Part 2.2. B-Type Stars

Radial and Nonradial Pulsations as Probes of Stellar Physics
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An Observational Overview of Pulsations in β Cep Stars and Slowly Pulsating B Stars

P. De Cat[1]

Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Belgium

Abstract. The observational characteristics of the p-modes of β Cep stars are compared to those of the g-modes of slowly pulsating B stars (SPBs). For the β Cep stars, previous reviews based on photometric surveys are updated with recent results from our high-resolution spectroscopic surveys. For the slowly pulsating B stars, it is the first time a broad observational overview can be given.

1. Introduction

Variability is common among B stars. Eclipsing binaries with (a) B-type component(s) are found, as well as chemically peculiar B-type stars. The variations of the latter are attributed to the non-homogeneous distribution of the elements on the stellar surface. Different types of variations occur in B-type supergiants, but their instability mechanism remains unknown. It is not clear whether the short-term variability of some of the Be stars is in general caused by stellar pulsation or not. We refer to Rivinius et al. (these proceedings) for a recent status on pulsations in a subsample of Be stars and restrict our overview to β Cep stars (β Ceps) and slowly pulsating B stars (SPBs).

The spectroscopic and photometric variability of β Cephei was noticed at the beginning of the last century (Frost, 1902). The star became the prototype of a group of early-B type p-mode pulsators with pulsation periods ranging from 3 hrs to 6 hrs later on. The 53 Per stars were introduced by Smith (1977) as a group of spectroscopic variables surrounding the β Ceps. Waelkens (1991) introduced the term "slowly pulsating B stars" for a distinct group of mid-B type photometric variables pulsating in high-radial-order g-modes with periods of the order of days. It turns out that the 53 Per stars and the SPBs have several members in common (e.g. Chapellier et al., 1998).

The variations of the β Ceps and the SPBs are recently understood in terms of the κ mechanism (e.g. Dziembowski et al., 1993a,b). Thanks to the HIPPARCOS mission, a total of some 100 objects are now classified as SPB (Waelkens et al., 1998). The group of β Ceps consisted already of such a number before the HIPPARCOS mission.

A lot of the ongoing photometric surveys are devoted to the detection of B-type variables in clusters (e.g. Pigulski et al., and Stankov, these proceed-

[1]Postdoctoral Fellow, Fund for Scientific Research, Flanders; e-mail: peter@ster.kuleuven.ac.be

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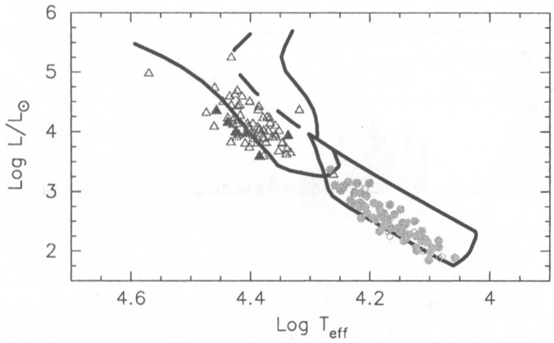

Figure 1. The SPBs (light grey circles) and the β Ceps (dark grey triangles) used in this work and their position in the HR diagram. The open symbols denote the confirmed members before the HIPPARCOS mission. The full symbols denote the new candidates after the HIPPARCOS mission. The full lines denote theoretical instability strips.

ings). On the other hand, high-resolution spectroscopy is often applied in the last decade to study stellar pulsations. In this work, all the currently known observational characteristics relevant for pulsational studies of the p-modes of β Ceps are compared to those of the g-modes of SPBs. The previous *photometric* view on β Ceps (Sterken & Jerzykiewicz 1993) is completed with the recent results of high-resolution *spectroscopic* surveys. For the SPBs we provide for the first time an extended observational overview.

