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Variability and pulsations in the Be star 66 Ophiuchi*

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Abstract. 66 Oph is a Be star seen under a moderate inclination angle that shows strong variability from UV to IR wavelengths. A concise review of long-term variability history is given. High resolution, high S/N spectroscopic observations obtained in 1997, 1998 and 2001 and spectropolarimetric observations obtained in 2000 are presented. These observations occurred during a long-term decrease of Hα intensity. Fundamental parameters of the star have been revisited from Barbier-Chalonge-Divan (BCD) calibrations. New $V \sin i$ values are obtained using Fourier transforms applied to observed helium lines and a rotational frequency $f_{\rm rot} = 1.29$ c d^{-1} is determined. Time series analysis and Fourier Doppler Imaging (FDI) of He I lines (4713, 4921, 5876 and 6678 Å) lead for the first time to the detection of multi-periodicity in 66 Oph. The two main frequencies found are $f = 2.22$ c d^{-1} and $f = 4.05$ c d^{-1} . They are attributed to non-radial pulsations and can be associated with mode degree $\ell = 2$ and $\ell = 3$, respectively. Inspection of Stokes V profiles suggests the presence of a weak Zeeman signature but further observations are needed to confirm the detection of a magnetic field in 66 Oph.

Key words. stars: emission-line, Be – stars: activity – stars: individual: 66 Oph – stars: oscillations – stars: magnetic field

1. Introduction

Be stars are non-supergiant, usually rapid rotators showing a near infrared excess and Balmer emission lines imputed to an equatorially concentrated envelope fed by sporadic mass ejection episodes. These stars also show light and line-profile variations in time scales ranging from hours to years. Several authors such as Frost & Conti (1976) and Andrillat et al. (1986) argued that some O and A stars also show many of the properties used to define the so-called Be phenomenon. Recently, Marlborough (2000) proposed the term *OBA phenomenon* as a better descriptive term that embodies all the objects showing the observational characteristics mentioned above. For the sake of brevity, we will use in this paper the term "Be star" to designate these objects.

Mass loss in Be stars is often separated schematically into two regimes: a rapid, low-density, variable, radiatively driven wind originating mainly in high latitude regions and characterized by resonance lines of "superionized" species (e.g. C IV, Si IV, N V) and a dense, slowly expanding, equatorially concentrated circumstellar envelope (often called equatorial disk). The disk seems to be mainly replenished during transient mass loss episodes. Be stars are not observed to rotate at the breakup velocity and the causes of the non-regular mass loss in these stars are as yet unknown. Non-radial pulsations (*nrp*) and stellar activity of magnetic origin have been proposed as mechanisms that could give rise to the additional amount of momentum needed to cause mass ejection (e.g. Smith 1977; Underhill 1987; Gies 1991, and references therein). Multi-periodicity has been detected in B-Be stars mainly in optical line profile variations (*lpv*) and has been generally attributed to *nrp* (e.g. Gies 1994). As a matter of fact, recent theoretical calculations by Balona & Dziembowski (1999) revealed the existence of unstable *p* and *g nrp* high-degree modes in the B temperature range that are compatible with some observed periods (Balona & Kambe 1999b and Jankov et al. 2000 for ζ Oph; Janot-Pacheco et al. 1999 for η Cen; Hubert et al. 1997 for 48 Per; Floquet et al. 1996 for 48 Lib).

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* Based on observations taken at OHP and Pic du Midi Observatory (France), at MBT/LNA (Brazil) and on Brazilian observing time at La Silla (ESO, Chile).

Aperiodic optical line profile variability on time-scales ranging from tens of minutes to hours has also been observed in several Be stars (Peters 1986; Smith 1989; Leister et al. 2000; Smith 2000).

Photometric variations in visual bands (up to several tenths of magnitude) on time-scales as short as one day have been reported by Percy et al. (1997) for a sample of active Be stars. In a study of the variability of 273 Be stars from the Hipparcos data base (August 1989-August 1993), Hubert & Floquet (1998) found the presence of short-term (≤3.5 d), mid-term (weeks, months) and long-term (years, decades) variations. Light outbursts and fading events were often observed in early type stars. Outbursts have been found mainly in stars showing low to moderate $V \sin i$, while fading events are more frequent in objects with high $V \sin i$. All the above-listed manifestations of "Be activity" have been attributed to sudden discrete ejections of matter that momentarily obscure or add light to the photosphere, depending on the angle through which they are seen. The brightening/fading dependence with $V \sin i$ seems to indicate that ejections are somewhat concentrated towards low latitudes.

Resonance UV lines often show extended shortward absorption and asymmetry which are signatures of a fast ($\gtrsim$1000 km s^{-1}) stellar wind. Wind variability is rather common among Be stars (e.g. Barker & Marlborough 1985; Snow 1987). It can be interpreted in terms of recurrent multiple shortward-shifted discrete absorption components (DACs) (Henrichs 1984; Grady et al. 1987; Prinja 1991) variable in number and distribution in radial velocity and optical depth. Doazan et al. (1987) and Telting & Kaper (1994) found a correlation between the long-term violet to red emission peak ratio V/R (i.e. disk activity) and the occurrence/intensity of DACs (wind activity) in γ Cas. For stars seen at moderate inclination angles, long term V/R variability has been successfully reproduced with a precessing one-armed density perturbation in the disk (Okazaki 1991, 1996; Mennickent et al. 1997 and references therein). The DACs - V/R correlation can be understood in the frame of a distorted disk in terms of column density variation in the DACs region caused by the density perturbation (Telting & Kaper 1994). Multiwavelength campaigns showed the presence of common periods in the UV and optical wavelength ranges for several Be stars. Moreover, the amplitude of light variations increases with decreasing wavelength and the wind mass loss tends to be enhanced when the star is brightest. UV and optical observations seem to imply that non-radial pulsations are responsible for line profile variations, light variability and also for the modulation of the hot stellar wind (Peters 1991a, 1997).

66 Oph (HD 164284, HR 6712, B2V, $V \simeq 4.6$, $V \sin i$ = 280 km s^{-1}, this paper) is a Be star seen at a moderate inclination angle. This star has a long history of conspicuous photometric and spectroscopic variability, both in UV and optical wavelengths. It is also known to exhibit linear polarization variations (Hayes 1983). Penrod (1985, private communication cited by Grady et al. 1987) suggested that 66 Oph could be a nonradial pulsator on the basis of spectroscopic observations.

In Sect. 2 we present high resolution, high signal-to-noise spectroscopic observations of 66 Oph obtained at Haute Provence Observatory (France) in June 1997 and June 1998 (He I 6678 and Hα) and spectropolarimetric observations at Pic du Midi Observatory (France) in June 2000 (4500–6600 Å). Additional observations were obtained at Pic du Midi Observatory in August 2001 (5400–8700 Å), at ESO (Chile) in April 2001 (3900–9000 Å) and at LNA (Brazil) in June 2001 (He I 6678 Å and Hα).

In Sect. 3 we reconsider the fundamental parameters of the star taking into account rotational effects. New values of $V \sin i$ are obtained.

In Sect. 4 we present a concise review on the variability of the star with emphasis on correlations found between optical and UV wavelengths behaviour.

Data were searched for rapid variability and results are interpreted in the frame of the non-radial pulsation model (*nrp*) in Sect. 5.

Finally in Sect. 6 we report the attempt to detect a stellar magnetic field from analysis of circular polarization measurements: the presence of such a field could be one of the keys towards the understanding of the Be phenomenon. Recall that a weak magnetic field has been detected in β Cep, a slowly rotating B1Ve star which is the prototype of a class of pulsating stars (Henrichs et al. 2000). Results are discussed in Sect. 7 and conclusions are presented in Sect. 8.

2. Observations

The highly variable behaviour of 66 Oph makes it a good candidate for a non-radial pulsator. In order to study the short-term variability of the star, observations were performed at Haute Provence Observatory during five nights in June 1997 and seven nights in June 1998; series of subexposures in spectropolarimetric observations carried out at Pic du Midi Observatory during seven nights in June 2000 were also investigated to this purpose. All three runs occurred during the long-term decrease of Hα emission as it will be seen in Sect. 4.

2.1. Spectroscopic observations

Spectroscopic observations were obtained at Haute Provence Observatory (OHP) in 1997 and 1998 with the 1.52 m telescope equipped with the spectrograph Aurélie and a 2048 linear THX detector. The resolving power was 22 000 (calculated over the 3px resolution element) and the wavelength range ≃200 Å. We observed spectral regions centered on Hα and He I λ 6678 Å lines.

