THE PULSATIONS AND POTENTIAL FOR SEISMOLOGY OF B STARS

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ABSTRACT

We review the nature of the oscillations of main-sequence and supergiant stars of spectral type B. Seismic tuning of the interior structure parameters of the β Cep stars has been achieved since three years. The results are based on frequencies derived from long-term monitoring and progress in this area is rapid. Oscillations in mid-B stars as well as Be stars are well established by now, but we lack good mode identification to achieve seismic modelling. We provide recent evidence of g-mode pulsations in supergiant B stars. The spherical wavenumbers of their modes are yet unidentified, preventing seismic probing of such evolved hot stars at present. Improving the situation for the three groups of g-mode oscillators requires multi-site long-term high-resolution spectroscopy in combination with either space photometry or ground-based multicolour photometry. The CoRoT programme and its ground-based programme will deliver such data in the very near future.

Key words: stars: oscillations; techniques: spectroscopy; techniques: photometry; Lines: profiles.

1. INTRODUCTION

A large fraction of the stars of spectral type B is known to be variable. Since more than a century now, these variables have been divided in different classes, according to their periods and morphology of the lightcurves. In this review, we concentrate on those classes of variable B stars with established periodic variability resulting from stellar oscillations and situated near or above the main sequence. This concerns the classes of the β Cep stars, the slowly pulsating B stars, the pulsating Be stars and the pulsating supergiant B stars. For a review on the oscillations of subdwarf B stars, we refer to the paper by Fontaine (these proceedings).

Large inventories of pulsating B stars were established during the first part of the $20th$ century. These were mainly based on photographic spectroscopy (see [1] for one of the earliest review papers). The introduction of photo-electric photometry in the second half of the $20th$ century allowed much larger systematic survey campaigns, resulting in fainter class members among them cluster stars. The Hipparcos mission subsequently allowed the discovery of more than 100 bright periodic B stars [2]. Still today, new pulsating B stars are found, mainly from large-scale surveys, as we will discuss below for each class separately. These early survey works resulted in a fairly good statistics of the frequencies and amplitudes of the oscillations, but not beyond that.

As of the 1970s, the research of pulsating B stars extended towards the area of mode identification from observations. The motivation for this was that, at that time, the samples of pulsating B stars were large enough to delineate the observational instability strips, but no instability mechanism was known to explain the oscillations. Identification of the mode wavenumbers (ℓ, m) could therefore help to discover such a mechanism and to understand the mode selection. Mode identification was first mainly attempted from multicolour photometry using the method introduced by [3] and based on previous theoretical works by [4] and [5], [6]. The degree of the oscillation modes can be identified from amplitude ratios and/or phase differences (see, e.g., [7] for a review of this method and [8] for a recent improvement). Later on, from the mid 1980s, the possibility of performing high-resolution spectroscopy emerged from improved instrumental technology. This, in combination with the suggestion of [9] that one can compute theoretical line profiles for various kinds of nonradial oscillations, initiated a series of still ongoing efforts to obtain high spatial- and time-resolution spectroscopic observations of pulsating stars B with the specific aim to perform mode identification.

Meanwhile, the instability mechanism is well known. It is the κ-mechanism acting in the partial ionisation zones of the iron-like elements (see [10] for an excellent review). The mode selection, however, is still totally unknown to us.

It was only a few years ago that accurate enough frequencies, combined with unambiguous mode identification, became available for several nonradial modes in a few selected B stars which had been monitoring since many years. In this paper, we report on the current status of B star asteroseismology, highlighting the recent successes in the seismic interpretation of the interior structure parameters of the β Cep stars, and pointing out the difficulties yet to overcome to achieve the same success for other B-type pulsators.

2. β CEP STARS

The β Cep stars are a well-established group of near-main sequence pulsating stars. They have masses between 8 and about $18\,M_\odot$ and oscillate in low-order p and g modes with periods between about 2 and 8 h excited by the κ mechanism acting in the partial ionisation zones of iron-group elements [11]. The agreement between observed β Cep stars and the theoretical instability strip is very satisfactory for the class as a whole, although the blue part of the strip is not well populated [12]. Most of the β Cep stars show multiperiodic light and line profile variations. The majority of the β Cep stars rotate at only a small fraction of their critical velocity. An recent overview of the observational properties of the class is available in [13].

