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# V/R Variations of Binary Be Stars

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**Abstract.** The analysis of V/R and RV H$\alpha$ variations is carried out for selected Be binary systems, monitored over 8-12 years. The V/R variations can exhibit quasi-periodic cycles or periodic variations locked to the orbital periods or their combination. The triple-peak profiles appear at a given phase of the V/R cycle in $\zeta$ Tau, independently of the orbital phase, and cannot be fitted by profiles computed for the model of global disk oscillations. Except for a few cases caused by radiational excitation, the mechanism locking the V/R variations to the orbital period in stars like 4 Her and $\epsilon$ Cap is not identified.

## 1. Introduction

V/R ratio, the ratio of the violet-to-red emission peaks is used as one of the main characteristics describing the double-peak emission lines of Be stars. About 2/3 of both single and binary Be stars show long-term variations of V/R ratio of Balmer H I, Fe II or He II emission lines. The variations are often quasi-periodic on a time scale of 5 - 10 years. Surprisingly, not many studies of V/R variations appeared during last years. The most complete compilation of Be stars showing the V/R variations was published by Okazaki (1997). It contains 62 Be stars with quasi-periods typically between 5 and 10 years, it is much longer than the rotational periods of the star or of the disk.

Okazaki (1991, 1997) explained the V/R variations by one armed oscillations proposed first by Kato (1983), who showed that the only possible global mode in a geometrically thin Keplerian disk is m = 1. The Okazaki's hybrid model assumes two following physical mechanisms driving the m = 1 oscillations in the inner part of the disks:

1. A quadrupole contribution to the potential around the rotationally distorted stars (Papaloizou et al. 1992) dominating for late B type stars.

2. The radiative force to optically thin lines, playing the main role in early Be type stars. However, this conclusion was drawn under the assumption that the Be stars rotate only at about 40% of the critical velocity. The effect of the close-to-critical rotation on driving of the one-armed oscillation still needs to be re-evaluated in view of the present ideas on rotational velocities of Be stars (see e.g. Townsend et al. 2004).

Eleven Be stars are marked as binaries in the Okazaki's list. For the binaries with indicated periods there seems to be no correlation between their orbital periods

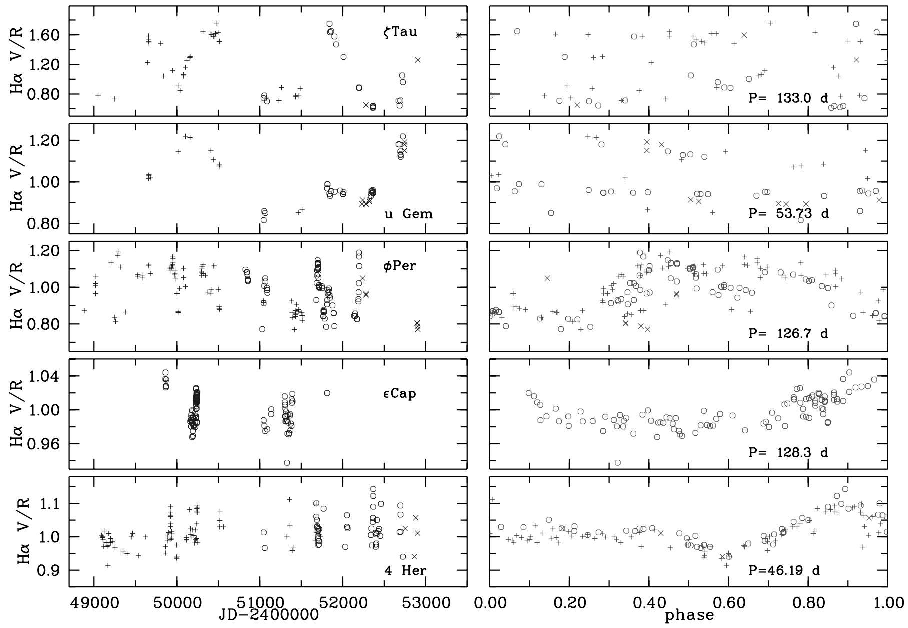


Figure 1. Temporal V/R variations of $\zeta$ Tau, $\nu$ Gem, $\phi$ Per, $\epsilon$ Cap and 4 Her, (left panels) and sorted with the orbital periods (right panels). Observations from Heros and Feros spectrographs are represented by the $\circ$ symbols, those from the Ondřejov slit spectrograph by the $\times$ symbols.

