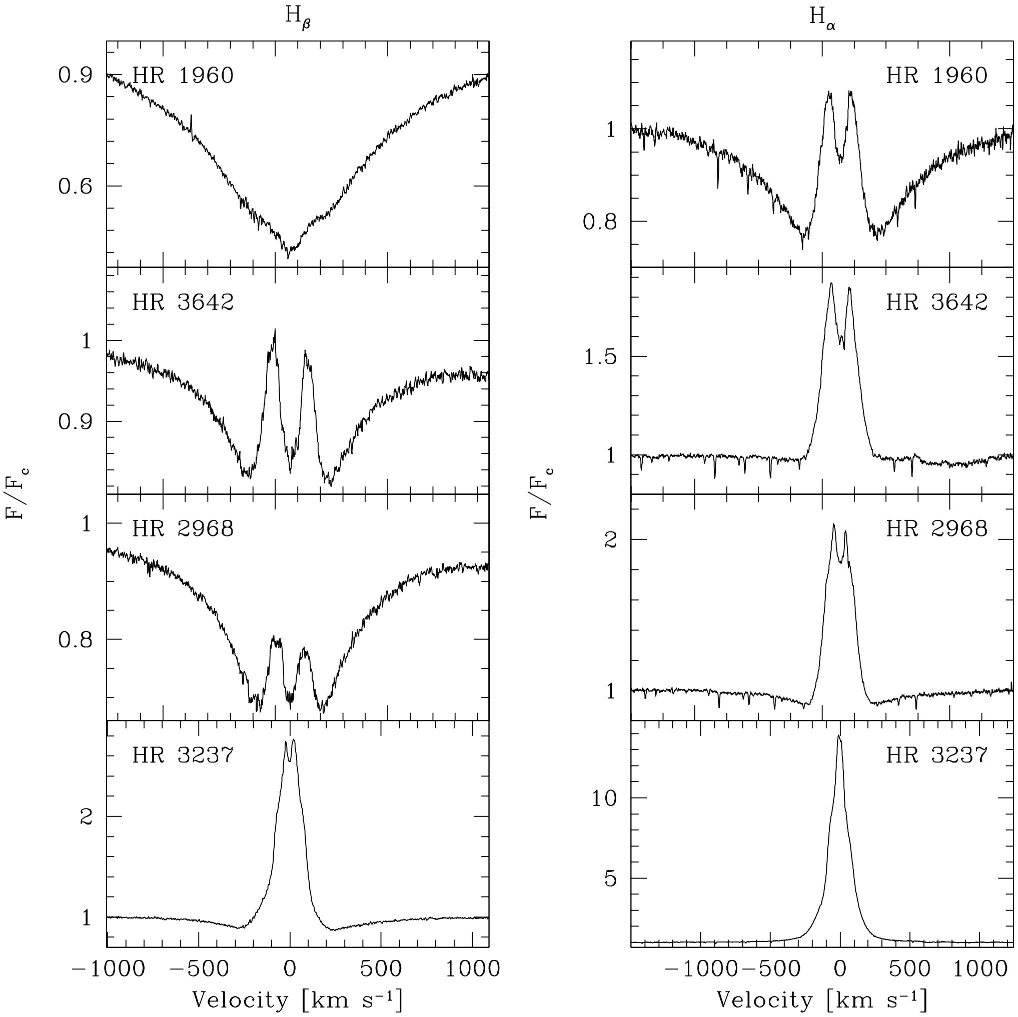

Fig. 1. Emission line profiles (H_α and H_β) for the four Be stars. The flux is normalized to the continuum. The stars are presented according to the intensity of their H_α line. HR 3237 has very strong emission line, it is supposed to be viewed pole-on.

Table 5. Orbital parameters of the binaries. For each star, the second line gives the corresponding estimated standard deviation.

Star name	P (days)	$T_\circ$ (HJD $-2\,451\,000$)	e	$V_\circ$ (km s^{-1})	ω_1 (°)	K_1 (km s^{-1})	$f_1(\mathcal{M})$ $\mathcal{M}_\odot$	$a_1 \sin i$ 10^6 km	N	(O−C) km s^{-1}
HR 1960	395.48	323.9	0.39	12.50	166.3	3.41	0.00127	17.1	44	2.19
	fixed	18.5	0.15	0.33	21.0	0.65	0.00077	3.5		
HR 3237	5.1526	232.64	0.46	23.20	74.4	10.04	0.00038	0.633	42	3.36
	0.0011	0.11	0.07	0.53	12.0	0.90	0.00011	0.062		

- Photometric and radial velocity data exhibit a peak at about 0.0025 d^{-1} (Figs. 2a and 3a) in the Fourier Transform. This clearly indicates that an orbital motion induces the photometric variability.
- A detailed examination of Fig. 3a reveals that the radial velocity frequency at the top of the peak is 0.0022 d^{-1}, a smaller value than the photometric frequency (0.0025 d^{-1}). However, the radial velocity frequency is not accurate because the duration of the survey was short, only about two periods (see Fig. 4a). Thus, we have adopted the value of the photometric period, 395.48 d (see Burki 1999), for the orbital solution.
- The peaks around 1 d^{-1} in the Fourier Transform (Figs. 2b and 3b) are spurious, i.e. due to the aliasing induced by the data sampling.
- After subtraction of the light or velocity curve, with the period $P = 395.48$ d, the Fourier analysis does not reveal any other significant periodic variation (see the thin lines in Figs. 2a,b and 3a,b).

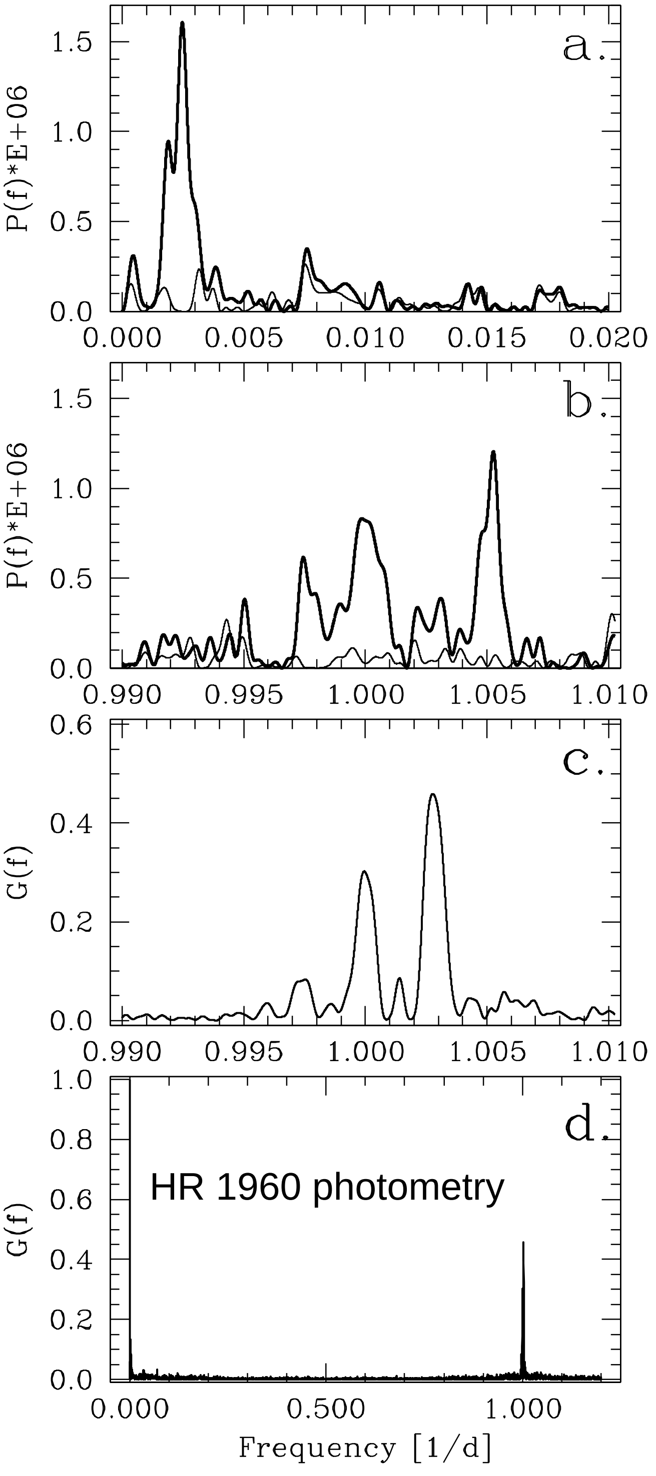

Fig. 2. The Fourier analysis of the Geneva and Hipparcos photometric data of HR 1960. **a)** Thick line: power in the Fourier Transform in the frequency range 0.00 to 0.02 d^{-1}; thin line: power of the Fourier Transform after subtraction of the main component at 0.002549 d^{-1} (with one harmonics). **b)** Same as Fig. **a)** in the range 0.99 to 1.01 d^{-1}. **c)** Spectral Window in the range 0.00 to 1.10 d^{-1}. **d)** General Spectral Window (range 0.00 to 1.20 d^{-1}).

