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Instability strips of slowly pulsating B stars and β Cephei stars: the effect of the updated OP opacities and of the metal mixture

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ABSTRACT

The discovery of β Cephei stars in low-metallicity environments, as well as the difficulty in theoretically explaining the excitation of the pulsation modes observed in some β Cephei and hybrid slowly pulsating B–β Cephei pulsators, suggest that the 'iron opacity bump' provided by stellar models could be underestimated. We analyze the effect of uncertainties in the opacity computations and in the solar metal mixture on the excitation of pulsation modes in B-type stars. We carry out a pulsational stability analysis for four grids of main-sequence models with masses between 2.5 and 12 $M_{\odot}$ computed with OPAL and OP opacity tables and two different metal mixtures. We find that in a typical β Cephei model the OP opacity is 25 per cent larger than OPAL in the region where the driving of pulsation modes occurs. Furthermore, the difference in the Fe mass fraction between the two metal mixtures considered is of the order of 20 per cent. The implication on the excitation of pulsation modes is non-negligible: the blue border of the slowly pulsating B star (SPB) instability strip is displaced at higher effective temperatures, leading to a larger number of models being hybrid SPB-β Cephei pulsators. Moreover, higher overtone p-modes are excited in β Cephei models and unstable modes are found in a larger number of models for lower metallicities, in particular β Cephei pulsations are also found in models with $Z = 0.01$.

Key words: radiative transfer – stars: abundances – stars: early-type – stars: interiors – stars: oscillations – stars: variables: other.

1 INTRODUCTION

At the beginning of the nineties, OPAL opacity tables (Rogers & Iglesias 1992) signified a revolution in stellar physics. In particular, an increase of the Rosseland mean opacity (κ_{R}) as large as a factor of 3 for temperatures near 3×10^5 K (known as 'Z-bump') allowed one to solve the long-standing problem of B-type pulsators: β Cep and slowly pulsating B stars (SPB) pulsate due to a κ-mechanism activated by this metal opacity bump (Cox et al. 1992; Kiriakidis, El Eid & Glatzel 1992; Moskalik & Dziembowski 1992; Dziembowski, Moskalik & Pamyatnykh 1993). Subsequent improvements in opacity calculations by including other iron-group elements in the metal mixture and intermediate-coupling for Fe transitions have led to an additional enhancement of opacity at $\log T \sim 5.2$ and low densities, and therefore to a decrease of the still remaining discrepancies between theoretical pulsation models and observations. The stability analysis of B-stars by Pamyatnykh (1999) for models computed with updated OPAL and OP opacity tables (Opacity Project, Seaton 1996, and references therein) allowed to conclude that theoretical standard models were able to explain most of the observed β Cep and SPB stars.

However, as observational capabilities progress, B-type pulsators are now found in low-metallicity environments (see e.g. Kołaczkowski et al. 2006, and references therein), and a large number of pulsation modes are being detected in B stars, with frequency domains sometimes revealing new discrepancies between theory and observations. For instance, the two β Cep stars 12 Lacertae and ν Eridani present low order p-modes with frequencies larger than those predicted by pulsation models, as well as high-order g-modes (SPB-type oscillation) (Handler et al. 2006; Jerzykiewicz et al. 2005, and references therein). In order to explain these pulsation features in ν Eri, Pamyatnykh, Handler & Dziembowski (2004) proposed a local enhancement of iron in the 'Z-bump' region, like Cox et al. (1992) suggested to overcome the difficulties to explain β Cep pulsations with the first OPAL opacity tables.

Regardless of whether or not other additional physical processes must be included in the B-type stellar modelling, we propose here to first analyse the uncertainties in the predictions of B-type pulsation models due to the uncertainties in the basic physical inputs in the standard model.

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It is known (see e.g. Moskalik & Dziembowski 1992) that stellar pulsation models are sensitive to ∼20 per cent changes in opacity. Recent improvements in OP opacity computations have, on the one hand, increased the opacity in the regions where OP values were previously much lower than OPAL values, leading to a good agreement between both calculations. On the other hand, the new atomic data provide a 18 per cent enhancement of opacity in the Z-bump region.

Besides, the chemical composition of the Sun and of B-type stars is still matter of lively debate (see e.g. the works of Asplund et al. 2005; Cunha, Hubeny & Lanz 2006). In this work we therefore investigate the impact that the uncertainties about the metal mixture have on the instability strips of B-type stars, as well as on the frequency domain of excited modes.

