1991A&A...241..159M

Astron. Astrophys. 241, 159–166 (1991)

ASTRONOMY
AND
ASTROPHYSICS

# $V/R$ variations in H$\beta$ emission profiles of Be stars

**R.E. Mennickent and N. Vogt**

Astrophysics Group, Pontificia Universidad Católica de Chile, Casilla 6014, Santiago, Chile

Received February 7, accepted April 25, 1990

**Abstract.** The $V/R$ ratio between the violet and red intensity peaks of the H$\beta$ emission line of 33 southern Be stars was examined, covering periods from several years to several decades. 76% of our sample stars were found to be $V/R$ variables. Long-term variables are characterized by quasiperiods mainly in the 2–13 years range with a mean $T=7$ yr. Six short-term variables were found which are best characterized by $V>R$ to $V<R$ changes on time-scales of 6–100 d. A statistical analysis of these data, including also data for 10 northern $V/R$ variables, did not reveal any correlation of the quasiperiod $T$ with the spectral type and projected rotational velocity ($v \sin i$) of the central star. Long-term quasiperiods do not depend on the envelope size. However, only stars with small envelopes ($r_\beta \lesssim 4 r_*$) show short-term variations. We discuss several possible mechanisms for these variations and have concluded that the most satisfactory general interpretation for the long-term variations seems to be expansion and contraction of the envelope, triggered by a variable stellar wind. On the other hand, the short-term $V/R$ variations could be caused by the rotation of inhomogeneities in the circumstellar envelope (blobs), possibly combined with atmospheric phenomena in the central star such as non-radial pulsations and/or anisotropic radiation fields.

**Key words:** Be stars – spectroscopy – emission lines

## 1. Introduction

Be stars are mainly characterized by Balmer emission lines in their optical spectra, which originate in an envelope of circumstellar matter. Long-term variations of stellar flux and emission line profiles are common in Be stars and their origin and connections are still an unresolved problem. One of the most fascinating and remarkable changes in the Be stars spectra are the $V/R$ variations between the violet and red intensity peaks of the double emission lines. Doazan et al. (1983) gave a general summary of these variations of $\gamma$ Cas, the prototype Be star, during the past decades. $V/R$ variability is mainly confined to active phases exhibiting quasiperiodic cycles $V>R \rightarrow V=R \rightarrow V<R \rightarrow V=R$ with a ~6 year period. During the active episode 1930–1942, these $V/R$ variations were accompanied by a considerable brightening ($1^{\rm m}.5$) in the $V$ magnitude and generally stronger Balmer emission with cyclic Be→shell→Be variations. In contrast, the more recent activity phase (1970–1985) of $\gamma$ Cas was only present in $V/R$ without other spectacular variations (Doazan et al. 1983; Doazan 1987). Outside the active phases $\gamma$ Cas displays quiet epochs which last about 25 yr and shows only weak double emission of the Balmer lines ($V=R$ without significant variability). Other typical examples for these variations are $\beta$ Mon (Cowley & Gugula 1973) and EW Lac (Kogure & Suzuki 1987). In various cases, quasi-cycles appear and disappear in a phase of emission and the quasiperiod itself may vary in a wide range.

According to statistical studies of Be stars at the northern hemisphere, about 67% of them are $V/R$ variables and display, in average, a quasiperiod of about 7 yr, independent from the spectral type between B 0 and B 5 (Hirata & Hubert-Delplace 1981). Recently, also evidence for variations at shorter time scales between days and months was found (Dachs et al. 1986; Mennickent & Vogt 1988).

New data in the entire range of Be spectral types (B 0–B 8e) now permit a more complete statistical study of $V/R$ variations. Most of the recent southern hemisphere data refer to our own spectra obtained between 1984 and 1989 at the Manuel Foster Observatory of the Catholic University in Santiago, Chile. In addition, we have collected dispersed information on $V/R$ ratios, peak separation of the H$\beta$ emission as well as equivalent widths of the H$\alpha$ emission line from the literature, including also data for ten known $V/R$ variables of the northern hemisphere. We discuss the infered variations in terms of envelope extension, temperature and projected rotational velocity of the central star, and give some constraints on the models currently in discussion concerning the physical mechanisms which cause the $V/R$ variability.

## 2. The data

Our southern hemisphere sample is based on the 85 bright Be stars listed by Mennickent and Vogt (1988, hereafter MV88), regularly monitored with the 93 cm Cassegrain Telescope of the Manuel Foster Observatory in Santiago, starting in February 1984. All those stars of this sample were selected which show double emission in Balmer lines (mainly H$\beta$, H$\gamma$). Individual $V/R$ values and other details of our observations up to July 1987 have already been published by MV88. In the present study we also analyze the $V/R$ variations based on our more recent plates up to 1989, and complete the data set with a literature search, compiling observations prior to 1984 (Table 1). In addition, Table 2 lists ten northern Be stars with published quasiperiods which were also included in our analysis.

