Part 4

Early-type stars: B, A and F pulsators

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g-mode pulsations in slowly pulsating B stars

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Abstract. In this paper, we give an updated overview of the observed characteristics of g-mode pulsations in slowly pulsating B stars. These characteristics are based on the combined results of linear nonadiabatic analysis of the oscillations and a photometric and spectroscopic mode identification for a sample of 13 members. For 4 stars, at least one mode is stable in all the considered theoretical models.

1. Introduction

As the result of a systematic, homogeneous photometric search for variable B stars, Waelkens (1991) discovered a group of 7 stars exhibiting the same photometric characteristics. These stars became the prototypes of an independent class of pulsating stars which he baptized "slowly pulsating B stars" (hereafter SPBs). They have masses between 3 and 7 $M_\odot$, spectral classes between B3 and B8, and show multiperiodic light variations with periods much longer than radial pulsations. All SPB prototypes are slow rotators. There are no phase lags between observations in different photometric passbands. The observed variations are understood in terms of g-mode pulsations with low spherical harmonic degrees, ℓ, and high radial order, n, excited by the κ-mechanism acting in the metal opacity bump (Dziembowski, Moskalik, & Pamyatnykh 1993; Gautschy & Saio 1993). For recent theoretical reviews, we refer to Pamyatnykh (2002) and references therein. In the following years, 5 new SPBs were found (North & Paltani 1994; Chapellier et al. 1996; Clausen 1996; Waelkens 1996) and 2 stars previously classified as "53 Per stars" could be reclassified as SPBs (Mathias &

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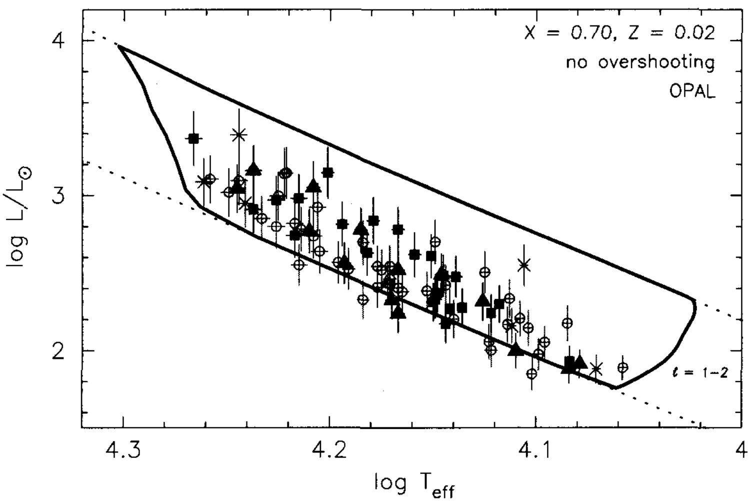

Figure 1. The position in the HR diagram of the confirmed SPBs detected before (triangles) and after (squares) the Hipparcos mission, together with the rejected (crosses) and remaining (circles) Hipparcos SPBs. We also show the ZAMS, the TAMS and the theoretical instability strip as given by Pamyatnykh (1999).

Waelkens 1995; Chapellier et al. 1998). This resulted in a total of 14 confirmed SPBs before the release of the photometric data of the Hipparcos satellite.

Thanks to the Hipparcos mission, some 100 new variable B stars were classified as "Hipparcos SPBs" (Waelkens et al. 1998) for which the SPB-character should be confirmed by additional observational evidence. In the scope of his PhD work, De Cat (2001) conducted a photometric and spectroscopic observational study of a sample of 19 bright *southern* candidate SPBs, including 5 of the original SPB prototypes. However, one target is an ellipsoidal variable without any evidence for intrinsic variability (De Cat et al. 2000) and four targets are spotted stars (Briquet et al. 2003). The spectroscopic follow-up study of Mathias et al. (2001) revealed the (multiperiodic) line-profile variations for 8 bright *northern* Hipparcos SPBs, confirming their SPB-character. Thanks to the multicolor photometric observations obtained during the first observation seasons of the Mercator telescope (La Palma, Spain), multiperiodic variations were found for another 6 northern Hipparcos SPBs while the variations seen for 3 other objects situated within the SPB instability strip point towards ellipsoidal variables or spotted stars (De Cat et al., these proceedings). Hence, there are currently 37 confirmed SPBs and some 50 Hipparcos SPBs (Fig. 1). Pigulski et al. (these proceedings) have recently found the first observational evidence for extragalactic SPBs in the LMC.