Bias, flat fields and wavelength calibration exposures (Th-Ar comparison lamp) were obtained regularly each night. Observations were reduced with IRAF[1] using standard techniques for CCD data. Reference regions were carefully selected for satisfactory determination of the pseudo-continuum over about ±50 Å around the lines. A cubic spline function was fitted to these selected regions to determine the continuum level. All spectra were corrected for heliocentric velocity. The mean S/N was 560.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

Table 1. Log of spectroscopic and spectropolarimetric observations.

date	hjd – 2 450 000.0	site	number of sp/ wavelength range	mean S/N near Hα	mean exp time (min)
1997/06/24	624.35–624.55	OHP	6 He I 6678	670	40
1997/06/27	627.35–627.60	OHP	6 He I 6678, 2 Hα	530	40
1997/06/30	630.59	OHP	1 He I 6678	600	60
1997/07/01	631.35–631.44	OHP	2 He I 6678, 1 Hα	400	30
1998/06/04	969.40–969.60	OHP	4 He I 6678, 1 Hα	500	40
1998/06/05	970.35–970.60	OHP	2 He I 6678, 2 Hα	630	40
1998/06/07	972.30–972.60	OHP	8 He I 6678, 1 Hα	640	40
1998/06/08	973.35–973.50	OHP	3 He I 6678, 1 Hα	430	60
1998/06/09	974.35–974.56	OHP	6 He I 6678, 1 Hα	640	40
1998/06/10	975.49–975.60	OHP	2 He I 6678, 1 Hα	530	40–60
1998/06/11	976.35–976.60	OHP	5 He I 6678, 1 Hα	595	60
2000/06/19	1715.48–1715.58	TBL	6, 4500–6600	270	20
2000/06/20	1716.42–1716.55	TBL	8, 4500–6600	245	30
2000/06/21	1717.50–1717.61	TBL	6, 4500–6600	210	20
2000/06/22	1718.38–1718.55	TBL	6, 4500–6600	240	20
2000/06/24	1720.38–1720.55	TBL	5, 4500–6600	290	35
2000/06/26	1722.48–1722.54	TBL	4, 4500–6600	310	20
2001/04/03	2002.84–2002.86	ESO	2, 3520–8900	80	20
2001/04/06	2005.81–2005.90	ESO	10, 3520–8900	150	10
2001/06/29	2090.67–2090.76	LNA	7 He I 6678	350	20
2001/06/30	2091.60–2091.76	LNA	11 He I 6678	330	20
2001/07/01	2092.59–2092.74	LNA	10 He I 6678, 1 Hα	260	20
2001/08/04	2126.38	TBL	1, 5400–8700	270	45
2001/08/06	2128.41	TBL	1, 5400–8700	270	45

We also used individual subexposures of echelle spectra obtained in 2000 at Pic du Midi Observatory with the 2 m telescope Bernard Lyot (TBL) (see Sect. 2.2) taken in various polarimeter configurations. During the spectropolarimetric observations, the original beam of light is divided into 2 beams allowing the observer to get simultaneous spectroscopic information from each subexposure. 35 spectra were obtained during this run and yielded additional informations on the rapid variability of 66 Oph previously detected at OHP. Data were reduced using ESpRIT (Donati et al. 1997) as the polarimetric data, except for the continuum determination which was done using IRAF. Unfortunately the He I 6678 line was not observed, so we considered other strong He I lines such as 4713, 4921 and 5876 and the Hα emission line. The mean S/N ratio was 260.

We also had additional observations collected in June-July 2001 at LNA Observatory (R = 60 000, Hα and He I λ 6678 Å lines), in April 2001 at ESO with FEROS spectrograph (R = 48 000, $\lambda\lambda$ 3520–8900 Å) and at TBL in August 2001 with the MUSICOS spectrograph (R = 35 000, $\lambda\lambda$ 5400–8700 Å). A summary of our gathered database is given in Table 1.

Parameters currently used to describe spectroscopic lines of Be stars (equivalent width EW, radial velocity of the centroid RV, peak intensity of V and R emissions $I(V)$ and $I(R)$ respectively, and their ratio V/R) have been measured for the individual He I lines in view of a search for rapid variability. In 1997 and 1998 EW and RV have been measured only in the absorption part of the He I 6678 line in view of the presence of emission on the outer parts.

2.2. Spectropolarimetric observations

Observations were carried out in June 2000 with the MUSICOS spectropolarimeter at TBL. The instrument consists of a fiber-fed cross dispersed echelle spectrograph with a dedicated polarimeter (Donati et al. 1999) mounted at the Cassegrain focus. Stellar light is collected in a 2 arcsec entrance over a spectral range from 4500 to 6600 Å and with a resolution R = 35 000. The log of these observations is reported in Table 1.

To detect stellar magnetic fields the circularly polarized light is analyzed, i.e. the Zeeman signatures generated in the shape and polarization of lines via the Stokes V parameter. A complete Stokes V measurement consists of 4 consecutive subexposures: one with a quarter-wave plate at azimuth −45 degrees, 2 at azimuth 45 degrees, and one more at azimuth −45 degrees. This procedure allows to suppress spurious polarization signals (Donati et al. 1997).

We obtained 4 Stokes V measurements over the 7-nights run. Flat-fields exposures, ThAr exposures for wavelength calibration and bias frames were obtained on each night. The reduction of spectropolarimetric data was done using the dedicated software package ESpRIT (Donati et al. 1997). The profiles of 62 lines without emission features for each of the 4 subexposure, properly weighted, were combined using a Least Square Deconvolution (LSD) method to give a mean intensity line profile. The enhanced Zeeman signature (combination of the very small signatures of circular polarization from each line) can then be extracted from the set of 4 subexposures and a mean Stokes V profile is obtained.

To study linear polarization both Stokes Q and U profiles are needed. A Stokes Q measurement consists of 4 subexposures with the polarimeter sequentially rotated at different angles: one at azimuth 90 degrees, two at 0 degrees and one more at 90 degrees. A Stokes U measurement consists of 4 subexposures with the polarimeter rotated at: 22.5 degrees, 67.5 degrees (two subexposures) and again 22.5 degrees. Due to poor weather conditions, these two measurements could not be performed at the same time. Nevertheless we obtained one Stokes U measurement and two Stokes Q measurements. The Stokes Q and U measurements were reduced with ESpRIT in the same way as the Stokes V measurements.

3. Fundamental parameters of 66 Oph

The determination of $V \sin i$ in Be stars is always a crucial problem due to the distortion of the star itself by rapid rotation and influence of *nrp*. Nevertheless in a rapidly rotating star the pulsation velocity field acts as a small perturbation to the dominant rotational velocity field. A previous determination by Slettebak (1982) gave 240 km s^{-1}. Recently Chauville et al. (2001) fitted the He I 4471 line profile with non-LTE rotationally broadened model line profiles (Stoeckley & Mihalas 1973) using high resolution ($R \sim 15000$) spectra. The averaged value obtained by these authors is $V \sin i = 262 \pm 18$ km s^{-1}.

Determination of $V \sin i$ using Fourier transform analysis (Gray 1976) was also performed on blue and red helium lines of our spectra. It has been applied to the mean spectra of the observing runs and to each individual spectrum as well. The first minimum of the Fourier transform of the mean spectrum was used to estimate $V \sin i$ assuming a limb darkening coefficient of $\varepsilon = 0.4$ (Jankov 1995). In Fig. 1 the Fourier frequency was reduced to velocity units so that the first minimum of the Fourier transform of the rotational profile points to the projected rotational+pulsational velocity of the star.

This analysis indicates for the mean TBL 2000 and FEROS 2001 blue He I line profiles: $V \sin i = 272$ km s^{-1} and 292 km s^{-1} respectively (see Table 2). The same analysis made for He I 6678 on OHP (1997, 1998) and LNA (2001) spectra gives lower values $V \sin i$ = 241, 223 and 250 km s^{-1}, respectively. Note that in 2001 emission has completely disappeared from this line as shown in Sect. 4 (Fig. 4). A similar trend between $V \sin i$ obtained from blue and red He I lines seems to occur for ω Ori (Neiner et al. 2002). In the following we will adopt the mean value deduced from the analysis of the blue He I lines i.e. $V \sin i = 280 \pm 15$ km s^{-1}.

