SEISMOLOGY OF BE STARS

C. Neiner[1,2], A.-M. Hubert[2], and M. Floquet[2]

[1]Research and Space Science Department of ESA, ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands
[2]GEPI, UMR 8111, Observatoire de Paris-Meudon, 5 place Jules Janssen, 92195 Meudon Cedex, France

Abstract

Be stars are main sequence or slighly evolved, usually rapidly rotating B stars that show a near infrared excess and Balmer emission lines imputed to an equatorially concentrated envelope, fed by discrete mass loss events. In the H-R diagram, early Be stars are located at the lower border of the instability strip of the β Cep stars, while mid- and late-Be stars are mixed with SPB stars. Be stars are not observed to rotate near the break-up velocity and the causes of the non-regular mass loss in these stars are still unknown. Non-radial pulsations (NRP) and stellar activity of magnetic origin have been proposed as mechanisms that could give rise to the additional amount of angular momentum needed to eject material.

Multiple periods detected in photospheric line profile variations of early Be stars and modelling of these variations strongly support that such stars do pulsate non-radially (see Baade 2000). In the case of the Be star μ Cen, the beating phenomenon within the main group of NRP modes with low, identical degree l and azimuthal order m ($l = m = 2$) seems to determine the times of mass loss events in the star (Rivinius et al. 1998, 2002). Whether this fact is valid for all Be stars has to be investigated.

An oblique magnetic dipole field has recently been detected in the Be star ω Ori (Neiner et al. 2003), which is also found to pulsate non-radially ($l = |m| = 2$, Neiner et al. 2002). The period observed in the magnetic measurements and in the wind modulation differs from the NRP period and corresponds to the rotational period. Though high rotation is thought to strongly alter the pulsation characteristics, magnetic fields also contribute to modify the spacing in the frequency spectrum of the pulsations of Be stars. *Eddington* will provide a very important and attractive opportunity to study the competing influence of rotation and magnetism on the pulsation characteristics of hot stars such as Be stars, as well as to better understand the build-up of the disk which surrounds these objects.

Finally, different driving mechanisms have been proposed to explain non-radial pulsations in Be stars. They could be tested with the observations of Be stars in young clusters of different metallicity.

Key words: Stars: Be, β Cephei, SPB - Stars: pulsations - Stars: magnetic field - Stars: circumstellar environment

1. Introduction

Be stars are main sequence or slightly evolved, usually rapidly rotating stars that show a near infrared excess and optical and infrared emission lines of hydrogen and several ions. The presence of emission in the lines and IR continuum, also called the "Be phenomenon", is attributed to an equatorially concentrated envelope, fed by discrete mass loss events.

About 20% of all B-type stars show this phenomenon. However this character is not permanent and B and Be phases is commonly observed to alternate in such stars. The early Be stars (B0e-4e) exhibit strong variable winds and complex spectral and photometric variations due to the superposition of non-radial pulsations, and stellar and circumstellar activity with different timescales.

It is generally accepted that the envelope of Be stars is flattened by their high rotational velocities (the ratio of the angular velocity to the critical velocity is $\Omega \,/\, \Omega_{\mathrm{crit}} \sim 0.8$, Chauville et al. 2001). Their rotation rates, however, are always lower than the critical velocities at which the centrifugal force balances gravitation at the equator and the causes of the non-regular mass loss in these stars are still unknown. NRP beating and stellar activity of magnetic origin have been proposed as mechanisms that could give rise to the additional amount of angular momentum needed to eject material.

2. Be stars as non-radial pulsators

In the H-R diagram, early Be stars are located at the lower border of the instability strip of the β Cep stars, while mid and late Be stars are mixed with SPB stars (Fig. 1).

Short periods have been commonly detected in photospheric line profile and photometric variations of Be stars, except in late sub-classes. From the Hipparcos database it was shown that short-term variability is present in the quasi-totality (86%) of early-Be stars, in 40% of mid-types (B4e-5e) and in only 18% of late-Be stars (Hubert & Floquet 1998). Up to now, a hundred Be stars have been claimed as short-term periodic variables (hours, tens of hours). Their number has been increasing continuously.