2 METAL MIXTURES

The recent re-analysis of the solar spectrum by Asplund et al. (2005) (hereafter AGS05), including the non-local thermodynamic equilibrium (NLTE) effect as well as tri-dimensional model atmosphere computations, has led to a significant decrease of C, N, O and Ne solar abundances leading to a solar metallicity 30 per cent smaller than the value provided by the 'standard' GN93 mixture (Grevesse & Noels 1993). The corresponding decrease in solar opacity (∼20 per cent) at the base of the convective envelope ruins the good agreement between the standard solar model and the seismic one. These new CNO abundances, however, agree with spectroscopic measurements in B-type stars, and solve the old discrepancy between a supermetallic Sun and the chemical composition of B-type stars and H II regions in the solar environment (Turck-Chièze et al. 2004; Cunha et al. 2006, and references therein). On the other hand, while the lower O abundance in AGS05 mixture decreases the opacity at the bottom of the convective envelope and increases the discrepancy between the standard solar model and helioseismology, an iron mass fraction 25 per cent larger in the new mixture with respect to the GN93 one will favourably affect the excitation of β Cep and SPB pulsation modes in early-type stars.

Among the different solutions suggested to recover the agreement between the standard model and helioseismology, an enhancement of the Ne abundance by a factor ∼3.5 with respect to the Asplund et al. (2005) value has been proposed by Antia & Basu (2005) and Bahcall, Basu & Serenelli (2005). The increase of Ne would compensate for the opacity lost due to the O abundance drop. The problem is that Ne cannot be directly measured in the solar photosphere. Cunha et al. (2006) suggested that determining non-LTE Ne abundances in a sample of 11 B-star members of the Orion association could help to solve the problem of Ne abundance. The studied stars span an effective temperature range from 20 000 to 29 000 K. The result of this work is a Ne abundance in B-type stars 0.3 dex larger than in the Asplund et al. (2005) mixture, but CNO in agreement with the new solar abundances.

In the following sections we will adopt Asplund et al. (2005) mixture with A(Ne) = 8.11 from Cunha et al. (2006) as the new metal mixture (AGS05 + Ne) for B-type stars, and we will compare results obtained with the 'standard' GN93. The renormalization of AGS05 + Ne to keep the same molecular weight results finally in an enhancement of ∼20 per cent in the iron and nickel mass fractions with respect to GN93. In Fig. 1 the dotted curves show the relative differences in the Rosseland mean opacity between GN93 and AGS05 + Ne (for the same metal mass fraction $Z = 0.02$) for the structure of a 4- and a 10-$\mathrm{M}_{\odot}$ model. The effect of the enhancement of Fe and Ni is to increase the height and the width of the Z-bump of the Rosseland mean opacity (κ_{R}). The consequences on the excitation of pulsation models are described in Section 5.

3 OPACITIES: OPAL VERSUS OP

OP opacity tables have recently been updated, including data for the inner-shell transitions, inter-combination lines and improvements in photoionization cross-sections (Seaton 2005; Badnell et al. 2005). These changes result in an enhancement of κ_{R} at high density and temperatures, and an increase of 18 per cent of opacity in the Z-bump due to the new Fe atomic data. The new OP opacity tables are much closer to the OPAL ones than they were previously (Seaton et al. 1994). In particular, the differences at high temperature and high density have almost disappeared. Some differences remain, however, at low temperatures ($\log T < 5.5$): the OP Z-bump in κ_{R} presents a hot wing slightly larger than the OPAL one. The comparisons between OP and OPAL by Badnell et al. (2005) at fixed $\log R (R = \rho/T_6^3)$ show that for high densities the differences