$T_{\rm eff}$ and $\log g$ were determined with the BCD (Barbier-Chalonge-Divan) method by deriving the photospheric spectrophotometric (λ_1, D_*) parameters of the star which are free from circumstellar emission/absorption and interstellar

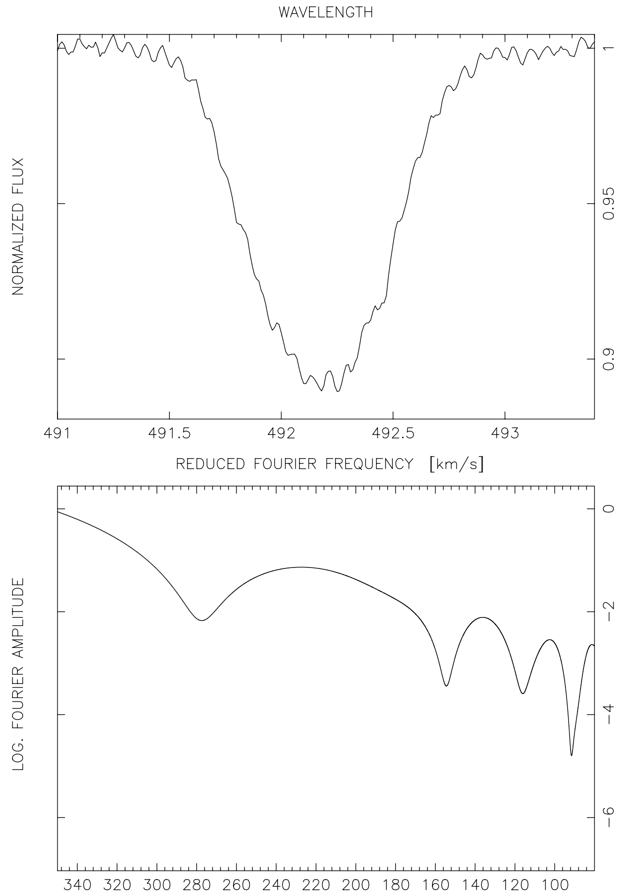

Fig. 1. Mean spectrum for the He I 4921 line (TBL, 2000) (top) and its Fourier transform (bottom).

extinction. In this method the MK spectral type, the absolute visual magnitude, the absolute bolometric magnitude, the effective temperature and the surface gravity of non-supergiant stars with masses $2 \lesssim M/M_\odot \lesssim 30$ were calibrated as a function of (λ_1, D_*) (Chalonge & Divan 1973; Divan & Zorec 1982; Zorec 1986; Zorec & Briot 1991). A total of 24 spectra taken in 1977-1978 with the Chalonge spectrograph (BCD archive of the Institut d'Astrophysique de Paris) have been used to determine the (λ_1, D_*) parameters of 66 Oph. Assuming that the unvarying components of these parameters are from the stellar photosphere, the resulting fundamental parameters and their uncertainties are given in Table 3.

These parameters represent only the average photosphere of the observed hemisphere of this rapidly rotating star. Thus, they do not relate in a simple way either to the actual stellar mass, or to its radius and evolutionary stage. To derive the equatorial radius and the mass of 66 Oph, we assumed that the observed (λ_1, D_*) BCD quantities and the corresponding stellar fundamental parameters, reliably represent the photospheric radiation field of the observed stellar hemisphere. We also assumed that the observed parameters and those of the star at rest are related as follows:

$$\left.\begin{array}{rcl} L(\lambda_1, D_*) & = & L_{\rm o}(M_{\rm o}, t) F_{\rm L}(M_{\rm o}, \omega, i, t) \\ D_* & = & D_{\rm o}(M_{\rm o}, t) F_{\rm D}(M_{\rm o}, \omega, i, t) \\ \lambda_1 & = & \lambda_1^{\rm o}(M_{\rm o}, t) F_{\lambda_1}(M_{\rm o}, \omega, i, t) \\ V \sin\, i & = & V_{\rm c}(M_{\rm o}, t) \frac{R_{\rm e}(M_{\rm o}, \omega, t)}{R_{\rm c}(M_{\rm o}, t)} \omega \sin i \end{array}\right\} \quad (1)$$

Table 2. $V \sin i$ values obtained for several He I lines. From 1991 to 1996 determinations were done fitting the line profile with non-LTE rotationally broadened model (Chauville et al. 2001). From 1997 to 2001 the values correspond to the first minimum of the Fourier transform of the mean rotational profile (this study). Accuracy for individual measurement is ±15 km s^{-1}.

Date	Observatory	Line	$V \sin i$ (km s^{-1})
1991	OHP	4471	250
1992	OHP	4471	290
1996	OHP	4471	262
1997	OHP	6678	240
1998	OHP	6678	220
2000	TBL	4713	268
2000	TBL	4921	277
2001	LNA	6678	250
2001	ESO	4026	296
2001	ESO	4388	294
2001	ESO	4713	294
2001	ESO	4921	286

Table 3. BCD and fundamental parameters of 66 Oph obtained from (λ_1, D_*) calibrations. Note that these parameters are averaged over the visible hemisphere.

$\lambda_1 = 3761.4 \pm 1.5$ Å	MK(λ_1, D_*) spectral type =
$D_* = 0.129 \pm 0.007$ dex	B2V
$T_{\rm eff} = 23\,850 \pm 900$ K	$\log g = 3.95 \pm 0.08$ dex
$M_{\rm V} = -2.50 \pm 0.25$ mag	$M_{\rm bol} = -5.12 \pm 0.50$ mag

where $L_{\rm o}$, $D_{\rm o}$ and $\lambda_1^{\rm o}$ are the bolometric luminosity, the Balmer discontinuity and the λ_1 parameter of the star as it would be rotationless, respectively; $F_{\rm L}$, $F_{\rm D}$ and F_{λ_1} are functions of the stellar rest mass $M_{\rm o}$, the angular velocity ratio $\omega = \Omega/\Omega_{\rm c}$ ($\Omega_{\rm c}$ is the critical angular velocity), the inclination i of the rotational axis and of the stellar age t. $V_{\rm c}$ is the critical linear equatorial velocity, $R_{\rm c}$ is the critical equatorial radius and $R_{\rm e}$ the equatorial radius at the rotational rate ω (Zorec et al. 2002, see also Sect. 2 in Floquet et al. 2000). Relations (1) are solved using the evolutionary tracks of Schaller et al. (1992) for $Z = 0.02$. Using $V \sin i = 280 \pm 15$ km s^{-1} and the data given in Table 3, relations (1) produced the results displayed in Table 4. The adopted $V \sin i$ and the obtained stellar radius $R_{\rm e}(M_{\rm o}, \omega)$ imply a rotational frequency $f_{\rm rot} = 1.29 \pm 0.26$ c d^{-1}.

From the visual absolute magnitude $M_{\rm V}(\lambda_1, D_*)$ given in Table 1, the apparent visual magnitude $V_{\rm obs} = 4.85$, which corresponds both to the lower value observed in 1999 and to the epoch around 1955 where the star is in a B phase (see Hubert-Delplace & Hubert1979), the interstellar colour excess $E(B-V) = 0.18 \pm 0.06$, derived from the 2200-ISM absorption bump (Beeckmans & Hubert-Delplace 1980; Zorec & Briot 1985) and using the surrounding stars of 66 Oph in a circle smaller than 1°, we obtain $d(\lambda_1, D_*) = 224 \pm 30$ pc. Note that this distance agrees fairly well with $d_{\rm HIPP} = 207^{+40}_{-29}$ pc obtained from the parallax measured by the Hipparcos satellite.

Table 4. Stellar parameters of 66 Oph derived by taken into account its rotation. The error bars do not include incertainties of the stellar evolution tracks.

$\omega = 0.82 \pm 0.08$	$M_{\rm o}/M_\odot = 12.0 \pm 1.0$
$i = 43° \pm 8$	$\log L_{\rm o}/L_\odot = 4.0 \pm 0.4$
$R_{\rm e}(\omega)/R_\odot = 6.3 \pm 0.5$	$t = (9.24 \pm 0.82) \times 10^7$ yr

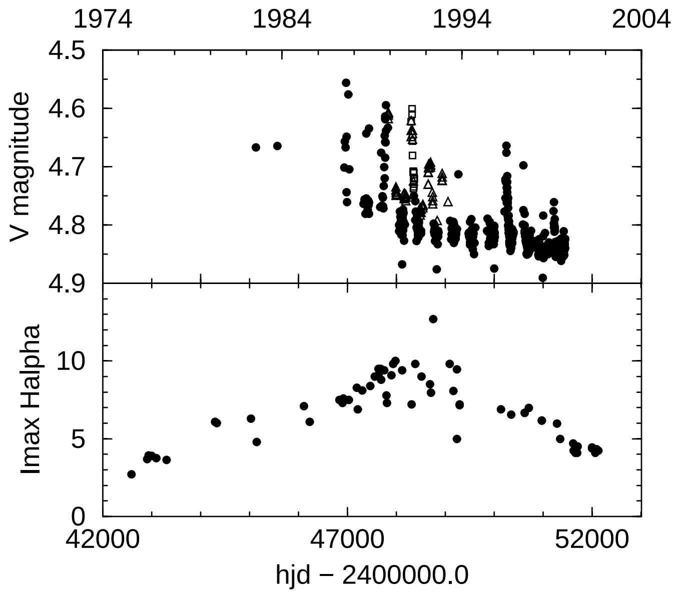

Fig. 2. Correlation between the long-term variation of V band magnitude and the Hα intensity. Upper panel: filled circles for Percy et al. (2001), open triangles for Hipparcos data and open squares for Adelman (1992) data. Lower panel: values of Imax taken from Andrillat & Fehrenbach (1982), Banerjee et al. (2000), Buil (2000), Fontaine et al. (1982), Lacy (1977), Hanuschik et al. (1995), Hummel et al. (1995), Peters (1987, 1988a,b,c, 1989a,b, 1990, 1991b,c, 1992, 1994), Slettebak & Reynolds (1978) and this paper.