In the following, we will focus on the most recent results obtained for the 5 SPB prototypes and the 8 confirmed SPBs resulting from the PhD work of De Cat (2001). Many of these stars have low frequencies, and it appears that in some cases it is impossible to get unstable modes, if the solar metal abundance

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Table 1. Overview of the 13 targets considered in this study. The SPB prototypes are indicated with $*$. For the meaning of the different columns, we refer to the text.

star	Geneva photometry			IUE/INES spectra			Si II	
	$\log T_{\rm eff}$	$\log g$	n_p	$\log T_{\rm eff}$	$\log g$	$[m/H]$	n_s	n_t
HD 74560$*$	4.210(4)	4.15(14)	5+	4.227(13)	4.07	-0.03(18)	2	5+
HD 74195$*$	4.208(3)	3.91(16)	4+	4.208(16)	3.75	-0.28(21)	4	4+
HD 123515$*$	4.079(2)	4.27(09)	4+				2	4+
HD 26326	4.182(3)	4.14(14)	2	4.176(18)	3.96	-0.27(22)	2	3
HD 85953	4.266(4)	3.91(17)	2				2	3
HD 138764	4.148(3)	4.20(12)	2				2	3
HD 215573	4.145(3)	4.09(13)	2	4.153(06)	4.05	-0.25(16)	1	2
HD 177863$*$	4.126(2)	4.15(12)	1+	4.158(58)	4.04	-0.16(37)	1	1+
HD 181558$*$	4.167(3)	4.16(13)	1+	4.175(19)	4.08	-0.15(22)	1	1+
HD 24587	4.142(2)	4.26(12)	1				1	1
HD 53921	4.136(2)	4.23(12)	1				1	1
HD 92287	4.215(4)	4.00(15)	1				1	1
HD 140873	4.144(3)	4.35(12)	1				1	1

is adopted. The results of these instability calculations and attempts to identify the excited modes will be discussed in Section 2. We end with an updated list of the observational SPB characteristics and some future prospects in Section 3.

2. Recent progress

2.1. Stellar parameters

The most recent determination of stellar parameters for a sample of 13 confirmed SPBs, of which 9 are multiperiodic, is given in Table 1. We list the number of frequencies detected in respectively the Geneva photometry (n_p), the line profile variations of the $\lambda\lambda$ 4130 Å Si II doublet (n_s), and all data sets combined (n_t). We also list the effective temperature $\log T_{\rm eff}$ and the surface gravity $\log g$ derived from the mean Geneva observations under the assumption of solar metallicity (De Cat & Aerts 2002). Recently, Niemczura (2003) used the ultraviolet IUE spectra, which contain a lot of metal lines for B stars, for the determination of, amongst others, $\log T_{\rm eff}$ and the metallicity $[m/H]$. She also used photometric observations for a redetermination of $\log g$ with different methods. In Table 1, we list the results found with IUE spectra obtained with the INES reduction procedure. In Fig. 2, we compare the Geneva and IUE parameters for all the candidate and confirmed SPBs considered by Niemczura (2003). In the left panel, a ($\log T_{\rm eff}$,$[m/H]$) diagram is given. The bold arrow on the left indicates the mean differences. The IUE metallicities are all lower than solar, with a mean value of $\overline{[m/H]} \simeq$ -0.23 dex ($\overline{Z} \simeq 0.012$). These metallicities are fully compatible with those found for normal B stars (Niemczura 2003). The IUE effective tem-

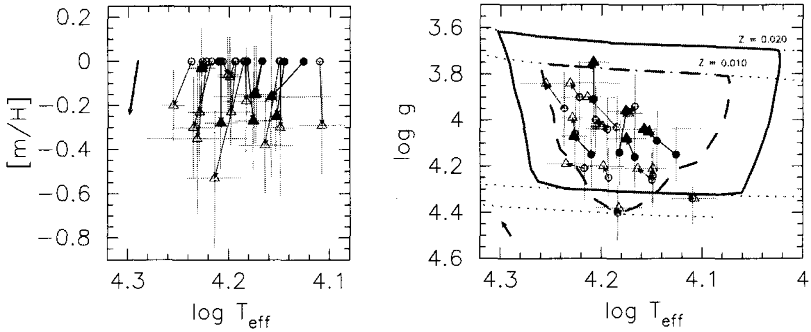

Figure 2. Comparison of the stellar parameters obtained from Geneva photometry (circles) and from IUE/INES spectra (triangles) for the sample of confirmed and suspected SPBs as given by Niemczura (2003). The targets discussed in this paper are given with full symbols. In each panel, the arrow represents mean differences from both data. In the right panel, we also show the ZAMS (lower dotted lines), the TAMS (upper dotted lines) and the theoretical instability strips for $Z = 0.020$ (full line) and $Z = 0.010$ (dashed line) for SPB modes with $\ell \leq 2$, computed using the OPAL opacities for stellar models with $X = 0.70$ for which effects of rotation and convective overshooting were not taken into account (Pamyatnykh 1999).