and quasi-periods of V/R variations. Although we know that the secondary component in the binary system causes the truncation of the circumstellar disk around the primary, the influence of the secondary component on the disk one-armed oscillations was only very little studied so far. We do not know, if there is some difference between the V/R quasi-periods of single Be stars and those in binary systems or if the observed long-term V/R variations can be really fitted by those computed for the one-armed oscillation or SPH (Smoothed Particle Hydrodynamics) models.

## 2. Monitored Binary Systems and the Data

In order to get a general picture on V/R variations in binary Be stars, we chose the following 6 binary systems, which were included in our long-term spectroscopic monitoring in the period 1993-2005: $\zeta$ Tau, $\epsilon$ Cap, 4 Her, $\phi$ Per, $\psi$ Per, $\nu$ Gem. Most data were obtained with the Heros echelle spectrograph (Kaufer 1998) attached to the Calar Alto 1.23m telescope (1998), Heidelberg 0.7m telescope (1994-2001), La Silla ESO 0.5 and ESO 1.5m telescopes (1995-2000) and Ondřejov 2m telescope (2001-2003). Their resolving power of 20 000 is constant over the whole spectral region 3500 - 8600 Å. More echelle spectra were obtained with the Feros spectrograph (Kaufer et al. 1997, 1999; spectral resolution 48 000, 3750-9200 Å) attached to the ESO 1.5m telescope (1999-2000) and 2m ESO/MPI telescope (2005) of the La Silla observatory. This database was completed by long-slit spectra obtained with the Ondřejov 2m telescope (Šlechta & Škoda 2002; $\sim 8\,500$ Å, 6300 - 6700 Å) between 1993 and 2000.

For a more detailed study and modeling of emission line profile variations we selected only 2 stars - $\zeta$ Tau and 4 Her. Their V/R variations were periodic during our monitoring, so that we can analyze the phase binned profiles and neglect long-term variations due to evolution or replenishment of the disk.

Table 1. Orbital parameters of $\zeta$ Tau and 4 Her.

| Binary | $\zeta$ Tau | 4 Her |
|---|---|---|
| Primary spect. type | B1IV | B7IV |
| Secondary spect. type | G? | ? |
| Orbital period [d] | 132.9735 | 46.1921 |
| K1 [km/s ] | 40. | 8.1 |
| mass-function | 0.0175 | 0.000545 |
| V/R | quasi-periodic 1500 d | orbit-synchronized |
| Reference: | Harmanec et al. (1984) | Koubský et al. (1997) |

## 3. Results

### 3.1. Character of V/R variations in Be Binaries

Fig. 1 shows the V/R variations for selected five Be binaries and documents their different character and relation to the orbital period. For $\zeta$ Tau we could monitor two cycles of 1500 days, indicating a remarkable repeatability. Obviously, the variations are not influenced by the orbital period. $\nu$ Gem also shows long-term cycles, but their length and amplitude vary from cycle to cycle. Both long-term cycles and orbital variations are combined in $\phi$ Per. However, the scatter in both plots may be also increased by the anisotropic flux distribution in the disk caused by the radiation field of the hot secondary component (Štefl et al. 2000; Hummel & Štefl 2001). The last two binaries, $\epsilon$ Cap and 4 Her show orbital-phase locked variations, which are coherent over more than 80 cycles in 4 Her. In $\psi$ Per, the V/R ratio was constant during our monitoring.