4. Long term variability history

66 Oph is a Be star that shows a rather conspicuous variability from UV through IR wavelengths.

Cousins (1952) observed irregular brightness variations with amplitudes ≲0.2 mag which are rather typical of Be stars. Page & Page (1970) reported two sudden, strong (1–2 mag) and very rapid (2–3 mn) "flare-like" optical brightening in 1969 recorded on photographic plates.

Pavlovski et al. (1997 and references therein) report variations in the V band up to 0.07 mag without clear periodicity in May–July 1982. Cuypers et al. (1989) detected some flickering at 0.01 mag level but did not find short-term light variations. Percy et al. (1997), Percy & Bakos (2001) observed an overall slow fading in V and B (∼0.10 mag) from 1982 to 1999. At the same time, a state of great activity was observed. In particular from 1987 through 1993 exceptional recurrent "outbursts" up to 0.25 mag were seen from ground-based and Hipparcos photometry (see Fig. 2, upper panel) with a period of about one year between 2 consecutive outbursts (Percy & Attard 1992; Percy & Bakos 2001; Hubert & Floquet 1998). They seem to show a rapid rise and a ≲100 day fading time scale (see also

Table 5. Spectral parameters of the Hα line in 66 Oph.

date	EW (Å)	$I(V)$	$I(R)$	V/R
June 1997	−40.6	6.66	6.54	1.018
June 1998	−35.1	5.94	6.09	0.975
June 2000	−30.6	5.25	5.34	0.983
April 2001	−24.3	4.36	4.39	0.991
June 2001	−22.4	4.35	4.33	1.005

Adelman 1992). The outbursts appear to be correlated with the UV wind behaviour (see below).

The star has shown large Balmer line emission changes since the early fifties (Hubert-Delplace & Hubert 1979). A minimun in Hα emission strength was observed around 1955 followed by the appearance of weak shell absorption at Hγ and Hδ in 1959. Hα emission EW changed steadily from ~ -23 Å in 1975 (Lacy 1977) to ~ -60 Å in 1993 (Hanuschik et al. 1995). Emission level entered then a period of strong variability until 1995 during which its intensity oscillated around a high level ($I/I_c \sim 9.2$) (see Fig. 2). Since then it has entered a declining phase, EW reaching −40.6, −35.1, −30.6, −24.5 Å in 1997, 1998, 2000 and 2001, respectively (this paper, Table 5). Hα showed $V/R \simeq 1$ at least from 1976 through 1988. A sudden onset of V/R variability occurred probably in late 1988 and a variability cycle of ~5 years was observed from 1989 to 1995 (Hanuschik et al. 1995 and references therein). During that period the star showed steeple line profiles in Fe II with inversion of V/R asymmetry quite typical of those predicted in the global one-armed disk oscillation model. Note that the onset of V/R activity coincides with the epoch of great photometric activity and of the highest Balmer emission level. Hanuschik et al. (1995) propose that to trigger the disk oscillation distortion a high level of emission is apparently required (see their Fig. 13).

IUE observations obtained between 1982 to 1987 revealed the presence of a recurrent episodic mass loss every year (Grady et al. 1987; Peters 1988a, 2000). The wind and Balmer-emission regions appear to be correlated, as changes in Hα EW lag behind wind activity by ~2 months (Peters 2000). She then argued that mass loss episodes detected in the UV in the 1980s seemed to be a precursor of the establishment of the massive Balmer-emitting disk in 1988–91; nevertheless Rivinius et al. (2001) suggested that the relation between UV wind and star-to-disc mass transfer could be the result of an opacity effect. Moreover it has to be noted that unlike γ Cas (see Sect. 1) no correlation seems to exist between the wind strength and the V/R phase in 66 Oph. On the other hand, a striking correlation is found between these mass loss episodes and brightness in 1980–1995: several optical brightenings up to $\Delta V \sim 0.3$ mag were observed by Percy et al. (1997) and with Hipparcos (see Figs. 2 and 3 upper panels). These maxima are close to epochs of rapid wind variations. They also seem to correspond to a temporary reduction in the intensity of Hα which afterwards recovers and surpasses its preceding level (see Fig. 3). A similar correlation is found in HD 58050 (Hubert-Delplace et al. 1982), μ Cen (Rivinius et al. 1998), 28 Cyg (Tubbesing et al. 2000) and HD 76534 (Oudmaijer & Drew 1997). Thus, whatever physical

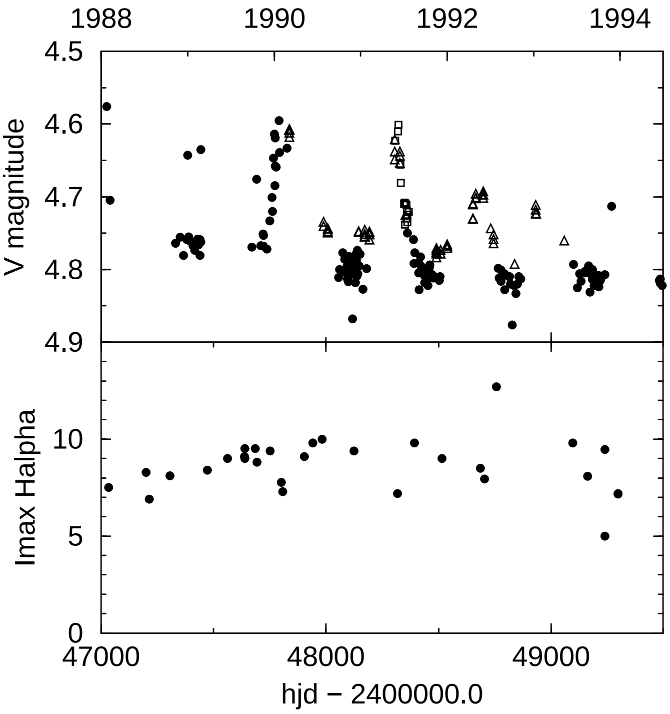

Fig. 3. Correlation between the V band magnitude and the Hα intensity during the period of great activity of the star. Symbols and references are the same as in Fig. 2.

mechanism causes the onset of mass loss and the filling up of the equatorial disk in 66 Oph, it seems to produce *beforehand* an optical brightening. In this context, it is important to mention the observation of two mass loss episodes of the Be star ω Ori by Hayes & Guinan (1984) and Guinan & Hayes (1984). Simultaneous optical photometry (Hα line and the near continuum) and linear polarimetry (B-band) showed in both cases the existence of a defined sequence of events: a brightening/fading of the star is followed by an increasing/decreasing of the polarization level then followed by an increasing/decreasing of the Hα emission. They propose that the morphology and time lags of light level, polarization and Hα line emission arise from acceleration/deceleration of the ejected matter in its crossing through the circumstellar envelope.

Putting together all the above information it seems quite tempting to suggest that the instabilities leading to mass loss in 66 Oph produce typically an optical brightening followed by a wind activation and polarimetric level increase and finally an emission line strengthening.

4.1. Long-term variation of Hα and He I 6678 lines

The Hα (1997, 1998, 2000 and 2001) and He I λ 6678 mean profiles (1997, 1998 and 2001) are shown in Fig. 4 in upper and lower panel, respectively. Hα is seen in strong emission with two well separated peaks. Emission intensity decreased from 1997 to 2001 following the waning tendency observed since 1995 (Fig. 2 lower panel). Average Hα EW, $I(V)$, $I(R)$ and V/R values are presented in Table 5. In 2000, the number of Hα profiles is large enough to notice a regular fading of the

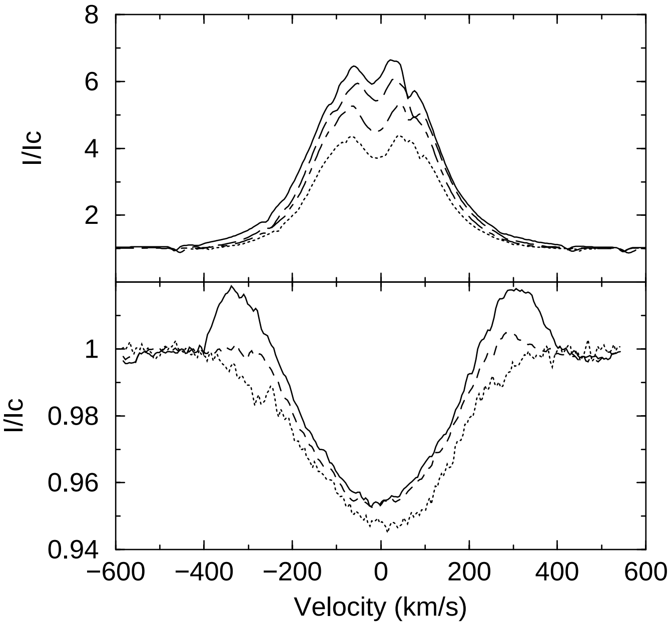

Fig. 4. Upper panel: mean Hα line profile. Lower panel: mean He I 6678 line profile. Solid line for 1997, long dashed line for 1998, dot-dashed line for 2000 and dotted line for 2001.