Multiperiodicity has been detected in light curves (Hubert & Floquet 1998, Aerts 2000) of a fraction of early

Proc. 2nd *Eddington* workshop *"Stellar Structure and Habitable Planet Finding"*, Palermo, 9–11 April 2003 (ESA SP-538,

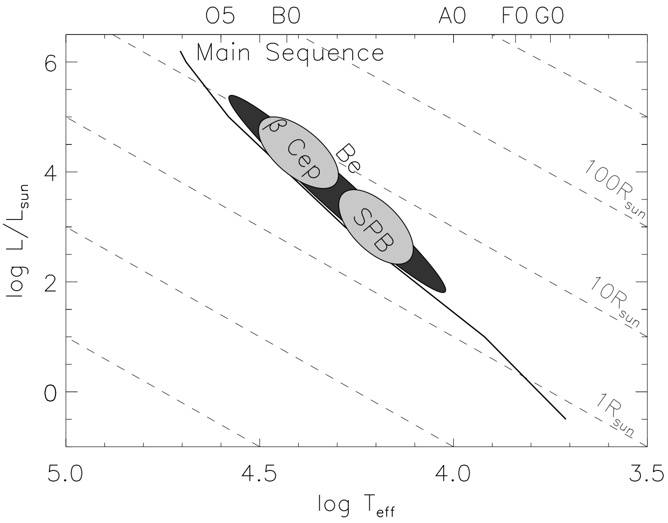

Figure 1. Location of Be stars (black ellipse) in the upper H-R diagram. They are mixed with β Cep and SPB stars (two grey ellipses).

Table 1. Examples of early Be stars in our galaxy, showing β Cephei-type pulsations.

Location	Star	Period (d)	Reference
NGC 7419	BND 551	0.262	K02
NGC 7419	BMD 451d	0.280 & 0.277	K02
field	19 Mon	0.191 & 0.204	Hipp & B02
field	27 CMa	0.092	BR91
field	60 Cyg	0.299	HF98
field	59 Cyg	0.280	HF98

K02 : Kolaczkowski et al. 2002, B02 : Balona et al. 2002, BR91 : Balona & Rozowsky 1991, HF98 : Hubert & Floquet 1998, Hipp : Hipparcos data

Be stars as well as in photospheric line profile variations (numerous references in IAU Coll. 175, 2000, ASP Conf. Series 214). Baade (2000) suggested that the change from double- to single-wave and vice versa, observed in the light curve of early Be stars, can be explained by the superposition of several modes. Modelling of the line profile variations of brighter Be stars supports that such stars do pulsate non-radially (Rivinius & Baade 2002).

3. B0e-1e stars

Early Be stars showing β Cephei-type pulsations have been photometrically detected in clusters such as NGC 7419 as well as in the field of our Galaxy (see Table 1 and Figs 2 and 3).

The distinction between hot Be stars and β Cep stars is not always clear. Some β Cep stars recently detected in young clusters seem to be rapid rotators and some of them could have shown the "Be phenomenon".

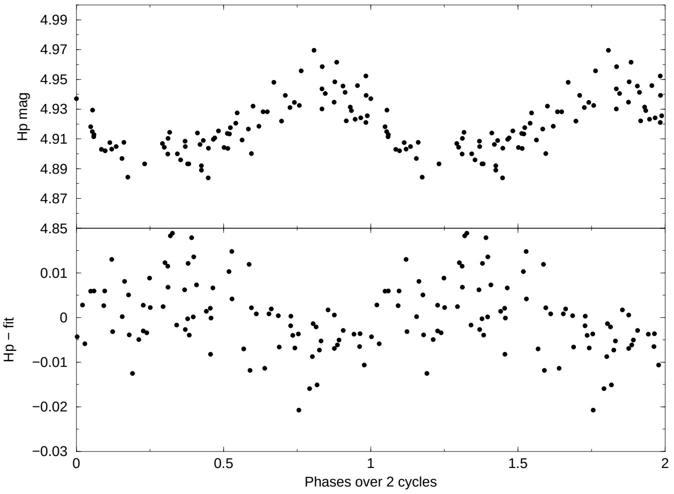

Figure 2. Variations of the magnitude of 19 Mon from Hipparcos data. Upper panel: folded in phase with P_1 = 0.191 d. Lower panel: folded in phase with P_2 = 0.204 d after removing P_1.