### 3.2. $\zeta$ Tau - One-Armed Oscillations?

Unlike most other Be stars, in almost 3 monitored cycles, the cycle length and amplitude are constant and the variations can be analyzed in the same way as the periodic ones. The H $\alpha$ V/R variations show the same period as radial velocities of the red Si II lines. The formal time-series analysis (Rivinius, Štefl & Baade, submitted to A&A) gives the period of (1503 ± 18) days.

The periodic character of the variations indicates that they are caused predominantly by one mechanism in the circumstellar disk. Long-term variations connected with the episodic replenishment or the decay of the disk can be neglected during the given time interval. After averaging the data in 16 phase bins, we get the phase diagram shown in Fig. 2. The larger scatter for phases 0.7 - 1.0 is caused by the more difficult identification of individual emission peaks in some spectra, but possibly also by intrinsic variations deviating from the sinusoidal

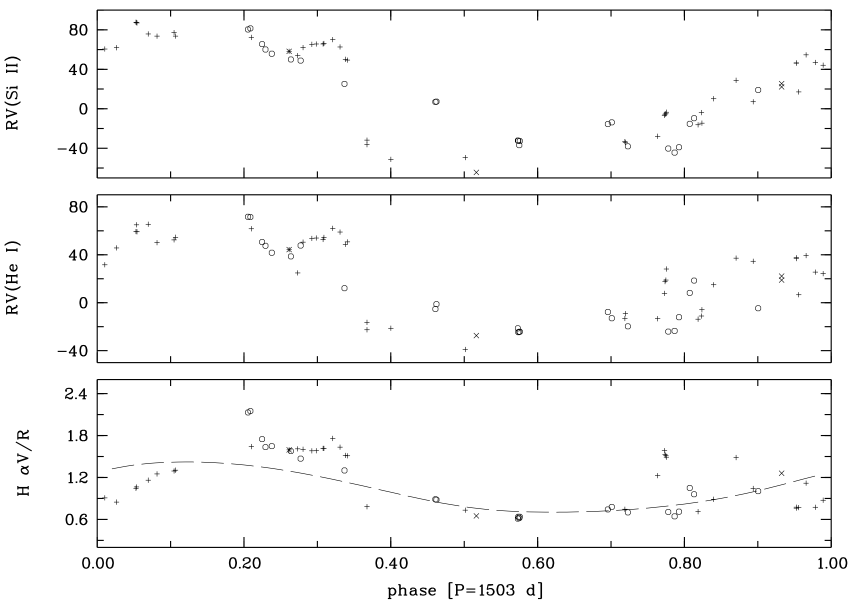


Figure 2. Spectroscopic phase variations of $\zeta$ Tau w.r.t. the 1503 d quasi-period. From bottom to top: H $\alpha$ V/R, He I 6678 and Si II 6347 RV (mode, in km/s). m = 1 mode V/R (dashed line) were measured in the profiles computed for $\tau_0 = 10^3$ and parameters summarized in Table 2.