Recently, numerous new candidate members have been found from large-scale surveys, in the LMC and SMC [14] as well as in our own Galaxy [15], [16]. Assuming that all these faint variable stars are indeed β Cep stars more than doubles the number of class members to over 200. The occurrence of so many β Cep stars in environments with very low metallicity implies new unanticipated challenges to the details of the mode excitation, which relies heavily on the iron opacity.

The amplitudes and frequencies of the β Cep stars seem quite stable, although very few dedicated long-term studies are available. The B2III star 12 Lac, e.g., was known to have six oscillation modes from photometry [17] and these same modes were recovered in high-resolution spectroscopy more than a decade later [18] and yet again, together with many more modes, in a recent multisite campaign [19]. The B3V star HD 129929, on the other hand, was monitored during 21 years in 3-week campaigns from La Silla with one and the same high-precision photometer attached to the 0.70-m Swiss telescope [20]. This also led to the detection of six independent oscillation modes, with very small amplitude variability for the triplet frequencies only, if any. Suggestions for evolutionary frequency changes from O-C diagrams have been made, but we regard these as premature.

Significant progress in the detailed seismic modelling of the β Cep stars has occurred since a few years. While such modelling was already attempted a decade ago for the stars 16 Lac [21] and 12 Lac [22], doubtful mode identification prevented quantitative results. It took until the exploitation of the 21-yr single-site multi-colour data set of the star HD 129929 to discover that standard stellar models are unable to explain that star's oscillation behaviour. Indeed, from the modelling of three identified $m = 0$ modes, [20] derived a core overshoot parameter of $0.10 \pm 0.05\,H_p$ (with H_p the local pressure scale height) and proved the star to undergo non-rigid internal rotation from the splitting within an $\ell = 2$ and an $\ell = 1$ mode, with the core rotating four times faster than the envelope. For details, we refer to [23] and [24].

This modelling result was soon followed by the one derived for the B2III star ν Eri, which was the target of a 5-month multisite photometric and spectroscopic campaign. Numerous new frequencies were found and identified compared to the four known before the start of the campaign [25], [26], [27]. The modelling was done by two independent teams using different evolution and oscillation codes. This led to different results depending on the number of fitted $m = 0$ components (three $m = 0$ modes were fitted by [28] while four by [29]). The main and far most important conclusion was, however, the same for both studies: current seismic models do not predict all the observed modes of ν Eri to be excited. One needs a factor four enhancement in the iron opacity, either locally in the driving region, or globally in the star, to solve this excitation problem. This led to the suggestion to include radiative diffusion in the models to solve this outstanding issue, in analogy to the subdwarf B pulsators [30]. Promising first attempts to compute main-sequence B-star models including diffusion were made by [31]. They found that the diffusion effects do not alter the frequency values in a significant way, but have indeed the potential to solve ν Eri's excitation problem (or, better phrased: our inability to explain its mode excitation . . .).

Meanwhile, two more β Cep stars were modelled seismically, each of them having two well-identified frequencies. The example of β CMa is illustrative of the power of asteroseismology: having two well-identified oscillation modes in a slow rotator is sufficient to derive a quantitative estimate of the core overshoot parameter, which was found to be $d_{ov} = 0.15 \pm 0.05\,H_p$ for this somewhat evolved B2III β Cep star. The way this is achieved, is illustrated nicely in Fig. 1, taken from the paper by [32]. Because the frequency spectra of β Cep stars are so sparse for low-order p and g modes, one does not have many degrees of freedom to fit the well-identified modes. This is why we can put limits on internal structure parameters as shown in Fig. 1, of course assuming that the input physics of the models is the correct one. A similar, but less stringent constraint was derived for the B2IV star δ Ceti from a combination of MOST space photometry and archival ground-based spectroscopy [33].

Additional multisite campaigns have been done for the stars θ Oph [34], [35], 12 Lac [19] and V 2052 Oph (Handler, unpublished). These have a somewhat higher projected rotation velocity, and it would be interesting to know if the range of values found so far for the core overshoot parameter and the level of non-rigidity of the internal rotation remains valid for them. The modelling is ongoing at present.