peratures are generally higher than those from the Geneva data. In the right panel of Fig. 2, we compare the positions of the stars in an HR diagram. We also show the ZAMS (lower dotted lines), the TAMS (upper dotted lines) and the theoretical instability strips for $Z = 0.020$ (full line) and $Z = 0.010$ (dashed line) for SPB modes with $\ell \leq 2$, computed using the OPAL opacities for stellar models with $X = 0.70$ for which effects of rotation and convective overshooting were not taken into account (Pamyatnykh 1999). The theoretical instability strip shrinks for lower Z and shifts towards higher $\log g$ values. The IUE $\log g$ values are lower than the Geneva $\log g$ values. This, in combination with the low IUE Z values, suggests that the SPBs are older than previously thought.

2.2. Instability for the observed frequencies

All theoretical calculations were performed using the Warsaw-New Jersey evolutionary code and the pulsational nonadiabatic code of Dziembowski (1977). For 6 of our target stars, we did not find unstable modes close to the observed frequencies *if* the stellar parameters from Geneva photometry and solar metallicity were adopted. Decreasing the metallicity parameter Z helped in most cases. This at first sight surprising result is explained as follows: for lower values of Z, the range of unstable modes is more narrow but this range is shifted towards lower frequencies. Additional, this result is in agreement with the recent metallicity determinations of Niemczura (2003). The detailed study of mode excitation for selected SPBs will be presented by Daszyńska-Daszkiewicz et al. (in preparation).

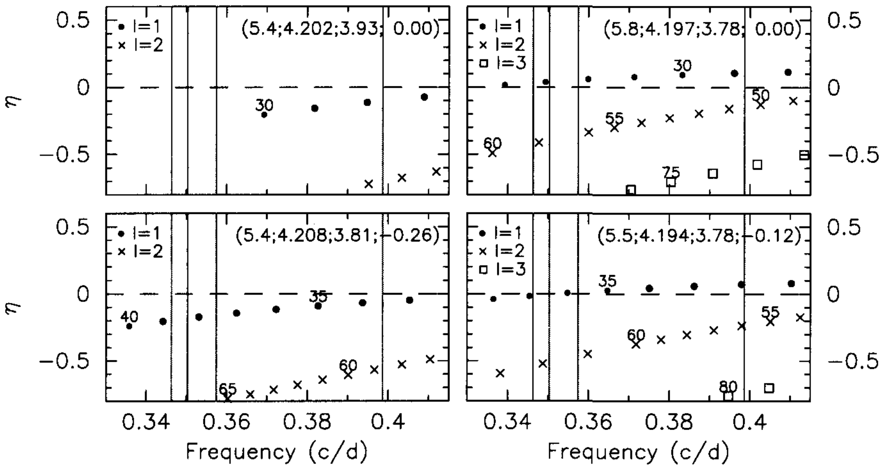

Figure 3. The normalized growth rate η as a function of frequency for several models of HD 74195, for different spherical harmonic degrees ℓ. The observed frequencies are indicated by vertical lines. The values of stellar parameters ($M/\mathrm{M}_\odot$, $\log T_{\rm eff}$, $\log g$, $[m/H]$) are given in each panel. Positive values of η correspond to unstable modes. For some modes, the value of the radial order, n, is also indicated.

We illustrate the instability of modes for HD 74195, for which there are 4 well-known observed intrinsic frequencies: $\nu_1 = 0.35745\,\mathrm{d}^{-1}$, $\nu_2 = 0.35033\,\mathrm{d}^{-1}$, $\nu_3 = 0.34630\,\mathrm{d}^{-1}$, and $\nu_4 = 0.39864\,\mathrm{d}^{-1}$ (De Cat & Aerts 2002). In Fig. 3, we show the normalized growth rate η as a function of frequency for some of the considered models. Positive values of η correspond to unstable modes. The intrinsic frequencies of HD 74195 are indicated by vertical lines. For the stellar parameters close to the Geneva parameters of HD 74195 (Fig. 3, upper left panel), there are no unstable modes in the observed frequency range. By increasing the mass (Fig. 3 upper right panel), $\ell = 1$ modes become unstable. The same instability problem occurs for stellar parameters close to the IUE parameters (Fig. 3, lower left panel). Again, by changing these parameters within the observed error boxes, we do find unstable $\ell = 1$ modes close to the observed frequencies but with slightly different n values (Fig. 3, lower right panel). Note at least two frequencies (ν_3 and ν_2) must be part of the same frequency triplet.

