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Multi-site continuous spectroscopy

V. Rapid photospheric variability in the Be star 48 Persei from the MUSICOS 1989 campaign*

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Abstract. Rapid variability in the photospheric He I 6678 line of the Be star 48 Per (HD 25940, HR 1273) has been detected from 258 high S/N CCD spectra taken with four 1.5–2.0 meter telescopes over three consecutive nights during the multi-site spectroscopic MUSICOS 1989 campaign. 48 Per is a rather moderate-V sin i star, known to have presented slight long-term variations in the intensity of Balmer emission lines and in the V/R ratio. It is shown that the MUSICOS 1989 observations preceded a new activity phase. Search for line-profile variations, hereafter lpv, was performed with time-series analysis using two methods (TF+CLEAN and Least-Squares) and with analysis of residuals. Weak blue-to-red and red-to-blue moving subfeatures with the same acceleration have been detected in the residuals. Their presence confirms that this star is seen under a moderate angle of inclination, $i \sim 40°$, in agreement with estimates based on fundamental stellar parameters. A 6.04 c/d frequency, associated with the moving subfeatures mentioned above, has been firmly established from time-series analysis and corresponds more closely, in the frame of non-radial pulsations (NRP), to a tesseral mode ($|m| = l - 1 = 9 \pm 2$). Two other possible frequencies (0.85 and 2.77 c/d) have been detected but need to be confirmed with new observations obtained over a longer time span. Despite additional spectra obtained at Haute Provence Observatory, we could not confirm the previous value of the orbital period or the amplitude of the radial velocity curve of 48 Per, and therefore it was premature to search for tidally-forced oscillations.

Key words: lines: profiles – stars: emission-line, Be – stars: individual, 48 Per – stars: oscillations

1. Introduction

As extensively stressed in recent workshops and IAU meetings (see for instance ESO workshop (1991), IAU Symposium 162 (1994), IAU Colloquium 137 (1992) and IAU Colloquium 155 (1995)), the development of high-accuracy, high-resolution spectroscopy and photometry has led to the classification of a growing number of B stars as pulsating variables. Besides the β Cephei stars, two other groups, the so-called line-profile variables (lpv) have been defined: the 53 Persei variables which are slow rotators, and the ζ Ophiuchi variables which are rapid

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* Based on observations obtained during the MUSICOS 1989 MUlti-SIte COntinuous Spectroscopic campaign from NSO McMath-Pierce, Univ. of Hawaii, Beijing Astronomical Observatory (BAO) and Xinglong Station, and Haute Provence Observatory telescopes

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rotators. The B-star instability strip has thus been widened to include late-B spectral types and to higher luminosity (Unno et al. 1989; Dziembowski 1994).

Since the discovery by Baade (1982) of rapid variations in photospheric line profiles of the Be star 28 CMa, many other bright Be stars have been monitored in CCD spectroscopy and have been found to show the lpv phenomenon, and intensive photometric surveys (Balona 1990) have led to the detection of light variations in many Be stars, principally of early types. Lengthy debates have ensued to try to explain periodic variability in these stars with the help of non-radial pulsations (NRP) or rotational modulation (RM) (Baade & Balona 1994). Non-radial pulsations coupled with high rotation could help trigger the start of episodic mass loss (Ando 1986; Osaki 1986). Progress has recently been made on possible driving mechanisms to produce pulsations in Be stars. A consequence of the κ-mechanism is the excitation of high order g-modes, which may explain slow variability (P$\leq$ 4d) in Be stars and provide a key for understanding their activity (Dziembowski et al. 1993). A challenge is offered by the model of Lee & Saio (1989; 1993), who suggest that overstable, prograde, low-frequency, non-radial pulsations in a rotating, massive, main-sequence star may transport angular momentum outwards and accelerate surface layers, giving rise to an excretion disk. If variable mass loss of Be stars is induced by the action of non-radial pulsations whose signature is rapid multiperiodic variability, we should find NRP in each Be star showing long time scale emission features.

The bright early-type star 48 Per (also MX Per, HD 25940, HR 1273; B3–4e, V=4.0, V sin i = 217 km s^{-1}) was chosen as a target of the first MUSICOS (MUlti SIte COntinous Spectroscopy) campaign for the study of intrinsic variability of Be stars. Though this star has shown in the past neither strong shell episodes nor recurrent outbursts, it is known to have presented slight long time-scale changes in the intensity and in the V/R ratio of Balmer emission lines as far back as the beginning of this century, when the first intensive surveys of emission line stars were performed; indeed, a V/R cycle of about 10 years was discovered by McLaughlin (1931). Furthermore, this star has been thought to be a very rapid rotator seen at an intermediate inclination angle (see Sect. 2.2). On the other hand, several authors (Kodaira 1991; Jarad et al. 1989) have suggested 48 Per is a binary star, but this possibility was rejected by Abt & Levy (1978). It was further suggested as a possible transient X-ray source by Peters (1982) and as a Be-X ray binary by Pols et al. (1991).

2. The Be star 48 Per

A short description is given of the emission line characteristics and their variations, and of constraints on the value of the inclination angle i of the star.

2.1. Variability

Regularly observed from different sites, between 1903 and 1986, the emission characteristics of 48 Per seemed to have been more marked in the past than in recent decades. Emission was observed to be double but close, up to Hδ in 1903–1920, sometimes up to Hϵ in 1924–1927 according to Lockyer (Merrill & Burwell 1933), and up to H12 only in September and October 1948 according to Miczaika (1949). That outburst rapidly faded, because from March 1949 emission has only been seen again up to Hδ (Miczaika 1950). Later on, a weak emission maximum between 1963 and 1968 was reported by Hubert-Delplace & Hubert (1979) from an intensive low-dispersion survey of Be stars at Haute Provence Observatory. It was confirmed by inspection of high-dispersion plates obtained at the same epoch and on the same site at the coudé focus of the 1.52-m telescope. Hα was a bright strong line and other Balmer emission lines were superposed on a broad absorption. There was no change in Hα between 1975 and 1980 (Slettebak & Reynolds 1978; Andrillat & Fehrenbach 1982); it was seen as a single emission with I/I$_c$=5.2. Weak inflection flanks could be observed in Andrillat & Fehrenbach data. At the same epoch, a narrowly-separated double peak emission (V=R) at Hβ and Hγ, in addition to weak Fe II emission, was reported by Slettebak (1982). The same features were found in high-dispersion plates taken at Haute Provence during the 1980's. Some months before the MUSICOS 1989 campaign the Hα emission line profile, corrected for photospheric absorption, had an equivalent width of 23Å and a single peak with I/I$_c$= 5.1 (Slettebak et al. 1992). During the MUSICOS 1989 campaign, observations on December 10/11 with the 1.5-m telescope of Wien Observatory gave similar results. Recent CCD spectra taken at Haute Provence Observatory in February 1994 revealed an increase in the Hα emission line (Wλ=27.8 Å) since the observations of MUSICOS 1989 and a slight asymmetry in the core of the line, with V/R=1.017 and I/I$_c$= 5.9 and consistent with measurements by Peters (1994) from observations obtained in 1993 September (I$_v$/I$_c$= 6.0). We therefore concluded that the MUSICOS 1989 observations preceded a new activity phase.