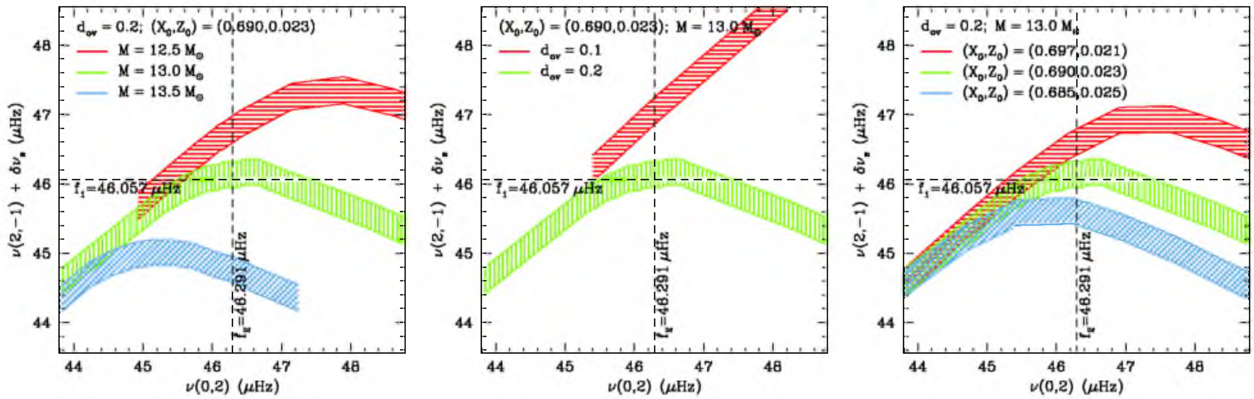

Figure 1. The variation of theoretical frequencies, computed for models appropriate for the β Cep star β CMa, with the stellar parameters M (left), $d_{\rm ov}$ (middle) and Z (right). In each panel, two of the parameters are fixed to visualise the effect of the other remaining parameter on the frequencies. The first radial overtone frequencies are plotted as abcissae and the $\ell = 2$ g_1 mode frequency, corrected for the rotational splitting, are plotted as ordinates. The dashed lines indicate the two observed frequencies, i.e. the point where they interset indicates a perfect match of theoretical and observed frequencies. Each area represents an evolutionary track whose width is due to the uncertainty in the measured rotational splitting. Figure reproduced from [32] with permission from A&A and from the authors.

3. SLOWLY PULSATING B STARS

The term "slowly pulsating B stars" (SPB stars) was introduced by [36], after years of photometric monitoring of variable mid-B stars with multiperiodic brightness and colour variations. After a few years, the Hipparcos mission led to a tenfold increase in the number of class members [2]. Subsequent huge long-term multicolour photometric and high-resolution spectroscopic follow-up campaigns concentrated on the brightest new class members found from Hipparcos [37], [38] and resulted in a much better understanding of the pulsational and rotational behaviour of the class members [39]. Accurate frequencies and mode identification are available for some 15 members [40], [41]. The mode identification results are in excellent agreement with theoretical computations made by [42] predicting mainly dipole modes to be excited. All confirmed SPB stars are slow rotators [39].

In Fig. 2 we show as an illustration the frequency spectrum of the Geneva B and Hipparcos light, and radial velocity variations of the brightest among the SPB stars, o Vel (B3IV). Despite the long-term monitoring of almost two decades in photometry, [40] found only four independent frequencies for this star. This is typical for single-site ground-based data of main-sequence stars with gravity modes, because the latter have periodicities ranging from 0.8 to 3 d. This leads to severe alias problems, as illustrated in Fig. 2 where the confusion between frequencies f and $1 - f$ is prominent. Only with multisite data, or, even better, with uninterrupted data from space, can one avoid such confusion. This is illustrated nicely by the MOST light curve (reproduced in Fig. 3) of the new SPB star HD 163830 discovered by that mission [43]. This lightcurve implied a five-fold of the number of gravity modes in one star compared to the best ground-based datasets for such pulsators.

As for the β Cep stars, numerous new SPB stars (some 70) were discovered in the Magellanic Clouds from OGLE and MACHO data [14]. The number of class members is therefore about 200 at the time of writing (assuming all the Magellanic Clouds variables to have been classified correctly). Trustworthy mode identification is only available for the highest-amplitude frequency of a handful of SPB stars, however, and it concerns only the spherical wavenumbers of the dominant mode [41]. This is why seismic tuning of the interior structure of SPB stars has not been achieved so far.