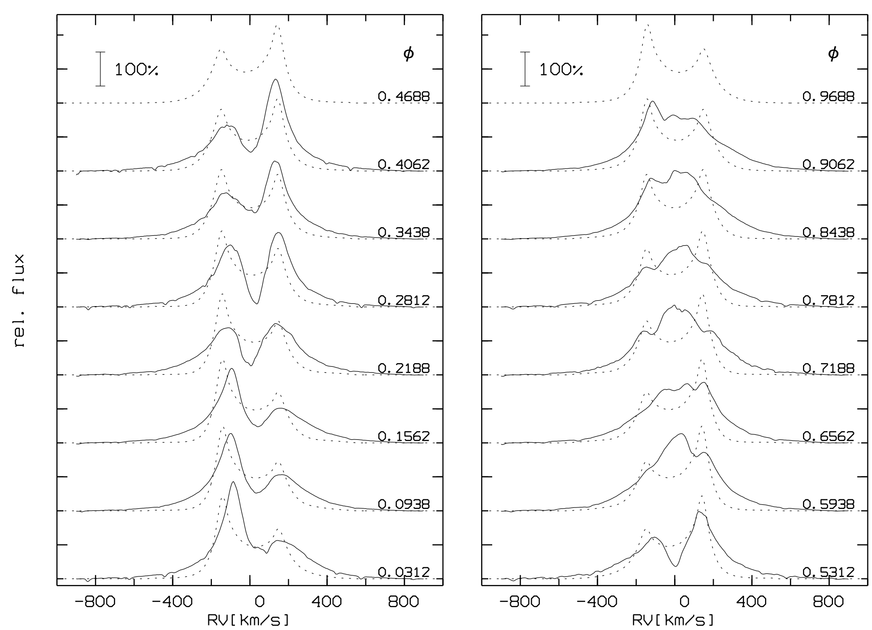


Figure 3. $\zeta$ Tau: H $\alpha$ line profiles. Observations averaged in 16 phase bins corresponding to the cycle of 1503 d. m = 1 model profiles (doted lines) were computed for $\tau_0 = 10^3$ and parameters summarized in Table 2. No profiles in phase bins around 0.4688 and 0.9688 were obtained.

Table 2. Parameters of the $\zeta$ Tau model profiles.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| stellar mass | 11.2 $M_\odot$ | stellar radius | 5.53 $R_\odot$ |
| v sin i | 320 km/s | inclination | 59 deg |
| disk temperature | 16 670 K | disk thickness | $0.024 \times r^{3/2}$ |
| binary period | 133 d | m = 1 period | 4.1 y |
| mass ratio | 0.124 | eccentricity | 0.0 |
| weak line force | $0.045 \times r^{0.1}$ | viscosity par. | 0.1 |
| apsidal motion constant | 0.006 | | |
| disk truncated at | 3:1 resonance | | |

curve. This becomes clear when we inspect the line profiles corresponding to the individual phase bins (Fig. 3). The theoretical profiles were computed for the m = 1 model with the optical thickness $\tau_0 = 10^3$ and under the assumption that the whole disk is the H-alpha emitting region. The truncation at the 3:1 resonance radius implies that the disk outer radius is at 0.46 × the binary separation (similarly as in the SPH simulation described in the next session). For $\zeta$ Tau we get the outer radius of 21.3 stellar radii. Fig. 3 represents the best fit of our preliminary modeling, in which we varied only $\tau_0$, but other model parameters summarized in Table 3 were fixed. We used the computer code described by Negueruela et al. (2001).

Neither is the V/R curve symmetric w.r.t. V/R = 1. Although the general trend agrees with the model in the first half of the cycle, the most conspicuous difference can be seen in the second half of the cycle due to appearance of the so called triple-peak profiles. These profiles can be detected also in other Be stars in our database, e.g. $\nu$ Gem or 59 Cyg. They were observed in Balmer and Fe II lines by Hanuschik et al. (1996) and then by other authors (e.g. Miroshnichenko et al. 2001; Arias, M. L., Zorec & Frémat 2007). Although their presence may indicate a hot binary companion as for $\phi$ Per and 59 Cyg (Maintz et al. 2004), our observations of $\zeta$ Tau and $\nu$ Gem unambiguously prove that the appearance of triple-peak profiles is not related to the binary period. In spite of only two V/R cycles monitored, in $\zeta$ Tau they seem to appear just in the m = 1 phase interval 0.6-0.95. In $\nu$ Gem they showed no significant change on a timescale several times longer than the orbital period, but they always appear during the V>R to V<R transition. These two cases suggest that the corresponding structure is always present in the disk and we can see it as a line-of-sight effect. However, the observed triple-peak profiles cannot be explained by the m = 1 model. Our observations neither support interpretation by Arias, M. L., Zorec & Frémat (2007), according to which the triple peak profiles (called the "multi-headed profiles" in their paper) are formed in rapidly expanding circumstellar rings. The clear link to the phase of the m = 1 oscillation and assumed Keplerian rotation are inconsistent with large radial velocity fields in the disks.