Few data were available before the MUSICOS 1989 campaign on the photometric variability of 48 Per. The star was noted as a possible variable by Alvarez & Schuster (1981). In addition, Percy & Lane (1977) and Percy et al. (1981) suspected rapid variability. Short-term variations in the strength of the Hα emission line were first reported by Bahng (1976), and then by Goraya (1985).

48 Per shows evidence of long-term variability, probably linked with a variable mass loss; it is also suspected to display rapid variability in the continuum and in Hα and in photospheric He I lines not affected by shell contamination. This star thus deserves attention as a good candidate for non-radial pulsations.

2.2. Inclination angle

Originally classified by Slettebak (1949) as a pole-on star, 48 Per was excluded by Schild (1973) from the list of true pole-on stars. No evidence of shell episodes on the one hand, but double though closely separated emission lines on the other, suggest that 48 Per is seen at an intermediate inclination. First, analysis of the line profiles of He I 4471 and Mg II 4481 brought Stockley

(1968) to the conclusion that 48 Per is seen at i = 30 − 50° and that it is rotating near the break-up velocity (solid body rotation). However, another study of He I and Mg II profiles of B and Be stars led Stockley and Buscombe (1987) to the conclusion that rapidly rotating stars are differential rotators. Those authors derived new values for 48 Per, viz. $V_e \sin i$ = 182 km s^{-1} and i = 28 ± 2°.

Further determinations compiled by Ruusalepp (1989 and references therein) led that author to obtain an estimate for $i \approx 30 - 50°$, with a reduced angular rotational velocity ω/ω_c= 0.6–0.8 (ω_c being the critical angular velocity). Recently, using interferometric measurements, Quirrenbach (1994) determined a lower limit to the inclination angle of 31 ± 11°, consistent with previous estimates. Furthermore, according to Hummel & Dachs (1992), an Hα emission line profile with a close double peak structure and inflection flanks, such as was observed with high resolution (0.29 Å) in February 1994, can be reproduced by line radiation transfer with a model having a homogeneous, single component, vertically extended, Keplerian, optically thick disk, and an inclination of i = 30 − 45°. A range for i between 30 − 50° will be considered in the following sections.

3. The 48 Per MUSICOS 1989 campaign

A summary of the goals and operations of the MUSICOS 1989 campaign can be found in Catala & Foing (1990), Catala et al. (1993), and Foing et al. (1994). Part of the observations was devoted to the study of the intrinsic rapid variability of Be stars. 48 Per was chosen as a target and the He I 6678 Å photospheric line was intensively monitored from 8 to 12 December 1989 at four sites:
– in China, at Xinglong Observatory (XL), with the 2.16-m telescope equipped with the French spectrograph ISIS (Felenbok & Guérin 1987) and a THX 576x384 detector
– in France, at Haute Provence Observatory (OHP), with the 1.52-m telescope equipped with the spectrograph Aurélie and a 2048 linear THX detector
– in the USA, at National Solar Observatory on Kitt Peak (KP), with the 1.5-m McMath-Pierce telescope equipped with the stellar spectrograph and a TI 800x800 detector
– at the University of Hawaii Observatory (UH), with the 2.2-m telescope equipped with the spectrograph ISIS-bis and a TI 800x800 detector.

Bias, flat fields and wavelength calibration exposures produced by Th-Ar or Th-Ne lamps were obtained every two hours. An early-type comparison star of low V sin i, γ Peg, was observed from each site in order to correct for telluric lines.

The effective time coverage of 48 Per was excellent: about 84% of the allocated time. An illustration of the coverage is provided by Fig. 2 in Catala et al. (1993).

Atmospheric conditions differed from one site to another. During the Be star campaign, the weather was sometimes cloudy, and transparency was highly variable throughout the night. Thus, atmospheric contamination, variable over each night and different from one place to another, is present on all CCD spectra.

In addition to telluric effects, the instruments lacked homogeneity; they used different gratings and filters, with different amounts of vignetting, and some were fiber-fed, all were calibrated with different lamps, etc...made data reduction rather complicated. Differences in exposure times were also another source of difficulty; Xinglong spectra, for instance, have a resolution close to that of Haute Provence, but their exposure times are two or three times longer.

A summary of the mean characteristics of the spectra of the He I 6678 line of 48 Per recorded during the campaign is given in Table 1. Data from Kitt Peak/National Solar Observatory, University of Hawaii and Xinglong Observatory were recorded with a 2D detector, those from Haute Provence Observatory with a 1D detector.

Additional observations of the Hα emission line were obtained on 10–11 December 1989 at Vienna Observatory with the 1.5-m telescope equipped with an echelle spectrograph and a Reticon detector.

Independently, photometric monitoring of this star was organized by Alvarez et al. (1990) from 6 to 16 December 1989. Photometric data reductions were carried out by M. Alvarez, coordinator of this photometric campaign. The present paper does not include those results. Preliminary and partial information can be found in Guo et al. (1991).

4. Data reduction

Spectra were firstly reduced using the VAX-8600 of the Paris-Meudon Observatory and the "eVe" software. For Hawaii (5-slices image) and Xinglong images, background subtraction, slice extraction and averaging were performed by programs provided by one of us (C.C, see Catala et al. 1993). Continuum normalization for multi-site spectra is generally a complex task. In the case of 48 Per spectra, major difficulties arise from the wide resolution range, signal-to-noise ratio and integration times in addition to the fact that the photospheric He I 6678 line is faint and diffuse for a B3–4 main-sequence star of moderate V sin i. Because of the difficulties outlined above, several analyses were made independently by some of us (Hubert et al. 1990 and Hao et al. 1994). Due to the fact that the softwares used do not allow a precise determination of the continuum, compared with the weak He I line deformations (less than 0.3% of the continuum), too many systematic errors still remained, and no conclusive results could be drawn on multi-frequency phenomenon and on the value of these frequencies.

These difficulties were removed after a new reduction and calibration of the spectra using the IRAF[3] package newly installed on the SUN workstation of the Computer Department of Meudon Observatory. Extracted KP spectra provided by one of us (J.N.) were used (see Neff et al. 1995 for a description of the reduction technique). All the spectra were wavelength

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

Table 1. Log of observations

Site	HJD span(d) (2447800+)	spectra number	Exp. time (mn)	R	$\Delta\lambda$ (Å)	FWHM (Å)	S/N
KP	68.57-68.96	34	6-15	42000	73	0.164	300-400
	69.61-69.99	63					
	70.57-70.86	54					
UH	68.86-69.08	11	10-20	63000	35	0.106	200-300
	69.78-70.06	15					
XL	69.09-69.35	11	30	26000	21	0.251	250-600
	70.04-70.39	9					
OHP	70.25-70.69	27	10-25	23000	207	0.293	500-600
	71.24-71.63	34					

calibrated by interpolating comparison lamp spectra and heliocentric corrections were applied. The stellar continuum was levelled by fitting a cubic spline function to identified continuum regions. For KP spectra, owing to the strong curvature of the stellar continuum, only their central part was used for the determination of the continuum.