4. PULSATING BE STARS

Be stars are Population I B stars close to the main sequence that show, or have shown in the past, Balmer line emission in their photospheric spectrum. This excess is attributed to the presence of a circumstellar equatorial disk. See the review on Be stars by [44] for general information on this rather inhomogeneous class of stars. Magnetic fields [45] and nonradial oscillations [46] have been detected in some Be stars. It is unclear at present if these mechanisms are able to explain a disk for the whole class of Be stars.

Be stars show variability on very different time scales and with a broad range of amplitudes. [47] studied a subclass of the Be stars showing one dominant period between 0.5 and 2 d in their photometric variability, with amplitudes of a few tens of a mmag which he termed the λ Eri variables. He provided extensive evidence of a clear correlation between the photometric period and the rotational period of the λ Eri stars and interpreted that correlation in terms of rotational modulation. When observed spectroscopically, several of the λ Eri stars turn

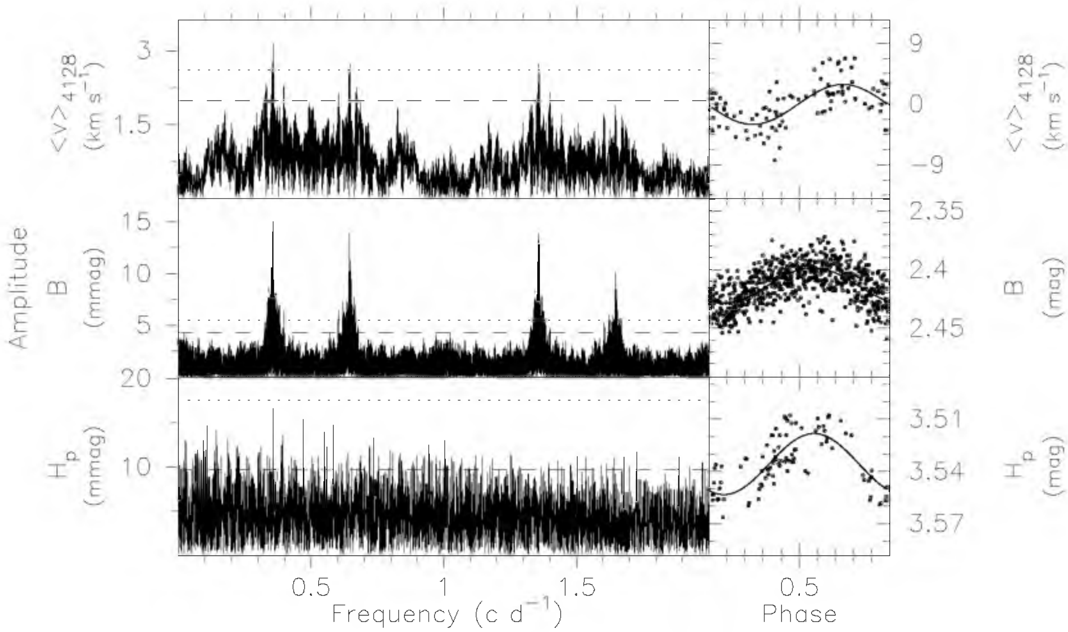

Figure 2. The frequency spectra of Geneva B, Hipparcos, and radial velocity data derived from the Si II 4128 Å line of the SPB star HD 74195. The horizontal dashed line indicates the 1% false-alarm probability and the dotted one the 3.7 S/N ratio level. Figure reproduced from [40] with permission from A&A and from the authors.