In conclusion, the spectroscopic survey confirms the hypothesis of the binarity for HR 1960. The spectroscopic

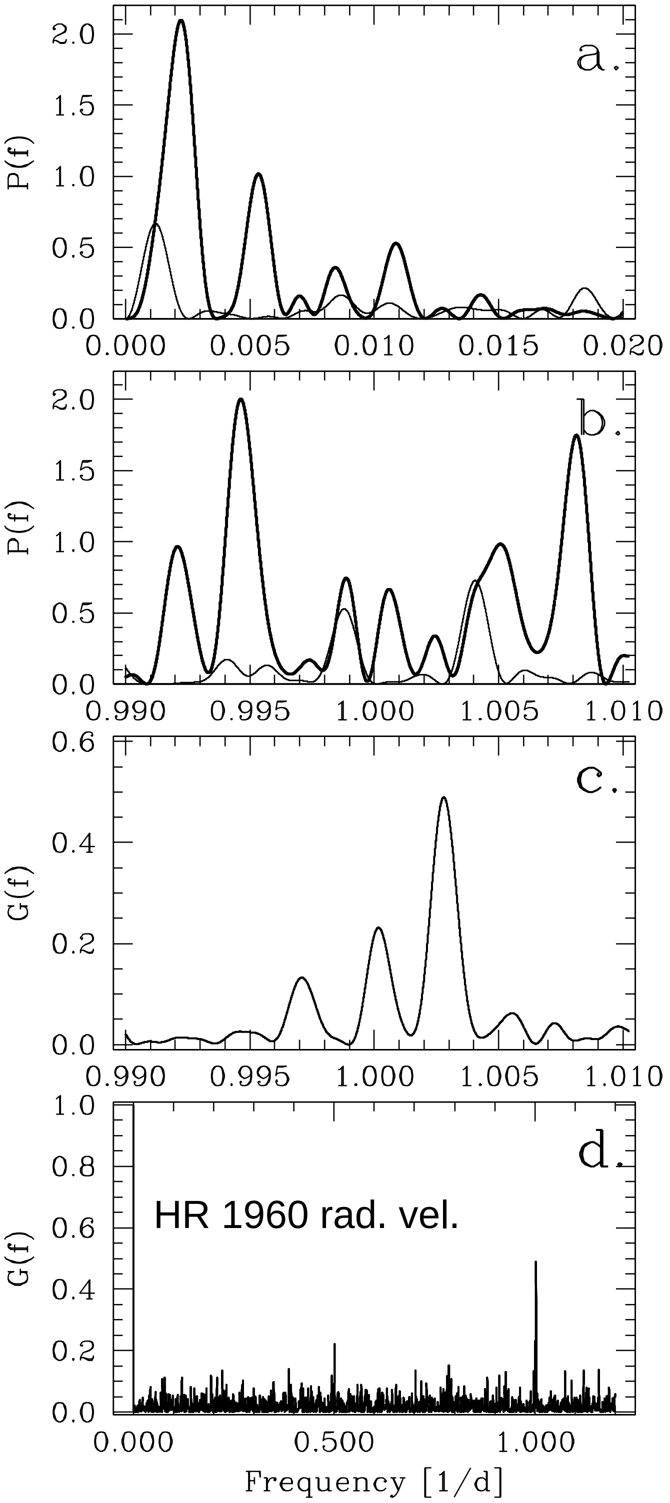

Fig. 3. Same as Fig. 2, but for the radial velocity survey of HR 1960.

orbit (Fig. 4) is in perfect agreement with the photometric variability. Besides, the period of 395.48 d has been fixed by the photometric data, which cover 14 cycles. The orbit is rather eccentric ($e = 0.39$) and the variation, as well as the luminosity, very weak. Indeed, the semi-amplitude K ($3.41\ \mathrm{km\,s^{-1}}$) is scarcely twice the radial velocity accuracy.

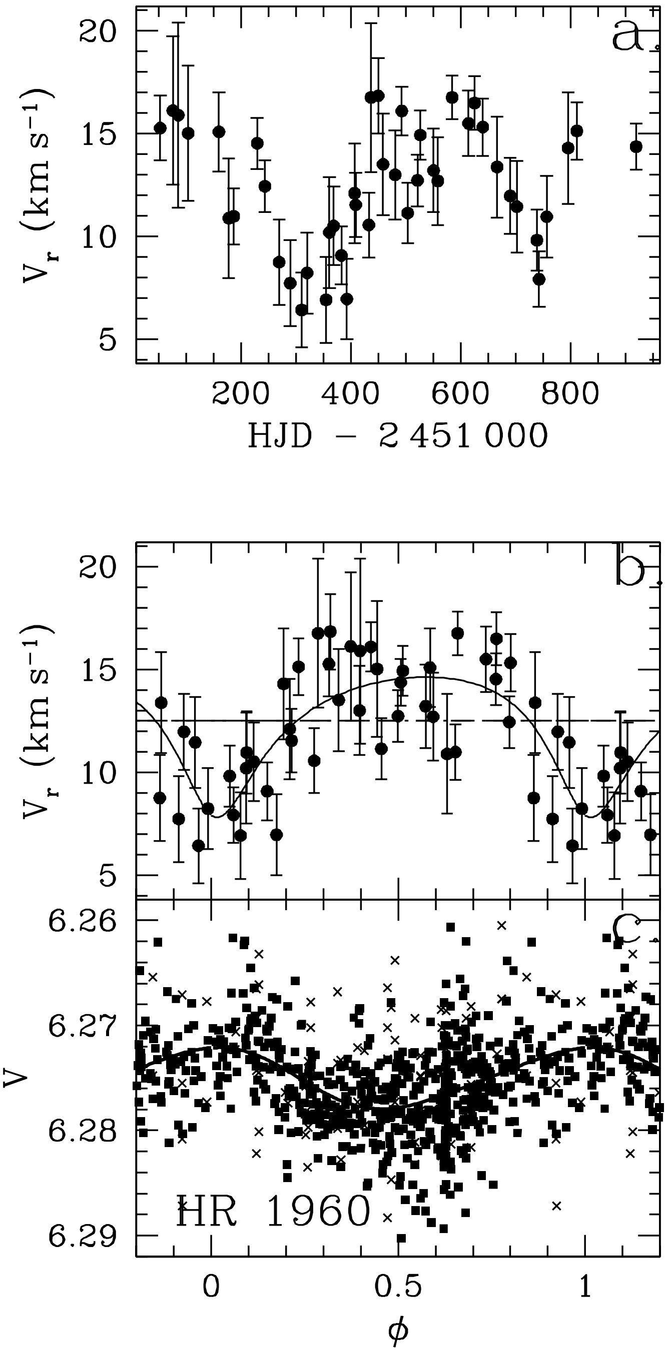

Fig. 4. a) Radial velocity measurements of HR 1960. **b)** Radial-velocity curve. The period is 395.48 d. T_0 is the time of the periastron. **c)** Light curve of HR 1960 with the same period and time of the periastron as **b)**. Data from Geneva photometry are identified by filled squares and Hipparcos V magnitudes by crosses.