### 3.3. 4 Her - Phase Locked Variations

We do not know what mechanisms in binary systems can lock V/R variations to the orbital period. Lubow & Artimowicz (2000) proposed that the phase of the m = 1 mode (the position angle of the elongated circum-binary disk) is locked at -90deg from the periastron direction. If the eccentricity of the disk edge becomes large, it begins to precess in the prograde direction. The same effect should appear in Be disks in binaries, but the small sample of our binaries does not fit this model. The eccentricity of both 4 Her and $\epsilon$ Cap is close to zero, but they show the orbital-phase locked variations. In contrast, the variations are not locked for $\nu$ Gem possessing much larger eccentricity (∼0.11).

In the SPH simulations, a tidally induced instability can appear also in circular binaries with the mass ratio between 0.05 and 0.25 (Hayasaki 2005, private com.) and their circumstellar disk truncated at the 3:1 resonance radius may become eccentric. This mechanism may apply to 4 Her (mass ratio $\sim 0.1$), but hardly to $\epsilon$ Cap with the mass ratio of $\sim 0.5$. However, the period of the tidally induced V/R variations should be by several percent longer than the orbital period. For 4 Her, our data cover almost 90 cycles and we can estimate that the period of V/R variations is equal to the orbital period within $\sim 0.005$ day, which is 0.01% of the orbital period. This preliminary test seems to exclude the tidally induced instability as the mechanism responsible for synchronization of the V/R variations.

At two phases corresponding to the RV maximum and minimum, a small absorption core appears in the blue emission wing (Maintz et al. 2004). The same effect was observed also in some other Be stars, known or suspected to be binaries: $\phi$ Per, 59 Cyg, HR 2142, $\kappa$ Dra. Our model profiles computed using the three-dimensional SPH code described by Okazaki et al. (2002), assuming the isothermal disk of $T = T_{\star\mathrm{eff}}/2$ and particles injected at the stellar surface with the Keplerian velocity, agree in general with the observed profiles, but do not show the absorption features in emission cores under any circumstances.

## 4. Conclusions

The preliminary results of our study of V/R variations in Be binaries can be summarized as follows:

- V/R variations in binary Be stars may either be locked to the orbital period, follow quasi-cycles typically of 5 - 10 years or combine these two types of variations with long-term trends. The length and amplitude of the quasi-cycle vary from cycle to cycle for most stars.
- We do not understand under which conditions the synchronization of V/R variations with the orbital periods occurs.
- A more detailed study of characteristics of emission lines and their line profiles shows peculiarities, which can hardly be explained by the present SPH and one-armed oscillation models.
- We need more statistics to be able to search for correlations (e.g. with orbital period or inclination)

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## Discussion

*J. Telting*: Do the triple-peak profiles appear at the same V/R phase for all stars?

*S. Štefl*: Yes, but so far we have only few stars to be able to draw such a conclusion. In our archive, the second well monitored star showing the triple-peak profiles is $\nu$ Gem. We observed them for the whole period January-March 2002 (JD 2452275 - 2452365), it is just close to V/R minimum (see Fig. 1). This corresponds to the V/R phase about 0.6-0.8 – exactly in agreement with $\zeta$ Tau. The appearance of triple peak profiles in other stars needs still to be examined in more detail.

*J. Bjorkman*: What value of $\delta\rho/\rho$ was required to fit the observed V/R amplitude of $\zeta$ Tau? In the past large values of $\delta\rho/\rho$ were required and I want to caution that such values are well outside the linear region used in the perturbation analysis.

*A. Okazaki*: We have used the same model for $\zeta$ Tau as in McDavid et al. (2000), in which the maximum value of $\delta\rho/\rho = 0.95$ was required to fit the observed, large V/R asymmetry. I agree with your caution. We need a nonlinear model.