---

*Send offprint requests to*: R.E. Mennickent

**Table 1.** $V/R$ Observations for 33 Southern Be stars

| HD | Name or HR | MK | $v \sin i$ (km s$^{-1}$) | Epoch | $T$ (yr) (H$\beta$) | Refs. | $\Delta\lambda_\beta$ (km s$^{-1}$) | $r_\beta/r_*$ | Ref. | $W_\alpha$ (Å) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 497 | 1423 | B 1Ve | 230 | 1960–80 | 7–9 | 30 | | | | | |
| | | | | 1980–85 | 7 | 22, 10 | 132 | 2.70 | 10 | 21.20 | 25 |
| | | | | 1985–87 | 2: | 19 | 134 | 2.70 | 24 | | |
| 37 490 | $\omega$ Ori | B 2IIIe | 160 | 1974–87 | $V=R$ | 8, 9, 10, 19, 22 | 164 | 1.53 | 24 | 5.74 | 25 |
| 37 795 | $\alpha$ Col | B 7IVe | 180 | 1953–84 | Pref. $V=R$ | 22, 10, 25, 16, 14 | 80 | 2.78 | 10 | 9.08 | 25 |
| | | | | 1984–89 | 0.04 | 19, 24 | 96 | 2.33 | 24 | 9.06 | 12 |
| 45 725 | $\beta$ MonA | B 4Ve-shell | 300 | 1905–25 | $V=R$ | 7 | | | | | |
| | | | | 1928–67 | 12.5 | 7 | | | | | |
| | | | | 1969–72 | $V=R$ | 7 | | | | | |
| | | | | 1980–87 | 7 | 22, 10, 2, 12, 19 | 148 | 2.95 | 24 | 30.82 | 12 |
| 48 917 | 10 CMa | B 2IIIe | 200 | 1961–67 | $V=R$ | 15,16,14 | | | | | |
| | | | | 1981 | 0.016 | 4 | 88 | 3.57 | 4 | 18.10 | 10 |
| | | | | 1980–87 | 9 | 19, 4, 24, 22 | 85 | 3.70 | 24 | 11.25 | 10 |
| 50 013 | $\kappa$ CMa | B 2IVe | 220 | 1965–87 | $>22$ | 10, 14, 22, 19, 15, 16 | 50 | 6.88 | 24 | 24.90 | 25 |
| 54 309 | 2690 | B 2IVe | 200 | 1980–87 | $V=R$ | 22, 10, 19 | 93 | 3.36 | 10 | 9.73 | 10 |
| 58 715 | $\beta$ CMi | B 8Ve | 245 | 1950–80 | $V=R$ | 22 | 130 | 2.22 | 21 | | |
| | | | | 1987–89 | 1.67 | 19, 24 | 114 | 2.53 | 24 | | |
| 60 606 | 2911 | B 3Ve | 230 | 1980–87 | 12: | 22, 10, 19 | 83 | 4.26 | 24 | 41.89 | 12 |
| 63 462 | o Pup | B 1IVe | 320 | 1980–89 | 2.5 (0.03) | 22, 10, 19, 24 | 122 | 4.12 | 24 | 14.03 | 12 |
| 68 980 | 3237 | B 1.5IVe | 115 | 1964–89 | 8: | 24, 6, 27, 10, 19 | | | | 36.62 | 12 |
| 78 764 | 3642 | B 2IVe | 120 | 1980–87 | $V=R$ | 22, 19 | 116 | 1.62 | 24 | | |
| 83 953 | 3858 | B 5Ve | 260 | 1974–82 | $V=R$ | 22, 10, 9 | 121 | 2.87 | 10 | 22.37 | 10 |
| | | | | 1984–89 | 0.27 | 19, 24 | 112 | 3.10 | 24 | 21.63 | 12 |
| 88 661 | 4009 | B 2IVe | 220 | 1978–87 | 6 | 9, 10, 19, 22, 24 | 59 | 5.88 | 24 | 28.19 | 12 |
| 89 080 | $\omega$ Car | B 8IIIe-shell | 220 | 1984–87 | 0.20 | 19 | 169 | 1.53 | 24 | | |
| 91 465 | pp Car | B 4Ve | 250 | 1953–63 | $>10\,(V>R)$ | 13, 14, 15 | | | | | |
| | | | | 1976–84 | 10 | 9, 10, 20, 18 | 104 | 3.48 | 10 | 27.48 | 10 |
| | | | | 1984–87 | 0.05 | 19 | 88 | 4.14 | 24 | 26.63 | 12 |
| 93 563 | 4221 | B 8III(e)-shell | 280 | 1980–87 | $V\approx R$ | 19, 22 | | | | | |
| 105 435 | $\delta$ Cen | B 2IVe | 220 | 1953–87 | 13 | 9, 10, 14, 19, 22 | 46 | 7.56 | 24 | 37.08 | 12 |
| 105 521 | 4625 | B 3IVe | 130 | 1980–87 | 8: | 19, 22, 24 | 48: | 4.17 | 24 | | |
| 110 335 | 4823 | B 6IVe | 250 | 1980–87 | $V=R$ | 19, 22 | 96 | 3.26 | 24 | | |
| 110 432 | 4830 | B 1IIIe | 300 | 1979–87 | $V=R$ | 10, 22, 19 | 48 | 9.77 | 24 | 45.64 | 12 |
| 112 091 | $\mu^2$Cru | B 5Ve | 220 | 1985–89 | 4: | 19, 24 | 49 | 5.99 | 24 | 27.00 | 10 |
| 135 734 | $\mu$ Lup | B 8Ve | 308: | 1984–87 | $V=R$ | 19 | 167 | 2.17 | 24 | 26.05 | 10 |
| 137 387 | $\kappa$ Aps | B 3IVe | 250/350 | 1980–88 | $>8$: | 10, 19, 22, 24 | 213 | 2.17 | 24 | | |
| 142 983 | 48 Lib | B 5IIIpe | 400 | 1953–72 | 11.8 | 3, 26, 28, 29 | 131 | 4.07 | 28 | | |
| | | | | 1972–79 | 6.8 | 3, 29 | 146 | 3.65 | 3 | | |
| | | | | 1979–89 | 9.3 | 19, 24 | 193 | 2.77 | 24 | 17.63 | 12 |
| 157 042 | $\iota$ Ara | B 2.5IVe | 320 | 1978–87 | 5.5 | 9, 10, 19, 22 | 85 | 5.88 | 24 | 27.19 | 12 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 158 427 | α Ara | B 3Ve | 250 | 1974–89 | 0.13 | 9, 10, 19, 24, 22 | 92 | 4.18 | 24 | 23.9 | 25 |
| 164 284 | 66 Oph | B 2IV-Ve | 240 | 1979–87 | $V=R$ | 22, 19 | 75 | 5.00 | 24 | | |
| 205 637 | ε Cap | B 3IIIe | 250 | 1971–82 | 6 (Hα) | 1, 9, 10, 11, 22, 25 | 198 | 1.94 | 10 | 1.22 | 25 |
| 209 409 | ο Aqr | B 7IIIe-shell | 300 | 1971–82 | Pref. $V\approx R$ | 9, 10, 22, 25 | 119 | 3.11 | 10 | 7.63 | 25 |
| | | | | 1988 | $V\approx R$ | 24 | 135 | 2.74 | 24 | | |
| 212 076 | 31 Peg | B 1.5Ve | 100 | 1979–82 | $V=R$ | 10, 25 | 37 | 4.22 | 10 | 12.3 | 25 |
| 212 571 | π Aqr | B 1III-IVe | 300 | 1912–24 | $V=R$ | 17 | | | | | |
| | | | | 1925–36 | 2.8 | 17 | | | | | |
| | | | | 1936–40 | $V=R$ | 17 | | | | | |
| | | | | 1940–44 | 3 | 17 | | | | | |
| | | | | 1944–56 | $V=R$ | 17 | | | | | |
| | | | | 1976–85 | 2 | 10, 19, 22, 25 | 101 | 4.64 | 10 | 31.00 | 25 |
| | | | | 1985–89 | 6 | 19, 24 | 73 | 6.42 | 24 | | |
| 214 748 | ε PsA | B 7IVe | 180 | 1974–83 | $V\approx R$ | 9, 10, 22 | 125 | 1.69 | 10 | 5.81 | 25 |
| | | | | 1985–89 | $>4 (V\leq R)$ | 19, 24 | 106 | 2.10 | 24 | | |