It should be emphasized that the continuum determination is always the most critical point in the reduction procedures. They can generate errors on equivalent width and radial velocity measurements. As slight systematic differences in equivalent widths were detected from site to site, a correction was applied, taking the mean equivalent width of OHP data ($W\lambda$ = 0.278±0.003 Å) as a reference because these spectra are the more homogeneous of all. Radial velocities were obtained by measuring the line centroid. It should be recalled that this measurement is difficult for rotationally broadened line profiles locally contaminated by telluric lines. The accuracy of each measurement, affected by the rectification of the continuum, was estimated to be about 1.5–2 km s^{-1}. Radial velocity variations over an interval of several tens of hours, such as the duration of the MUSICOS 1989 campaign, can be explained both by the presence of low-degree NRP modes and by a radial velocity modulation due to the orbital motion of 48 Per, which is possibly the primary component of a binary system. In a few cases, observations obtained at different sites were taken at the same time. A generally good agreement is found between measurements of OHP and KP overlapping observations. Chinese data (XL) are found to be systematically shifted by about +6 and +4 km s^{-1} for the two nights respectively (see Table 1). Thus, XL spectra were corrected to obtain the same radial velocity as with OHP and KP data. In Table 2, the average of the radial velocities measured on each night at the different sites is given. We decided not to use UH line profiles because they show too many fringes, with intensity comparable with the line variations detected in other sites.

An example of the He I 6678 line profiles is given in Fig. 1, which shows spectra obtained at Kitt Peak/National Solar Observatory, Xinglong, and Haute Provence Observatories on the second night of the MUSICOS campaign. For the study of line profile variations, all the spectra were rebinned in the range 6673-6683 Å with a step of 0.101 Å corresponding to the lowest resolution used (OHP data).

Table 2. Mean radial velocity of the line He I 6678 for nightly individual run.

Site	Mean HJD (2447800+)	RV (km s^{-1})	σ (km s^{-1})
KP	68.77	-1.00	2.56
UH	68.97	1.04	4.94
XL	69.22	1.85	1.68
KP	69.80	1.83	1.78
XL	70.18	2.91	1.88
OHP	70.47	2.67	1.05
KP	70.72	1.17	1.41
OHP	71.44	1.85	0.94

5. Line-profile analysis

The mean absolute deviation or *variance* indicates the presence of lpv in a series of spectra; variations are readily seen detached from the noise level in spectral regions where lpv are present (see Kambe et al. 1993a; Leister et al. 1994). In Fig. 2 we show the variance for night 2 on OHP data. The contamination of atmospheric lines is clearly seen at 6683.7 Å, on the mean photospheric line profile (Fig. 2a) and on its variance (Fig. 2b). This feature is mentioned in the Atlas of the Solar Spectrum (Moore et al. 1966).

Several different methods were used to search for *lpv* between $\lambda\lambda$ 6673 and 6683 Å, which corresponds roughly to the rotational width of the He I 6678 photospheric line. Firstly, we scanned the line profile every 0.101 Å (4.54 km s^{-1}). Fourier analysis and CLEAN algorithm were applied to the time-series of spectra in a manner similar to that introduced by Gies & Kullavanijaya (1988). Periods shorter than 1.2 hours ($\nu \geq 20$ c/d) and longer than the total duration of the observing run of 3.06 days ($\nu \leq 0.327$ c/d) cannot be detected. The frequency resolution is 0.327 c/d. Secondly, the least-squares sinusoidal fitting method was applied to the same time series, with the same exploration step. Thirdly, we searched for moving bumps on the residuals obtained separately from OHP, KP and XL spec-

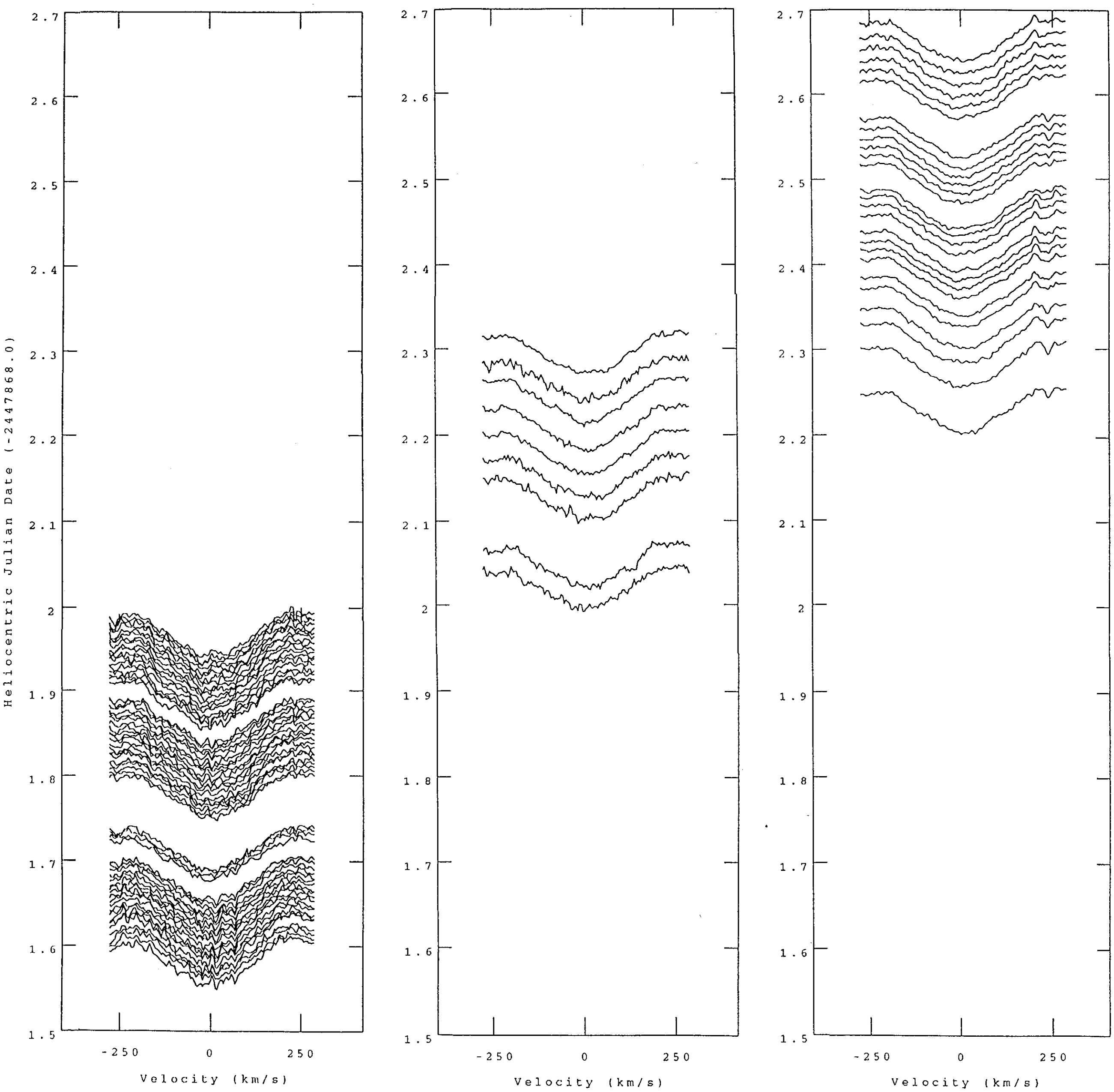

Fig. 1. He I 6678 line profiles of 48 Per obtained at Kitt Peak/NSO, Xinglong and OHP on the second night of the campaign (HJD 2447869 to 2447870). In this figure, time increases upward and corresponds to HJD-2447868.0

tra, by subtracting the mean profile for the relevant night from individual spectra.

