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Coupled long-term photometric and V/R variations in Be stars: evidence for prograde global one-armed disk oscillations *

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Abstract. We review theoretical work on global oscillations of Be star disks and summarize possible observational tests. In addition, we analyze existing records on photometric data and V/R ratio for a sample of 6 V/R variable Be stars. Five stars showed coupled long-term photometric-V/R variations. In all cases the photometric extrema coincided with times of $V = R$ transits, the fainter state being followed by a $V < R$ phase. V 1294 Aql, 48 Lib and MX Pup showed anticorrelated c_1 and $b - y$ colors during light cycles, the stars being redder in $b - y$ when brightest. 48 Lib shows a complex color behaviour, exhibiting two minima during a V/R cycle and a pronounced $b - y$ drop just at maximum light. In addition, this star shows enigmatic, non-periodic, eclipse-like features in its light curve. In general, the V/R-photometric observations can be grouped in three main groups, depending on the degree of correlation exhibited by the V/R ratio and the photometric fluxes and the rate of change of the u flux. These groups are compatible with *prograde* global disk oscillations observed under different system inclinations.

Key words: stars: emission-line, Be - stars: individual: V 923 Aql – V 1294 Aql – γ Cas – 48 Lib – MX Pup – ζ Tau

1. Introduction

In recent years, there has been a burst of theoretical and observational papers on the phenomenon of quasi-cyclic changes in the asymmetry of emission profiles of Be stars. This asymmetry is defined as the ratio $V/R = (I_\mathrm{v} - I_\mathrm{c})/(I_\mathrm{r} - I_\mathrm{c})$ between the violet and red peak intensity of optically-thin double emission lines referred to the continuum level, although the definition has been recently extended to include also optically-thick asymmetric emission profiles with subordinate peaks or *shoulders* (Hummel & Vrancken 1995, Hanuschik et al. 1995). Most observational studies have been focused on the statistical properties of time scales of V/R cycles or their empirical relationship with changes in the radial velocity and/or line emission of selected stars. The present paper deals with the hitherto untreated aspect of photometric changes associated with V/R quasi-cycles and their implications on the model of global oscillations of Be star disks.

2. Previous observational work on V/R variations

The main properties of V/R variations are:
- They occur in quasi-cycles with characteristic time scales between 2–13 years with an average of 7 years (e.g. Hirata & Hubert-Delplace 1981, Mennickent & Vogt 1991).
- The quasi-period sometimes switchs into another period in a spectacular way (e.g. PP Car from 10 years → 2 years, Mennickent 1991).
- The time scale does not depend on $v\,sin\,i$ nor on spectral type (e.g. Hirata & Hubert-Delplace 1981, Mennickent & Vogt 1991).
- The intensity of line emission does not correlate with V/R changes (Hirata & Hubert-Delplace 1981).
- The whole line profile shifts redward when the blue component is stronger and blueward when the red component is stronger (McLaughlin 1962).
- At least in γ Cas, V/R variations do not correlate with the shape or strength of the IR continuum (Telting et al. 1993).
- V/R phase shifts have been observed between different emission lines (e.g. EW Lac, Kogure & Suzuki 1987).
- Some stars exhibit long periods of *quiescence* followed by a revival of the V/R activity (Mc Laughlin 1937). Sometimes the oscillations appear rather abruptly after a long quiet phase (e.g. β Mon, Cowley & Cugula 1973, 66 Oph, Hanuschik et al. 1995). Then, after several quasi-cycles, they gradually disappear while

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** Belgian Fund for Scientific Research (NFWO) the amplitude decreases or are strongly damped on a short time scale (e.g. β Mon, Cowley & Cugula 1973).

• For shell stars, the V/R variations are strongly correlated with the shell's radial velocity (e.g. V 1294 Aql, Ballereau & Chauville 1987, see also Mc Laughlin 1961).

• In γ Cas the strength of discrete absorption components observed in ultraviolet resonance lines is stronger when the emission profiles exhibit $V > R$ (Doazan et al. 1987, Telting & Kaper 1994).

3. Previous theoretical work

First models explaining the V/R cycles include an elliptical precessing disk, a gravitationally-distorted envelope in a binary system and a rotating-pulsating envelope. These models present several handicaps which have been discussed, e.g. by Hanuschik et al. (1995), Telting et al. (1993) and others. Another model valid for X-ray emitting Be binaries, which assumes line emission excess from an ionized sphere around a compact companion, was proposed by Apparao & Tarafdar (1986). In general, the nature of the V/R phenomenon seems to be different for Be star interacting binaries, where the V/R ratio varies with the orbital phase in a strictly periodic way. In these cases the V/R variations can be explained by a hot spot produced in the site where the stream hits the accretion disk (e.g. CX Dra, Simon 1996, ϕ Per, Gies et al. 1993), in the same way that hot spots produce the V/R variations observed in dwarf novae (e.g. Marsh & Horne 1990). Recently, a model based on low frequency, one-armed oscillations in quasi-Keplerian disks was proposed for V/R variations in single Be stars (Okazaki 1991). Because of its importance for the V/R phenomenon, we give a historical review of the main features of this model:

– Based on the theory of global oscillations in nearly Keplerian disks (e.g. Kato 1983, 1989, Okazaki & Kato 1985) Okazaki (1991) found that possible global oscillations in nearly Keplerian disks are very low-frequency, one-armed oscillations alone. He examined the behaviour of small-amplitude, one-armed isothermal oscillations in axisymmetric isothermal disks with finite radial sizes. Okazaki (1991) found that the oscillation periods of the fundamental mode and first overtones range from years to decades for some range of the parameter values. Second, the periods are not sensitive to the spectral types of the stars. In Okazaki's model a point-mass central potential is considered, the disturbance pattern precesses in a *retrograde* way as a result of pressure forces in the disk. The periods depend on the details of the disk's size and structure.
– Papaloizou et al. (1992) took into account the deviation from a point mass potential for the rotationally-flattened Be star. As a result of this, the natural precession of free particle orbits could manifest itself as the *prograde* pattern rotation of a one-armed mode that is confined within a few stellar radii in a thin ($H/r \leq 10^{-2}$) equatorial disk. For plausible values of the Be star parameters, the precession period turns out to be of the order of 10 years, which falls in the observed regime. The period of the fundamental mode is:

$$P = \frac{2\pi\eta^{7/2}(GMR)^{1/2}}{k_2 v^2} \quad (1)$$

where M, R and v are the mass, radius and rotational velocity of the Be star, k_2 is the apsidal motion constant and η defines the turning point of the $m = 1$ density wave as $r_{tp} = \eta R$. In this point the pattern frequency equals the local prograde precession frequency. Beyond the turning point the mode is evanescent. In this model the fundamental period strongly depends on the η parameter.
– Savonije & Heemskerk (1993) refined the above model, solving the hydrodynamics equations governing linear density waves in nearly Keplerian disks. For plausible values of the Be star's rotational flattening and for the disk's characteristic temperature, they found prograde precession modes naturally confined to a few stellar radii with periods in the range of the observed V/R variations. In this model the precession period of the $m = 1$ mode turns out to be fairly insensitive to the size of the disk or to the adopted density distribution.
– Assuming that nonlinear perturbation patterns are similar to the linear $m = 1$ eigenfunctions and that the source function is constant over the entire disk, Okazaki (1996) computed the optically-thick line profiles for various values of the disk parameters. He found that the line-profile variability due to the $m = 1$ perturbation patterns agrees with the observed V/R variability. He also found that the amplitude of the profile shifts associated with the V/R variation is sensitive to the density gradient in the radial direction. Okazaki (1996) gave arguments showing that the effect of rotational deformation of the central star is comparable to the pressure effect even in the innermost region of the disk, but its relative importance rapidly decreases to the outer regions, so being negligible in most Be stars.

In summary, observations can discriminate between the Okazaki and Papaloizou et al. models by establishing the *prograde* or *retrograde* nature of the motion as well as by the degree of the confinement exhibited by the enhanced density pattern inside the disk. In addition, whereas Okazaki's model implies a dependence of the observed periods and profile shifts with the disk's size and density gradient, the model by Papaloizou et al. (1992) and Savonije & Heemskerk (1993) do not require any strong dependence of the periods on the disk's structure but on its temperature and on the rotational velocity of the central star.

4. The model and observational tests

The existence of enhanced density patterns slowly precessing in the disks of Be stars leads to important photometric and spectroscopic variations which strongly depend, in principle, on the system's inclination and on the retrograde-prograde nature of the motion. In the following, we model the disk's vertical section as a cone with opening angle i_0 (Fig. 1), the enhanced density pattern being located in the region $r_\star < r < \eta r_\star$. We define three class of V/R variable Be stars based on the system's inclination (Table 1):

1. *V/R Class 1:* when $i > i_0$, absorption of radiation by the disk's atoms and Thompson scattering by electrons along the line of sight dominate the photometric variations. Large variations, mainly in the u band, are expected.
2. *V/R Class 2:* when $i_1 > i > i_0$ (where $i_1 \approx$ arcsin $1/\eta$) i.e. at intermediate latitudes, the variations should be milder. Occultation of the density pattern by the central star could be important.
3. *V/R Class 3:* when $i < i_1$ the projected stellar disk is practically never occulted by the enhanced density pattern, so no photometric variation is expected.

In this scenario we obviously do not include random (large) photometric variations due to an accretion-ejection process, for example. In practice, these random variations could appear in combination with the variations described above, which are only based on geometrical aspects of the system. We now list to enumerate several observational tests based on the above simplified scenario.

• In edge-on systems, the absorption and isotropic re-emission associated with scattering is greater when the density pattern is facing the observer, so we can expect a minimum of brightness when $V = R$ prior to the $V < R$ ($V > R$) phase when the precession is *prograde* (*retrograde*). Due to the observed short nature of the $V = R$ transit, this implies slightly anti-correlated photometric–V/R curves. On the basis of this test, we present evidence of *prograde* motion in all cases discussed in Sect. 5.

• At intermediate latitudes, smoother photometric minima are expected when compared with the edge-on case. We can, in principle, estimate lower limits for η in medium-inclination systems showing no correlated V/R-photometric patterns (see the discussion of γ Cas below).

• In low inclination systems, we expect to see traces of V/R variations in single-peak asymmetric emission profiles and practically non-existent associated photometric patterns.

• The difference between prograde and retrograde modes can be established by looking to the transition phase between $V < R$ and $V > R$ in edge-on systems. In fact, prograde precession requires the phase with $V < R$ to be followed by a (partial) eclipse of the region with enhanced density before this region reappears at the other side of the disk and V/R becomes larger than unity. If this region is an enhanced emitting region (EER) emitting mainly at longer wavelengths, we might expect an eclipse in the $b-y$ color. Such a phenomenon is, in fact, observed in 48 Librae (Sect. 4).

• Prograde motion also requires the $V = R$ state following $V > R$ to be accompanied by an increasingly deep central absorption in emission profiles. This behaviour has been observed in β^1 Mon (Telting et al. 1994).