*References*: 1) Andrillat (1983); 2) Andrillat & Feherenbach (1982); 3) Aydin & Farraggiana (1978); 4) Baade (1984); 5) Bahng & Hendry (1975); 6) Buscombe (1970); 7) Cowley & Gugula (1973); 8) Dachs et al. (1977); 9) Dachs et al. (1981); 10) Dachs et al. (1986); 11) Fontaine et al. (1982); 12) Hanuschik (1986); 13) Hendry & Bahng (1981); 14) Jaschek et al. (1964); 15) Jaschek & Jaschek (1965); 16) Jaschek et al. (1969); 17) Mc Laughlin (1962); 18) McLean (1979); 19) Mennickent & Vogt (1988); 20) Neto & de Freitas Pacheco (1982); 21) Slettebak (1976); 22) Slettebak (1982); 23) Slettebak & Reynolds (1978); 24) Mennickent (unpublished); 25) Hanuschik et al. (1988); 26) Underhill (1953); 27) Slettebak (1975); 28) Geuverink (1970); 29) Hubert-Delplace & Hubert (1979)

Both tables contain quasiperiods $T$ of the $V/R$ variability (often depending on the epoch), the mean half peak separation $\Delta\lambda$ in the H$\beta$ emission line profile, the corresponding relative radius $r_\beta$ of the H$\beta$ emitting envelope (in units of the stellar radius $r_*$) and, if available, the equivalent width $W_\alpha$ of the H$\alpha$ emission. As "quasiperiod" we define, in most cases, the typical time which passed to complete a cycle, e.g. $V>R \rightarrow V=R \rightarrow V<R \rightarrow V=R \rightarrow V>R$. In some cases, however, the observations are not sufficiently closely spaced to document such a cycle in a unique way, especially in stars with short cycles ($T\leq 1$ yr) which also tend to display a more erratic behaviour. In these cases we define $T$ as twice the shortest time interval observed for the transition from $V>R$ to $V<R$ or vice versa. In these cases, $T$ refers more to a typical time scale of variability rather than to a real period.

Uncertain cases with few data points and/or only partial coverage of a quasicycle are indicated with colon (:) in Table 1. Our quasiperiod of HR 3237 (8: yr) is based on spectra of Dachs et al. (1986) and Hanuschik (1986) which show emission profiles with $V>R$ asymmetry, as well as on our 1984–89 spectra, which sometimes show H$\beta$ single emission profiles with $V<R$ asymmetry, being symmetrical on other occasions. This indicates possible changes in minor time scales.

"$V\approx R$" in Table 1 corresponds to cases whose data show uncertain, sporadic excursions to $V\geq R$ or $V\leq R$; we consider them as constant for our statistical analysis. "pref. $V=R$" in Table 1 refers to cases that mostly show $V=R$, and sporadic, but significant excursions to $V>R$ or $V<R$. Although no period determination was possible for these cases, we consider them as variables in our statistics.

The radius $r_\beta$ of the H$\beta$ emitting envelope listed in Table 1 was estimated from the half peak separation ($\Delta\lambda$, in km s$^{-1}$) of the emission lines, using the following relation:

$$\Delta\lambda = v_\beta \sin i \qquad (1)$$

which is valid for a disk shape envelope with outer rotation velocity $v_\beta$ (Hirata & Kogure 1984). If the envelope rotation is given by:

$$v(r) = \left(\frac{v_0}{r/r_*}\right)^j \qquad (2)$$

where $v_0$ is the critical velocity ($\sqrt{(Gm_*)/(r_*)}$) and $j$ is a rotation exponent, then $r_\beta$ is given by:

$$\frac{r_\beta}{r_*} = \left(\frac{v_\beta}{v_0}\right)^{-1/j} = \left(\frac{\Delta\lambda\ 350}{v \sin i\ v_0}\right)^{-1/j} \qquad (3)$$

where we assumed $v = 350$ km s$^{-1}$. This seems to be a good approximation for the rotational velocity of Be stars with double peak emission lines (Mennickent 1989). In this paper $j\approx 1$ was estimated from H$\beta$ data. That value was used to calculate the $r_\beta$ listed in Tables 1 and 2. The $v_0$ values used are those of normal B type stars and were deduced from Table 2–12 of Doazan (1982).

## 3. $V/R$ variability of individual stars

In this section we discuss the behavior of several stars of special interest. Nine examples of long-term $V/R$ variations are shown in Figs. 1a and 1b. $\beta$ Mon displays a quasiperiod (7 yr) near half the period reported by Cowley & Gugula (1973) during 1928–67 (12.5 yr). In addition, this star shows a phase shift between the H$\alpha$

**Table 2.** *V/R* observations for 11 northern Be stars

| HD | Name or HR | MK | $v \sin i$ ($\mathrm{km\,s^{-1}}$) | Epoch | $T$ (yr) (H$\beta$) | $\Delta\lambda$ ($\mathrm{km\,s^{-1}}$) | $r_\beta/r_*$ | Ref. | $W_\alpha$ (Å) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 5394 | $\gamma$ Cas | B 0.5IVe | 230 | 1932–40 | 4 | | | 1 | | |
| | | | | 1972–81 | 5 | 80 | 4.49 | 1 | 22.00 | 1 |
| 23 862 | 28 Tau | B 8 (V:)e-shell | 320 | 1938–54 | 22: | 112 | 3.36 | 10 | | |
| | | | | 1969–71 | >3 | 110 | 3.42 | 10 | | |
| 24 534 | $\chi$ Per | O 9.5III | 200 | 1949–62 | 12 | | | 11 | | |
| | | | | 1971–80 | 10 | | | 8 | | |
| 32 991 | 105 Tau | B 3Ve | 200 | 1930–65 | 10 | | | 9 | | |
| 35 439 | 25 Ori | B 1Ve | 320 | 1915–35 | 3–5 | | | 7 | | |
| 37 202 | $\zeta$ Tau | B 1IVe-shell | 220 | 1960–67 | 7 | 267 | 1.29 | 2 | 27.28 | 2 |
| | | | | 1967–81 | 5 | | | 8 | 17.70 | 14 |
| 162 732 | 88 Her | B 6IVe$^c$ | 300$^a$ | 1963–79 | 0.24 (H$\alpha$) | 204 (H$\alpha$) | 1.14+ | 12, 13 | 3.90+ | 13 |
| 184 279 | | B 1IV-V$^b$ | 256$^b$ | 1971–84 | 5.5 | 175 | 2.29 | 4 | 11.59 | 15 |
| 200 120 | 59 Cyg | B 1Ve | 260 | 1979–84 | 2(H$\alpha$) | 183 (H$\alpha$) | 1.37+ | 3 | 5.56 | 3 |
| 217 050 | EW Lac | B 4IIIep$^a$ | 300 | 1976–84 | 6 | 113 | 3.85 | 5, 6 | 45.80 | 14 |
| 224 559 | LQ And | B 4Ven$^a$ | | 1960–80 | 5–7 | | | 8 | | |