So far, the instability problems could not be solved for one of the observed frequencies of HD 26326 and HD 74560. For HD 85953 and HD 92287, none of the observed frequencies are unstable in the considered models.

2.3. Photometric mode identification

When considering a multicolor photometric system, amplitude ratios and phase differences can be used to identify the degree ℓ of modes. From a theoretical point of view, a large variety of both amplitude ratios and phase differences

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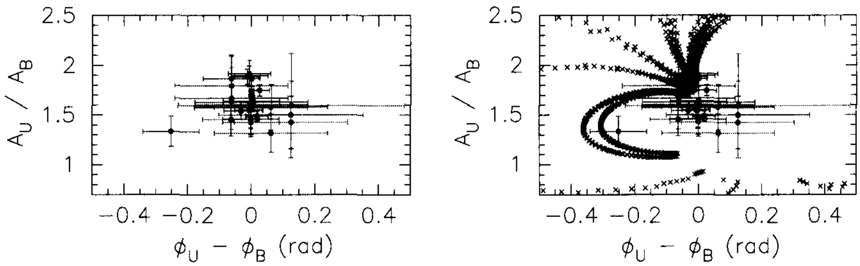

Figure 4. Photometric diagnostic diagram for the Geneva U and B filters, for $\ell = 1$ (left) and $\ell = 2$ (right) unstable modes. The observed values are shown with error box. The theoretical observables were calculated for stellar parameters corresponding to the observed values and their error box.

can be found for SPB pulsators. This is illustrated in Fig. 4 where we show a photometric diagnostic diagram for the Geneva U and B filters, for $\ell = 1$ and $\ell = 2$ unstable modes. However, from an observational point of view, we only find a very small range of observed phase differences centered around 0 radians. When minimizing a χ^2 based on *all* the amplitude ratios and all phase differences in the different passbands of the Geneva photometric system, the results point towards $\ell = 1$ modes for all modes except those of HD 123515 for which we can not discriminate between $\ell = 1$ and $\ell = 2$. For HD 53921, we find a very high χ^2-value. This is not surprising since we are dealing with a close visual binary for which both components have comparable stellar parameters. Hence, the observed light originates from both visual components.

2.4. Spectroscopic mode identification

In the moment method as given by Aerts (1996), the modes are identified by comparing the observed *amplitudes* of the first 3 velocity moments of a line profile with the theoretical ones found for a grid of parameters including ℓ, the azimuthal number m, the inclination i and the projected rotational velocity v_Ω. For multiperiodic pulsators, the amplitudes of interaction terms are neglected. Recently, Briquet & Aerts (2003) introduced a new version where the discriminant Σ compares the observed moment *values* with theoretical ones calculated by considering all the interaction terms for multiperiodic pulsators, and, if wanted, the Coriolis force. Unfortunately, for SPBs, the results of the moment method are generally not conclusive. This is illustrated in Table 2 and Fig. 5, where we show the five best models found for HD 74195 with the new code. The difference in Σ-value for these models is negligible pointing out that all these combinations of modes are equally probable, thus their moment variations are hard to distinguish (see Fig. 5). None of these 5 models solely consist of $\ell = 1$ modes. However, the difference in Σ-value with the best such model is still small, so this combination is also among the possibilities. This example is illustrative for most other SPBs.

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Table 2. Results of the moment method for HD 74195 when neglecting the Coriolis force (Briquet & Aerts 2003). We show the five best overall models together with the best model solely consisting of $\ell = 1$ modes. The last column denotes the line style used in Fig. 5.