5.1. Time-series analyses of lpv

The results of time-series analyses of the He I line profile variations obtained by several methods are recorded in Table 3. An analysis was performed to find the most appropriate value of the oversample interval for exploring frequencies. The best value found was ν_{min}/100, which was obtained by a numerical test using the MUSICOS 1989 window and the most probable determined frequencies (see below) in a similar way to Kambe et al. (1990).

With Fourier Transform Analysis and CLEAN algorithm (hereafter method 2), the gain factor has been taken as equal to 0.8 and the number of iterations was limited to 50. The window function is given in Fig. 3. The search for frequencies was interrupted when the amplitude of the signal corresponding to the frequency ν_n had become larger than that of the preceding frequency ν_{n-1}.

For the least-squares sinusoidal fitting method (hereafter method 1), we introduced the Akaike Information Criterion

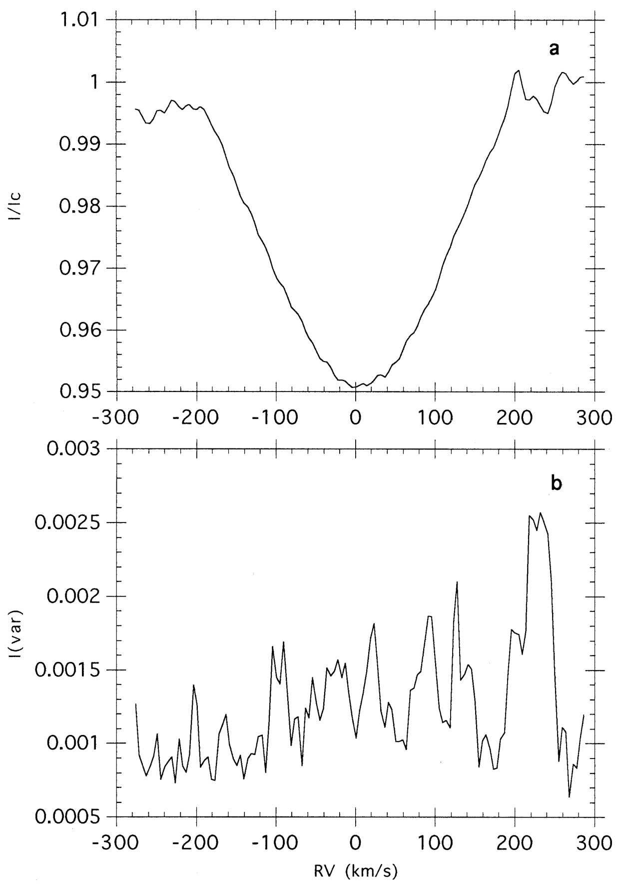

Fig. 2. **a** Mean photospheric line profile of He I 6678 for OHP data of 48 Per. **b** variance of this line obtained for OHP data during 10–11 December 1989 (Mean HJD 2447870.47)

(AIC), (see Kambe et al. 1993b and references therein), to optimize the most appropriate number of frequencies that can reproduce the line-profile variations. In the case of our spectra of 48 Per, that criterion decreases steeply for the first two frequencies, less steeply for the four following ones, and finally slightly varying. However, this number is unrealistic in view of the uncertainty induced by the weakness of the signal. We decided to exclude frequencies for which the signal has about the same power value as that of the minimal frequency (see Fig. 4). Thus postulating that at least two and at most four frequencies could be responsible for the observed spectral variations. Numerical tests on an artificial noisy signal showed that method 1 gives better accuracy in the determination of frequencies, amplitudes and phase velocities. The following frequencies and their respective amplitudes were detected by method 1:
ν_1 = 0.85 c/d and A_1 = 0.0030
ν_2 = 6.04 c/d and A_2 = 0.0019
ν_3 = 2.77 c/d and A_3 = 0.0018
ν_4 = 2.09 c/d and A_4 = 0.0012
The fourth frequency is in fact linked to the first ones, according to the relation $\nu_4 + \nu_{min} = \nu_2 - (\nu_1 + \nu_3)$ with ν_{min}=0.33 c/d. As its amplitude is very weak, it was subsequently discarded.

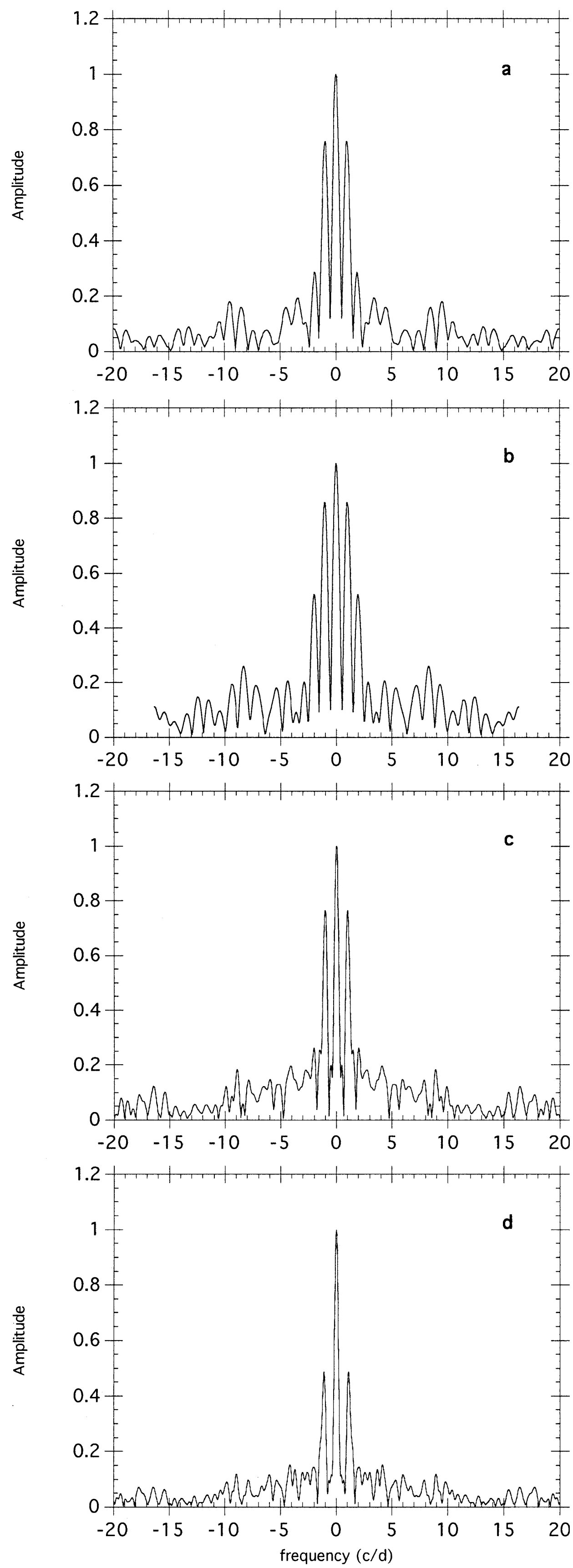

Fig. 3a–d. Amplitude of the window function for the observing run. **a** OHP data; **b** XL data; **c** KP data; **d** all sites

Table 3. Possible frequencies (c/d) deduced from analysis of different time series using a least-squares sinusoidal fitting (method 1), Fourier Transform + CLEAN (method 2), and from the moving bumps across residuals of nightly OHP and KP line profiles (method 3).

	method 1	method 2	method 3
KP profiles	1.85	0.80	
	6.03	6.03	6.13
	2.20	2.90	
		2.10	
OHP profiles	6.05	6.04	6.17
	1.44	2.0?	
	2.05?	1.40??	
KP+OHP+XL	0.85	0.80	
profiles	6.04	6.03	
	2.7	2.77	
	2.09?	2.06??	