• Finally, the passage of an enhanced density pattern through the projected stellar disk should increase the amount of photons scattered by electrons along the observer's line of sight in the wings of the emission profiles. This has been seen in Be stars in the context of mass ejection episodes (Dachs & Rohe 1990) but not yet during V/R cycles in Be stars showing constant emission. This effect might be detected as increased strengths and extensions of Balmer emission-line wings during photometric minimum.

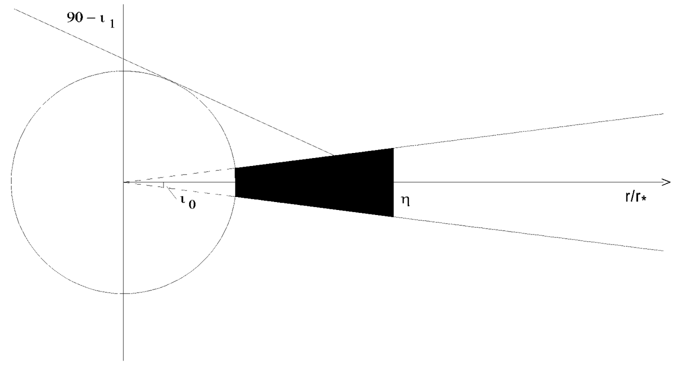

Fig. 1. Schematic geometrical model for one-armed oscillation in the fundamental mode

Table 1. A scenario for V/R-photometric patterns. The expected amplitude of photometric variations Δ for different inclination angles defines the V/R class. Angles are defined in Fig. 1

Δ	Inclination	Effect	V/R Class
Large	$i > i_0$	occult. + abs. + Thomp. scatt.	1
Medium	$i_1 > i > i_0$	occultation	2
Absent	$i > i_1$	none	3

The possible weakness of the above tests is the lack of a reliable method for calculating the inclination angle of Be stars. However, a useful guess can be inferred from the projected rotational velocity $v\ sin\ i$ and the short-term photometric periods when available (e.g. Balona 1995) or from interferometric and polarimetric studies (e.g. for γ Cas Clarke 1990, Mourard et al. 1989).

5. V/R-photometric patterns of selected Be stars

In this section we present a discussion of photometric data of a sample of Be stars along with V/R measurements. Data taken in the framework of the "Long-term Photometry of Variables" (LTPV) project (Sterken 1983, 1994) during 1983–1991 and discussed by Mennickent et al. (1994b, here and thereafter MVS94) is supplemented with new LTPV data obtained during 1991–1994 (all data have been published by Sterken et al. 1993, 1995 and Manfroid et al. 1992, 1994). The observing strategy and procedures of the LTPV project are summarized in MVS94 and in the data catalogues. Among the stars studied by MVS94 we have selected those with reported V/R quasi-cycles (i.e. V 923 Aql, V 1294 Aql, 48 Lib and MX Pup). In addition, we have included γ Cas and ζ Tau because quasi-simultaneous V/R-photometric records are available.

5.1. HR 7415 = HD 183656 = V 923 Aql

This star is a spectroscopic binary with an orbital period of $214\overset{\mathrm{d}}{.}75$ (Koubsky et al. 1989). Photometric fluxes show a quasi-cyclic oscillation with a period of about 7 years in 1983–1991, with a notoriously larger u amplitude and an apparent phase shift of almost 1000 days between the vby and u light curves (MVS94). The literature for V/R data has very few records. Ringuelet & Sahade (1981) give an almost symmetrical double Hα profile on HJD 244 4451. Denizman et al. (1994) report Hα and Hβ profiles with $V \approx R$ between HJD 244 6585 and 6990. Andrillat et al. (1994) reported a Paschen-7 line characterized by $V \geq R$ on HJD 244 8404 and Hanuschik et al. (1995) showed Hα profiles with $V/R \approx 1.5$ during HJD 244 9095–9239. From the above data we can conclude that:

- If the star is a V/R quasi-cyclic variable, the period should be $\sim$ 12 years or a sub-multiple of 5–6 years. In this case, the V/R transition reported by Denizman et al. roughly corresponds to the u photometric minimum (MVS94, their Fig. 10), according to test 1.
- The star does not exhibit long-term V/R variations. This hypothesis is strengthened by the apparently long duration ($\sim$ 400 days) of the $V = R$ transit.

In the first case, the star should fit the definition of V/R class 3 (Table 1). The V/R and photometric variations exhibited by V 923 Aql are certainly not due to the revolution of an envelope distorted by the attraction of the secondary, as was suggested by Koubsky et al. (1989) (the same is valid for ζ Tau discussed below). In fact, the two-dimensional hydrodynamical simulations and numerical calculations (e.g. Whitehurst 1988, Hirose & Osaki 1990, Whitehurst & King 1991) indicate that the precession period (P_{pr}) of a disk immersed in the Roche Lobe of the primary of a binary system should be related to the system's mass ratio ($q = M_2/M_1$) and orbital period by:

$$\frac{P_{pr}}{P_{orb}} \approx \frac{3.85(1+q)}{q} \quad 0.1 \leq q \leq 0.22 \tag{2}$$

In the case of V 923 Aql, $q \approx 0.13$ (Koubsky et al. 1989) and the predicted $P_{pr} \approx 19.7$ years is too long when compared with the observed time scale of photometric variations.