The orbital parameters are listed in Table 5. The light curve with the same period and T_0 (i.e. time of the periastron) is presented in Fig. 4. It is important to note that the phase of the luminosity maximum corresponds perfectly to the periastron passage. This is a strong confirmation of the model proposed by Carrier et al. (1999).

Due to an eccentric orbit and to a large separation of both components, the Be rotation and orbit axes are not necessarily aligned. Therefore it is impossible to determine the orbital inclination i (Porter 1996). Thus, in spite of the determination of the primary mass ($\sim 3\ M_\odot$) by photometric calibrations (Burki 1999), only a poor estimate of the companion's nature can be derived from the mass function $0.5 \lesssim M_2 \lesssim 3\ M_\odot$.

6.3. Spectroscopic variability

The spectra of HR 1960 confirm that the Be star was not very active during the whole survey and that the disc was of low importance and stable in shape. All the emission lines are quite weak (see Fig. 1 and Table 4). Moreover, no EW or V/R ratio variations are detected in hydrogen lines.

6.4. Model

The origin of the photometric and radial velocity variabilities can be explained by a model similar to the one proposed by Carrier et al. (1999):

- The Be star is the main component of a binary system having an eccentric orbit ($e = 0.39$) of period 395.48 d.
- At each periastron passage, the companion star interacts gravitationally and/or radiatively with the disc around the Be star.
- This interaction induces the observed periodic modulation of the luminosity of the system (stars and disc).
- The maximum of luminosity occurs around the passage at the periastron.
- This light modulation is very weak and therefore does not imply observed EW or V/R ratio variations.

The validity of this model for HR 1960 is reinforced by the fact that the maximum of luminosity occurs during the passage of the binary components at the periastron.

7. HR 2968

7.1. Description

HR 2968 (HD 61925, NGC 2451–187, HIP 37345) is a Be-type star belonging to cluster NGC 2451B (Carrier et al. 1999). The star is classified B6IVe in SIMBAD. It has a high rotational velocity, namely 150 km s^{-1} deduced from Coralie spectra and 200 km s^{-1} determined by Slettebak (1982). The Be characteristic was found by Neubauer (1930), who detected H_β emission. Since then, weak emissions in H_α (Jaschek et al. 1964) or H_β (Jaschek et al. 1965), or no emission at all (Morris 1961; Slettebak 1982) were observed.

7.2. Photometric variability

HR 2968 was observed in Geneva photometry between 1978 and 1998. Until 1990, the star remained stable in

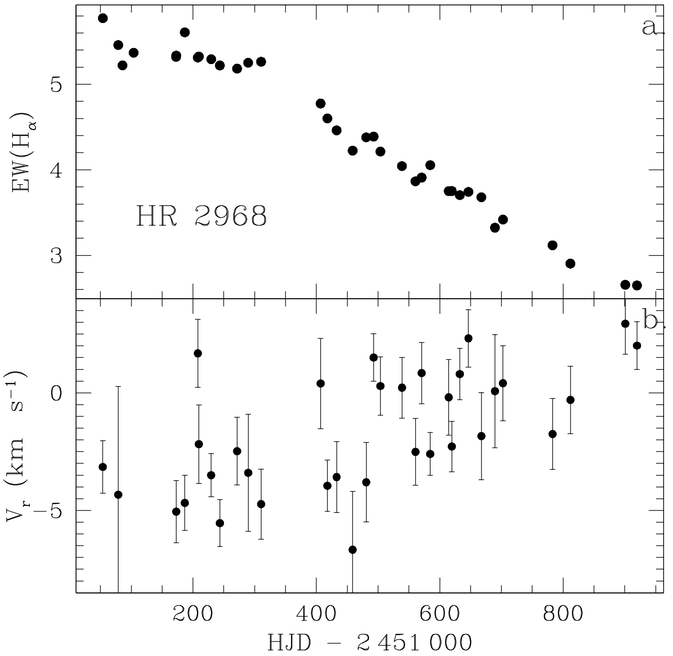

Fig. 5. a) Equivalent width variations of the H_α line of HR 2968. The intensity of the hydrogen lines decreases. **b)** Radial velocity measurements of HR 2968. A small trend of 3-4 km s^{-1} seems to be present among the data.

luminosity and colours. Afterwards, the mean luminosity started to increase, and this brightening continued until 1995. Then the mean luminosity decreased until the end of the photometric survey in 1998 (Carrier et al. 1999). In addition, the star exhibited a very surprising kind of photometric variation with a period of 371 d (Carrier et al. 1999). This period is clearly the correct one and cannot be a spurious one induced by the aliasing with the classical peak at the frequency 1 d^{-1} in the spectral window (see Figs. 6, 7, 9 and 10 in Carrier et al. 1999). The interpretation of these photometric variabilities was: i) the increase of the mean luminosity was due to the development of the Be star disc; ii) the periodic variability, which started simultaneously, was induced by the interactions in a binary system with an orbital period of 371 d.

7.3. Spectroscopic variability

Figure 5 shows a continuous decrease in the equivalent width of the H_α emission line during our spectroscopic survey, which started in September 1998 (see Fig. 5a). This is due to the diminishing importance of the disk around HR 2968, and is in agreement with the observed decrease of the mean luminosity between November 1995 and October 1997 (see Carrier et al. 1999). The photometric and spectroscopic evidences of the disk variation around this Be star are in agreement one with the other. However, it must be noted that the V/R ratio was stable during our survey.

7.4. Radial velocity variability

The 33 radial velocities do not reveal any periodic variation (see Fig. 5b). In particular, the photometric period of 371 d is not put into evidence. As the binarity is indeed the most reasonable cause to explain the photometric periodic variability, it is important to estimate the probability of such a spectroscopic detection. This was done with the help of the following simulation:

- The orbital parameters of the "binary" HR 2968 are randomly chosen: the distribution of the primary mass is a Gaussian centred at 5.9 $M_\odot$ with $\sigma = 0.5\ M_\odot$ (Carrier et al. 1999), the period is fixed at 371 d, the orbital elements T_0, ω and i are randomly distributed, the eccentricity e and the mass ratio q are fixed to a given value.
- Thus, a radial velocity is obtained for each observation date.
- Afterwards, the variability criterion, the probability $P(\chi^2)$ that the variations in velocity are only due to the internal dispersion, is calculated. The star will be considered as double or intrinsically variable if $P(\chi^2)$ is less than 0.01 (Duquennoy & Mayor 1991).
- These operations are repeated 10 000 times to obtain the detection probability.
- Moreover, this simulation is made for different mass ratios q and eccentricities e.

Detailed results are shown in Fig. 6. We find that for $q > 0.2$ (i.e. $M_2 > 1.2\ M_\odot$) the detection probability of a companion is 80%.

Thus, the conclusions are the following. If the photometric variability of HR 2968 is due to the interaction with a companion (and this is the simplest explanation), then:

- either the mass of the secondary is $M_2 \leq 1.2\,M_\odot$;
- or the system is viewed nearly pole-on.

In addition, the companion would not be a compact object because the X-ray luminosity measured by the ROSAT satellite was $10^{30.07}$ ergs s^{-1} (Berghöfer et al. 1996). This value is in agreement with the X-ray luminosity of stars of same spectral type (Meurs et al. 1992) and is thus not exceptional. Note that HR 2492 and HR 2855 exhibit similar periodic photometric variations of this kind and no sign of a companion has been detected either (see Table 1).