2. Studied objects

This study is restricted to β Ceps and SPBs for which measurements in the Geneva photometric system are available. The resulting β Cep sample consists of 72 *confirmed* members: 53 field stars and 19 cluster stars. A large number of β Cep *suspects* was not included. For 22 of the 32 *confirmed* SPBs we used the results of detailed studies based on a combination of follow-up spectroscopic and photometric measurements presented by De Cat & Aerts (2002) and Mathias et al. (2001). About 20% of the bright southern candidate SPBs in the sample of Aerts et al. (1999) were misclassified (see also Briquet et al., these proceedings). The remaining 50 faint SPB *suspects* which were discovered thanks to the HIPPARCOS mission, but for which no follow-up studies are available yet, are also considered here. Their SPB-nature still has to be confirmed. The final list of β Ceps and SPBs, together with the relevant derived parameters used in this review, can be found on the internet (http://www.ster.kuleuven.ac.be/~peter/Bstars). In the following figures, the β Ceps and SPBs are given in dark and light grey respectively.

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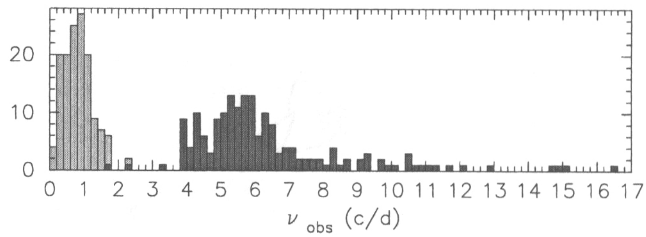

Figure 2. The distribution of the *observed* frequencies $\nu_{\rm obs}$ (c/d) for the SPBs (light grey) and the β Ceps (dark grey).

3. Observational overview

For the photometric part of this observational overview, the HIPPARCOS H_p and Geneva V data of the target stars were used. The spectroscopic results are mainly based on radial velocities determined from high-resolution, high S/N profiles of the $\lambda\lambda$ 4130 Å Si II-doublet (SPBs) and of the $\lambda\lambda$ 4560 Å Si III-triplet (β Ceps) which are available at our institute.

3.1. Stellar properties

The position in the HR diagram of the studied sample of β Ceps and SPBs derived from Geneva photometry is given in Fig. 1. The HIPPARCOS parallaxes lead to compatible results in view of the large errors of the luminosity, which for clarity are not shown in Fig. 1. The full lines in Fig. 1 denote theoretical instability strips. The position and the extent of these strips depend on unknown parameters such as the extent of convective overshoot and metalicity (e.g. Pamyatnykh, 1999). *Before* the HIPPARCOS mission (open symbols), the β Cep instability strip was already considerably filled. For the SPBs, this was only the case *after* this mission (full symbols). Although targets are found near the common part of both instability strips, no observational evidence has been found so far for the simultaneous excitation of p- and g-modes in a B-type star.

3.2. Pulsational properties

In Fig. 2, the distribution of the *observed* frequencies $\nu_{\rm obs}$ is given. The self-determined frequencies in HIPPARCOS, Geneva and/or radial velocity data are shown together with additional frequencies found in the literature. The resulting 138 SPB frequencies and 179 β Cep frequencies are respectively centered around 0.8 c d^{-1} and 5.5 c d^{-1}. Note that in theoretical calculations, the frequencies $\nu_{\rm corot}$ in the *co-rotating frame* are considered. Particularly for the g-modes of the SPBs $\nu_{\rm obs}$ can differ significantly from $\nu_{\rm corot}$.

The *observed* frequencies are used to determine the pulsation constant $Q = 1/\nu\sqrt{\overline{\rho}/\overline{\rho}_\odot}$ (days). For the study of the line profile variations, the key value is the K-value, which is defined as the ratio of the horizontal component of the velocity amplitude to the vertical component of the velocity amplitude. To a good approximation, it is given by $K \approx GM/(2\pi\nu)^2R^3$ (dimensionless). The Q-

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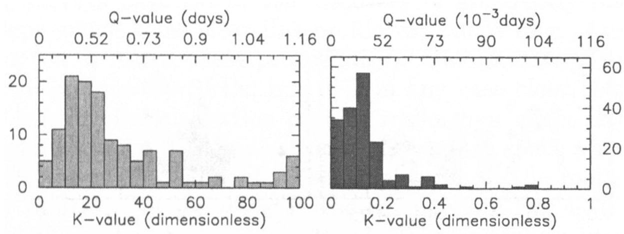