*Note to Table* 2: MK and $v \sin i$ by Slettebak (1982) except when specified by ($^a$): Bright Star Catalogue; Hoffleit and Jaschek (1982), ($^b$): Ballereau and Chauville (1987), ($^c$): Divan and Zorec (1982). The symbol + refers to values deduced from H$\alpha$ data using the relations (3.3.3) and (3.3.9) given in Mennickent (1989)

*References*: 1) Doazan et al. (1983); 2) Delplace (1970); 3) Doazan et al. (1985); 4) Ballereau & Chauville (1987); 5) Kogure & Suzuki (1987); 6) Hubert et al. (1987); 7) Dodson (1936); 8) Hubert-Delplace et al. (1982); 9) Mc Laughlin (1966); 10) Gulliver (1977); 11) Cowley et al. (1972); 12) Doazan et al. (1982a); 13) Doazan et al. (1982b); 14) Andrillat (1983); 15) Alvarez et al. (1990)

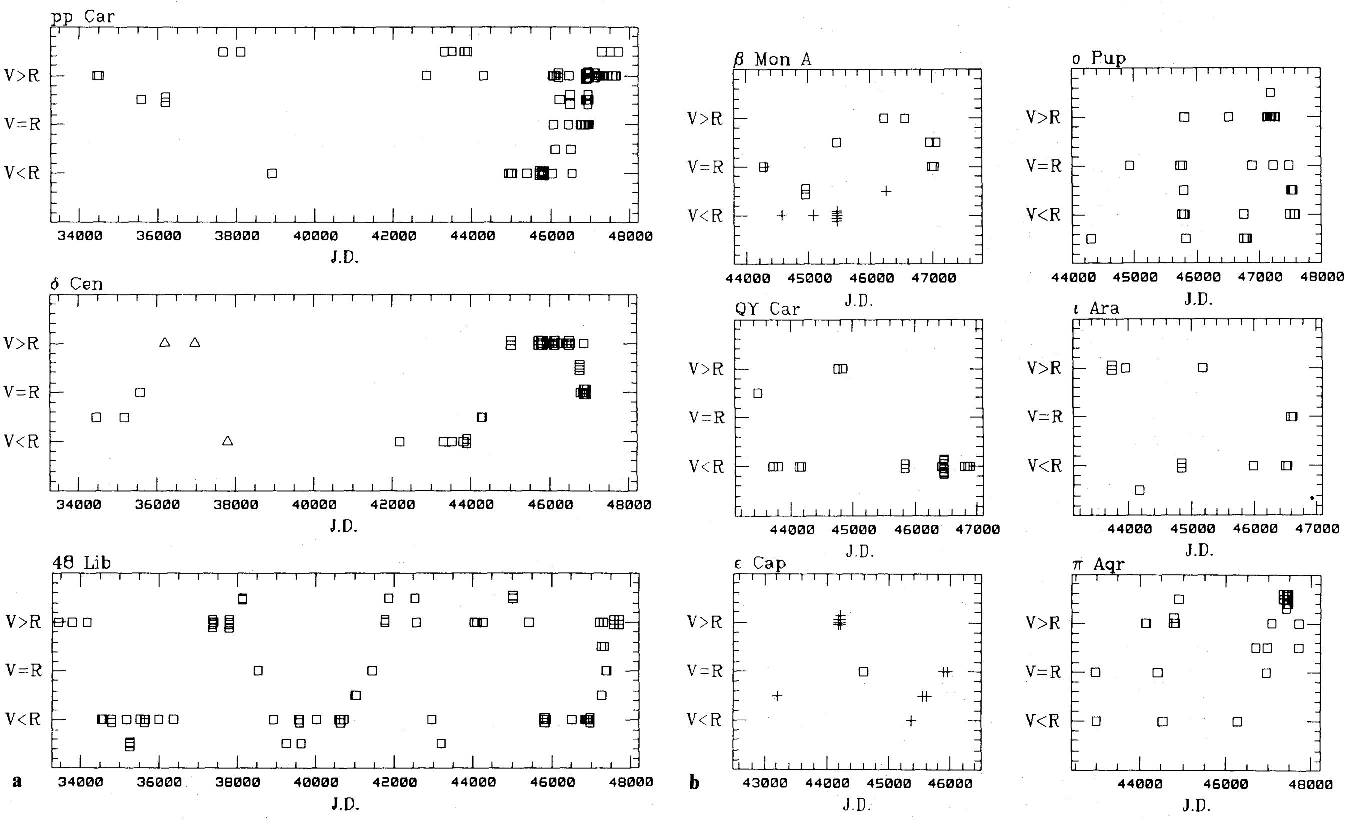

**Fig. 1a and b.** Long-term *V/R* variations for 9 Be stars. Note the changes in the quasiperiod of 48 Lib and the rapid *V/R* changes superimposed to long-term variations in o Pup and pp Car