8. HR 3237

8.1. Description

HR 3237 (HD 68980, MX Pup, HIP 40274) is classified B1.5IIIe in SIMBAD and B1.5IVe by Slettebak (1982). This suspected pole-on Be star (Mennickent et al. 1994) was discovered in 1892 by Fleming. Its spectra already showed emission lines. Moreover this star has a moderate rotational velocity of 120 km s^{-1} (see Sect. 5 and Slettebak 1982). The light curve of HR 3237 shows a long-term variability with a time scale of about 9 years accompanied

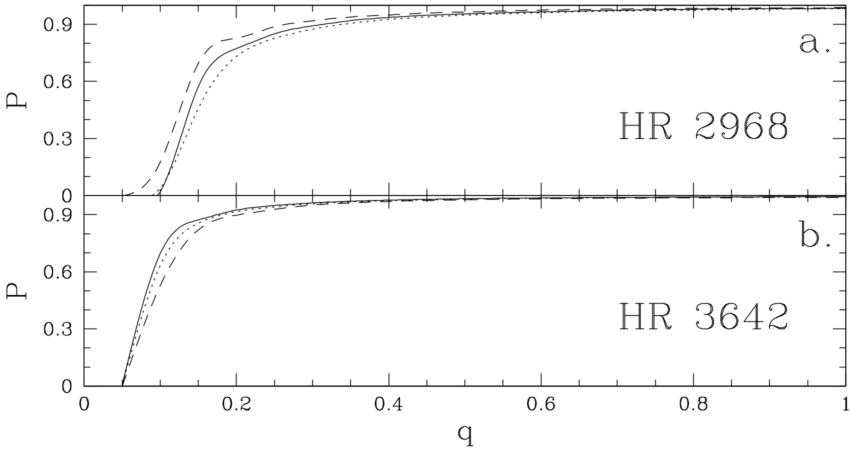

Fig. 6. **a)** Mass ratio (q) versus detection probability of the binarity of HR 2968, supposing that this star is a binary. Three eccentricities are drawn: 0 (solid line), 0.4 (dotted line) and 0.8 (dashed line). **b)** Same as **a)** but for HR 3642.

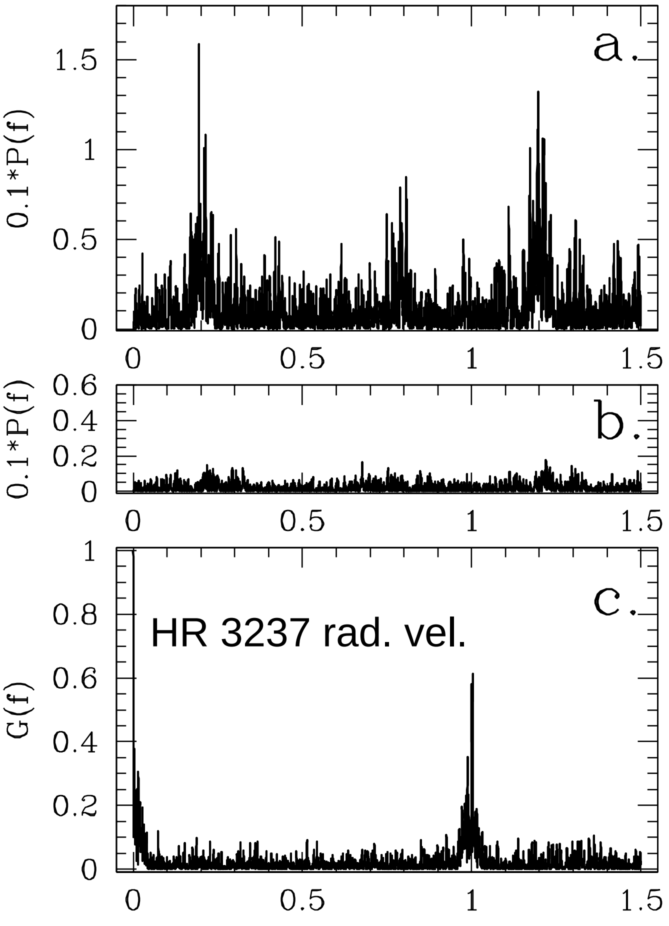

Fig. 7. The Fourier analysis of the radial velocity data of HR 3237 in the frequency range 0.00 to 1.50 d^{-1}. **a)** Power in the Fourier Transform; **b)** power of the Fourier Transform after subtraction of the main component at 0.1941 d^{-1} (with 3 harmonics). **c)** General Spectral Window.

by a V/R variation (Mennickent et al. 1997; Hanuschik et al. 1995). Hubert & Floquet (1998) detected quasi periodic oscillations from HIPPARCOS magnitude (Hp) ($P = 11.546$ d) superimposed to long-term variations.

8.2. Radial velocity variability

The results of the Fourier analysis of the 42 radial velocities obtained during our survey are presented in Fig. 7. The power spectrum and the spectral window are very classical for ground based observations and a periodic variability is very clearly shown, at frequency 0.1941 d^{-1}, corresponding to the period 5.1526 d. As shown by Fig. 7b, no other periodicity is present in our data.

According to our measurements, HR 3237 is a new spectroscopic binary with a period of 5.1526 d. Indeed, this period is too long to be due to the rotation of the star; moreover others signs should be present as line profile variations. The radial velocity curve is shown in Fig. 9 and the orbital parameters are listed in Table 5. In spite of a relatively short period, the orbit is very eccentric ($e = 0.46$) and for the same reason as for HR 1960 it is not possible to define the nature of its companion. Such an eccentricity with a short period is not so exceptional in Be stars: for example, LQ And has a period of 7.413 d and an eccentricity in the range 0.27–0.57 depending of the line used for the radial velocity determination (Matthews et al. 1991).

According to its very low mass function, the binary system should be viewed almost pole-on. Assuming a mass of 15 $M_\odot$ for the primary according to its spectral type (Schmidt-Kaler 1982), the secondary mass has a value of $0.6 \lesssim M_2 \lesssim 6.6\ M_\odot$ if the angle of view is contained between 5° and 50°.

8.3. Spectroscopic variability

- This Be star has very strong emission lines (see Fig. 1 and Table 4) (reinforcing the fact that HR 3237 is viewed pole-on) and is very active.
- At the beginning of the survey only one emission peak is observed for the hydrogen lines.

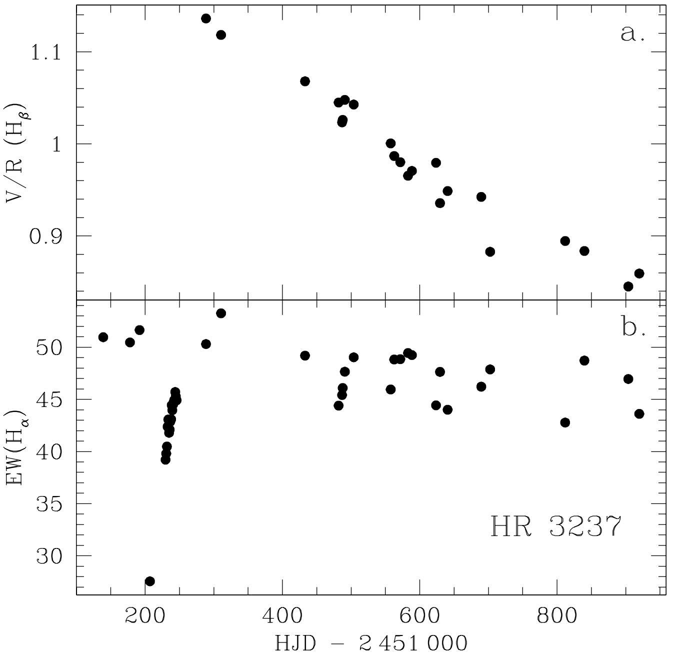

Fig. 8. a) V/R variations of the H$_\beta$ line of HR 3237. Before HJD ∼ 2 451 270 only one peak can be distinguished. **b)** Equivalent width variations of the H$_\alpha$ line. No periodicity could be found.