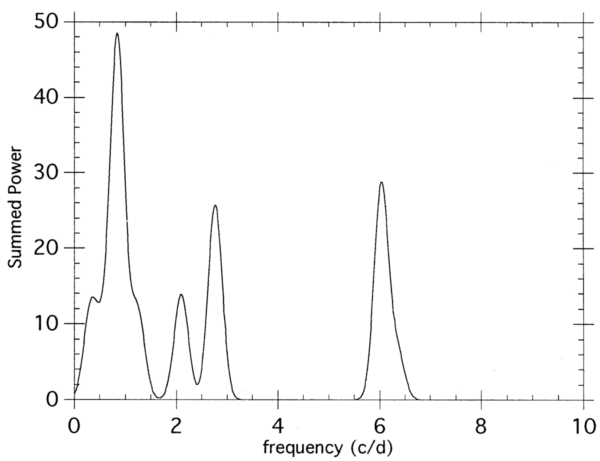

Fig. 4. Power spectrum obtained with the Least-Squares method, summed over the line profile

An illustration of the power summed across the He I 6678 line using method 1 is given in Fig. 4, while the distribution of the amplitude of the three most probable frequencies over the line profile is shown in Fig. 5. It is to be noted that 6.04 c/d frequency is the only one present all over the He I line profile; the two others essentially affect the line center.

Furthermore, separate analysis of KP and OHP data by both methods shows that the 6.04 c/d is present in each sample (see Table 3). The situation is not so clear for the other frequencies. The 0.85 c/d frequency (or its one-day alias 1.85 c/d) is dominant in KP data but absent in OHP data. In the latter, it is close to the lower detectable frequency.

In conclusion, it can be said that rapid variability is present in the photospheric He I 6678 Å line and that multi-periodicity cannot be excluded.

5.2. Analysis of residuals

Residuals, formed by subtracting the mean nightly profile from each spectrum were obtained for KP, OHP and XL data (hereafter method 3). The gray scale of the residuals obtained at OHP

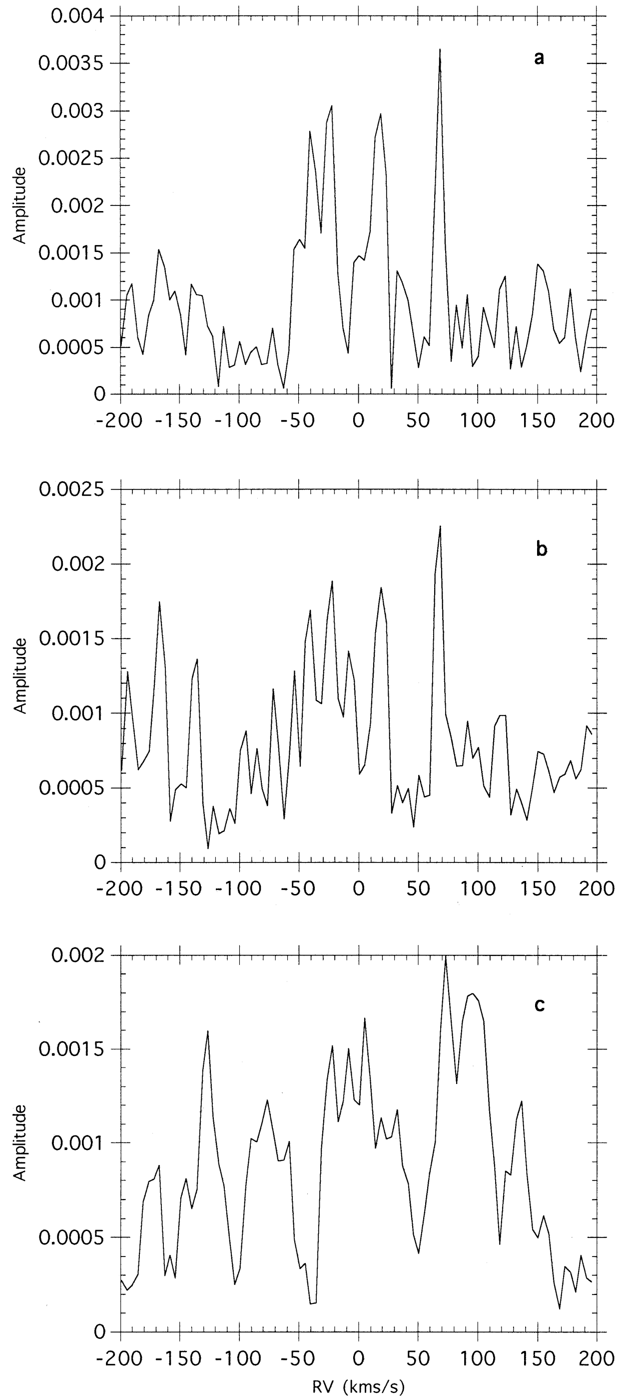

Fig. 5a–c. Amplitude distribution for frequencies detected over the line profile, expressed in km s^{-1}. **a** ν = 0.85 c/d; **b** ν = 2.77 c/d; **c** ν = 6.04 c/d.

during the night of 11th December 1989 is given in Fig. 6. It can be seen that moving bumps, crossing the profile from blue to red (prograde bumps) are interfaced with bumps moving in the opposite direction (retrograde bumps). Examination of the gray scale images of nightly OHP and KP residuals has led to the same conclusion: prograde and retrograde bumps, in the observer's frame, are apparently present. This result is unambiguous for both nights of OHP and to a lesser degree for the first

Table 4. Mean subfeature accelerations and time delays deduced from prograde and retrograde moving bumps observed on OHP residuals, together with the number of measured bumps.