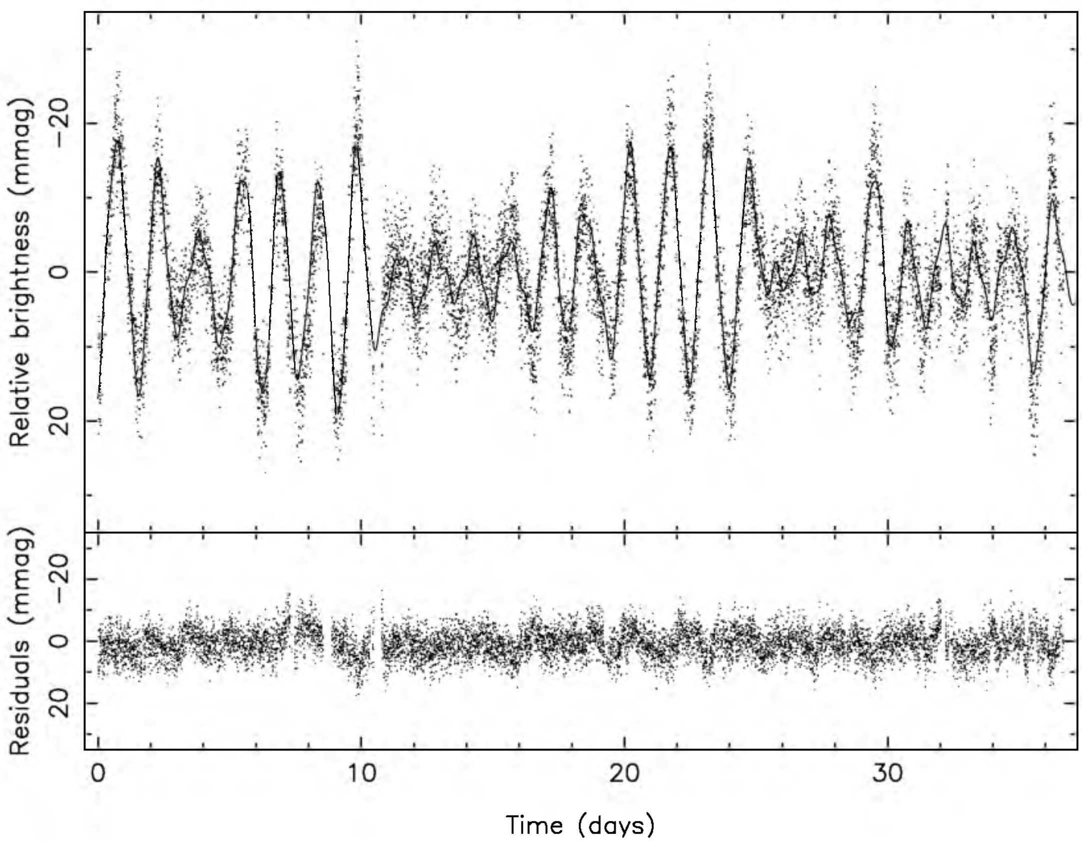

Figure 3. The MOST light curve of the SPB HD 163830 (upper panel, dots) and the best fit based on the 21 significant frequencies (upper panel, full line). The residuals after subtraction of the fit are shown in the lower panel. Figure reproduced from [43] with permission from the ApJ and from the authors.

Figure 4. Line profile variations in Be stars, with increasing $v \sin i$ for FW CMa (top left, $v \sin i = 40\,km\,s^{-1}$), ω CMa (bottom left, $v \sin i = 100\,km\,s^{-1}$), μ Cen (top middle, $v \sin i = 155\,km\,s^{-1}$), DX Eri (bottom middle, $v \sin i = 180\,km\,s^{-1}$), α Eri (top right, $v \sin i = 225\,km\,s^{-1}$), η Cen (bottom right, $v \sin i = 350\,km\,s^{-1}$). Data taken from [46].

out to have complex line profile variations with travelling sub-features similar to those observed in the rapidly rotating β Cep stars, except for the much longer periods (days versus hours). This rather seems to suggest oscillations as origin of this complex spectroscopic variability.

Nonradial oscillations were already discovered in the Be star ω CMa [48], a star listed among the λ Eri variables in [47]'s list. An extensive summary of the detection of short-period line profile variations due to oscillations in hot Be stars is provided in [46]. They monitored 27 early-type Be stars spectroscopically during six years and found 25 of them to be line profile variables at some level. Some of their data are shown in a grey-scale plot in Fig. 4. For several of their targets the variability was interpreted in terms of nonradial oscillations with $\ell = m = +2$. Almost all stars in the sample also show traces of outburst-like variability rather than a steady star-to-disk mass transfer. The authors interpreted the disk formation in terms of multimode beating in combination with fast rotation.

The view on pulsating Be stars became more complicated when [49] introduced the class of ζ Oph variables. These are late-O type stars with clear complex multiperiodic line profile variations which he attributed to high-degree nonradial oscillations. They are named after the prototypical O9.5V star ζ Oph, whose rotation is very close to critical and whose photometric variability was recently firmly established by the MOST space mission. [50] disentangled a dozen significant oscillation frequencies in the 24-d photometric light curve assembled from space. These frequencies range from 1 to 10 d^{-1} and clearly indicate the star's relationship to the β Cep stars.