V/R ratio of Hα from 1 to 0.956 over the run. This fading is due to a decrease in the V intensity, the R component being stable at that time. No large-scale V/R variation has been detected from 1997 to 2001 while the Hα emission is going to a minimum of intensity (see Fig. 2 lower panel).

In 1997 and 1998 the He I λ 6678 Å line presents a quite variable profile, especially in its V and R emission components. As for Hα, the emission intensity decreases from 1997 to 1998 (see Fig. 4 lower panel) especially the V component. V/R values are globally fainter in 1998 than in 1997 by 0.0046.

In 2001 emissions seem absent from the He I line and the mean profile seems to be redshifted (Fig. 4 lower panel). In fact this is due to a strong asymmetry of the individual profiles which showed the same distortion at LNA and TBL; we will see in Sect. 5 that their time distribution covers less than half a period corresponding to the main frequency detected in line profile and spectral parameters variation: f = 2.22 c d^{-1}.

4.2. Circumstellar lines

Near the maximum of Hα emission (see Fig. 2 lower panel) Hanuschik et al. (1995) observed Fe II lines in emission showing strong profile variations, essentially with a sharp moving emission peak superimposed on the broad emission profile. In 2000 and 2001 Fe II lines are absent from our echelle spectra taken near a minimum of emission. Differently, the Si II 6347 and 6371 lines, which are good indicators of stellar activity, are seen as faint, weakly variable emissions (I/Ic $\sim$ 1.015 in Si II 6347 Å).

5. Time series analysis of He I lines

Frequency analysis of line profile variations (*lpv*) of He I lines present in the three principal data sets (OHP 1998, TBL 2000 and LNA 2001) was performed on each resolution bin of line profile time series. In 1997 the number of spectra (14 spectra over 7 nights) was too scarce to allow frequencies analysis.

Table 6. Short-term variability in the He I 6678 line of 66 Oph. Main frequencies (in c d^{-1}) obtained by the Least Squares method are listed by order of decreasing power. Only line profiles obtained in 1998 have been considered but other quantities include 1997 and 1998 data.

profiles	EW	RV	$I(V)$	$I(R)$	V/R
4.05	4.45	2.21	2.17	2.21	2.19
2.22		4.10		4.36	4.36
0.89					

Periodicities were also searched in the line parameters EW, V, R and V/R time series for both 1997 and 1998 data, and RV for all 1997, 1998, 2000 and 2001 data.

Fourier analysis + CLEAN algorithm (as in Gies & Kullavanijaya 1988) and Least-Squares sinusoidal fitting with the AIC criterion (Kambe et al. 1993) were used in the time series analysis. In both methods, weighting by the signal to noise ratio was introduced in the calculation of averaged data.

The Fourier Doppler Imaging (hereafter FDI) method developed by Kennelly et al. (1992) was also applied to the time series obtained in 1998 and 2000 in the same way as in Janot-Pacheco et al. (1999). The method works in the general case, when sectoral and/or tesseral modes are present, and the obtained normalized wavelength frequency more closely represents the nonradial degree l rather than the azimuthal order m (Kennelly et al. 1996). The application of this technique to the 1998 and 2000 data gives similar results as the two first methods.

The frequency resolution was ~0.14 c d^{-1} for the OHP 1997 and 1998 data, ~0.17 c d^{-1} for the TBL 2000 data and ~0.34 c d^{-1} for the LNA 2001 data.

5.1. Line profile variations

5.1.1. He I 6678 line

Firstly, we analyzed 32 spectra taken in 1998 at OHP over 7 nights. Two main frequencies are detected (by order of decreasing power): 4.05 and 2.22 c d^{-1}. Results are given in Table 6 and the summed power across this line profile is shown in Fig. 5. The power and phase distribution ($\Delta\Phi$ being the slope of the phase diagram over the whole profile) of both frequencies across the line profiles are displayed in Figs. 6 (upper figure: f = 2.22 c d^{-1}, $\Delta\Phi \sim 2.5\pi$ and lower figure: f = 4.05 c d^{-1}, $\Delta\Phi \sim 3.5\pi$). Note that the power is higher in the extreme blue and red sides of the He I 6678 line which shows V and R emission components in 1998. Time evolution of residuals folded modulo f = 4.05 and 2.22 c d^{-1} is displayed in Figs. 7 and 8 upper panel, respectively.

The 0.89 c d^{-1} frequency seen on the summed power (Fig. 5) do not present any coherent phase variation. Moreover, it can be due to a combination of the two main frequencies 2.22 and 4.05 c d^{-1}. It is not detected with the FDI method, so we do

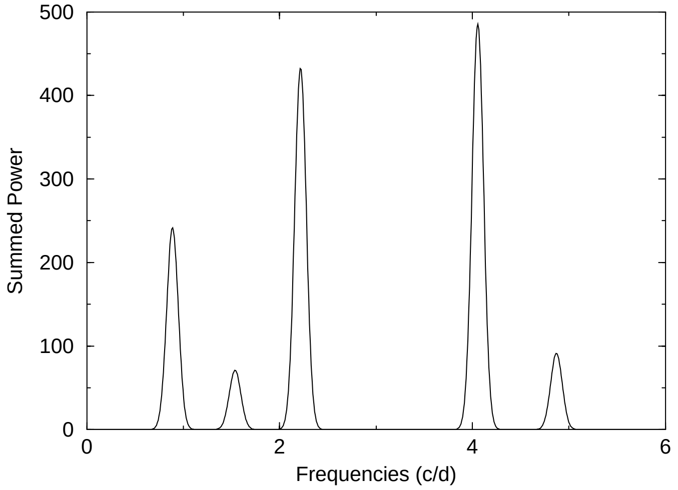

Fig. 5. Power summed across the line profile obtained with the Least Squares method for He I 6678 in 1998.

not retain this frequency. The two fainter frequencies present in Fig. 5 can also be combinations of the two main frequencies.

Secondly, we analyzed 28 spectra of the He I 6678 Å region obtained in 2001 at LNA over 3 nights. Note that emission has then disappeared from this line (see Fig. 4 lower panel). The 2.22 $c\,d^{-1}$ frequency is clearly present and 4.05 $c\,d^{-1}$ is also detected but with a very low power.

5.1.2. He I 4713, 4921 and 5876 lines

Thirty-five spectra obtained at TBL in 2000 over 6 nights were used for these 3 lines. Profiles seem to be essentially photospheric. The results are the same as for He I 6678 in 2001. We detect a main frequency 2.22 $c\,d^{-1}$ for the He I 4713, 4921 and 5876 lines and also a faint secondary frequency 4.05 $c\,d^{-1}$. For these three lines the power distribution is significant at about $\pm V \sin i$.

5.2. Line parameter variations

5.2.1. Stellar *RV* and *V* and *R* emission components

In 1997 and 1998 the frequency 2.22 $c\,d^{-1}$ is dominant in *RV*, *V*, *R* and *V*/*R* data of the He I 6678 line. Its first harmonic appears in *EW*, *R* and *V*/*R* data.

As it is mentioned in Sect. 4.1, the mean *V*/*R* ratio differs in 1997 and 1998 by 0.0046. This decrease could be related to the slow *V*/*R* cycle of about 5 years discovered by Hanuschik et al. (1995) in this star and still present at the end of the nineties but strongly damped. A correction taking into account this difference was applied to individual *V*/*R* values deduced from spectra taken in 1997. Then a very good agreement is found in the *V*/*R* variation for both epochs 1997 and 1998 for the 2.19 $c\,d^{-1}$ frequency (see Fig. 9).

In 2000 and 2001 the same frequency is detected in *RV* for the observed helium lines. The frequency 2.22 $c\,d^{-1}$ appears stable over a 5 year duration; note the good agreement in the variation of *RV* folded modulo $f = 2.218$ $c\,d^{-1}$ for He I 6678 over the OHP 1997, OHP 1998 and LNA 2001 runs (see Fig. 10). Note also the same tendency for He I 4921 during the TBL 2000 and FEROS 2001 runs for 2.209 $c\,d^{-1}$ (see Fig. 11).