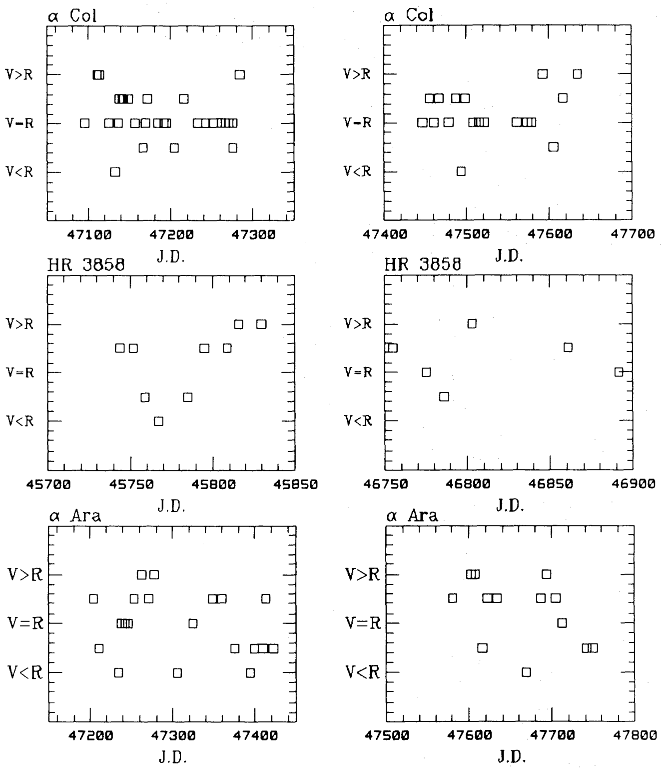

**Fig. 2.** Six examples of short-term $V/R$ variations

and H$\beta$ $V/R$ curves. Note also the changes in the quasiperiod of 48 Lib (11.8→6.8→9.3 yr). These changes also occur in other Be stars listed in Tables 1 and 2 including HR 1423 (7→2: yr) and $\pi$ Aqr (2→6 yr). It is remarkable that these changes are not necessarily correlated with changes in the envelope size.

The relatively high time-resolution in our 1984–89 spectra (sometimes 7 d) allowed us to also detect rapid $V/R$ variations in five stars, some of which are shown in Fig. 2. These changes are of two types: quasiperiodic (e.g. $\alpha$ Col, HR 3858, pp Car and $\alpha$ Ara) and sporadic, apparently erratic (e.g. $\alpha$ Col and o Pup). In the case of o Pup the changes are superimposed to a 2.5 yr quasiperiod. 10 CMa also showed rapid $V/R$ changes in 1981 (Baade: 1984), which are superimposed on a long-term variation. During late 1984 and early 1985 pp Car, which is of special interest, showed rapid $V/R$ changes from $V>R$ to $V<R$ in time-scales of 20 d, superimposed on a 10 yr quasiperiod. These changes are well documented by a series of 29 H$\beta$ emission line profiles obtained and analyzed by Mennickent (1989). This analysis shows that the rapid $V/R$ changes occur after a strong increase in the equivalent width of the H$\beta$ emission during early 1984.

We see that for several stars short-term variations occur simultaneously with long-term variations. This fact probably points to different physical mechanisms which will be discussed in Sect. 5.

## 4. Statistical properties of the $V/R$ variability

From the data in Table 1 we conclude that about 76% of our sample do exhibit $V/R$ variations. This percentage may even be higher if we consider the possibility that some Be stars display

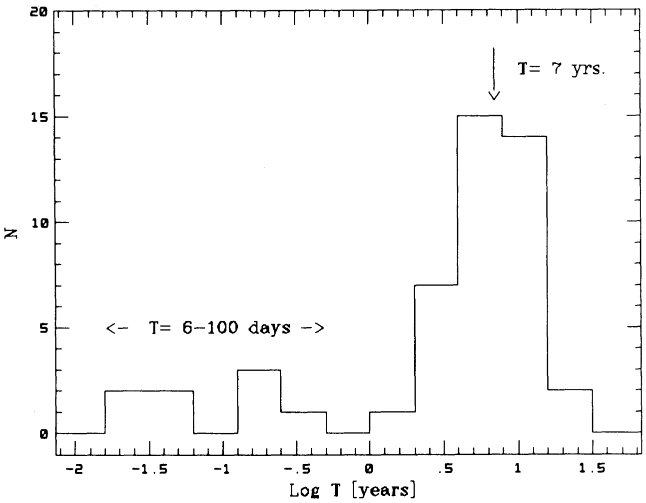

**Fig. 3.** The quasiperiod distribution from Tables 1 and 2. Long-term variables show quasiperiods grouped mainly in the 2–13 years range with a mean $T=7$ yr. Time-scales of short-term variables run between 6–100 d