5.2. HD 184279 = V 1294 Aql

This shell star showed remarkable long-term oscillations in the light and radial velocity curves during the past decades (e.g. Horn et. al 1982, Ballereau & Chauville 1987, MVS94). In Fig. 2 we show a photometric record spanning 30 years along with some V/R measurements. The star shows 5 well-defined photometric quasi-cycles with minima around HJD 244 2000, 244 4100, 244 5600, 244 7700 and 244 9600. Surprisingly, minima repeat after 6.1, 3.9, 5.9 and 3.9 years respectively, the amplitude of every quasi-cycle being much variable. We were unable find any periodicity after removing the long-term tendency shown by the combined photometric data. Interesting for us is the fact that V/R oscillations appear correlated with photometric cycles, in the sense that photometric extrema are associated with $V = R$ transits, the fainter state being followed by a $V < R$ state, according to test 1 if prograde precession is assumed. A strange situation seems to occur at the third photometric minimum, which practically coincides with the previous maximum. The time resolution of the V/R dataset is too low for resolving any short V/R cycle which might follow this rapid photometric half-cycle. Surprisingly, the posterior Hα $V > R \rightarrow V < R$ transition is associated with a *rising* photometric branch, contrary to that seen in Hβ. It is not clear whether this is due to a poor data sampling — a lag of the Hα V/R data — or a change in the properties of the V/R oscillation. The $uvby$ light curves during the 1983–1994 period show that the amplitude in the u bandpass is larger than in other filters by a factor ~ 2. In addition, the rate of u change clearly differs from other filters during rising and fading phases, this is clearly visible in Fig. 3 where the c_1 color index appears anticorrelated with the y light curves. A peculiar event occured on HJD 244 1863 (Fig. 2), when the star faded by $0\overset{\mathrm{m}}{.}29$ in the V band, appearing at normal brightness after 54 days. Another interesting fact is the redder $b - y$ colors observed during maximum light. The star can be classified as V/R class 1, according to criteria of Table 1.

5.3. HD 5394 = γ Cas

γ Cas was the first emission line star that was discovered (Secchi 1867) and is now one of the best-studied Be stars. Our classification as V/R class 3 is based on data given by Telting et al. (1993). These authors show in their Fig. 1 three entire V/R cycles whereas the brightness smoothly increases from $V = 2\overset{\mathrm{m}}{.}4$ to $V = 2\overset{\mathrm{m}}{.}2$. No cyclic photometric pattern is observed.

5.4. HR 5941 = HD 142983 = 48 Lib

In Fig. 4 we show the data analyzed by MVS94 along with new data covering the period 1991–1994. A steady decrease of the u-brightness from February 1988 to July 1993 followed by a new increment of brightness is observed. This spectacular u decline is completely absent in v, b and y. In fact, after the maximum of February 1988 light smoothly declined until November 1990 after which the light output continued varying with smaller amplitude around a relatively constant level until 1993. The photometric variations were accompanied by cyclic changes in the V/R ratio while the Hα emission line strength and shell absorption were approximately constant (Hanuschik et al. 1995). This contrasts with the behaviour observed in the Fe II lines, where the line depth seems to be strongly variable. The new set of photometric data confirms the strong correlation suspected in MVS94 in the sense that $V < R$ is observed during the rising branch and $V > R$ during decline. In addition, the photometric maxima and minima related to the transition phase between symmetric and asymmetric emission profiles. In addition, an inspection of the color changes in Fig. 5 reveals a cyclic behaviour also in $b - y$ and c_1, the m_1 index being practically constant. Two remarkable facts are observed in the $b - y$ color:

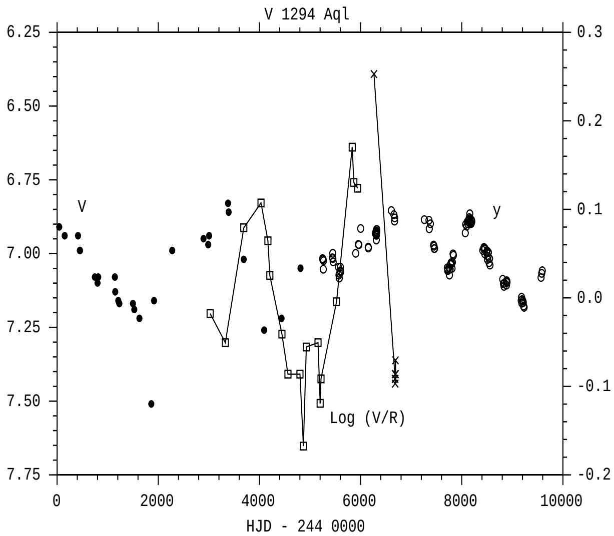

Fig. 2. Long-term light curve of V 1294 Aql. In this picture we show V data (•) from Horn et al. (1982) and y data (○) from MVS94 and supplementary LTPV data, which are read at the left vertical axis, along with the logarithms of V/R for Hβ (□, Ballereau & Chauville 1987) and Hα (×, Alvarez et al. 1990) at the right vertical axis. Observations indicate photometric extrema coinciding with $V = R$ transits, the minimum around HJD 244 5200 being very shallow