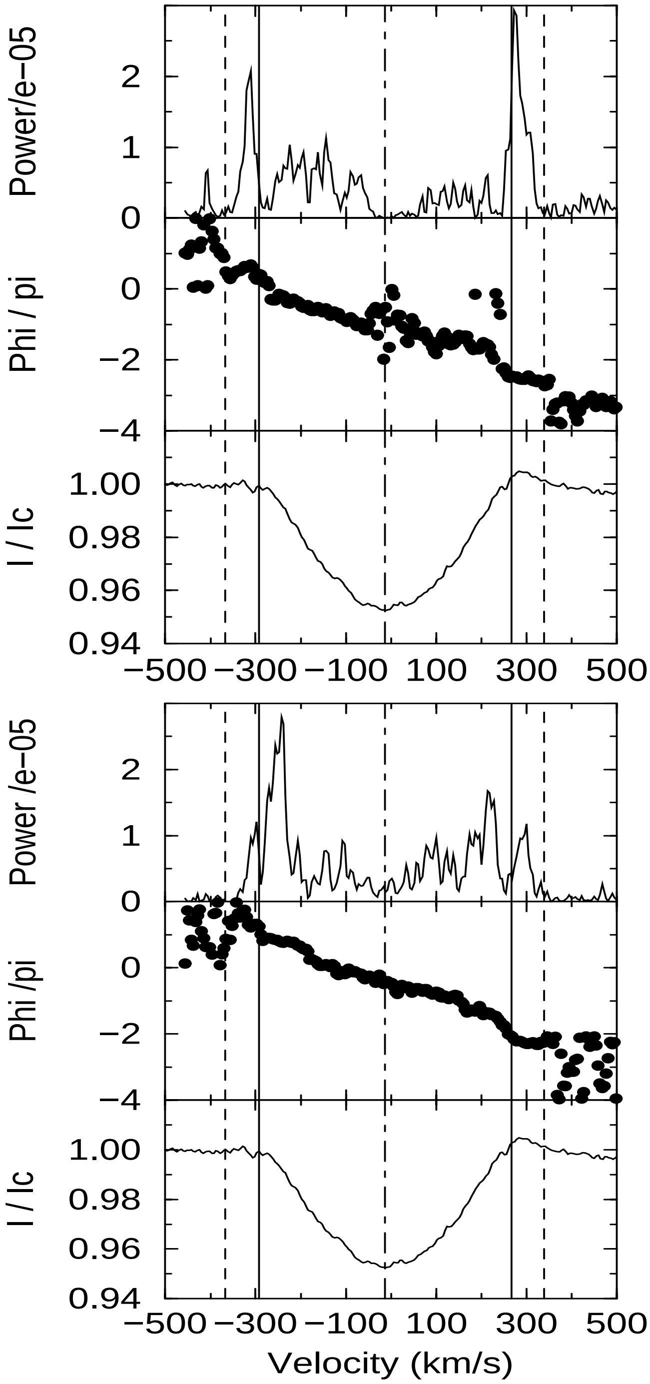

Fig. 6. Line profile variations of He I 6678 in 1998 corresponding to the two detected frequencies 2.22 $c\,d^{-1}$ (upper figure) and 4.05 $c\,d^{-1}$ (lower figure). In each figure power distribution is shown in the upper panel, phase distribution in the middle panel and mean line profile in the lower panel. The vertical lines symbols are: dotted-dashed line for the stellar radial velocity, solid line for the $\pm V \sin i$ extension and dashed lines for the extreme limits of power extension of the two frequencies.

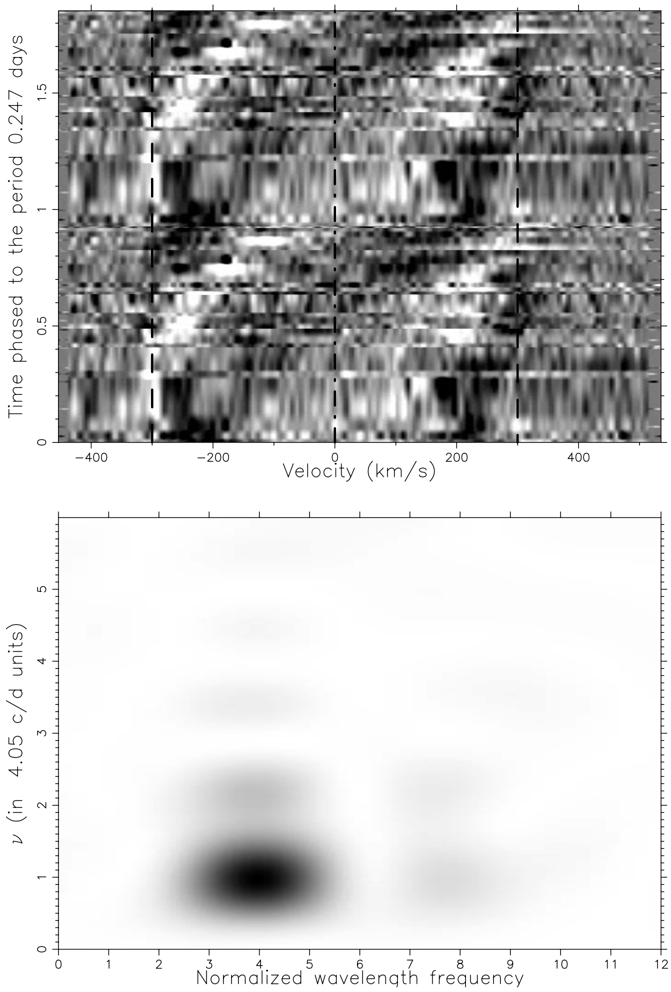

Fig. 7. FDI applied to He I 6678 line. Top: time evolution of residuals in 1998 folded modulo $f = 4.05$ c d^{-1}, after pre-whitening the frequency 2.25 c d^{-1}. Bottom: corresponding two dimensional Fourier spectrum of the variations.

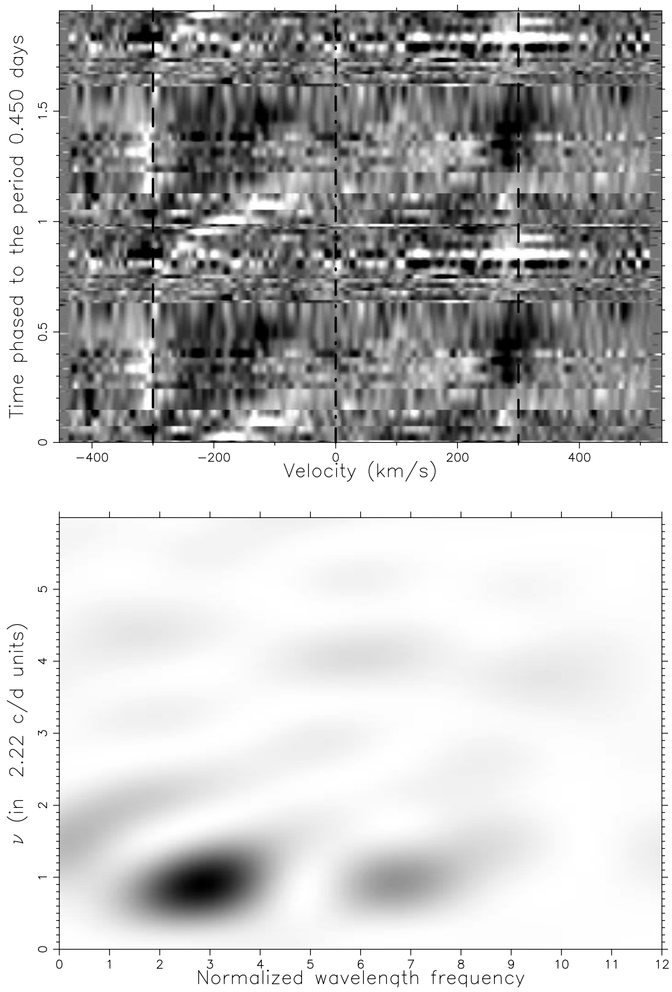

Fig. 8. FDI applied to He I 6678 line. Top: time evolution of residuals in 1998 folded modulo $f = 2.2$ c d^{-1}, after pre-whitening the frequency 4.05 c d^{-1}. Bottom: corresponding two dimensional Fourier spectrum of the variations.

5.2.2. Apparent variations of line width

The first minimum of the Fourier transform of each He I 6678 profile was used to estimate apparent variations of the projected equatorial rotational velocity $V \sin i$. Figure 12 shows the corresponding variations of minima positions for the individual spectra obtained in 1998. In this figure the frequency 4.05 c/d has been filtered out. This has been done by subtracting the corresponding sine fit from the original time series: minima positions (parameter representing $V \sin i$) versus time. Further, the filtered minima positions were folded modulo the frequency 2.25 c/d. Figure 13 shows similar variations of minima positions but the frequency 2.25 c d^{-1} has been filtered out and the minima positions were folded modulo the frequency 4.05 c d^{-1}. These apparent variations can result from an horizontal velocity field and/or temperature oscillations.