Prograde bumps	a_0 (km s^{-1} d^{-1})	$\sigma(a_0)$ (km s^{-1} d^{-1})	δt (d)	$\sigma(\delta t)$ (d)	n bumps
10/12/1989	894	66	0.162	0.014	4
11/12/1989	960	162	0.162	0.005	3
Retrograde bumps	a_0 (km s^{-1} d^{-1})	$\sigma(a_0)$ (km s^{-1} d^{-1})	δt (d)	$\sigma(\delta t)$ (d)	n bumps
10/12/1989	-752	21	0.193	-	2
11/12/1989	-744	30	0.175	0.015	3

night of KP. Four moving features moving from blue to red, and four others moving from red to blue, were often seen on nightly residuals. Subfeature accelerations and time delays could be determined from OHP data (December 10 and 11th, 1989) (see method 3 in Table 3). Results, given in Table 4, are similar for the two kinds of bumps, presenting a strong argument for a common origin for these features of apparently opposite direction. The mean acceleration and time span between two consecutive prograde bumps are respectively a_{mean}=927±114 km s^{-1} d^{-1} and δt=0.162±0.010 d. We find similar results for the best night of KP data (December 8th, 1989). The frequency associated with this mean time delay is ν = 6.17 ± 0.20 c/d which is consistent with the 6.04 c/d frequency found from time-series analysis with methods 1 and 2.

The fact that bumps moving from red to blue having the same acceleration have a similar strength supports a low to moderate inclination angle (i≤ 45°) in the frame of NRP, according to Kambe & Osaki (1988); this is also consistent with other indicators, see Sect. 2.2.

On both nights of OHP as well as on the first night of XL, in addition to the subfeatures noted above, a slowly moving subfeature with an acceleration of about 500 ± 50 km s^{-1} d^{-1} was found.

5.3. Radial velocity

Analysis of the radial velocity of the KP and OHP profiles, obtained by measurements of centroids on one hand, and by cross-correlation of line profiles on the other hand, did not reveal any detectable periodicity that could be connected with NRP of low-degree mode or with the rotational period. The amplitude of a possible radial velocity variation is of the same order as the accuracy on the radial velocity measurements ≤ 2 km s^{-1}. In the cross-correlation method, the derived auto-correlation peak is poor, as is commonly expected for broad weak lines. Such negative results could be expected because, even in the case of low-degree NRP mode, the radial velocity component would be only a few km s^{-1} (Balona 1995).

6. Estimate of fundamental stellar parameters

As is well known, it is not easy to determine parameters of Be stars whose photospheric lines are often strongly contaminated by emission. Generally there is an inaccuracy of at least 1-2 subtypes in the spectral type; this is the case in 48 Per, classified as a B3Ve star by Jaschek et al. (1980), B4Ve by Slettebak (1982) and B4IVe by Underhill et al. (1979). Thus, the estimate of mass and radius of Be stars remains highly imprecise in so far as the determination of parameters of standard B stars is also inaccurate.

6.1. Mass and radius

We have tried to summarize the different estimates of the mass and radius of 48 Per according to the different calibrations published by Underhill (1982), Harmanec (1988), Slettebak et al. (1992) and Andersen (1991) for hot main-sequence stars. In the following, we only consider extreme values provided by Underhill (1982) and Harmanec (1988).

a) If 48 Per is a B3 or B4 main sequence star, according to Underhill (1982)

$$6.8 \leq M/M_{\odot} \leq 8.8$$

$$4.7 \leq R/R_{\odot} \leq 5.1$$

and according to Harmanec (1988)

$$5.1 \leq M/M_{\odot} \leq 6.1$$

$$3.25 \leq R/R_{\odot} \leq 3.55$$

With these parameter values, we estimate the critical velocity and a lower limit to the inclination angle as, V_c = 445±20 km s^{-1} and i≥30°.

b) If we adopt the parameters derived specifically for 48 Per by Underhill et al. (1979), with a spectral classification B4IV (T_{eff} = 16300 ± 300° and log g=4.0), we obtain:

$$M/M_{\odot} = 6.8 \pm 1.8$$

$$R/R_{\odot} = 5.6 \pm 0.5$$

and V_c = 393 km s^{-1} and $i \geq 35°$.

We note that the average equivalent width of the He I 6678 line profile obtained at OHP, i.e. W_λ=0.28 Å, is consistent with the value predicted by the NLTE models of Auer & Mihalas (1973) for a star with the above parameters.

To a lesser degree, inaccuracy also exists in the V sin i value. Considering all the values found in the literature, except that determined by Stockley & Buscombe (1987) which is very much lower than all the others, we have adopted 217±17 km s^{-1}.

6.2. Rotational frequency

As summarized in Sect. 2.2, the inclination angle i has been estimated to lie between $30 - 50°$. However, as moving bumps are seen from blue to red and from red to blue, having roughly the same acceleration and similar time spans (see Sect. 5.2), this result strongly supports an $i \leq 45°$. So, with this new constraint, we have taken $35° \leq i \leq 45°$. In this scheme, for i = 35°, the star is found rotating with an angular velocity rate ω/ω_c = 90% (we therefore adopt R_e=1.5 R_*=1.5 R_p), whereas for i = 45°, the angular velocity is lower, with ω/ω_c = 60% and in that case