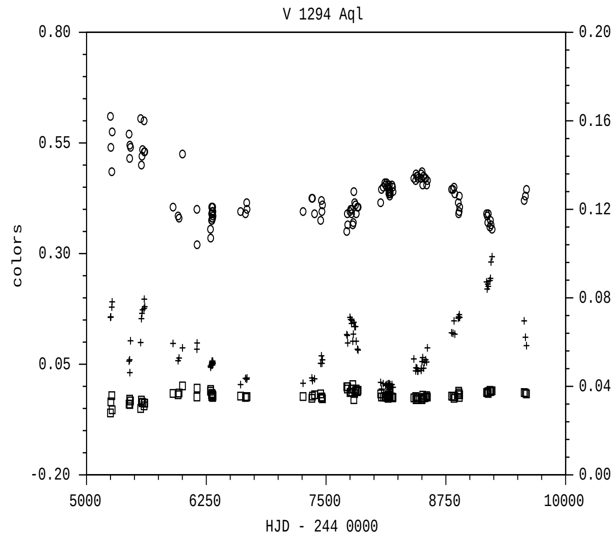

Fig. 3. Long-term color behaviour of V 1294 Aql during 1983–1994. Left vertical axis refers to c_1 (+) and m_1 (□). $b-y$ (○) are indicated at the right vertical axis. $b-y$ roughly follows the y changes, the star being redder when brightest.

the presence of two minima (contrary to the single-band and c_1 curves) and the strong dip observed just before maximum (around HJD 244 7400). A period analysis using the *PDM* routine (Stellingwerf 1978) of the $b-y$ data also reveals a cyclic behaviour in 2587 ± 20^d (7.1 years, but excluding the data sample around HJD 244 7250). Unfortunately, our time baseline for the u, v, b, y and c_1 curves is too short for deriving any reliable periodicity. However, a raw estimation based on the timings of the u and c_1 extrema indicates a possible $\sim$ 5000 day (13.7 years) period. The V/R data, on the other hand, show a noisy minimum at 3670 ± 100 days but their reliability is questionable due to the poor data sampling (less than one cycle) and mixing of data belonging to different lines.

We can interpret the above behaviour in the framework of global oscillations if the 10-year V/R period were an artifact due to the mixing of data of different lines, the true periodicity being close to 14-years, i.e. the same period exhibited in u. In this case the half-period found in $b-y$ could reflect a larger vertical extension of the EER so a secondary maximum would be seen when the EER is backside the star. The lack of increased Hα shell absorption as predicted by test 5 could be the result of a short-lived, undetected episode. This is a very probable assumption, because of the short-lived nature of the $V = R$ transit and the poor sampling of the 5 spectra given by Hanuschik et al. (1995). The correlated V/R-photometric patterns and larger u amplitude exhibited by 48 Lib fit a V/R class 1 as given in Table 1.

5.4.1. Eclipse-like episodes (ELEs):

A conspicuous feature in the light curve of 48 Lib is the presence of sudden drops in irradiance, reminiscent to eclipses, in all bandpasses. The magnitudes and colors of such events relative to the seasonly average values are shown in Table 2. Dips range from $0^{\rm m}06$ to $0^{\rm m}14$ in y, the mean colors and their standard deviations relative to the mean seasonal values are $\overline{\Delta(b-y)}$ = 0.006(6), $\overline{\Delta c_1}$ = 0.018(28) and $\overline{\Delta m_1}$ = 0.000(4), i.e. the fadings are of the same magnitude in all wavelengths. The duration of the "eclipse-like" episodes seems to be well constrained between 1–3 days.

Another strange feature observed in 48 Lib, possibly related to ELEs, is the presence of transient narrow absorption components (NACS) at the Fe II and Na I spectral lines (Hanuschik & Vrancken 1995; here and thereafter HV95). NACS were characterized by widths $\sim$ 10 km s^{-1}, depths $<$ 0.11–0.13 continuum units and changing radial velocities on time scales of hours. HV95 quoted the difference between these NACS and the discrete absorption components observed in highly-ionized stellar wind lines. They also gave evidence against the hypothesis of local clumps moving across the stellar disk in elliptical Keplerian orbits and finally suggested that NACS are due to higher-order components of density waves producing the cyclically changing line profile asymmetries in 48 Lib. HV95 rejected cool clumps as a viable hypothesis due that the viscous thermalizing time is larger than the keplerian orbital period, whereas the observed phenomenon lasted for less than one cycle. However, these authors did not consider the heating due to irradiation by the central star, which could significantly decrease the heating time.

So, both the photometric dips as well as the NACS observed in 48 Lib could imply sudden changes of optical depth related to the rotation of the disk's inhomogeneities or high-order modes

Table 2. Minima of 48 Lib as derived from LTPV data. The $y, b-y, c_1, m_1$ parameters and their differences [Δy, $\Delta(b-y)$ etc.] with respect to the mean seasonal values are given. We also give an upper or lower limit for the duration of the episodes (ΔT) and the rate of decline dy/dt (mag/day) relative to the corresponding preceding observation

HJD - 244 0000	ΔT (days)	y	$b-y$	c_1	m_1	dy/dt	Δy	$\Delta(b-y)$	Δc_1	Δm_1
5450.81	< 1.95	5.031	-0.006	0.762	0.078	0.08	0.063	0.011	-0.030	-0.005
6137.84	< 3.00	4.959	-0.012	0.711	0.081	0.07	0.065	-0.001	0.061	0.002
6674.49	> 1.00	4.980	0.001	0.605	0.077	0.00	0.119	0.012	0.037	0.002
6675.50	> 1.00	4.985	-0.008	0.586	0.081	0.00	0.124	0.003	0.018	0.006
7611.83	< 2.97	5.025	0.004	0.551	0.075	0.15	0.116	0.011	0.004	-0.003
8099.48	< 2.96	5.115	-0.002	0.775	0.086	0.06	0.135	0.009	0.051	0.000

of global density oscillations. The question in the second case is why the overtones appear only in 48 Lib and not in other V/R variables.