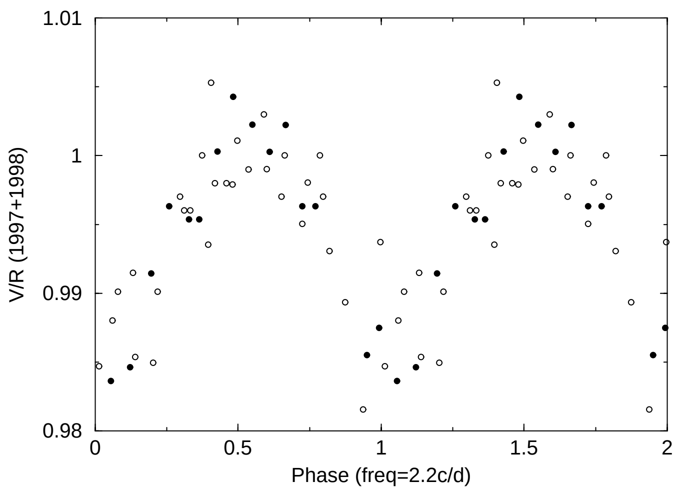

Fig. 9. V/R variation for the He I 6678 line in 1997 and 1998 folded modulo $f = 2.2$ c d^{-1} and with $T_0 = 2\,450\,624.0$. Symbols are: open circles for 1997 data and filled circles for 1998 data. 1997 data have been shifted by −0.0046 (see text).

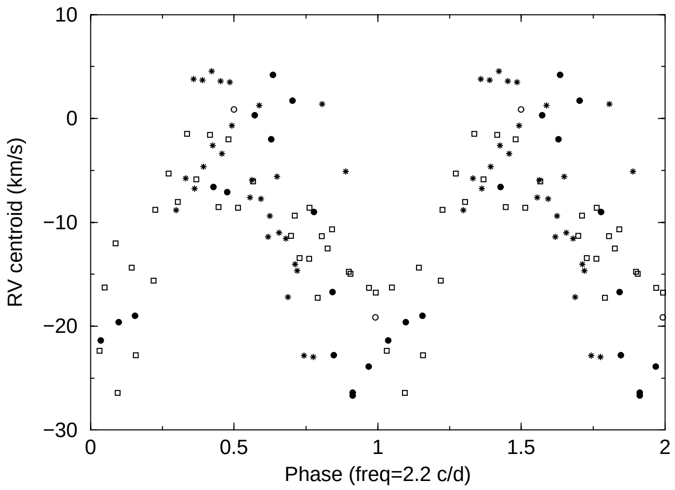

Fig. 10. *RV* variation of the centroid of the He I 6678 line folded modulo $f = 2.2$ c d^{-1} and with $T_0 = 2\,450\,624.0$ for 1997, 1998 and 2001. Symbols are: filled circles for OHP 1997, open squares for OHP 1998, stars for LNA 2001 and open circles for TBL 2001.

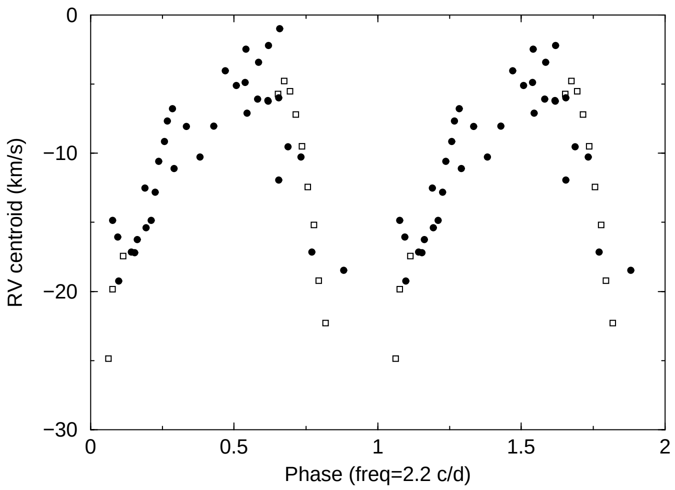

Fig. 11. *RV* variation of the centroid of the He I 4921 line folded modulo $f = 2.2$ c d^{-1} and with $T_0 = 2\,451\,715.0$ over 2000 and 2001. Symbols are: filled circles for TBL 2000 and open squares for FEROS 2001.

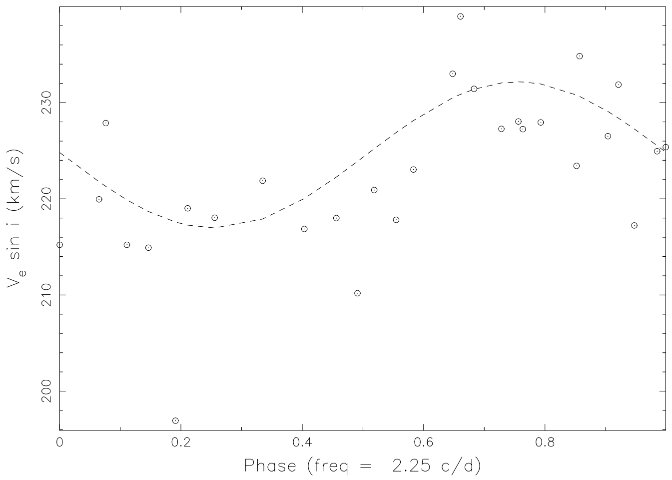

Fig. 12. First minima of the Fourier transform of each HeI 6678 line profiles in 1998 folded modulo $f = 2.25$ c d^{-1} and with $T_0 = 2\,450\,969.0$. The frequency $f = 4.05$ c d^{-1} has been filtered out.

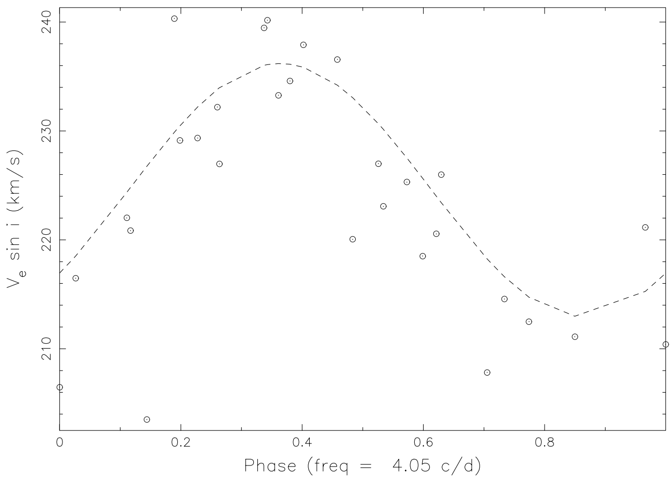

Fig. 13. First minima of the Fourier transform of each HeI 6678 line profiles in 1998 folded modulo $f = 4.05$ c d^{-1} and with $T_0 = 2\,450\,969.0$. The frequency $f = 2.22$ c d^{-1} has been filtered out.

6. Polarimetry

6.1. Circular polarization

The profiles of 62 relatively faint and purely photospheric lines selected with a table appropriated for a B2 star were combined by means of a least square deconvolution (LSD) method (Donati et al. 1997). The quarter-wave plate introduces fringes in the Stokes *V* profiles, which could not be removed. Moreover, the quality of the data is very poor and only 4 measurements were obtained. Therefore, the longitudinal magnetic field of 66 Oph could not be determined. However, looking at the Stokes *V* profiles (Fig. 14), one cannot exclude the presence of a weak Zeeman signature. Measurements of better quality are needed to clearly establish the presence (or absence) of a magnetic field in this star.

6.2. Linear polarization

Two Stokes *Q* and *U* measurements obtained at the same rotational phase were used to study the stellar linear polarization. Because the instrumental accuracy in continuum polarization is about 1% and the expected stellar continuum polarization is of the same order, the results obtained in the continuum cannot be trusted (see Donati et al. 1999). However, polarization across emission lines can be studied with respect to the surrounding continuum. On the other hand, the instrumental cross-talk between Stokes *Q* and *U* can be up to 7%, leading to a wrong determination of the position angle (see Wade et al. 2000). Therefore only the relative changes in angle should be considered. Although the absolute polarization level and angle cannot be established, depolarization across Hα line profile is similar to that measured in 66 Oph by Poeckert (1975). The decrease in polarization in the emission line can be explained by electron scattering of radiation which is higher for the stellar continuum than for photons emitted by the envelope.