Figure 3. The distribution of the *observed* K- and Q-values for the SPBs (left) and the β Ceps (right)

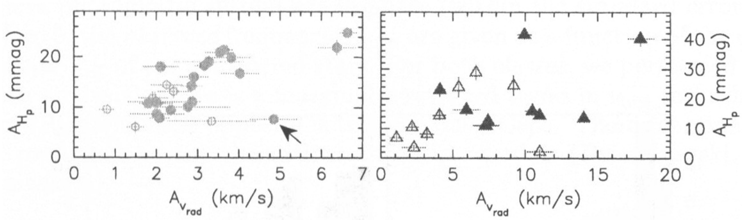

Figure 4. A comparison of the *observed* amplitudes $A_{\mathrm{H_p}}$ (mmag) and $A_{\mathrm{V_{rad}}}$ (km/s) of respectively the HIPPARCOS $\mathrm{H_p}$ and radial velocity variations for the SPBs (left) and the β Ceps (right). The full symbols correspond to the amplitudes of the main frequencies.

and K-values are related as follows: $K = 74.41Q^2$. In Fig. 3, distributions of both the *observed* K- and Q-values are shown. For the β Ceps, similar distributions were already given by other researchers (e.g. Sterken & Jerzykiewicz, 1993). Our recent results for the SPBs allow us to provide also a statistically justified distribution for these pulsators. The observed K-values of the SPBs and β Ceps are respectively centered around 18 and 0.12, reflecting that the horizontal component of the velocity is dominant for the g-modes of the SPBs, while the vertical component of the velocity is dominant for the β Cep p-modes.

The *observed* amplitudes and phases of harmonic fits were (re-)determined by imposing the known frequencies to the available data-sets. Some additional values were found in the literature. In Fig. 4, the *observed* amplitudes of the variations in the HIPPARCOS $\mathrm{H_p}$ data are compared to those in the radial velocity variations. From here on, the properties of the main frequencies are given in full symbols. The extremely large amplitude of the β Cep star BW Vul is not shown for clarity. The lack of observations in the lower part of the left panel suggests that all SPBs have large photometric amplitudes, which is not the case for β Ceps. However, this is due to a selection effect. Most of the SPBs are discovered thanks to the photometric measurements of the HIPPARCOS mission, which imply photometric amplitudes above the detection threshold. Recent

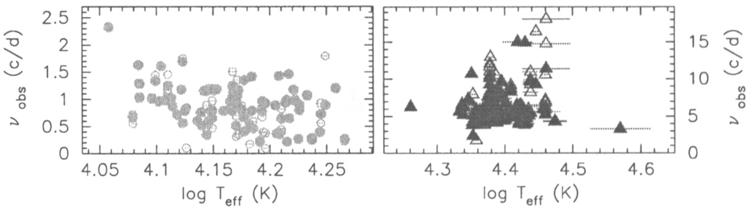

Figure 5. The observed frequency $\nu_{\rm obs}$ (c $\rm d^{-1}$) as a function of the effective temperature $T_{\rm eff}$ (K) for the SPBs (left) and the β Ceps (right). The full symbols correspond to the main frequencies.