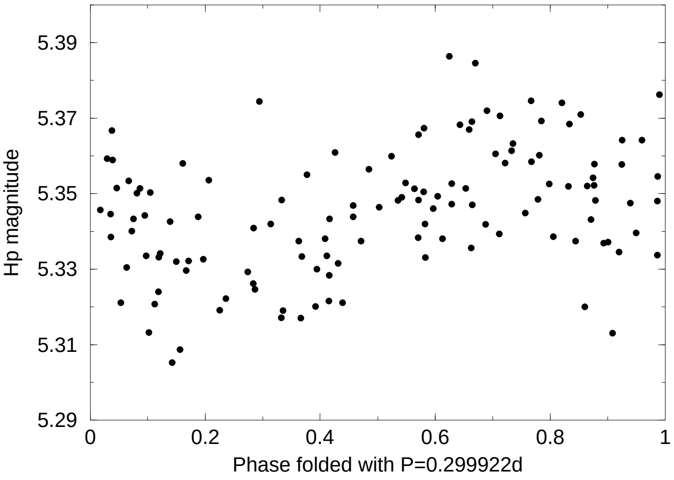

Figure 3. Variations of the magnitude of 60 Cyg from Hipparcos data, folded in phase with P = 0.299 d.

Indeed, some β Cep stars detected in NGC 4755 (Stankov et al. 2002) are found with a rather high rotational velocity ($v\sin i \geq 200$ km.s^{-1}) in the WEBDA database of Mermilliod. In the field, the star 19 Mon has been reported by Balona et al. (2002) as a β Cep star; its $v\sin i$ is also rather high (274 km.s^{-1}) and it showed in the past a weak emission in the Hα line. β Cep itself, which is a slow rotator ($P_{\rm rot}$ = 12 days), has shown recurrent Hα emission phases (Henrichs et al. 2000).

The number of B0e-1e stars known as β Cep stars is still very limited and the frequency spectrum of such objects has to be investigated. High degree, low amplitude pressure modes ($\Delta m \leq 1$ mmag) have been predicted for B0-1 stars (Balona & Kambe 1999).

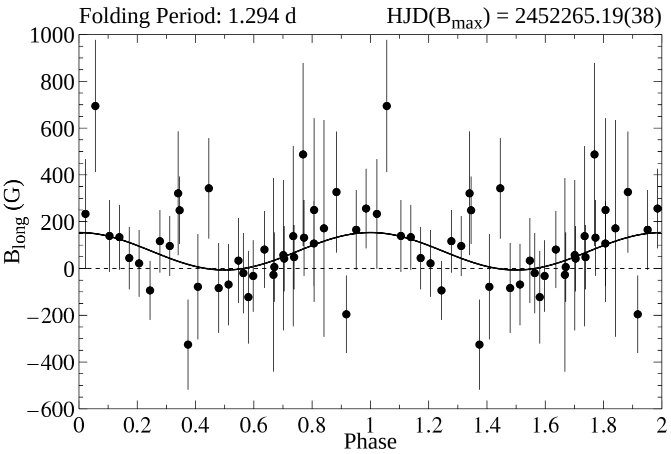

Figure 4. Variation of the longitudinal component of the magnetic field of ω Ori folded in phase with the rotation period $P_{\rm rot}$ = 1.29 d.