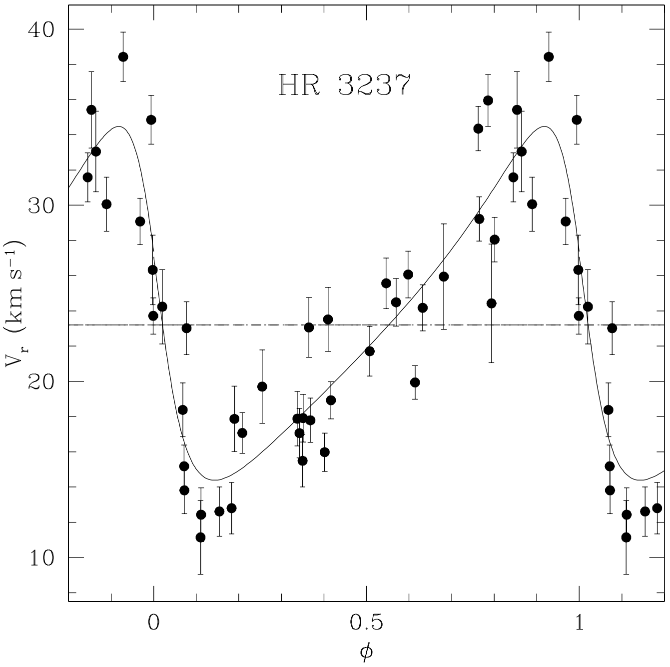

Fig. 9. Radial-velocity curve of HR 3237. The period is 5.1526 d.

- Then the red peak develops. So the V/R ratio decreases until the end of our survey for at least 800 days (see Fig. 8).
- In the same time, the equivalent width (EW) of the H$_\beta$ lines decreases too (see Fig. 8).
- The EW also exhibits some variations. This variability is non-periodic and should be due to the star itself, burst or ejection of matter.

8.4. Photometric variability

The Hipparcos photometry also presents some long-term variations showing the Be star activity. Hubert & Floquet (1998) detected among these data a periodic signal for 2 448 400 < HJD < 2 449 200 (P 11.546 d). This period is in fact not real. Indeed, if the time lapse of selected observations is slightly changed, others period values are obtained. Moreover, this period is not confirmed by our spectroscopic data.

9. HR 3642

9.1. Description

HR 3642 (HD 78764, V345 Car, HIP 44626) is classified B2IVe in SIMBAD and B2IVn in the Michigan Catalogue (Houk & Cowley 1975). Its rotational velocity is also moderate for a Be star and has a value of 110 km s^{-1} (see Sect. 5) (120 km s^{-1}, Slettebak 1982). In 1897 this star was already known as a B star with H$_\beta$ in emission (Pickering & Fleming 1897). In addition, Baade (1992) did not find any spectral lines of a cool companion, and the Rosat satellite does not detect X-ray luminosity higher than expected for such stars (Berghöfer et al. 1996).

9.2. Photometric variability

HR 3642 is variable with a nearly sinusoidal light curve of period P = 137.99 d and peak-to-peak amplitude of 0.07 mag on the basis of the Hipparcos photometry (Grenon 1997). Such a long periodic variation could imply a low-mass companion. In addition, Hubert et al. (1997) detected a short-term variation of period $P = 0.698$ d but this period is not confirmed by our analysis (see below).

Figure 10 shows that the main peak in the Fourier spectrum of the Hipparcos (112 measurements) and Geneva (5 measurements) photometric data is at the frequency 0.007247 d^{-1}, corresponding to a period of 137.99 d already detected by Grenon (1997). No other significant peak is detected after subtraction of the corresponding light curve. This period is confirmed by the Fourier analysis of the Tycho photometric measurements in V and B, as shown in Fig. 11, where the main peak is observed at the same frequency for the 3 data samples. The corresponding light curves in Hipparcos Hp and Tycho V and B magnitudes are presented in Fig. 12.

9.3. Radial velocity and line profile variability

The Fourier spectrum from the 40 radial velocity measurements exhibits a well-defined main peak at the frequency 0.884737 d^{-1}, as shown by Fig. 13a. The corresponding radial velocity curve is presented in Fig. 15a. In addition,

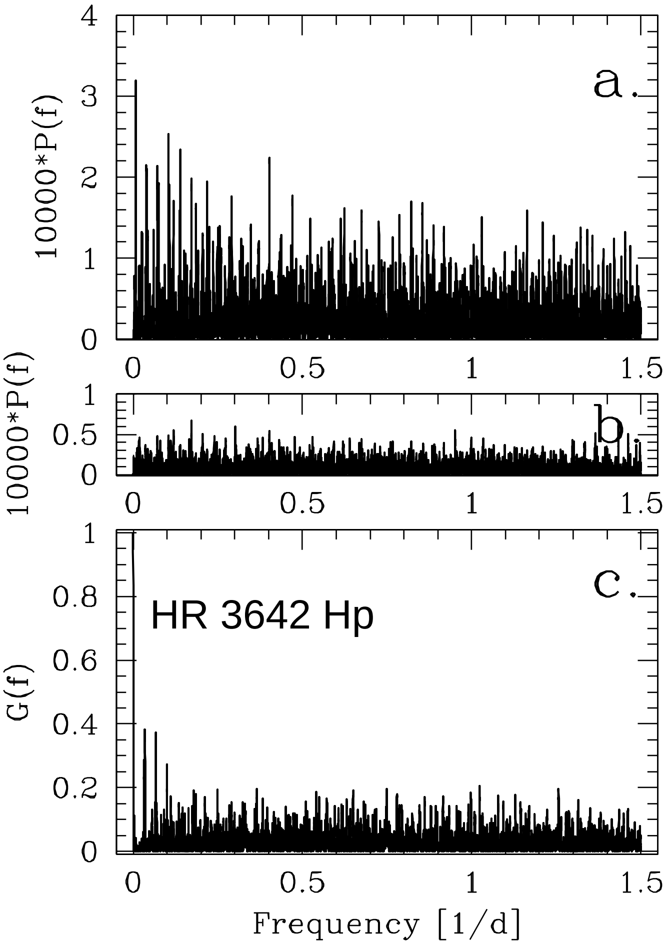

Fig. 10. The Fourier analysis of the Hipparcos and Geneva photometric data of HR 3642 in the frequency range 0.00 to 1.50 d^{-1}. **a)** Power in the Fourier Transform; **b)** same as **a)** after subtraction of the main component at 0.007247 d^{-1}; **c)** general Spectral Window.

it is noteworthy that no radial velocity variation related to the mid-term photometric period is detected.

Is the observed spectroscopic short period related to the binarity of HR 3642? Variations of the line profile similar to the observations reported in Fig. 14 have been observed in the binary V436 Per ($P = 26$ d) by Harmanec et al. (1997). In this case the binary character of this object is undoubtable because this is an eclipsing system and, moreover, the lines of the two components appear at some phases. Another interesting case is SX Aur (see Linnell et al. 1988), an eclipsing system of period 1.21 d, with components of type B2e and B5. This is the binary Be star with the shortest period in the list by Harmanec (2001). HR 3642 could be a system similar to SX Aur, however this is very improbable because:

- it would be seen nearly pole-on because the radial velocity variations are small;
- the orbital period would be the shortest known among the binary Be stars;
- the system would then be triple, if the explanation of the mid-term photometric period by the interactions with a companion is correct (see below).