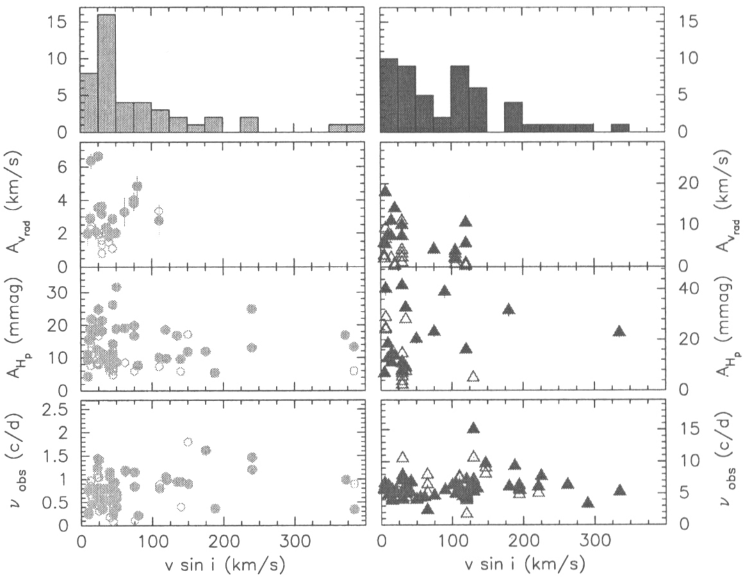

Figure 6. Top: the distribution of the projected rotational velocity $v \sin i$ (km/s). Middle: the *observed* amplitude of the variations in, respectively, the radial velocity data ($A_{\rm v_{rad}}$) and the HIPPARCOS $\rm H_p$ data ($A_{\rm H_p}$) as a function of $v \sin i$. The full symbols correspond to the amplitudes of the main frequencies. Bottom: the *observed* frequency $\nu_{\rm obs}$ (c $\rm d^{-1}$) as a function of $v \sin i$ (km/s). The full symbols correspond to the main frequencies. The SPBs and the β Ceps are given in the left and right panels respectively.

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spectroscopic surveys have led to the discovery of apparently photometrically constant β Ceps which show clear line-profile variations (e.g. Ausseloos et al., and Uytterhoeven & Aerts, these proceedings). Unfortunately, similar surveys have not yet been done for SPBs, but it is in any case clear that high-degree modes cause moving bumps in line profiles while their effect is cancelled out in ground-based photometric measurements (but not in space photometry – see Cuypers et al., these proceedings). The amplitudes of the main frequency of HD 92287 are indicated by an arrow in the left panel of Fig. 4. It is attributed to an $\ell = 4$ mode (De Cat & Aerts, 2002), which is the highest identified ℓ-value for an SPB so far. Unfortunately, the number of reliable mode identifications is too limited to draw conclusions (see below).

In general, the *observed* amplitudes of the variations of the *space-based* HIPPARCOS H_p data are compatible to those of the *ground-based* Geneva V data. Both for the SPBs and the β Ceps, the variations in the different filters of the Geneva photometric system are in phase (within the standard error).

In Fig. 5, the *observed* frequencies ν_{obs} are given as a function of the effective temperature T_{eff} of the considered stars. For both classes, we performed a linear regression analysis. There is a marginal downward trend in ν_{obs} towards hotter stars for SPBs while the opposite is true for the β Ceps. These marginal trends are not predicted by the theoretical excitation models (Dziembowski, private communication).

3.3. Rotational properties

The observed projected rotational velocity $v \sin i$ provides an upper limit to the rotation frequency ν_{rot} of the considered star. For the SPBs and β Ceps for which there are high-resolution spectra available at our institute, the total broadening of the line-profiles was taken as an upper limit for $v \sin i$. For the others, $v \sin i$-values were collected in the literature, bearing in mind that the majority of these values are based on low-resolution spectra. For the targets with more than one $v \sin i$-estimation, the lowest value was preferred. Unfortunately, for most of the candidate SPBs, no $v \sin i$-estimations are available yet. The resulting $v \sin i$-distributions are given in the top panels of Fig. 6. Most targets are relatively slow rotators. In the middle panels of Fig. 6, the *observed* amplitudes of the variations in the radial velocity and HIPPARCOS H_p data are given as a function of $v \sin i$. Linear regression analyses reveal no downward trends towards higher $v \sin i$. Therefore, no direct evidence for pulsation damping due to stellar rotation is found. In the lower panels of Fig. 6, the *observed* frequencies are given as a function of $v \sin i$. Again, no trends are found.