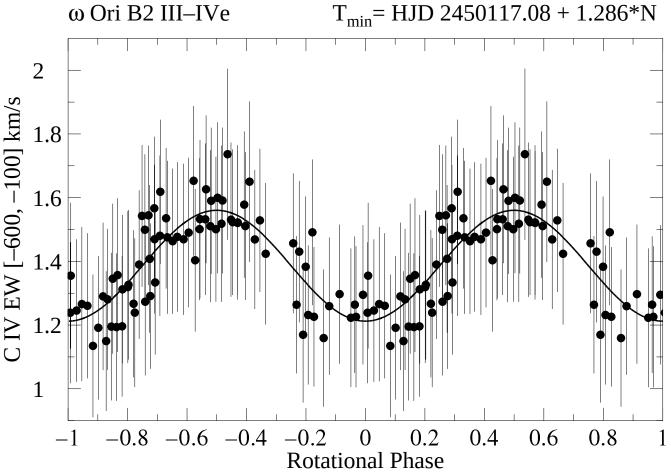

Figure 5. Variation of the equivalent width of the UV resonance C IV line at 1550Å of ω Ori, folded in phase with the rotation period $P_{\rm rot}$ = 1.29 d.

4. B2E-5E STARS

In the so-called λ Eri stars the photometric period is often considered to be close to the expected rotational period (Baade & Balona 1994). Therefore, the competing explanation in terms of NRP or rotational modulation of corotating clouds raised many debates.

Nevertheless these objects do pulsate: modelling line profile variations of brighter B2e-3e stars has shown that they form an homogeneous group pulsating with low degree gravity modes ($l = m = 2$, Rivinius & Baade 2002). Taking into account the geometric deformation and the non-uniform surface gravity and temperature distributions, induced by fast rotation, in the determination of fundamental parameters, has allowed to constrain the rotational period (Zorec et al. 2002). In a sample of ten Be stars seen equator-on, the ratio of the frequency observed in photometry to the rotation frequency $f_{\rm phot}$ / $f_{\rm rot}$ is about 1.5 ± 0.5.

Moreover, an oblique magnetic dipole field, i.e. that has its axis not aligned with the rotation axis of the star, has recently been detected in the rapidly rotating Be star ω Ori (Fig. 4, Neiner et al. 2003). This star is also found to pulsate non-radially ($l = |m| = 2$, Neiner et al. 2002). The period $P = 1.29$ d observed in the magnetic measurements (Fig. 4) and in the wind modulation (Fig. 5) differs from the NRP period $P_{\rm puls} = 0.97$ d and corresponds to the rotational period. Though high rotation is thought to strongly alter the pulsation characteristics, magnetic field also contributes to modify the spacing in frequency.

In the case of the B2e star μ Cen, the beating phenomenon between the main group of NRP modes, with low, identical degree l and azimuthal order m ($l = m = 2$) and a frequency spacing of about 0.005 to 0.01 cycle per day, determines the times of mass loss events in this star (Rivinius et al. 1998, 2002). Whether this fact is valid for all Be stars has been investigated but could not be established with ground-based observations. High accuracy data, sampled over a long time span, are needed to determine periods associated with NRP. In particular, close spaced periods can be detected thanks to long runs of spatial photometric observations.

5. B6E-9E STARS

A lack of short-period variables is observed towards B6e-9e stars. Theory predicts low amplitude gravity mode pulsations ($\Delta m \leq 5$ mmag for $l > 1$) for those stars, i.e. undetectable by ground-based observations. Baade (1989) looked for moving bumps, a manifestation of NRPs, in a sample of 22 late B-type stars and did not detect any. No pulsation modes at all are expected for spectral types between B9 and A2 (Pamyatnykh 1999), although Mc Manara (1987) proposed that Maia variables may exist beyond B7 towards δ Scu stars. Moreover, a lack of Be stars is found for spectral types later than B7 (Zorec 2000).

The low amplitude pulsation modes in late Be stars, however, will be easily detected by space-borne missions. Hubert & Floquet (1998) found variability in 20% of the late Be stars observed with the high accuracy Hipparcos satellite.

6. BE STARS IN CLUSTERS

Two mechanisms are generally considered (Baade & Balona 1994) to explain NRP in Be stars: the κ-mechanism and the convective core oscillation of rapidly rotating stars.