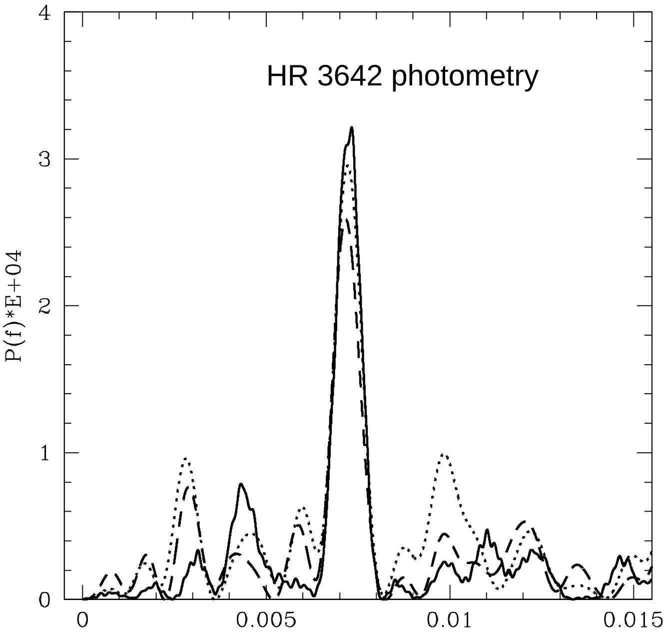

Fig. 11. The Fourier analysis of the Hipparcos and Geneva photometric data of HR 3642 in the frequency range 0.000 to 0.015 d^{-1}. The type of line refers to: continuous line for *Hp* and Geneva *V* magnitude, dashed line for Tycho *V* magnitude, dotted line for Tycho *B* magnitude.

Consequently, the line profile variations seem to be due to non-radial pulsations or to inhomogeneities in the disk around the Be star (see the patch model by Balona et al. 1999). HR 3642 is probably a new λ Eri star with a period of 1.13028 d.

The V/R ratio of the H_α line varies with the same short period as the line profile or the radial velocity, i.e. 1.13028 d (see Fig. 13b and Fig. 15b). The amplitude of this variation is very small and is due to the changes of the hydrogen absorption line profile.

The variability of the equivalent width of the hydrogen line H_α is complex, as shown in Fig. 16:

- The first half of the survey is characterized by a variation with a pseudo-period of about 250 d. However, note that only two minima were observed.
- The second part of the survey (after HJD 2 451 500) is characterized by a global continuous increase of *EW*.
- Some shorter variations are observed, for instance at HJD 2 451 420 and 2 451 550.

9.4. Model

The observational facts on HR 3642 which must be explained are the following:

- The luminosity vary with a period of 137.99 d (see Fig. 12).

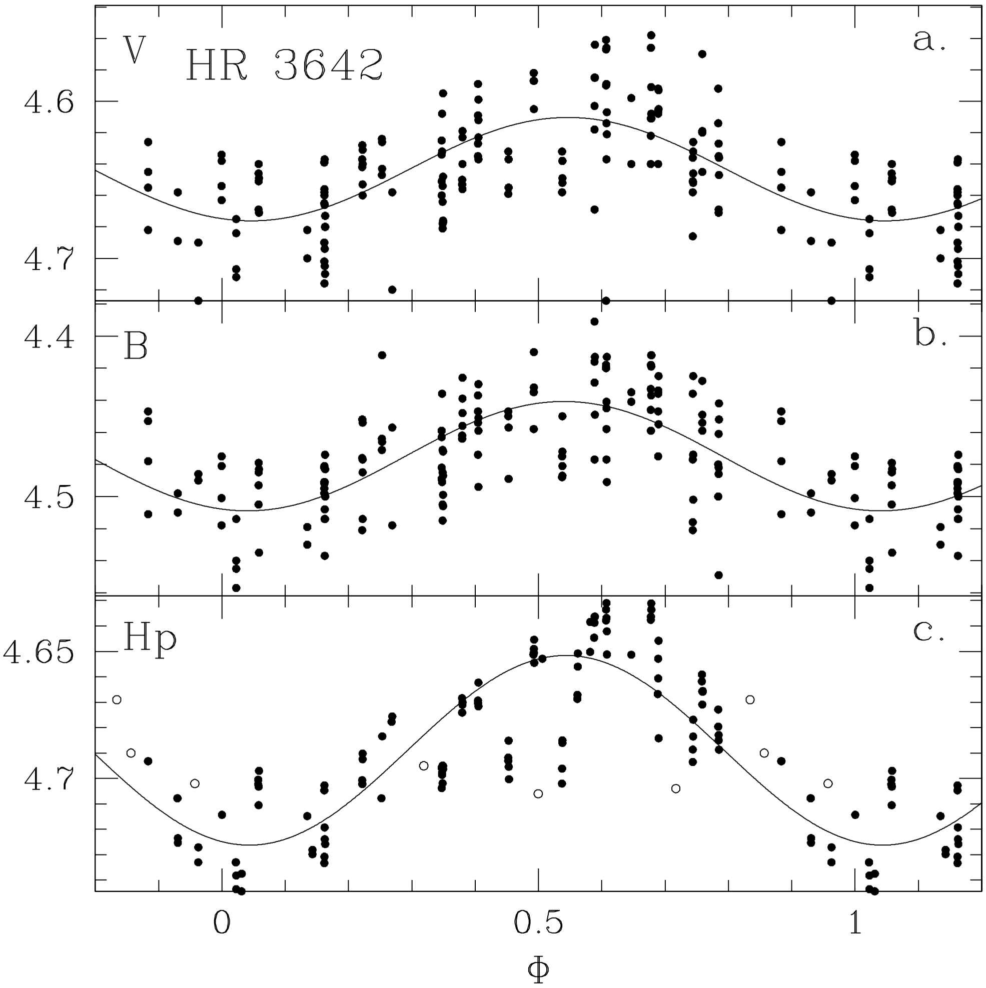

Fig. 12. a) Magnitude V Tycho versus the phase for HR 3642. The period is 137.99 d. **b)** Same as **a)** for the magnitude B Tycho. **c)** Same as **a)** for the magnitude *Hp* (filled dots) and V of GENEVA (open dots).

- The radial velocities and the V/R ratio show a short period of 1.13028 d (see Fig. 15).
- These two periods are not detected together in the same data, as it is the case for 60 Cyg and ζ Tau (see Tables 1 and 2).
- The equivalent width of H_α does not exhibit the photometric period, but is variable with a complex behaviour (see Fig. 16).

The mid-term periodic photometric variation (137.99 d) is most likely produced by the interactions in a binary system : the passage of the companion at the periastron can perturb the central system (star+disc) or induce a light reflecting effect (see Sect. 6.4). However, the radial velocities survey does not reveal this companion. To test the probability of detection, a simulation similar to that made for HR 2968 (see Sect. 7.4) has been performed. The distribution of the primary mass is a Gaussian centred at 13 $M_\odot$ with $\sigma = 2$ $M_\odot$ and the period is fixed at 137.99 d. Detailed results are shown in Fig. 6. We find that for $q > 0.13$ (i.e. $M_2 > 1.7$ $M_\odot$) the detection probability of a companion is larger than 80%. Thus, our conclusions are the following:

- either the mass of the secondary is $M_2 \leq 1.7\,M_\odot$;
- or the system is viewed nearly pole-on.

The short-term spectroscopic period indicates the presence of an inhomogeneity in the circumstellar matter of the Be star or perhaps non-radial pulsations.

10. Conclusion

The long-term spectroscopic survey of the four Be stars was extremely fruitful, since we found two new spectroscopic binaries (HR 1960 and HR 3237) and a new λ Eri star (HR 3642). In addition, the complexity of the variability in Be stars, even restricted to the periodic ones, is once more put into evidence. Indeed, our results show that:

- In the case of HR 1960, a perfect agreement between the photometric and spectroscopic surveys is obtained (same period of 395 d and small amplitudes).
- This is not the case of HR 2968, which shows a similar photometric variability to HR 1960, but for which