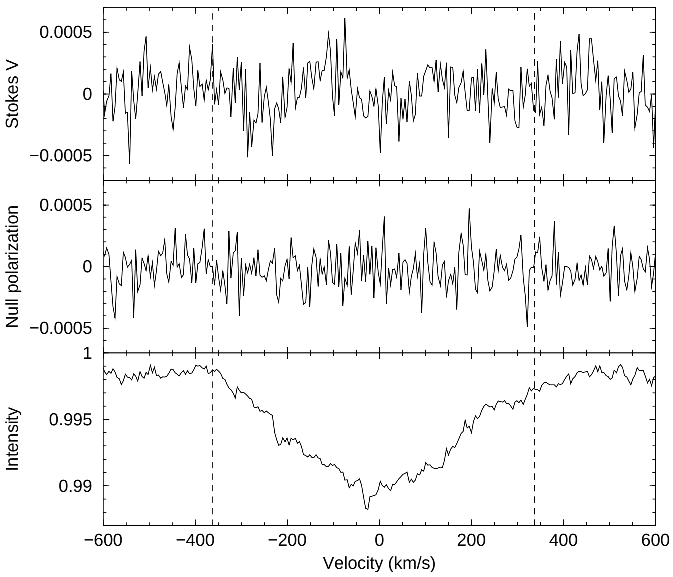

Fig. 14. Example of circularly polarized (Stokes V, upper panel) and unpolarized (lower panel) mean stellar profile of 66 Oph. The null profile is shown in the middle panel.

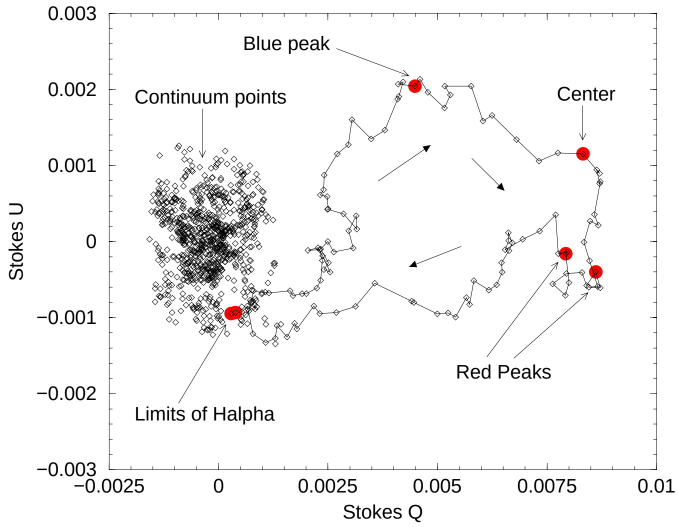

Fig. 15. Polarization across the Hα line of 66 Oph in the Q−U plane. Q and U are given in percent. The arrows indicate the increasing wavelength across the line profile. Center, V and R emission peaks are indicated as well as continuum points. The apparent duplicity of the red peak is due to a telluric absorption line.

Changes in the QU plane (Fig. 15) deviate from a straight line. This had already been observed in 66 Oph (e.g. Hayes 1983) and in other Be stars (e.g. γ Cas, Poeckert & Marlborough 1977). The sense of the loop formed by the variation of U and Q across the emission line profile can be related with the sense of envelope rotation (Poeckert & Marlborough 1978a; McLean 1979). It is to be noted that for 66 Oph the shape of the loop in the QU plane is in good agreement with the modelled shape corresponding to $i = 45°$ in Fig. 5 of Poeckert & Marlborough (1978b), this i value being close to the one determined above (see Sect. 3). Linear polarization effects have usually been attributed to a non-spherical envelope of Be stars (Capps et al. 1973) but could also be partly due to the presence of a magnetic field.

7. Discussion

In spite of the scarce data for each observing run (1997, 1998, 2000 and 2001) we have been able to detect two frequencies from *lpv* and spectral parameters analysis of several blue and red helium lines. Frequency 2.22 $c\,d^{-1}$ is detected in all runs with roughly constant power. Frequency 4.05 $c\,d^{-1}$ is strong in 1998 data (see Fig. 6, lower figure); in 2000 and 2001 it is only detected on helium lines having the higher S/N ratio, and its power summed over the line profile is of the same order as in 1998 ($\sim 7 \times 10^{-6}$). This restricted detection results probably from a lower S/N ratio (∼250), comparatively to 500–600 in 1998. This can also be due in part to the fact that this frequency is probably associated with a *nrp* mode of higher degree than the 2.22 $c\,d^{-1}$ frequency (see below), the amplitude of the resulting deformations across the line profile being smaller and therefore more difficult to detect.

The presence of a multiperiodicity in 66 Oph is a strong argument in favour of *nrp*. Furthermore these two independent frequencies are clearly distinct from the stellar rotational frequency determined in the present study. In terms of *nrp* and following Telting & Schrijvers (1997, Eq. (9)), the phase variations indicate $\ell = 2 \pm 1$ and $\ell = 3 \pm 1$ for 2.22 $c\,d^{-1}$ and 4.05 $c\,d^{-1}$, respectively. Similar ℓ values are obtained in 2000 from *lpv* of the He I 4921 line and from the FDI method applied to the He I 6678, 4713 and 4921 lines (see e.g. Fig. 7, lower panel).

The power distribution across the He I 6678 line profile shows a similar behaviour for both 2.22 $c\,d^{-1}$ and 4.05 $c\,d^{-1}$ frequencies (see Fig. 6): maximum power occurs at the extreme line wings which are disturbed by V and R variations. Nevertheless, the signal power peaks at about $\pm 1.1 V \sin i$ for 2.22 $c\,d^{-1}$, and at ±0.8 and $1.05 V \sin i$ for 4.05 $c\,d^{-1}$. The presence of *lpv* variability outside the $\pm V \sin i$ range is observed in red He I lines contaminated by V and R emission in other Be stars seen under a moderate inclination angle (μ Cen, Rivinius et al. 2001; ω Ori, Neiner et al. 2002). In the case of μ Cen, note that a quadruple peak structure in the power signal corresponding to period P1 can be seen in both He I 5876 and 6678 lines (Rivinius et al. 2001, their Fig. 3): the signal power peaks at $\pm 0.8 V \sin i$ as in blue He I lines and also at $\pm 1.1 V \sin i$. The origin of *lpv* variability outside the $\pm V \sin i$ range gives rise to distinct interpretations, e.g. a rotationally accelerated region occuring at the photospheric level during the emission phase as in λ Eri (Kambe et al. 1993), or a geometrical effect of the ϑ-component of the *nrp* velocity in the case of low inclination stars such as μ Cen (Rivinius et al. 2001).

It has to be stressed that present spectroscopic observations are too scarce to allow any correlation analysis between oscillation state and activity.

8. Conclusion

66 Oph is a Be star which shows a high degree of variability in light and in Hα emission intensity. The present study confirms

the long-term slow weakening of circumstellar emission which started around 1990. From 1997 to 2001 we observed a strong decrease in Hα emission as well as in V and R emission components of He I 6678 line which were present in 1997 and 1998 and absent in 2001. So a minimum level of emission is expected in the near future.

Fundamental parameters of the star derived from BCD calibrations have been re-investigated and a rotational frequency was estimated ($f_{\rm rot} = 1.29 \pm 0.16$ c d^{-1}). $V \sin i$ derived from red helium lines seems to be lower than that derived from blue ones but this result needs to be confirmed by high S/N ratio echelle spectra observations.

A concise review of the variability of 66 Oph is presented. Nicely complementary ground-based and Hipparcos photometric observations allow to confirm a one-year recurrent light outbursts between 1985 and 1995 similar to the time-scale in the wind variation between 1980 and 1987 reported by Peters (2000). Maxima of light outbursts are found to be anticorrelated with Hα emission as reported in other Be stars. The summary of informations gathered in previous studies seems to suggest the following sequence: optical brightening occurs, UV wind activates, polarimetric level increases and optical line emission strengthens.

Time series analysis of He I line data leads for the first time to the detection of multi-frequencies in 66 Oph. The main frequencies present are: $f = 2.22$ c d^{-1} and $f = 4.05$ c d^{-1}. They are attributed to non-radial pulsation modes and their phase distribution over the line profile indicate $\ell = 2\pm1$ and $\ell = 3\pm1$, respectively. More observations are needed to model the *lpv* and to determine the nature and the characteristics of *nrp* modes involved.

Search for stellar magnetic field through the analysis of circularly polarized light has been attempted for the first time in 66 Oph. In spite of the poor quality of our spectropolarimetric data, we cannot exclude the presence of a weak Zeeman signature.

Our observational material is inappropriate to investigate discrete and recurrent emission line outbursts thought to be associated with beating of *nrp* modes as in μ Cen (Rivinius et al. 1998). Nevertheless, taking into account the high degree of variability of 66 Oph, it can be considered as a very good target to search for a correlation between oscillating state and episodic mass loss events. Futhermore, more accurate determination of Zeeman signatures allowing the detection of magnetic fields in the star would be available with the future experiment such as the Echelle SpectroPolarimetric Device for the Observation of Stars at CFHT (ESPaDOnS).

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