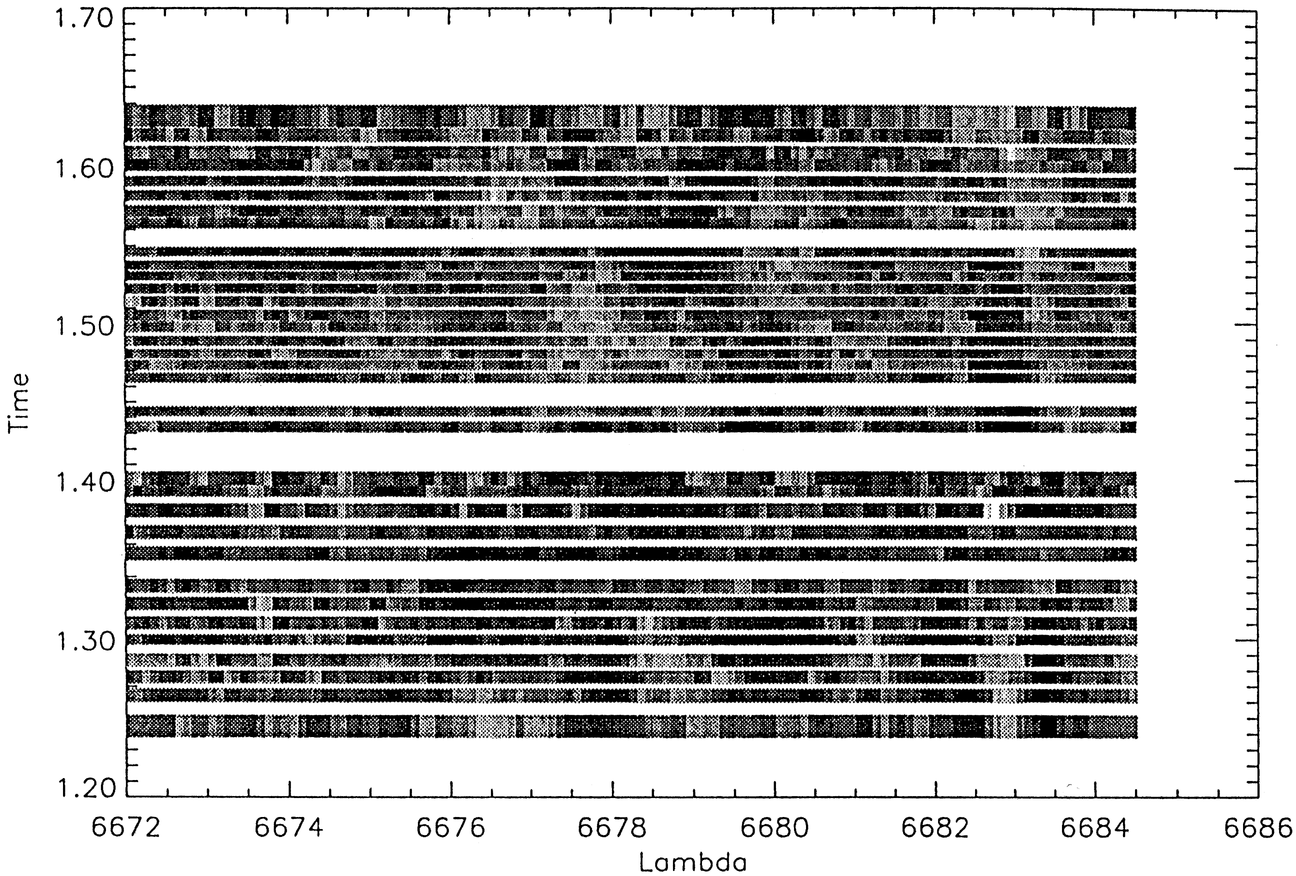

Fig. 6. Gray scale of residuals for data obtained at OHP during the night 11-12 December 1989 (mean HJD 2447871.44). The extreme values of intensity are ±0.0066

we adopt R_e=1.25 R_*=1.25 R_p. The break-up rotational angular velocity is denoted by ω_c.

Finally, taking into account the inaccuracy in the mass and radius of 48 Per, we investigated two possibilities with $35° \leq i \leq 45°$:

a) 48 Per is a B3 or B4 main sequence star, so 0.95 c/d $\leq \sigma_{rot} \leq$1.53 c/d with $\delta\sigma_{rot} \sim$0.15 c/d

b) 48 Per is a B4IV star and, according to the stellar parameters derived by Underhill et al. (1979) for this star we find 0.72 c/d $\leq \sigma_{rot} \leq$0.88 c/d with $\delta\sigma_{rot} \sim$0.10 c/d.

6.3. Binary properties

The presence of radial velocity variability was first suspected by Harper (1919). Measurements from earlier observations at Lick Yerkes and McDonald Observatories were added to those obtained at Mt Wilson from 1968 to 1969 and analyzed by Kodaira (1971), who proposed 48 Per as a possible binary with P=16.93 d and K=10 km s^{-1}. Abt & Levy (1978) re-observed the star with a 2.1-m coudé spectrograph (16.9 Å mm^{-1}) and did not confirm the binarity. They concluded for a constant velocity, but with a scatter of about 6 km s^{-1}. New spectra with a lower dispersion (30 Å mm^{-1}) were collected at St Andrews University Observatory and analyzed by Jarad et al. (1989), who detected a possible periodicity of P=28.8 d in their data. They then combined their data with the radial velocities published by Abt (1970), Kodaira (1971) and Abt & Levy (1978), and found a value P=16.59 d, close to that originally suggested by Kodaira. However, the scatter is high (σ=7.0 km s^{-1}) and of the same order as the semi-amplitude (K=8.5 km s^{-1}). The mass function estimated by Jarad et al. (1989) is $f(m)$ = 1.07 10^{-3} $M_\odot$ and leading to the secondary mass of 0.4-0.8 $M_\odot$ for orbital inclinations in the range of 30-90°.

In order to obtain complementary information on the binary system, spectra with a high S/N ratio ($\geq$300), were obtained at Haute Provence Observatory in 1989, 1994 and 1995, in the same observational setup as employed in the MUSICOS 1989 campaign. On those spectra, as on MUSICOS 1989 OHP spectra, only one line of He I was available for radial velocity measurements, unlike previously analyzed classical spectra; however, with the high S/N ratio, the scatter of measurements is lower than σ=1.5 km s^{-1}. We determined the radial velocity of each profile from measurement of the position of its centroid. The amplitude of the variations is small for each run of observations and of the same order as the scatter of measurements (see Table 5). Some slight variation could be suggested with a period of about 89.0 d or around 16.2 d and weak semi-amplitudes K=4.2 km s^{-1} and 3.5 km s^{-1} respectively; but those values are

Table 5. Mean radial velocity of 48 Per for complementary observing runs between 1989 and 1995; n is the number of spectra of the run

date	RV $km\ s^{-1}$	σ $km\ s^{-1}$	n
September 1989	5.65	1.39	6
January 1994	0.16	2.24	8
August 1994	0.39	2.77	3
November 1994	0.72	2.18	8
February 1995	-2.41	0.80	13
August 1995	1.36	1.35	6

much too close to the rms value of 2 km s^{-1} for a positive conclusion. The question of the binary character of 48 Per, and therefore of the existence of tidal effects between the components, remains an open question even with additional high S/N data. If 48 Per proved to be a binary with a period of about 89 d and a semi-amplitude of 4.2 km s^{-1}, then assuming that the rotational axis of the Be primary is perpendicular to the orbital plane, a separation of about 157 $R_{\odot}$ between the primary and the secondary would be expected. In that case, tidal interactions would be weak. That would not be the case if the orbital period was around 16 d, when the separation between the two components would be about 48 $R_{\odot}$.

7. Discussion

The presence of the 6.04 c/d frequency has been firmly established from time-series analyses by both methods (least-squares method and Fourier Transform + CLEAN method), and from the analysis of nightly residuals. The other possible frequencies (0.85 and 2.77 c/d) derived only from the time-series analyses, deserve further investigation, principally because they are not observed independently from each site. However, it has to be noted that the 0.85 c/d frequency cannot be distinguished from the expected rotational frequency, according to Sect. 5.1. Taking into account the uncertainties on fundamental stellar parameters on the one hand, and with the constraint on frequency separation of 0.33 c/d, provided by the observational window, on the other hand, the 0.85 c/d frequency corresponds to the lower limit of the rotational frequency of a B3–4 main sequence star seen at a low inclination angle of about 40°; it is also in good agreement with the rotational frequency of a B4IV star, according to the stellar parameters deduced by Underhill et al. (1979) specifically for 48 Per.

According to Percy (1987) 48 Per has been suspected to be a possible rapid photometric variable. Therefore, up to now, no photometric frequency has been detected.

7.1. The 6.04 c/d frequency

The most interesting point concerning this frequency comes from the fact that, from analysis of nightly residuals, it has been deduced simultaneously from blue to red (prograde bumps), and red to blue (retrograde bumps) moving features. This can be explained by non-radial pulsations in a star seen with a rather low inclination angle (∼40°), as demonstrated by Kambe & Osaki (1988): prograde and retrograde bumps can exist simultaneously in an inertial frame of reference (i.e. in the observer's frame) for stars of low inclination angle. Low inclinations allow such a situation in the case of spheroidal or toroidal modes. Tesseral modes with $|m| = l - 1$ give a better contrast for travelling bumps. According to those authors, retrograde bumps are more conspicuous in the case of toroidal modes than spheroidal modes, but in a rapidly rotating star a tesseral toroidal component can easily be produced from a sectoral g-mode.

In a close binary system, tidally-forced oscillations of a massive main sequence component can be effective (Kato 1974). However our attempt to confirm or refute a binary motion and to determine orbital parameters for 48 Per was unfruitful. So, in the absence of a well established binary character, we have only raised the possibility of the presence of free g-modes in the star.