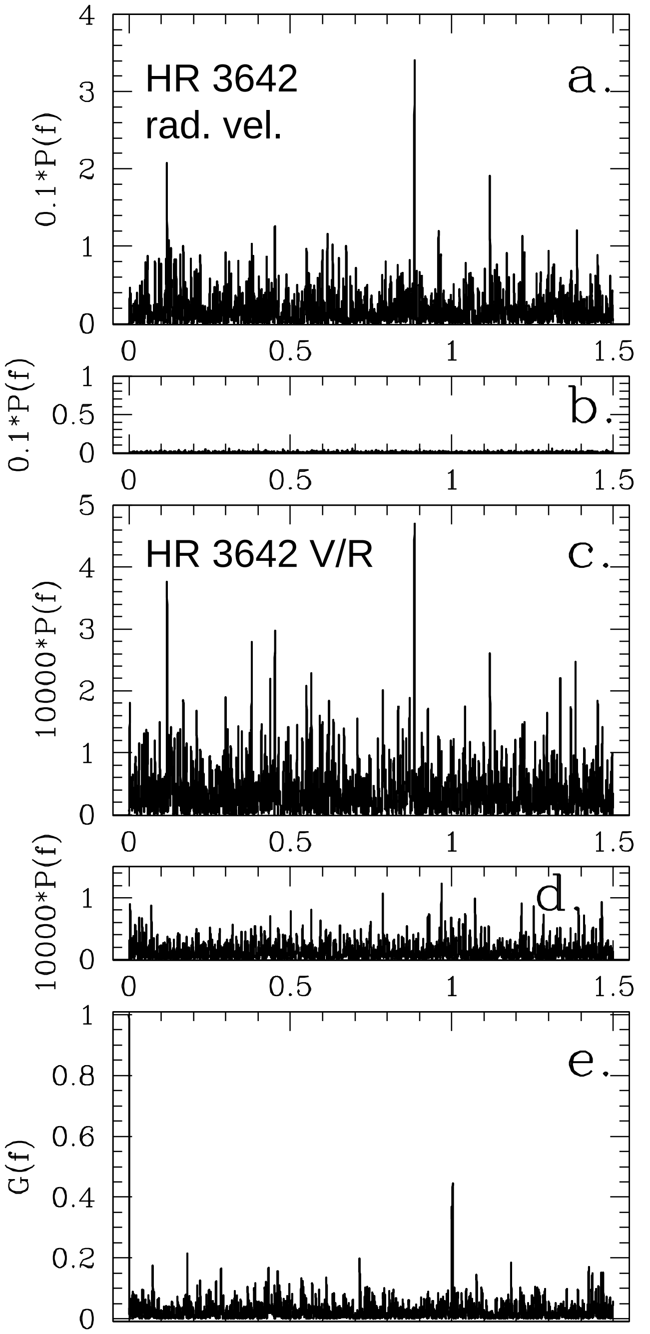

Fig. 13. The Fourier analysis of the radial velocity and V/R data of HR 3642 in the frequency range 0.00 to 1.50 d^{-1}. **a)** power in the Fourier Transform of the radial velocity data; **b)** same as **a)** after subtraction of the main component at 0.884737 d^{-1} (with 3 harmonics); **c)** power in the Fourier Transform of the V/R data; **d)** same as **c)** after subtraction of the main component at 0.884737 d^{-1} (with 3 harmonics); **e)** General Spectral Window, for both radial velocity and V/R data.

no evidence of a long-term spectroscopic variation was observed.

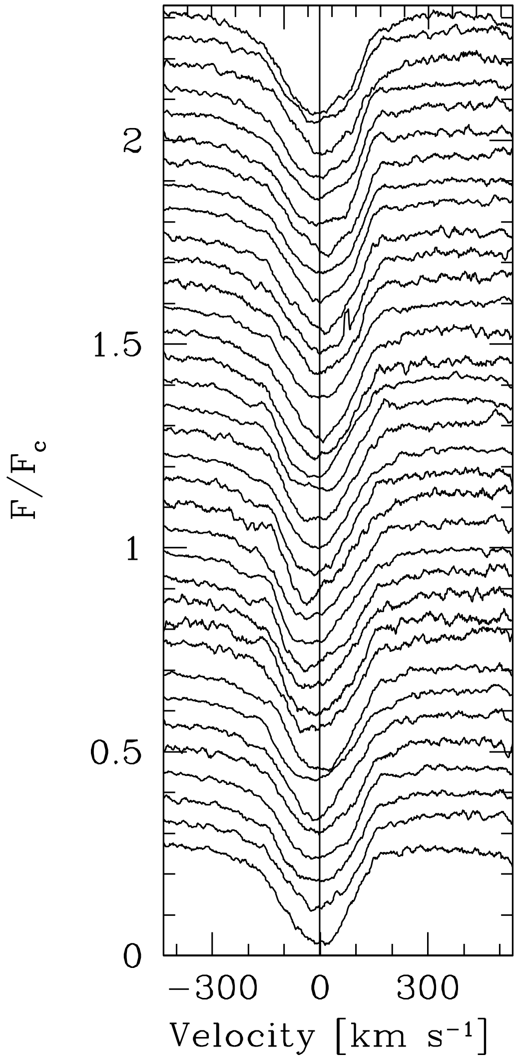

Fig. 14. Observed line profiles HeI 4471.5 Å for HR 3642. The line profiles are sorted in function of the phase with the period of 1.13028 d. The Flux is normalized.

- In the case of HR 3642, a complex variability is observed, with a short-term spectroscopic behaviour ($P = 1.13028$ d) of λ Eri type, and a mid-term ($P = 137.99$ d) variability in photometry and H_α equivalent width.
- In the case of HR 3237, the orbital period (5.1526 d) is well defined when the photometric variability does not exhibit a clear period, corresponding to the orbital one or not.

Finally, we can note than in spite of the fact that CORALIE is a spectrograph dedicated to searching planets , it is also well adapted for hot stars survey. Such mid-term spectroscopic survey is needed to improve our knowledge of the Be stars. It would be, even more so, very important to obtain simultaneously photometric and spectroscopic data.

Acknowledgements. We would like to express our warm thanks to all the observers at the 120 cm Swiss telescopes at La Silla

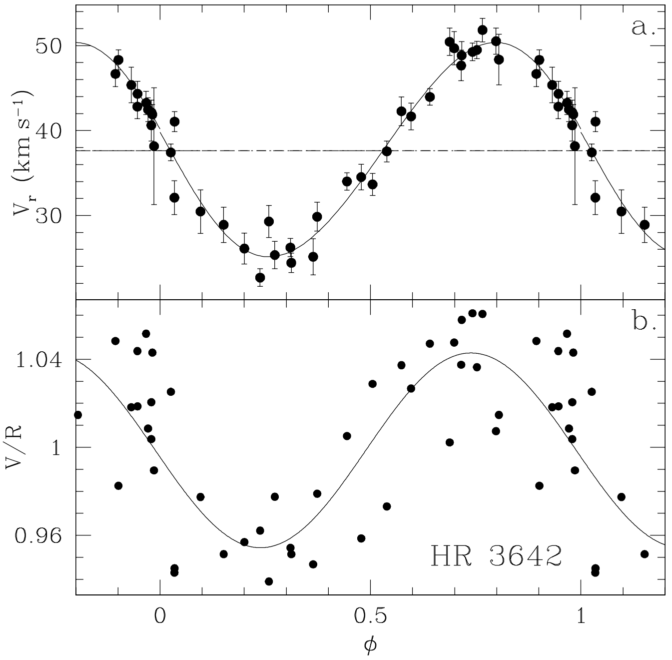

Fig. 15. Spectroscopic variation of HR 3642 with the period of 1.13028 d: **a)** radial-velocity curve; **b)** V/R variations of the H_α line versus phase.

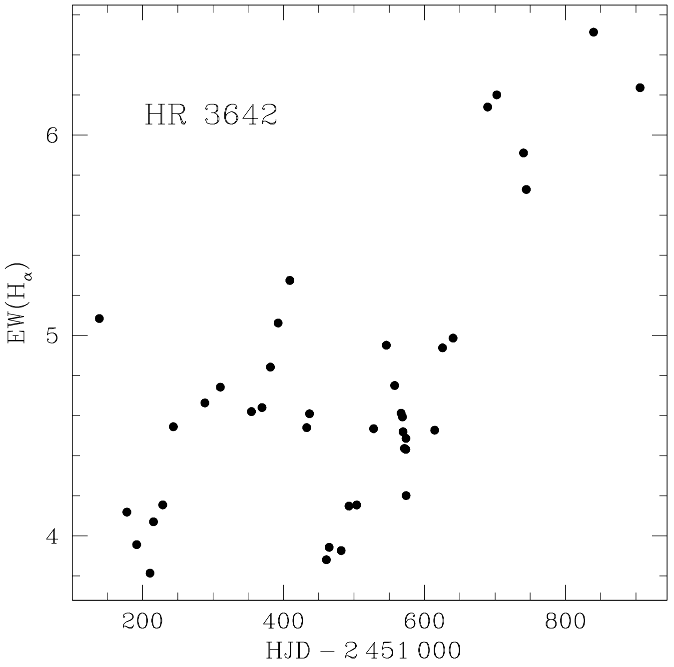

Fig. 16. Variation of the equivalent width of H_α line of HR 3642 during our survey.

having observed during the past 2 years. This monitoring has been successful thanks to their assiduity. We also thank the referee Dr. Harmanec for his extremely detailed comments and helpful remarks. This work has been partly supported by the Swiss National Science Foundation.