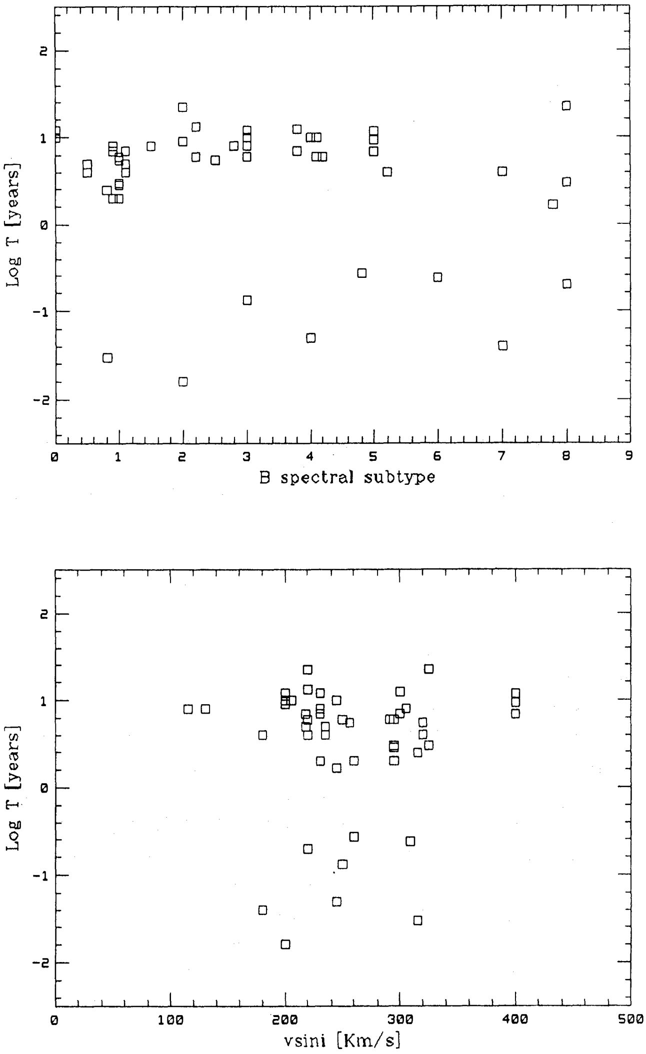

**Fig. 4.** Logarithm of the quasiperiod $T$ versus spectral type and $v \sin i$ of the central star

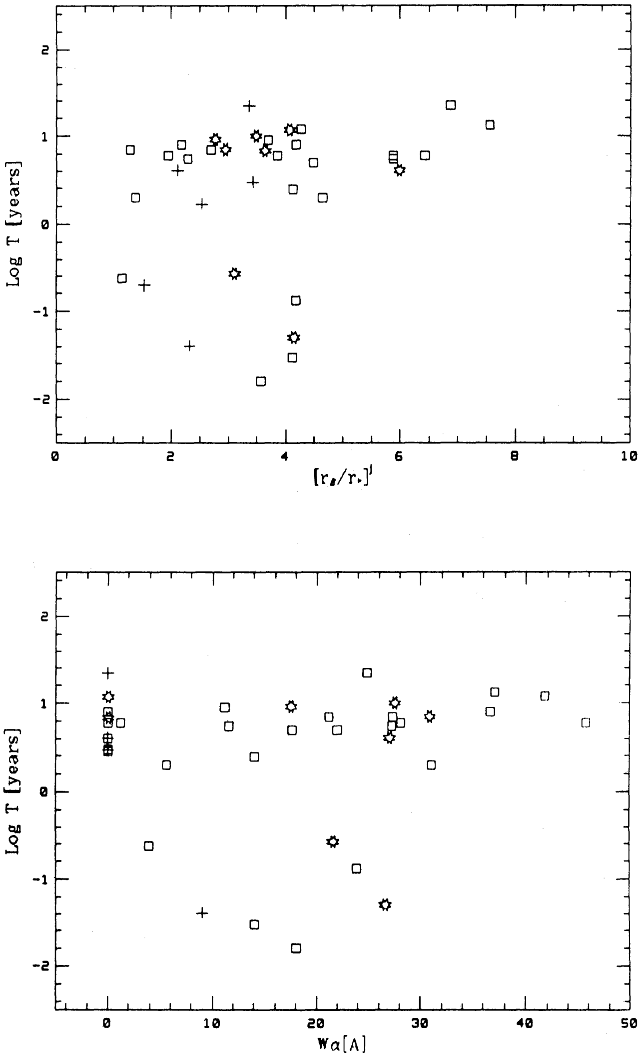

**Fig. 5.** Logarithm of the quasiperiod $T$ versus equivalent width of the Hα emission (Wα) and extension of the envelope $r_\beta/r_*$. B0–B3e stars are marked with squares, B4–B6e stars with stars and B7–B9e stars with crosses

quiet $V/R$ phases for long periods of time, e.g. $\gamma$ Cas for 25 yr, as mentioned above. The period distribution (see Fig. 3) shows a strong concentration around a mean $T=7$ yr (extrems $\kappa$ CMa with $T>22$ yr and $\beta$ CMi with $T=1.67$ yr), and a weaker concentration between 6–100 d. In Figs. 4 and 5 we have plotted the quasiperiods $T$ as a function of spectral type, projected stellar rotation velocity $v \sin i$, equivalent width of the Hα emission line and radius $r_\beta/r_*$. Some of the stars which, according to Tables 1 and 2, display different $T$ values at different epochs, contribute two or more data points in Figs. 3 to 5.

The following conclusions can be obtained:

(i) $T$ does not depend on spectral type nor $v \sin i$.

(ii) Long-term quasiperiods ($T>1$ yr) do not depend on the envelope size.

(iii) The presence of short-term $V/R$ variations ($T \leq 1$ yr) is restricted to stars with relatively weak Hα emission ($W_\alpha \lesssim 25$ Å) and, as a consequence, with small envelope radii ($r_\beta \lesssim 4 r_*$).

## 5. Discussion

The long-term variations in cycles with $T>1$ yr have been interpreted in a series of papers by Huang (1972, 1973, 1976, 1977, 1978) and Albert & Huang (1974) as being caused by the precession of an elliptical ring of circumstellar material and its interaction with ejections and stellar winds. These models would be consistent with the $V/R$ variations reported here, but do not reproduce the line profiles of Be stars generally observed, in particular thin rings are not able to reproduce the shape of the central reversal observed in most double emission line profiles (Huang 1972). On the other hand, Kriz (1976, 1979a, b) calculated Hα and Hβ profiles for elliptical rings and concluded that they must be optically thick in Hα up to a radius $\sim 5 r_*$ in order to fit the observed line profiles. His models predict that the eccentricity of the elliptical ring or disk increases with the amplitude of $V/R$ variations revealing typical eccentricities between 0.2 and 0.4 for the observed $V/R$ amplitudes. According to Kogure & Suzuki (1987), these variations first begin in Hγ, later in Hβ and Hα with a delay of typically 1.5 yr in the case of EW Lac. The amplitude of the $V/R$ variations is smaller in lines of lower excitation potential while the period is the same in all lines. Apparently the precession of the circumstellar material would start in more asymmetrical, internal regions of the envelope and afterwards propagate towards the external, less eccentric parts of the disk.

As a first possible cause of the precision of the elliptical disk we may consider the equatorial deformation of the star due to its rapid rotation. The line of apsides of this disk would turn around with a precession period $U$, which has been calculated by Kopal (1965) to be

$$\frac{P}{U} = K \left(\frac{V_{\rm eq}}{V_0}\right)^2 \left(\frac{r_*}{r}\right)^2 \tag{4}$$

where $P$ is the orbital period of a particle with small mass at distance $r$ from the star, $K$ is the mass concentration coefficient, $V_{\rm eq}$ the stellar rotation velocity and $V_0$ its critical velocity. Inserting typical values for a rapidly rotating B2 star [$r=5 r_*$, $V_{\rm eq}/V_0=0.64$, and, according Kopal (1965), $K=0.011$] we derive $P/U=1.8\,10^{-4}$. The observed variations $U=7$ yr (our $\bar{T}$ above) and $P=14$ d (orbital period at $5 r_*$) turn out to be a factor 30 more rapid than expected from (4). In addition, (4) implies a very strong dependence between $P/U$ and $r$, which causes serious doubts on the stability of an eccentric disk with some radial extension. Finally, the stellar deformation would always be present and could, therefore, not explain why $V/R$ variations suddenly appear and disappear during Be phases.