5.5. HR 3237 = HD 68980 = MX Pup

The light curve of this suspected "pole-on" Be star showed a long-term period of $\sim$ 10 years during 1983–1991 (MVS94). We have supplemented the above data with new measurements obtained by the LTPV team during 1991–1994. A period of about 8 years seems to fit the light curve, though the ascending branch after the 1990 September minimum reveals higher variability on shorter time scales compared to the previous cycle (Fig. 6). A notable fact is the similar amplitude observed in all bandpass. In addition, we found a photometric–V/R pattern similar to that found in 48 Lib, in the sense that photometric extrema are associated with $V = R$ transits (Fig. 6). Unfortunately we cannot confirm the existence of a drop of magnitude just at maximum due to a gap in the data during HJD 244 6700–7100. In general, $b-y$ follows y, the color being bluer when the star is fainter, a fact already noted by MVS94 (Fig. 7). Bluer $b-y$ colors around HJD 244 7200 could be associated with a $b-y$ minimum similar to that seen in 48 Lib. Another interesting fact is the presence of several spikes in the c_1 curve, revealing important changes in the flux distribution, probably associated with a higher rate of response of the u filter during brightening events (compare with the case of 48 Lib, documented in Fig. 5). In fact, a close examination of Fig. 6 really reveals such magnitude changes on time scales of hundreds of days in the long-term tendency. Contrarily to the absorption components seen in the UV spectra of γ Cas, these c_1 events are not associated with any particular V/R phase, revealing a photospheric nature rather than a disk-wind interaction. The high sensitivity of the $c1$ index to medium-term photometric variability in HR 3037 is notable; the long-term tendency is almost missed in the $c1$ data. This is contrary to that seen in V 1294 Aql and 48 Lib, where $c1$ tightly follows long-term tendencies.

5.6. HR 1910 = ζ Tau

ζ Tau is a single-lined spectroscopic binary with an orbital period of 133 days which has been extensively studied by several investigators (e.g. Guo et al. 1995 and references therein). The star undergoes cyclic V/R and photometric variations during the period 1988–1993, the photometric extremum being associated with $V = R$ transits according to test 1. In addition, the amplitude of the photometric oscillation in the U band is only slightly larger than in the V band, the star being classified as V/R class 2 (Table 1). As in the case of V 923 Aql, the V/R oscillations are probably not due to the revolution of a tidally distorted envelope.

Table 3. Photometric properties of V/R variable Be stars and their classification accordingly to criteria of Table 1. We give the amplitude of long-term photometric variations *correlated* with V/R changes. For V 1294 Aql, the last quasi-cycle was considered. Inclination for V923 Aql, 48 Lib (assuming a double-wave light curve) and ζ Tau are from Balona (1995), for γ Cas from Clarke (1990) and for V 1294 Aql and MX Pup they have been calculated from the $v\,sin\,i$ value assuming the mean rotational velocity inferred for a sample of 53 Be stars by Balona (1995)

Star	i	Δu	Δv	Reference	V/R Class
V 923 Aql	55	$0^{m}_{.}3$	$0^{m}_{.}1$	2,7	1?
V 1294 Aql	67	$0^{m}_{.}6$	$0^{m}_{.}3$	1,7	1
γ Cas	45		$0^{m}_{.}0$ (V)	8,9	3
48 Lib	55	$1^{m}_{.}0$	$0^{m}_{.}2$	7	1
MX Pup	25	$0^{m}_{.}2$	$0^{m}_{.}3$	4,5,7	2
ζ Tau	55	$0^{m}_{.}3$ (U)	$0^{m}_{.}15$ (V)	3	2

References: 1) Alvarez & Chauville 1987, 2) Denizman et al. 1994, 3) Guo et al. 1995, 4) Hanuschik et al. 1995 5) Mennickent & Vogt 1988, 6) Mennickent & Vogt 1991, 7) This paper, 8) Telting & Kaper 1994, 9) Telting et al. 1993.

6. Discussion

6.1. V/R photometric patterns and their implications

In the previous section we have presented spectroscopic and photometric data of six V/R variable Be stars. We have pointed out that long-term V/R variations cannot be due to *tidally* distorted envelopes in binary Be stars in the case that P_{orb} is not in the range of $\approx (0.02 \rightarrow 0.05)\,P_{v/r}$ (Eq. 2). This probably excludes precessing elliptical envelopes in V 923 Aql and η Tau. In this section we interpret the V/R-photometric variations in terms of global density oscillations in the scenario mentioned in Sect. 3. Our analysis is forcedly semi-qualitative, due to the poor time resolution of the published V/R data.