Multiperiodic oscillations were recently also reported in the rapidly rotating B5Ve star HD 163868 from a 37-d MOST light curve. [51] derived a rich frequency spectrum, with more than 60 significant peaks, resembling that of an SPB star and termed the star an SPBe star in view of its Be nature. They interpreted the oscillation periods between 7 and 14 h as high-order prograde sectorial g modes and those of several days as Rossby modes (e.g. [52] for a good description of such modes). There is remaining periodicity above 10 d which cannot be explained at present. Finally, nonradial oscillations at low amplitude were also detected in the bright B8Ve star β CMi [53].

As for the SPB stars, seismic modelling of the interior structure of Be stars has not yet been achieved, in this case by lack of enough frequencies, of frequency accuracy, of unambiguous mode identification and of appropriate stellar models for rapid rotators.

5. PULSATING B SUPERGIANTS

Oscillations have not yet been firmly established in luminous stars with $\log L/L_\odot > 5$ and $M > 20\,\mathrm{M}_\odot$, although they are predicted in that part of the HR diagram. [12] and [54] predicted SPB-type g modes to be unstable at such high luminosities for respectively pre- and post-TAMS models (Fig. 5).

[2] discovered a sample of B supergiants to be periodically variable with SPB-type periods from the Hipparcos mission. These stars, and additional similar ones, were subjected to detailed spectroscopic and frequency analyses by [55], who found their masses to be below $40\,\mathrm{M}_\odot$ and photometric periods between 1 and 25 d. The stars were found to be situated at the high-gravity limit of κ-driven pre-TAMS g-mode instability strip ([12], see Fig. 5). This implies that the interpretation of their variability in terms of nonradial g-mode oscillations excited by the κ mechanism, as first suggested by [2], is plausible.

A new step ahead in the understanding of these stars was achieved by [54], who detected both p and g modes in the B2Ib/II star HD 163899 from MOST space-based photometry. The authors deduced 48 frequencies below $2.8\,\mathrm{d}^{-1}$ with amplitudes below 4 mmag and computed post-TAMS stellar models and their oscillation frequencies which turn out to be compatible with the observed ones.

Further research is needed to evaluate if seismic modelling in terms of internal physics evaluation of these SPB supergiants, as [54] termed their target, is feasible.

6. DISCUSSION AND FUTURE PROSPECTS

The classes of the β Cep and SPB stars are now well established, containing more than 200 members each. Four of the brightest and slowest rotators among the β Cep stars have been modelled seismically since 2003, resulting in stringent constraints on the core overshoot parameter of $d_{\rm ov} \in [0.05 \pm 0.05, 0.20 \pm 0.05]\mathrm{H_p}$. Note that this range is lower than the one found from a handful of eclipsing binaries with a B-type star [56], implying that the latter probably also experience rotational mixing near their core, which mimics additional core overshoot. In two stars (besides the Sun), seismic evidence for non-rigid internal rotation was established. Both these stars have a core spinning faster than the envelope, one with a factor three and the other one with a factor four. This