As another possible cause for eccentricity and precession of a Be envelope we may consider the presence of the secondary in a binary system, orbiting around the Be star at distances larger than the envelope extension. Its gravitational interaction could distort the disk and trigger periodic $V/R$ variations. Castle's (1977) calculations of this configuration in a wide range of parameters predict periods similar to those found for Be stars. A case in our sample of Be stars could be 88 Her which showed through decades a very stable period of 86.7221 d in its radial velocity and $V/R$ variations (Doazan et al. 1985). However, it would be difficult to explain $V/R$ variations of all Be stars with the binary model since, in several cases and for a same star, constant $V=R$ phases alternate with quasiperiodic $V/R$ variations, for which often different periods not even correlated with the envelope size (see Sect. 3), are present. Finally, according to Castle

(1977) the eccentricity of the circumstellar rings increases with distance from the central star, in contradiction to the behavior found for EW Lac by Kogure & Suzuki (1987).

The above arguments probably rule out the precession model as a general explanation for the $V/R$ variations. As an alternative we suggest a variable stellar wind which causes and regulates the expansion and contraction of the envelope in accordance with Doazan's (1987) ideas. One expects that a homogeneously expanding envelope displays emission line profiles with $V<R$ while contraction would lead to $V>R$. For some stars, Doazan (1987) showed that the long-term variation of the $V/R$ ratio and the emission strength of the H$\alpha$ and H$\beta$ emissions are correlated to corresponding variations of equivalent widths of C IV resonance lines, as well as to the occurrence of high velocity components of UV resonance lines of N V, Si IV and C IV. She suggests a generally valid pattern of behavior which relates the sub-ionized regions (where Balmer emission lines are formed) to the superionized regions (where the resonance lines originate). She proposes a model in which a variable stellar wind with high radial velocity, high temperature and low density fills an ellipsoidal cave whose borders are given by an egg-shaped shell of cool material with low velocities and moderate densities. The successive expansions and contractions of this subionized shell would be triggered by the variable intensity and spatial distribution of the underlying stellar wind. A confirmation of this model requires, of course, extensive simultaneous spectroscopic observations in the visible and the UV wavelength regions, in order to find out whether superionized and subionized envelope regions are generally correlated in their behaviour.

On the other hand, the short-term variability is restricted to Be stars with relatively weak Balmer emission. Therefore, they could be artifacts, being constant in time but display only variations of the underlying photospheric absorption line profiles, probably due to non-radial pulsation as was suggested by Baade (1984) or an anisotropic surface radiation field as was claimed by Smith & Penrod (1985). However, since these phenomena have typical periods of $0.3$–$2^{\mathrm{d}}$, they could be the cause of the rapid and sporadic $V/R$ changes found in $\alpha$ Col, 10 CMa, o Pup and reported also in the H$\alpha$ and He I $\lambda$ 6678 lines of some active Be stars (e.g. $\mu$ Cen: Baade et al. 1988, and $\lambda$ Eri: Smith 1989), but do not explain the short-term variations resolved in time-scales of weeks and months as shown in Fig. 2.

We have seen that short-term $V/R$ variability occurs only in small circumstellar envelopes which may be more sensitive in building up inhomogeneities and blobs. If the envelope rotates according to the law (2), its rotation period $P$ as a function of distance $r$ to the central star would be given by

$$P=P_0\left(\frac{r}{r_*}\right)^{j+1} \tag{5}$$

where $P_0$ is the period of material orbiting with the critical velocity near the stellar surface. For $j=1$, $r=5r_*$ and $P_0\sim 0.5$ d (see Sect. 2), we derive $P$ of the order of several days or weeks, compatible with the observed time-scales of the short-term $V/R$ variations. The example of pp Car during 1984–85 (see Sect. 2) may be a confirmation of that hypothesis; the observations may be interpreted as a gradual input of material from the stellar surface into the base of the envelope, which causes an increase in the amount of H$\beta$ emission, and a subsequent segmentation in blobs probably due to the action of an anisotropic stellar wind. The rotation of these blobs would originate in the observed short-term $V/R$ variations.

## 6. Conclusions

The $V/R$ activity in Be stars present in time scales of hours to years is one of the most remarkable features displayed by their visual spectra. We have studied a rather large sample of Be stars, investigating, for the first time, the $V/R$ variations in the entire spectral range of Be stars. We found no dependence of the quasiperiod $T$ with $v \sin i$ nor with spectral type of the central star, and no dependence of the long-term quasicycles with the envelope size. However, short-term variations with time scales in the range of 6 to 100 d, found for seven stars, were present only in small envelopes ($r_\beta/r_* \lesssim 4$ and $W_\alpha \lesssim 25$ Å).

We analyzed the current models proposed to explain the $V/R$ variations. First we consider the precession of an elliptical envelope and concluded that this cannot be due to rotational distortion of the star, since this would imply periods of precession 30 times greater than the observed ones. Another cause of precession could be binarity, i.e. a companion star outside the envelope which causes its apsidal motion. This, however, can probably be ruled-out as a general explanation of the phenomenon, because $V/R$ variations appear and disappear with different quasiperiods inside a Be phase, and these are not necessarily correlated with the envelope size. As an alternative to the precession model we proposed a variable stellar wind acting as a piston at the base of the envelope which completely determines the long-term quasiperiods, in accordance with the Doazan's (1987) model. In this case, the $V/R$ variations reflect the expansion and contraction of the envelope. This explanation has observational support: associated patterns of long-term variations between the measurements made in the ultraviolet spectra (e.g. equivalent width of the C IV lines) and the visible (e.g. $V/R$ ratio of the H$\alpha$ line) appear in some stars studied up to now. More quasi-simultaneous UV and optical observations for long periods are necessary to elucidate whether this fact is common to all $V/R$ variables. If it is, the Doazan (1987) model will appear as the more convincing explanation for the long-term $V/R$ quasicycles.

On the other hand, the fact that the short-term variations are present only in small envelopes can be interpreted in terms of rotation of inhomogeneities in the envelope which are more prominent in weak emission profiles; the time-scales of their rotation are of the order of weeks in accordance with the observed values. Other explanations such as variations in the underlying photospheric profile due to non-radial pulsations of the stellar surface or rotation of an anisotropic radiation field may be responsible for the scatter found in our $V/R$ curves and for the rapid and sporadic variations found in some stars sometimes superimposed on the long-term variations.

We hope that the analysis of our data base of Be star spectra obtained continually since 1984 will be of great utility both in the study of long-term variations when they are compared with UV observations and in the detailed investigation of the emission profiles of the short-term variable stars.