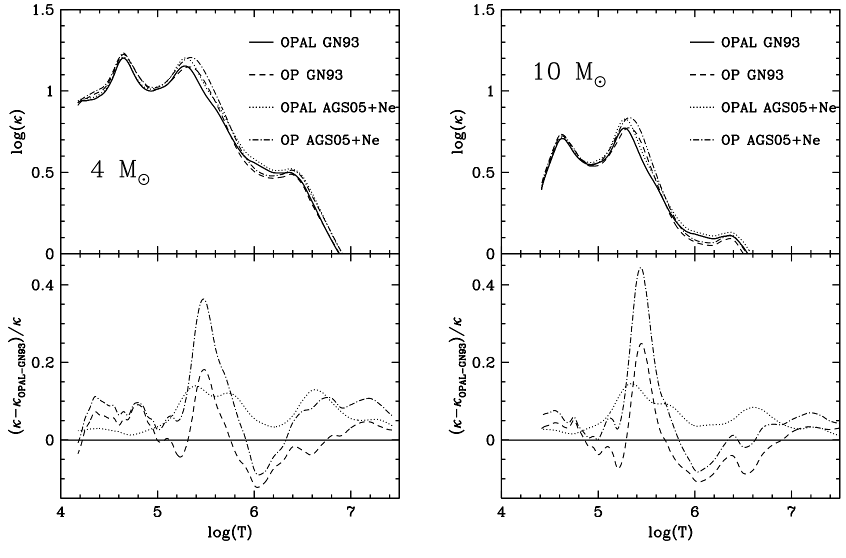

Figure 1. Comparison between opacities computed with OPAL, OP and with different metal mixtures in the structure of a 4- and a 10-$\mathrm{M}_{\odot}$ model on the ZAMS.

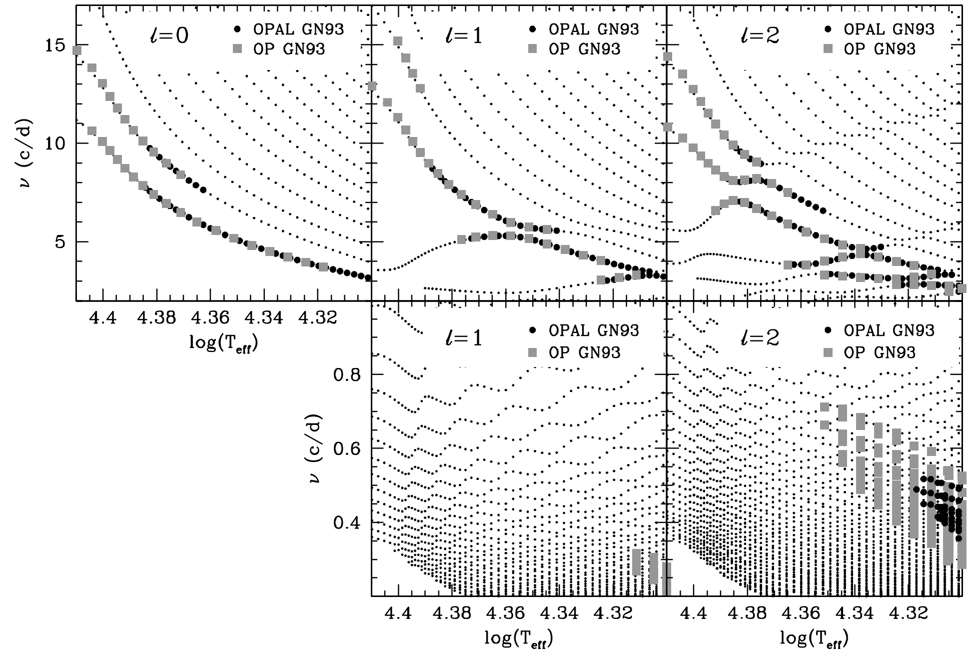

Figure 2. Frequencies of pulsation modes as a function of $\log T_{\mathrm{eff}}$ for main-sequence models of a 10-M$_{\odot}$ $Z = 0.02$ star. Unstable modes are described by large black dots and grey squares when models are computed, respectively, with OPAL-GN93 and OP-GN93 opacity tables. Lower panels represent high-order g-modes.

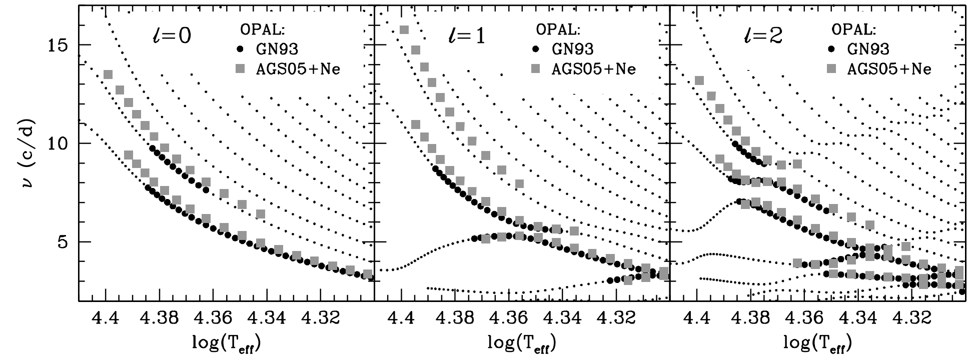

Figure 3. As in Fig. 2, but comparing models computed with OPAL-GN93 and OP-AGS05 + Ne opacity tables.

are of the order of 5–10 per cent, but at low density ($\log R \sim -4$), differences of up to 30 per cent appear due to the differences in the high-temperature wing of the Z-bump.