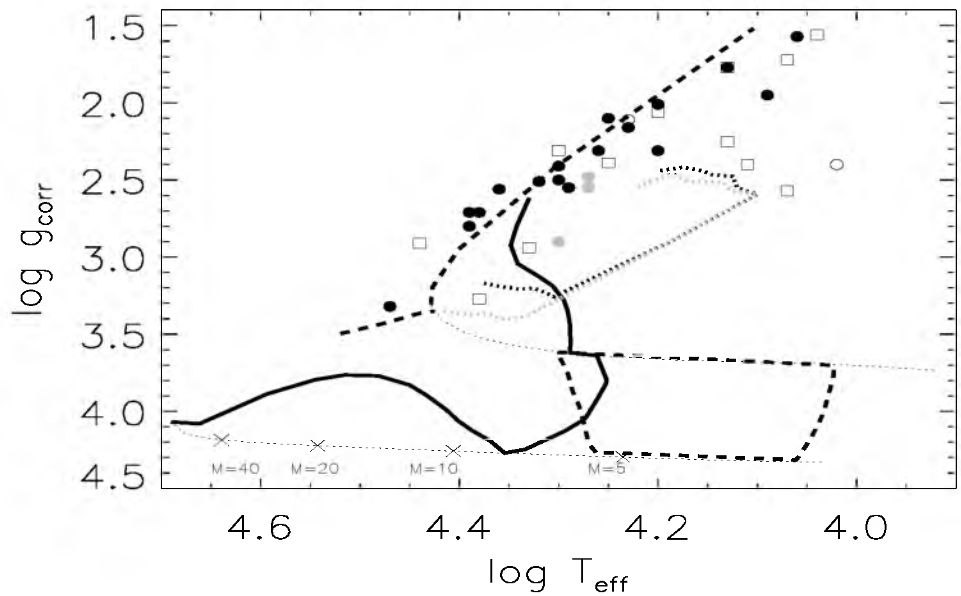

Figure 5. The position of B supergiants discovered to be periodically variable from the Hipparcos mission is compared with instability computations for p modes (full lines) and g modes (dashed lines) of main sequence models [12] and with post-TAMS model predictions for $\ell = 1$ (grey dotted) and $\ell = 2$ (black dotted) for B stars with masses up to $20 M_\odot$ computed by [54]. Figure reproduced from Lefever et al. (2006) with permission from A&A and from the authors.

was derived from the computation of the Ledoux splitting coefficients, after successful seismic modelling of the zonal components of observed frequency multiplets, and a confrontation with the high-precision observed values of these coefficients. We conclude that asteroseismology of β Cep stars has been highly successful during the past few years, and its future looks very promising given that several multisite campaigns of moderate rotators have been done but are not yet exploited and CoRoT will be launched very soon.

Between one and five frequencies of g modes have been established in the brightest among the SPB stars, from long-term photometric and spectroscopic campaigns. This is rather disappointing, given the large observational effort that went into this result. The example of the SPB star HD 163830 observed by MOST makes it clear that one needs photometry from space with a high duty cycle to make efficient progress in the detection of frequencies for these stars. The same holds true for the g modes in Be stars and B supergiants. We are eagerly awaiting the results from CoRoT in this respect.

The oscillations detected in Be stars and very-late Oe stars show a multitude of different behaviour, which is in full accordance with the one of β Cep stars and SPB stars. It seems that pulsating Be stars are complicated analogues of the SPB stars, while the ζ Oph stars undergo the same oscillations than β Cep stars, but the members of both these classes having emission lines in their spectrum rotate typically above half of the critical velocity, with some rotating very close to critical velocity. It remains to be studied what the role of the oscillations is in the disk formation for the class of Be stars as a whole.

Probing of B supergiant models has recently come within view, with the discovery of nonradial g modes in such a star by the MOST mission. This case study is complemented by the interpretation of the variability of the Hipparcos lightcurves of a sample of some 40 B supergiants in terms of g modes. These two entirely independent studies open the upper part of the HR diagram for seismic tuning of stellar evolution models of supergiant stars, which are the precursors of stellar black holes. At present, none of the existing analysis codes include the effects of a radiation-driven stellar wind, which would be the next step towards apropriate modelling of detected oscillation frequencies in such stars.

By far the largest stumbling block in the application of asteroseismology to g-mode pulsators among the B stars is the lack of unambiguous mode identification and good models including rotation in a consistent way. On the observational side, this can only be resolved from coordinated initiatives, because it requires long-term multisite multitechnique campaigns, including multicolour photometry and high-resolution spectroscopy. Space photometry has the potential of detecting a much higher number of oscillations than ground-based photometry, as the MOST mission has shown us and will hopefully continue to do so. However, it cannot deliver the badly needed mode identification, because we do not have the comfort of dealing with frequency spacings as in solar-like oscillators. Moreover, the rotational splitting is of the same order or even larger than the separation between zonal g-mode frequencies of subsequent radial order, implying that the measured frequency spectrum is insufficient to unravel the nature of the detected modes. On the theoretical side, it is fair to state that we do not have appropriate seismic models for stars rotating at a considerable fraction of their critical velocity. Moreover, it was recently discovered that half of the SPB stars turn out to have a magnetic field [57], such that not only the Coriolis is important for such pulsators, but likely also the Lorentz force.

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