According to Dziembowski et al. (1993), the metal abundance influences the opacity mechanism in B stars: in the case of low metallicity ($Z = 0.01$), the β Cep domain is absent while the SPB domain can survive. As a large number of Be stars are located in the theoretical domain of the high order gravity mode instability where SPB stars are found, it can be expected that in low metallicity young clusters, hotter Be stars do not pulsate (or do not exist if pulsations play an important role in the "Be phenomenon") while λ Eri variables (B2e-4e stars) do exist.

The analysis of light curves of Be stars in young clusters of different age and metallicity will allow to select the mechanism responsible for NRP in these objects.

7. CONCLUSION

Be stars are very good candidates to study the competing influence of high rotation and magnetic field on pulsations.

The combination of high rotation rate and beating of NRP with closely spaced frequencies is considered to be one of the possible explanation for the "Be phenomenon". Whether this fact is true for all Be stars has to be investigated from space, for example with *Eddington*. This will help to better understand the build-up of the disk which surrounds these objects.

Long-term continuous space observations of Be stars will not only allow to detect new pulsation periods, especially beating periods, in early-Be stars, but also to detect high degree, low amplitude pressure modes in earlier B and Be stars and very low amplitude gravity modes for late-B and Be stars, predicted by theory (Balona & Dziembowski 1999) and not detected from the ground.

Eddington will also provide a very important and attractive opportunity to study the influence of the magnetism on the pulsation characteristics of hot stars such as Be stars. The role of the presence of a magnetic field, as recently discovered in ω Ori, in the beating effect of pulsation modes has to be investigated. An oblique magnetic dipole field also creates modulations with the rotation period, and local enhancements of chemical abundances.

Finally, different driving mechanisms have been proposed to explain the presence of NRP in Be stars. They could be tested with space observations of Be stars in young clusters of different metallicity.

REFERENCES

Aerts C. 2000, IAU Coll.175, ASP Conf. Ser. 214, 192

Baade D. 1989, A&AS 79, 423

Baade D. & Balona L.A. 1994, IAU Symp. 162, p 311

Baade D. 2000, IAU Coll. 175, ASP Conf. Ser. 214, 178

Balona L.A. & Dziembowski W.A. 1999, MNRAS 309, 221

Balona L.A. & Kambe E. 1999, MNRAS 308,1117

Balona L.A. & Rozowsky J. 1991, MNRAS 251, 66

Balona L.A., Koen C. & van Wyk F. 2002, MNRAS 333, 923

Chauville J., Zorec J., Ballereau D. et al. 2001, A&A 378, 861

Dziembowski W.A., Moskalik P. & Pamyatnykh A.A. 1993, MNRAS 265, 588

Henrichs H.F., de Jong J.A., Donati J.-F. et al. 2000, IAU Coll.175, ASP Conf. Ser. 214, 324

Hubert A.-M. & Floquet M. 1998, A&A 335, 565

Kolaczkowski Z., Pigulski A. & Kopacki G. 2002, IAU Coll. 185, ASP Conf. Ser. 259, 150

McNamara, B.J. 1987, "Stellar Pulsation", Proc. of the Conf. held in Los Alamos in 1986, Lecture Notes in Physics 274, p.92

Neiner C., Hubert A.-M., Floquet M., et al. 2002, A&A, 388, 899

Neiner C., Hubert A.-M., Frémat Y., et al. 2003, A&A in press

Pamyatnykh A.A. 1999, AcA 49, 119

Rivinius T., Baade D., Stefl S., et al. 1998, A&A 336, 177

Rivinius T., Baade D., Stefl S & Maintz M. 2002, IAU Coll. 185, ASP Conf. Ser. 259, 240

Stankov A., Handler G., Hempel M. & Mittermayer P. 2002, MNRAS 336, 189

Zorec J. 2000, IAU Coll. 175, ASP Conf. Ser. 214, 51

Zorec J., Frémat Y., Hubert A.-M. & Floquet M. 2002, IAU Coll. 185, ASP Conf. Ser. 259, 244