In the top panel of Fig. 7, the degrees ℓ of the modes for which a "reliable" identification is available are given as a function of $v \sin i$. The ℓ-values shown with open symbols are solely based on multicolor photometry. When the results are compatible with, or solely based on, high-resolution spectroscopy, full symbols are used. Our current view on SPB and β Cep pulsations reveals no relation between ℓ and $v \sin i$. Note, though, that there is a lack of ℓ-determinations for fast rotators. In the lower panel of Fig. 7, the $v \sin i$-distribution for the β Ceps is given after adding the new candidate β Ceps in the sample of Schrijvers et al. (these proceedings). Most of these candidates are photometrically constant but do show clear line-profile variations. The targets with asymmetric line pro-

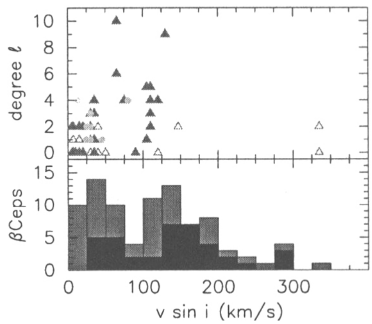

Figure 7. Top: The degree ℓ of the identified modes as a function of the projected rotational velocity $v \sin i$ (km/s) for SPBs (circles) and β Ceps (triangles). The open symbols are solely based on photometry. Bottom: The distribution of $v \sin i$ for the β Ceps, including the new candidate β Ceps (black) of Schrijvers et al. (these proceedings).

files are considered as candidate β Ceps pulsating in low-degree modes and those with moving bumps as candidate β Ceps pulsating in high-degree modes. High-resolution spectroscopic follow-up campaigns are needed to confirm or reject the suggested pulsational nature. A similar systematic spectroscopic study to search for fast rotating candidate SPBs has not been done yet.

4. Summary and future challenges

Thanks to the combined results of our photometric and spectroscopic campaigns, the pulsations of SPBs and β Ceps can be characterized as follows: (1) all SPBs and β Ceps exhibit line-profile variations, (2) the *observed* K-values are centered between 10-25 for SPBs and between 0.05-0.2 for β Ceps, (3) the variations in the different photometric filters of the Geneva system are in phase, (4) marginal trends are found in the *observed* frequencies as a function of the effective temperature. Due to selection effects, no low amplitude SPBs have been detected yet. However, future asteroseismic space missions (MOST, MONS, COROT) will allow us to detect numerous low-amplitude modes in B-type stars.

Photometric methods have been used intensively to study the pulsations of SPBs and β Ceps. However, the complementary use of high-resolution spectroscopy has been crucial for the detection/study of low amplitude variations and high degree modes. In the last decades, different mode identification techniques were developed using multicolor photometry *or* high-resolution spectroscopy. Unfortunately, photometric and spectroscopic techniques do not always lead to compatible results (e.g. De Cat & Aerts, 2002). There is an urgent need for unified identification methods using photometric *and* spectroscopic measurements simultaneously.

We have investigated the influence of stellar rotation on pulsation, but no firm evidence is found for amplitude damping due to rotation, nor for the excitation of higher degree modes in rapid rotators. We do stress that only a

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limited number of rapid rotators has been studied. More observations of fast rotating B-type stars are needed for more definitive conclusions.

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Discussion

D. Welch : Do you have any insight into how the SPBs might behave in the LMC and the SMC field ? The microlensing surveys have excellent S/N in the appropriate mass range.

P. De Cat : I am only aware of one candidate SPB in the LMC, i.e. EROS 1003, which is found in the list of probable eclipsing binaries (Grison et al., 1995, A&A, 109, 447). At $Z \approx 0.0085$ the theoretical instability strip is very narrow and only very few SPBs are expected.

Y. Wu : Since SPBs are photometrically selected and they still show the same distribution against $v \sin i$ as β Ceps do, perhaps both of them do indeed not pulsate at fast rotation?

P. De Cat : Not necessarily. Fast rotating candidate β Ceps are currently being detected by high-resolution spectroscopic search surveys and a similar systematic survey to search for fast rotating SPBs has not been done yet.

L. Balona : I would like to point out that, as your sample results from HIPPARCOS photometry, it is unbiased with regard to rotational velocity. So I think it is fair to conclude that rapid rotation among SPBs does not occur.

P. De Cat : I am not so sure; we are currently gathering spectra of a few rapid rotators among the HIPPARCOS SPB candidates for further study.

H. Henrichs : An additional challenge to add to your list is to explain the presence of a magnetic field in some β Ceps (poster by Neiner et al.). Such stars are particularly interesting from an asteroseismological point of view.