It should be recalled that the power spectrum across the He I 6678 line profile is very weak for the 6.04 c/d frequency and that the star is a very rapid rotator. Lee & Saio (1990) have included the effect of rotation on the eigenfunction of non radial pulsations. They have shown that the strength of bumps is strongly reduced, this effect being particularly severe in the case of retrograde modes (in the co-rotating frame). By including the effect of temperature and velocity variations in the computation of line profiles, they have shown that the amplitude of travelling bumps is enhanced across the line center for prograde modes. For a moderate inclination, spheroidal g-modes $l = |m|$ and $l = |m| + 1$ can be responsible for the observed variations in line profiles. In this picture, we have calculated for 48 Per the degree of the g-mode associated with 6.04 c/d. In the hypothesis of a sectoral mode, the pulsation mode is related to the bump motion across the profile by the relation:

$$|m| = \frac{2\pi V \sin\ i}{a_0 \delta t}$$

where a_0 is the acceleration of bumps at line center and δt the time span between two successive bumps. With the values given in Table 5 and V sin i=217 km s^{-1} we found $l = |m| = 10 \pm 2$ (conservative estimate). The same m value is provided by the two-dimensional Fourier spectrum of the line profile variations. The travelling frequency of the bumps (corresponding to the superperiod) is

$$\sigma_{bumps} = \frac{a_0}{2\pi(V_e + V_\phi)\sin\ i\ f(\theta)}$$

where V_ϕ is the velocity of the wave and f(θ) a function of the latitude (see also Reid et al. 1993). The horizontal velocity of g modes is estimated to be 20-30 km s^{-1} (Kambe & Osaki 1988). For a sectoral mode, f(θ)=1 and $\sigma_{bumps} = 0.6 \pm 0.2$ c/d. In this case, the travelling frequency does not seem to correspond to a prograde mode, because it is slightly lower than the lower value of the estimated rotational frequency, see Sect. 5.2.

In the hypothesis of a tesseral mode with $l = |m| + 1$, we obtain $|m| = 9 \pm 2$. According to Lee and Saio (1990), the maximum amplitude is concentrated at about $10 - 20°$ on both sides of the equator. As the star is distorted by rotation, we roughly estimated $f(\theta) \leq \cos\theta = 0.9$ and $\sigma_{bumps} = 0.7 \pm 0.2$ c/d. In that picture, the presence of a prograde mode could be reconciled with the estimated rotational frequency (0.72 c/d $\leq \sigma_{rot} \leq$0.88 c/d) in the case of a B4IV star and using Underhill et al. (1979) parameters. It should be remembered that only prograde (in the corotating frame) tesseral modes are efficient for giving bumps in line profiles (Lee & Saio 1990). The fact that no velocity phase could be deduced from our data can be explained by the weakness of the signal associated with the wave and by the simultaneous view of prograde and retrograde bumps allowed by the moderate inclination angle $\leq 45°$, which induces a jamming effect.

Another explanation for the 6.04 c/d frequency could be that it was generated in the lower part of the circumstellar envelope by some corotating jets or spikes as it suggested by Harmanec (1991) to explain short-term line-profile variability. Gies (1994) has also proposed that narrow subfeatures associated with high frequency are formed in the inner part of the disk, in localized high density regions. The observational run of the MUSICOS 1989 campaign on 48 Per was too short for a thorough investigation of this possibility. However the 6.04 c/d frequency is clearly present in the periodogram provided by time series analyses and in residues of line profiles; a similar result was reported in 48 Lib (Floquet et al. 1996) for the highest frequency detected, ν = 10.6 c/d.

8. Conclusions

Intensive spectroscopic monitoring of the Be star 48 Per over 78 hours during the MUSICOS 1989 campaign enable us to detect rapid variability in the HeI 6678 photospheric line, though the amplitude of the variations was very weak ($\leq$0.3% of the stellar continuum). This star is seen under a rather moderate inclination ($35° \leq i \leq 45°$) according to constraints arising from fundamental stellar parameters and the shape of the close double peak structure and inflection flanks of the Hα emission line. This situation gives a fair view of moving subfeatures on the hemisphere facing the observer and on the far hemisphere.

Previously, Baade (1991) detected in μ Cen (B2 IV, V sin i=175 km s^{-1}) quasi-emission/absorption features moving from blue to red and from red to blue with the same absolute rate of propagation. That author proposed that an NRP velocity field with at least two components, a sectoral and a tesseral one (l = 2, $|m|$ = 2 and l = 2, $|m|$ = 1) could explain such prograde and retrograde features as well as the double-wave light curves of many Be stars.

48 Per appears, from this study, to be another example of a rather moderate V sin i Be star in which blue to red and red to blue moving subfeatures with the same absolute acceleration have been detected. However, these patterns are very weak, which is merely explained in the frame of a NRP model as corresponding to higher degree modes than in the case of μ Cen; indeed, the tesseral and/or sectoral associated modes are $|m| = l - 1 = 9$ and $|m| = l = 10$, with σ=6.04 c/d, and respectively σ_{bumps} = 0.7 and 0.6 c/d. The other possible frequencies 0.85 and 2.77 c/d could be associated with low and moderate modes respectively, but, due to the lack of accurate determination of stellar parameters and frequency (from homogeneous data) we can only speculate on the mode determination. The slow-moving feature sometimes observed with $a_0 = 500 \pm 50$ km s^{-1}d^{-1} is not explained with the present data. It is not linked with some co-rotating structure because its travelling frequency (0.40 c/d) is too weak to be consistent with the expected stellar rotational one's. It could be linked to some inhomogeneities in the circumstellar envelope.

We have only attempted to explain our observations in terms of non-radial pulsations. However, the lower possible frequencies 0.85 and 2.77 c/d also detected, as well as the stability of the higher one's, 6.04 c/d, need to be confirmed. The origin of high frequencies is questioned. From an observational point of view, they might be intermittent and irregular (Gies 1994); however, in the case of η Cen (Leister et al. 1994), a high frequency (15.4 c/d) was detected in moving subfeatures in line profiles from several runs of observations (March and June 1990, and July and August 1992). On the other hand, a confrontation between computed and observed line profiles is essential. It could resolve ambiguity over the interpretation of high frequencies in the frame of NRP. On the one hand, according to Lee & Saio (1990) and Lee et al. (1992), the effects of temperature variation on high-degree non-radial g-modes ($l \geq 4$) of rapidly rotating stars are sufficient to induce travelling features across line profiles consistent with observations. On the other hand, Aerts & Waelkens (1993), including Coriolis forces in their computations of line profiles for rotating pulsating stars, concluded that toroidal terms induce additional bumps in the case of low-degree g-modes, mimicking the presence of high-degree g modes.

In another aspect, we were unable to decide whether the star is single or double, so no meaningful investigation of tidally forced oscillations (Kato 1974) could be undertaken. However, 48 Per deserves attention for a broad wavelength spectroscopic survey to determine accurate radial velocity from a substantial number of photospheric lines. Further multi-site and multi-technique campaigns are needed on 48 Per, and also on other Be stars with a low V sin i.

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