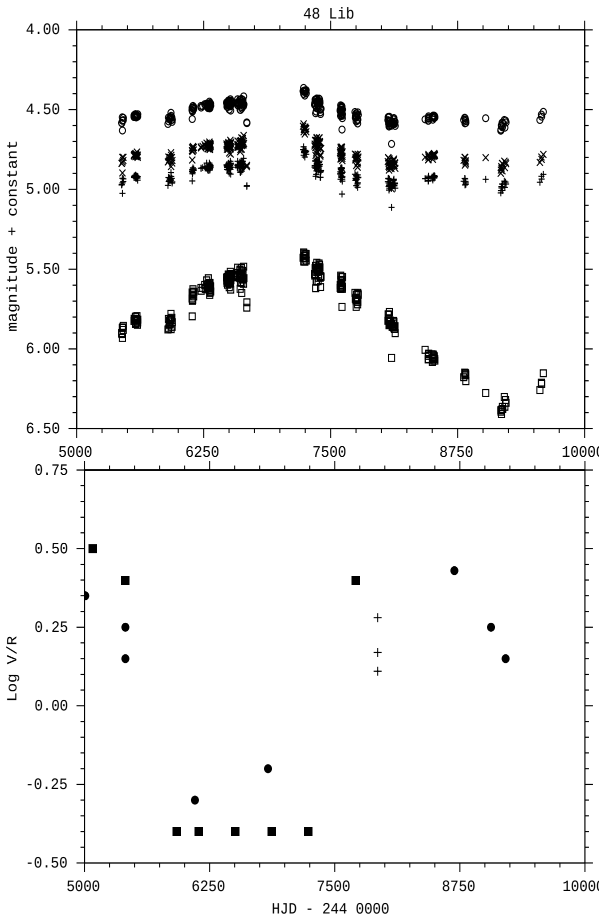

Fig. 4. *Upper panel*: Overall light curve of 48 Lib. The $uvby$ magnitudes are shown as □ × + and ○, respectively. vy are shifted by $-0\overset{m}{.}2$ and $-0\overset{m}{.}4$, respectively. *Bottom panel*: The V/R ratio between the violet and red peak intensity of the double emission lines as derived from Fig. 11 of Hanuschik et al. (1995) and from Table 3 of Ballereau et al. (1995). • indicate Hα values, filled boxes indicate Hβ and + Fe II (λ 5198, 5317 and 5363 Å) values. Photometric extrema roughly coincide with $V = R$ transits

In Table 3 we summarize photometric amplitudes related to V/R cycles. It is evident that, in general, large amplitude photometric variations correlated with V/R changes occur only if the inclination angle is larger than $\sim 50^o$, according to the proposed scenario of Sect. 3. The exception is MX Pup (HR 3237), in spite of the pole-on nature (an inclination angle of 20^o is estimated), notorious photometric variations associated with the V/R cycles are present. The most obvious interpretation is a slow rotator seen under a medium-inclination angle. The 55^o angle inferred for 3 stars of Table 3 is a relatively large angle when compared with computed opening angles of Be star disks (e.g. $i_0 \sim 13°$, Hanuschik 1996) and could be evidence of a higher height scale in disks of V/R variable Be stars. On the other hand, the fact that γ Cas does not show any photometric oscillation during several V/R cycles necessarily implies, in the proposed picture, a density pattern located roughly at $r > 1.4r_\star$.

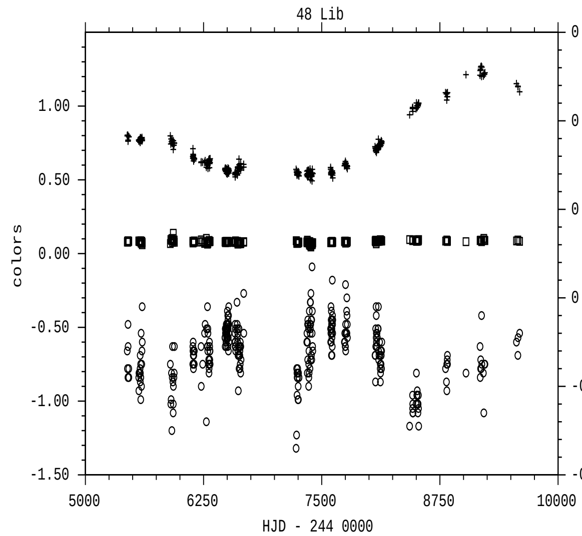

Fig. 5. Long-term behaviour of color indices of 48 Lib. Symbols are as in Fig. 3. Note the double-wave nature of the $b-y$ color when compared with the u flux and the notable drop just at maximum light

To our opinion, the most important result of this paper is the discovery of correlated V/R-photometric quasi-cycles exhibited in 5 of the 6 studied V/R variable Be stars. Moreover, a very significant observational fact is that, in all cases, photometric extrema coincide with $V = R$ transits, the fainter state being followed by a $V < R$ phase. In principle, this is strong evidence for *prograde* global one-armed oscillations, as found for β Mon by Telting et al. (1994) based on spectroscopic analysis. The fact that redder $b-y$ colors are observed at maximum light in edge-on systems (when the EER is located behind the star) could be due to a projection effect if an important contribution of the EER to the y radiation is present. The presence of a double-wave $b-y$ curve in 48 Lib could be explained if the EER contributes to the total y flux inclusive when in front to the stellar disk. A peculiar fact is the anticorrelation between c_1 and $b-y$ colors — a fact already noted by MVS94 — that seems to be common to Be stars. This could be due to an EER with a large population of neutral hydrogen in the $n = 2$ state, so photons with $\lambda \leq 3646$Å are more absorbed than lower energy photons during the passage of the EER in front to the stellar disk.

Prograde motion as derived in this paper is compatible with the Papaloizou et al. (1992) and Savonije & Heemskerk (1993) models but not with the Okazaki (1991) picture. The fact that V/R time scales appear independently of disk structure, as derived from the non-correlation exhibited with emission line strengths (an apparently good indicator of disk's size in optically thin disks, e.g. Dachs et al. 1986), also violates the principal result of the Okazaki's model, viz. the strong dependence of the V/R period with the outer disk radius. However, the alternative model given by Papaloizou et al. (1992) and Savonije & Heemskerk (1993), predict a strong dependence of time scales with disk temperature (through the Mach number) and rotational velocity of the central star, a fact that should be reflected in a dependence on spectral type, which is not observed. In addi-