The previous OP tables (Seaton et al. 1994) already presented a Z-bump in κ_{R} shifted by 15 000–20 000 K to higher temperatures compared with OPAL. The effect of this difference on the instability strip of β Cep and SPB stars was studied by Pamyatnykh (1999). In that study, however, OP and OPAL opacity tables had also small differences in heavy elements abundances: Ni is 5 per cent more abundant in OP than in OPAL, and Ne and Fe are ~2–3 per cent more abundant in OP.

Ni and Fe are the main contributors to the Z-bump, and Ni contributes to the Z-bump in κ_{R} at higher temperatures than Fe (see e.g. Jeffery & Saio 2006). In order to separate metal mixture effects from opacity calculation ones, we obtained OP opacity tables from the OPserver[1] for the same GN93 and AGS05 + Ne metal mixture as OPAL. The abundances of the four elements that are not included in OP (P, Cl, K, Ti) are redistributed among the other 15 elements. Doing so, the abundance differences between OP and OPAL opacity table computation are at maximum 0.06 per cent.

In Fig. 1 we show the difference in opacity for the internal structure of two stellar models with the typical masses of an SPB (4 M$_{\odot}$) and a β Cep (10 M$_{\odot}$). We see that for the lower-mass model the opacity differences in the Z-bump region are of the order of 20 per cent, and even larger for the 10-M$_{\odot}$ model.

4 STELLAR MODELS

Stellar models have been computed with the code CLES (Code Liégeois d'Evolution Stellaire, Scuflaire 2005). The main physical inputs are: the OPAL2001 equation of state (Rogers & Nayfonov 2002) and Caughlan & Fowler (1988) nuclear reaction rates with Formicola et al. (2004) for the $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ cross-section. Convective transport is treated by using the classical Mixing Length Theory of convection (Böhm-Vitense 1958), and a convective overshooting

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[1] http://vizier.u-strasbg.fr/topbase/op.html

parameter of 0.2 pressure scaleheight was assumed in all the models. For the chemical composition we have considered: GN93 and AGS05 + A(Ne) = 8.11. We have computed models with: (i) OPAL opacity tables with GN93 and (ii) AGS05 + Ne chemical composition, then models with (iii) OP opacity tables assuming GN93 and (iv) AGS05 + Ne mixtures. All the opacity tables are completed at $\log T < 4.1$ with the corresponding GN93 and AGS05 low temperature tables by Ferguson et al. (2005). The masses considered span from 2.5 to 12 $\mathrm{M}_{\odot}$, and the chemical composition considered are: $X = 0.70$ for the hydrogen mass fraction and three different metal mass fractions; $Z = 0.02$, 0.01 and 0.005. For all the models the evolution was followed from the pre-main sequence.

5 STABILITY ANALYSIS

As oscillations in β Cep and SPB stars are driven by the κ-mechanism acting in the Z opacity bump, the location of the instability strip in the HR diagram and the frequency of the excited modes are determined by the properties of the metal opacity bump. In models with the new OP opacity tables, the driving region, that is, the region where $\kappa_{\mathrm{T}} = (\partial \log \kappa_{\mathrm{R}} / \partial \log T)_{\rho}$ increases outwards, is found deeper in the star with respect to the models computed with OPAL. As a consequence, we expect hotter B-type pulsators with OP models compared to OPAL ones.

We perform stability analyses of main-sequence models from our grid using the non-adiabatic code MAD (Dupret et al. 2003). Fig. 2 shows different effects of OP and OPAL on the excitation of the p-modes (upper panels) and the high-order g-modes (lower panels) for main sequence models of a 10-$\mathrm{M}_{\odot}$ star with initial chemical composition given by $X = 0.70, Z = 0.02$ and the GN93 metal mixture. For p-modes (or low-order g-modes), we see that in the common instability region, OPAL and OP predict the same excited modes, and their frequencies are not affected by opacity differences. There is, however, a significant effect on the hottest unstable models. While OPAL models with excited radial modes are expected only for $X_{\mathrm{c}} < 0.5$, zero-age main sequence (ZAMS) OP models have $\ell = 0$ modes excited.