Σ	(ℓ_1,m_1)	(ℓ_2,m_2)	(ℓ_3,m_3)	(ℓ_4,m_4)	i (°)	v_Ω (km s^{-1})	σ (km s^{-1})	Fig. 5
5.03	(1,0)	(3,-3)	(1,0)	(3,2)	65	11	9	full
5.04	(2,0)	(3,-3)	(2,0)	(3,2)	75	12	9	dashed
5.06	(2,0)	(1, 1)	(2,0)	(1,-1)	40	23	1	dash-dot
5.06	(1,0)	(3,-2)	(1,0)	(3,2)	50	13	9	dotted
5.07	(1,0)	(3,-2)	(3,0)	(3,2)	55	15	8	dash-dot-dot-dot
⋮								
5.11	(1,0)	(1, 1)	(1,0)	(1,-1)	45	23	3	bold full
⋮								

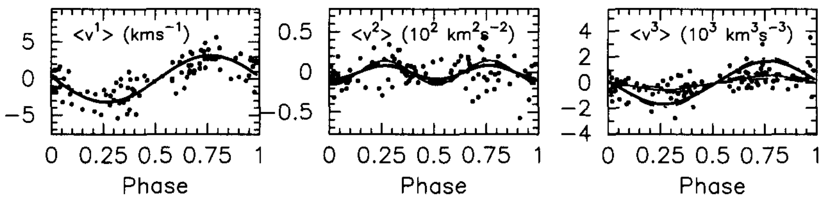

Figure 5. Phase diagrams for $\nu_1 = 0.35745\,\mathrm{d}^{-1}$ for the observed moments (dots) of HD 74195 after prewhitening with the $\nu_2 = 0.35033\,\mathrm{d}^{-1}$, $\nu_3 = 0.34630\,\mathrm{d}^{-1}$, and $\nu_4 = 0.39864\,\mathrm{d}^{-1}$ and the appropriate interaction frequencies. The lines correspond to prewhitened theoretical moments calculated for pulsational parameters as given in Table 2.

3. Conclusions and Future Prospects

The majority of the confirmed SPBs show multiperiodic photometric and spectroscopic variations. In some cases, we observe *small* phase lags between observations in different photometric passbands. According to photometric identification methods, the observed modes are *generally* $\ell = 1$ modes. Unfortunately, spectroscopic identification methods do not lead to conclusive results in most cases. According to the theoretical models, the values for the radial order n are found between 10 and 40. However, not all of the observed frequencies correspond to unstable modes. From the instability calculations, we find $Z < 0.020$, which is in agreement with the chemical analysis of IUE spectra.

For the most promising targets with evidence for frequency multiplets, we will conduct a more in-depth theoretical modeling.

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Discussion

Handler: If you look at the positions of the coolest SPB stars in the HR diagram for each mass, the *observed* instability strip becomes wider if you go from low to high mass. If true, how is this to be understood?

De Cat: If this were true, I would not have an explanation, but I am not convinced that there is such an observed trend. There are still a lot of candidate Hipparcos SPBs which are not studied in full detail yet which might enlarge the observed instability strip for low masses.

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Jerzykiewicz: How many singly-periodic stars are there among the SPB stars?

De Cat: At this moment, 9 out of 37 confirmed SPBs *appear* to be monoperiodic. In my opinion, one should be very careful before classifying a star as a monoperiodic SPB, especially when only photometric observations are available. First of all, they are only monoperiodic up to the current detection limits. Moreover, these stars can still show multiperiodic line-profile variations. On top of that, I have experienced that it is very easy to confuse variations of ellipsoidal variables and/or spotted stars with those of a "monoperiodic SPB".

Guzik: Does the observation that $Z < 0.02$ for all those stars surprise you? Are the surface abundances representative of the entire star, or of the driving region at 200 000 K, or could they have been reduced/changed by levitation or diffusion?

De Cat: At this moment, we are not at all sure that the surface abundances are representative for the abundance in the driving region. There is an urgent need for diffusion calculations for stars with $M > 2\,M_{\odot}$. As far as I know, such calculations have not been done yet.

Percy: Historical comment: in addition to slowly-pulsating B stars, and β Cep stars (which are radial pulsators), there are non-radially pulsating stars ("line profile variables") which are *not* slowly pulsating. They should not be forgotten.

De Cat: Line-profile variable counterparts of SPBs are indeed known. Already in the late 1970s, Myron Smith and his collaborators had done a search for line-profile variability in stars surrounding the β Cep stars. In this way, spectroscopic variables with spectral types between O9 and B5 were discovered. These stars were termed 53 Per stars after one of the targets. It has meanwhile become clear that the coolest among Smith's variables are SPBs, but the explanation for the hotter stars in Smith's list is less clear. For this reason, the term SPBs was chosen, as these stars have common pulsational properties and one well-understood pulsation mechanism, while this is not the case for the 53 Per stars. I also want to stress that β Cep stars not only pulsate in radial modes. β Cru is a good example of a β Cep star for which only non-radial modes are observed (so far).