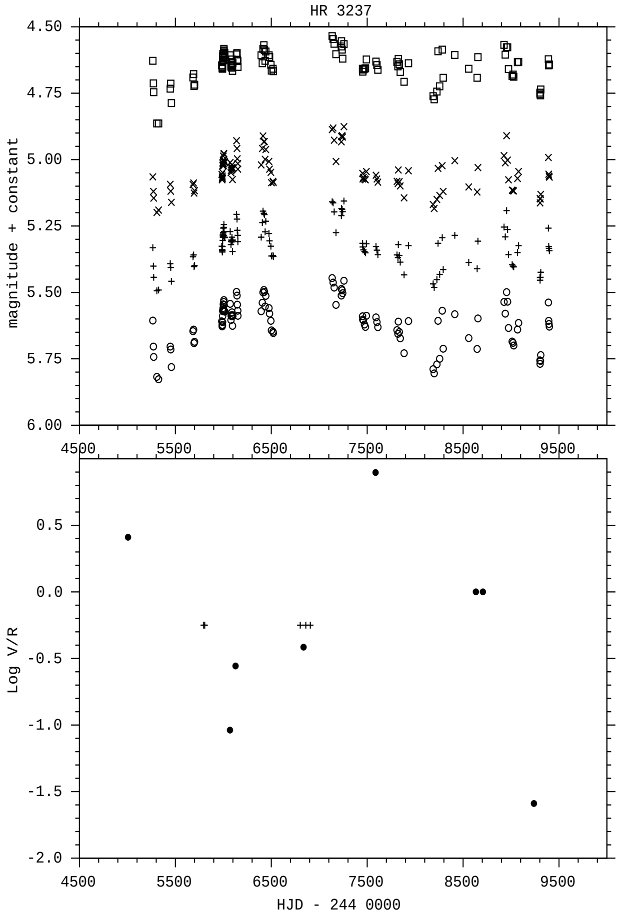

Fig. 6. *Upper panel*: Overall light curve of HR 3237. Symbols are as in Fig. 4. vby are displaced by $0.^{\rm m}3$, $0.^{\rm m}6$ and $0.^{\rm m}9$, respectively. *Bottom panel*: The V/R ratio between the violet and red peak intensity of the double emission lines. Filled circles indicate Fe II (λ 5198, 5317 and 5363 Å) values from Hanuschik et al. (1995) and plusses indicate Hβ values from Mennickent & Vogt (1988) and Mennickent et al. (1994a) assuming $V \leq R \rightarrow log(V/R) = -0.25$. Photometric extrema roughly coincide with $V = R$ transits

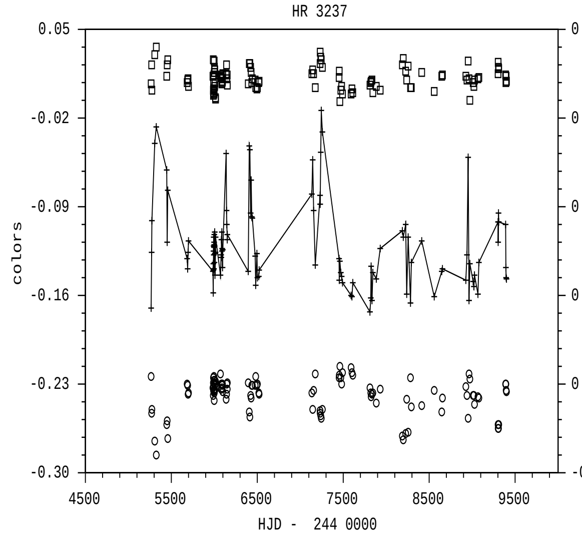

Fig. 7. Long-term behaviour of color indices of HR 3237. Symbols are as in Fig. 3. Note the strong variability at the c_1 index and the $b - y$ minima associated with minimum brightness

tion, there is no obvious correlation between V/R time scales, as derived from Table 1 of Mennickent & Vogt (1991) and equatorial velocities, as derived from Table 1 of Balona (1995), for 10 commonly studied Be stars with well-defined V/R time scales. Probably, models are still too crude, and more realistic assumptions, including non-linear effects along with a non-uniform source function, need to be considered.

6.2. V/R mode switching: possible mechanism and test

We can speculate about the mechanism controlling the sudden appearance and time scales of V/R variations. A "quantum" jump in the disk's global temperature theoretically implies a switch between two oscillation modes. Such changes between high-temperature and low-temperature disks are common in dwarf novae *accretion* disks due to a thermal-instability operating in a selected range of mass accretion rates (e.g. Meyer & Meyer-Hoffmeister 1981). In the case of rapidly rotating Be stars, mass could be supplied from the equator to the inner disk, and then drift outward by effect of viscous stress, producing an *excretion* disk. This kind of disk also possesses thermally unstable regions when the mass excretion rate is $\sim 10^{-7} M \odot /y$ (Lee et al. 1991). If the "V/R mode switching" were due to some kind of thermal instability operating in one-armed excited disks, we should be able to see changes in emission line fluxes during changes of V/R time scales.

7. Conclusion

Photometric observations strongly support the thesis that an enhanced density pattern precessing in a *prograde* way (i.e. in the sense of the disk's rotation) causes the long-term V/R variations observed in Be stars. This is exactly the picture resulting from the model proposed by Papaloizou et al. (1992) and Savonije & Heemskerk (1993). However, the main challenge for their model is how to explain the apparent constancy of the precession period with disk's temperature and stellar rotational velocity, along with explaining the process producing the disk's density enhancements. We emphasize the importance of long-term multiwavelength photometric and spectroscopic campaigns for selected targets, specially covering the phase of period switching, in order to test possible mechanisms controlling the appearance and change of V/R oscillations in Be star's disks.

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