References

Andersen, J., & Nordström, B. 1983, A&AS, 52, 471
Andersen, J., Nordström, B., Mayor, M., & Polidan, R. S. 1988, A&A, 207, 37
Andersen, J., Pavlovski, K., & Piirola, V. 1989, A&A, 215, 272
Baade, D. 1992, Evolutionary Processes in Close Binary Stars, IAU Symp., 151, 147
Balona, L. A., Cuypers, J., & Marang, F. 1992, A&AS, 92, 533
Balona, L. A. 1995, MNRAS, 277, 1547
Balona, L. A. 1999, MNRAS, 306, 407
Balona, L. A., Aerts, C., & Štefl, S. 1999, MNRAS, 305, 519
Balona, L. A., & Kambe, E. 1999, MNRAS, 308, 1117
Balona, L. A., & Kaye, A. B. 1999, ApJ, 521, 407
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 1
Berghöfer, T. W., Schmitt, J. H. M. M., & Cassinelli, J. P. 1996, A&AS, 118, 481
Božić, H., & Pavlovski, K. 1988, Hvar Obs. Bull., 12, 15
Božić, H., Harmanec, P., Horn, J., et al. 1995, A&A, 304, 235
Božić, H., Ruždjak, D., & Sudar, D. 1999, A&A, 350, 566
Brown, A. G. A, & Verschueren, W. 1997, A&A, 319, 811
Burki, G., Cramer, N., Burnet, M., et al. 1989, A&A, 213, L26
Burki, G., Cramer, N., & Nicolet, B. 1991, A&AS, 87, 163
Burki, G. 1999, A&A, 346, 134
Burki, G., et al. 1998, `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. 2002, A&A, submitted
Doazan, V., Harmanec, P., Koubský, P., Krpata, J., & Zdárský, F. 1982, A&AS, 50, 481
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Fleming, M. 1892, A&A, 11, 765
Floquet, M., Hubert, A.-M., Hubert, H., Ballereau, D., & Chauville, J. 1995, A&A, 294, 227
Golay, M. 1980, Vistas in Astronomy, 24, 141
Gray, D. F. 1976, The Observation and Analysis of Stellar Photospheres, 1st. ed., chap. 17
Gray, R. O., & Corbally, C. J. 1994, AJ, 107, 742
Grenon, M. 1997, The Hipparcos and Tycho Catalogues, Hipparcos Variability Annex, ESA SP-1200, vol. 12, A205
Hanuschik, R. W., Hummel, W., Dietle, O., & Sutorius, E. 1995, A&A, 300, 163
Harmanec, P. 1984, BAICz, 35, 164
Harmanec, P., Hadrava, P., Yang, S., et al. 1997, A&A, 319, 867
Harmanec, P. 1998, A&A, 334, 558
Harmanec, P. 2001, Publ. Astron. Inst. Acad. Sci. Czech Rep., 89, 9
Harmanec, P., Morand, F., Bonneau, D., et al. 1996, A&A, 312, 879
Hill, G., Harmanec, P., Pavlovski, K., et al. 1997, A&A, 324, 965
Houk, N., & Cowley, A. P. 1975, Catalogue of two-dimensional spectral types for the HD stars, vol. I (Univ. of Michigan, Ann Arbor)
Hubeny, I., Lanz, T., & Jeffery, C. S. 1994, TLUSTY and SYNSPEC: A User's Guide, Newsletter on Analysis of Astronomical Spectra (Univ. of St. Andrews)
Hubert, A. M., Floquet, M., Gomez, A. E., & Aletti, V. 1997, Hipparcos – Venice '97, ESA SP-402, 315

Hubert, A. M., & Floquet, M. 1998, A&A, 335, 565

Jaschek, C., Jaschek, M., & Kucewicz, B. 1964, Zeitschr. Astrophys., 59, 108

Jaschek, C., & Jaschek, M. 1965, PASP, 77, 376

Katahira, J., Hirata, R., Ito, M., et al. 1996, PASJ, 48, 317

Koubský, P., Gulliver, A. F., Harmanec, P., et al. 1989, BAICz, 40, 31

Koubský, P., Harmanec, P., Kubát, J., et al. 1997, A&A, 328, 551

Koubský, P., Harmanec, P., Hubert, A.-M., et al. 2000, A&A, 356, 913

Kupka, F., Piskunov, N. E., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119

Kurucz, R. L. 1994, CD-ROM 19 (Solar abundance atmosphere models for 0, 1, 2, 4, 8 km s^{-1})

Linnell, A. P., Peters, G. J., & Polidan, R. S. 1988, ApJ, 327, 265

Mennickent, R. E., & Vogt, N. 1988, A&AS, 74, 497

Mennickent, R. E., Vogt, N., & Sterken, C. 1994, A&AS, 108, 237

Mennickent, R. E., Sterken, C., & Vogt, N. 1997, A&A, 326, 1167

Mennickent, R. E., Sterken, C., & Vogt, N. 1998, A&A, 330, 631

Matthews, J. M., Harmanec, P., Walker, G. A. H., Yang, S., & Wehlau, W. H. 1991, MNRAS, 248, 787

Meurs, E. J. A., Piters, A. J. M., Pols, O. R., et al. 1992, A&A, 265, L41

Morris, P. M. 1961, MNRAS, 122, 325

Morse, J. A., Mathieu, R. D., & Levine, S. E. 1991, AJ, 101, 1495

Neubauer, F. J. 1930, Lick Obs. Bull., 15, 47

Nordström, B., Latham, D. W., Morse, J. A., et al. 1994, A&A, 287, 338

Pavlovski, K., Harmanec, P., Božić, H., et al. 1997, A&AS, 125, 75

Peters, G. J. 2001, Publ. Astron. Inst. Acad. Sci. Czech Rep., 89, 29

Pickering, E. C., & Fleming, W. P. 1897, ApJ, 5, 350

Porter, J. M. 1996, MNRAS, 280, L1

Raboud, D. 1996, A&A, 315, 384

Rufener, F. 1964, Publ. Obs. Genève, A, 66, 413

Rufener, F. 1985, in Calibration of Fundamental Stellar Quantities, ed. D. S. Hayes, et al. (Reidel Publ. Co., Dordrecht), IAU Symp., 111, 253

Rufener, F. 1988, Geneva Photometric Catalogue, 4th ed., Obs. Genève

Schmidt-Kaler, Th. 1982, in Landolt-Bornstein, ed. K.-H. Hellwege (Springer, Group VI), 31

Šimon, V. 1996, A&A, 308, 799

Slettebak, A. 1982, ApJS, 50, 55

Stagg, C. 1987, MNRAS, 227, 213

Štefl, S., Harmanec, P., Horn, J., et al. 1990, BAICz, 41, 29

Štefl, S., Aerts, C., & Balona, L. A. 1999, MNRAS, 305, 505

Sterken, C., Manfroid, J., et al. 1993, Second Catalogue of Stars Measured in the Long-Term Photometry of Variables Project (1986–1990), ESO Scientific Report No. 12

Sterken, C., Vogt, N., & Mennickent, R. E. 1996, A&A, 311, 579