*Acknowledgements.* We wish to thank Maria Ester Acuña who obtained most of our spectrograms used in this study. We also thank the European Southern Observatory in La Silla, and, in particular, D. Hofstadt, H.E. Schuster and J. Perez for their continuous and important support of our work, especially in donating plate material and in regularly aluminizing our telescope optics. We acknowledge the economic support given by the Fondo Nacional de Ciencias y Tecnología (Grant Fondecyt 369/88) and by Dirección de Investigación de la Pontificia Universidad Católica de Chile (Grant DIUC-39-86), as well as the Stiftung Volkswagen-werk through a cooperative project with Universitätssternwarte München, West Germany.

## References

Albert E., Huang S.S., 1974, ApJ 189, 479
Alvarez M., Ballereau D., Chauville J., 1990, to be published
Andrillat Y., 1983, A&AS 53, 319
Andrillat Y., Feherenbach Ch., 1982, A&AS 48, 93
Aydin C., Farraggiana R., 1978, A&AS 34, 51
Baade D., 1984, A&A 134, 105
Baade D., Dachs J., van de Weygaert R., Steeman F., 1988, A&A 198, 211
Bahng J.D.R., Hendry E.M., 1975, PASP 87, 137
Ballereau D., Chauville J., 1987, A&AS 70, 229
Buscombe W., 1970, MNRAS 148, 79
Castle K.G., 1977, PASP 89, 862
Cowley A.P., McLaughlin D.B., Toney J., Mac Connel D.J., 1972, PASP 84, 834
Cowley A., Gugula E., 1973, A&A 22, 203
Dachs J., Maitzen H.-M., Moffat A.F.J., Sherwood W.A., Stift M., 1977, A&A 56, 417
Dachs J., Eichendorf W., Schleicher H., Schmidt-Kaler Th., Stift M., Tüg H., 1981, A&AS 43, 427
Dachs J., Hanuschik R., Kaiser D., Ballereau D., Bouchet P., Kiehling R., Kozok J., Rudolph R., Schlosser W., 1986, A&AS 63, 87
Delplace A.M., 1970, A&A 7, 459
Divan L., Zorec J., 1982, in: IAU Symp. 98 Be stars, eds. M. Jaschek, H.G. Groth, Reidel, Dordrecht, p. 61
Doazan V., 1982, in: B stars with and without emission lines, NASA SP-456, eds. A. Underhill, V. Doazan, p. 277
Doazan V., 1987, in: IAU Coll. 92 Physics of Be Stars, eds. A. Slettebak, T.P. Snow, Cambridge University Press, Cambridge, p. 384
Doazan V., Harmanec P., Koubsky P., Krpata J., Zdarsky F., 1982a, A&AS 50, 481
Doazan V., Harmanec, P., Koubsky P., Krpata J., Zdarsky F., 1982b, A&A 115, 138
Doazan V., Franco M., Rusconi L., Sedemak G., Stalio R., 1983, A&A 128, 171
Doazan V., Grady C.A., Snow T.P., Peters G.J., Marlborough J.M., Barker P.K., Bolton C.T., Bourdonneau B., Kuhi L.V., Lyons R.W., Polidan P.S., Stalio R., Thomas R.N., 1985, A&A 152, 182
Dodson H.W., 1936, ApJ 84, 180
Fontaine G., Villeneuve B., Landstreet J.D., Taylor R.H., 1982, ApJ 49, 259
Geuverink H.G., 1970, A&A 5, 341
Gulliver A.F., 1977, ApJS 35, 441
Hanuschik R.W., 1986, A&A 166, 185
Hanuschik R.W., Kozok J.R., Kaiser D., 1988, A&A 189, 147
Hendry E.M., Bahng J.D.R., 1981, JApA 2, 141
Hirata R., Hubert-Delplace A., 1981, in: Workshop on Pulsating B Stars, eds. G.E.V.O.N., C. Sterken, Nice Observatory, p. 217
Hirata R., Kogure T., 1984, BASI 12, 109
Hoffleit D., Jaschek C., 1982, Bright Star Catalogue, 4th ed., Yale University Observatory, New Haven, Conn
Huang S.S., 1972, ApJ 171, 549
Huang S.S., 1973, ApJ 183, 541
Huang S.S., 1976, PASP 88, 448
Huang S.S., 1977, ApJ 212, 123
Huang S.S., 1978, ApJ 219, 956
Hubert-Delplace A.M., Hubert H., 1979, Atlas of Be stars, published by Observatoire de Meudon
Hubert-Delplace A.M., Jaschek M., Hubert H., Chambon M.Th., 1982, in: IAU Symp. 98 Be stars, eds. M. Jaschek, H.G. Groth, Reidel, Dordrecht, p. 125
Hubert A.M., Floquet M., Chauville J., Chambon M.T., 1987, A&AS 70, 443
Jaschek C., Jaschek M., Kucewicz B., 1964, ZA 59, 108
Jaschek C., Jaschek M., 1965, PASP 77, 376
Jaschek M., Jaschek C., Malaroda S., 1969 A&A 3, 485
Kogure T., Suzuki M., 1987, in: IAU Coll. 92 Physics of Be Stars, eds. A. Slettebak, T.P. Snow, Cambridge University Press, Cambridge, p. 192
Kopal Z., 1965, in: Advances in Astronomy and Astrophysics, ed. Z. Kopal, Academic Press, New York, vol. 3, p. 89
Kriz S., 1976, BAIC 27, 321
Kriz S., 1979a, BAIC 30, 83
Kriz S., 1979b, BAIC 30, 95
Mc Laughlin D.B., 1962, ApJS 7, 65
Mc Laughlin D.B., 1966, ApJ 143, 285
Mc Lean I.S., 1979, MNRAS 186, 265
Mennickent R.E., Vogt N., 1988, A&AS 74, 497
Mennickent R.E., 1989, Master Thesis: Estudio de Perfiles de Lineas de Emisión de Estrellas Be y su Conexión con la Envoltura Circumestelar, Universidad Católica de Chile, Santiago
Neto A.D., de Freitas Pacheco J.A., 1982, MNRAS 198, 659
Slettebak A., 1975, ApJ 197, 137
Slettebak A., 1976, in: IAU Symp. 70 Be and Shell Stars, ed. A. Slettebak, Reidel, Dordrecht, p. 123
Slettebak A., Reynolds R.C., 1978, ApJS 38, 205
Slettebak A., 1982, ApJS 50, 55
Smith M.A., 1989, ApJS 71, 357
Smith M.A., Penrod G.D., 1985, in: Relations between Cromospheric Coronal Heating and Mass-Loss in Stars, Trieste Workshop Ser. 1984, eds. R. Stalio, J.B. Zirken, p. 394
Underhill A., 1953, Publ. Dom. Astr. Obs. 9, 363