The differences between OP and OPAL are even more pronounced for high-order g-modes. There are many more excited modes for OP models than for the OPAL ones. For instance, for a 10-$\mathrm{M}_{\odot}$ star, the OP model with $X_{\mathrm{c}} = 0.2$ presents excited modes of $\ell = 2$ going from g_{16} to g_{21}, and the terminal-age main-sequence (TAMS) model has $\ell = 1, g_{31}$–g_{43} and $\ell = 2, g_{28}$–g_{53} excited. In OPAL models, instead, no $\ell = 1$ high-order g-mode is excited; the first excited $\ell = 2$ g-modes appear at $X_{\mathrm{c}} = 0.1$, and in the TAMS model the order of the excited g-modes goes from $n = 34$ to $n = 48$. The T_{eff} domain for which we find excited SPB-modes is therefore ~3000 K larger than for OPAL models. As a consequence, the number of expected hybrid β Cep–SPB objects is also larger for OP models [see right-hand panels in Fig. 2, and panels a and c in Fig 4(below)]. These results are similar to those obtained by Pamyatnykh (1999) with the previous OP opacity tables. In fact, the higher Fe and Ni abundances in the original OP mixture are balanced now by a 18 per cent higher opacity at the Z-bump. Pamyatnykh (1999) noted that the shift of the Z-bump towards higher temperatures leads to an increase of the β Cephei and SPB instability domains towards higher T_{eff} and luminosity with respect to OPAL models. These results, however, have not been taken into consideration to explain the high-order g-modes detected in the β Cep stars 12 Lac and ν Eri. The instability strips for OP and OPAL models, with GN93 mixture and metal contents $Z = 0.02$ and $Z = 0.01$ are shown (below) in Fig. 4, panels a and b. We see that the impact of OP is more important for lower metallicity. In fact, the expected OP β Cep pulsators in the Large Magellanic Cloud (LMC) ($Z = 0.01$) would be more than two times larger than estimated from OPAL stellar models.

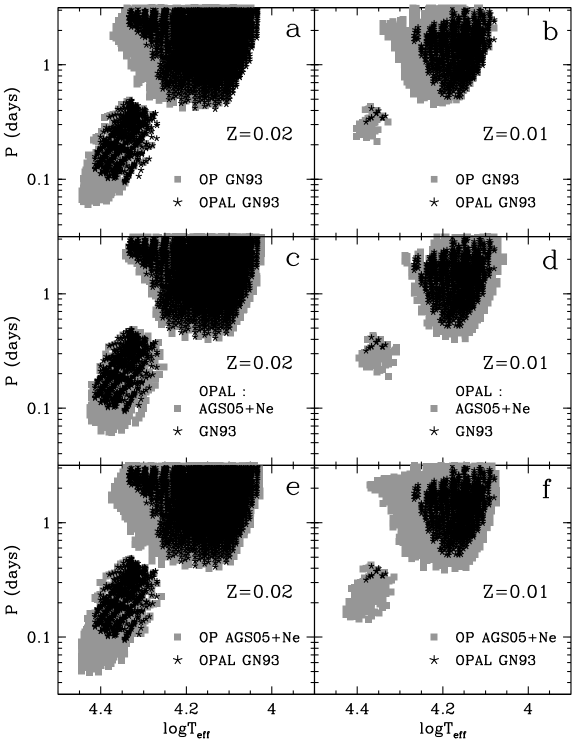

Figure 4. Instability strips represented in a $\log T_{\mathrm{eff}}$–$\log P$ diagram. In each panel, the two regions of unstable modes represent β Cep- and SPB-type pulsations.

The Fe-mass fraction enhancement in the AGS05 + Ne mixture, compared with GN93, has the main effect of extending towards higher overtones the range of excited frequencies. Fig. 3 shows the $\ell = 0$, 1 and 2 excited p-modes for 10-$\mathrm{M}_{\odot}$ main-sequence models calculated with OPAL opacity tables for the two different metal mixtures. AGS05 + Ne models also provides slightly wider instability bands, and this effect increases as metallicity decreases (see Figs 4b and d), thus, the expected β Cep pulsators for LMC predicted with AGS05 + Ne would be more than three times larger than with GN93.

Finally, if we consider the combined effect of the OP opacities and AGS05 + Ne metal mixture, we see that the large difference in κ_{R} described in Fig. 1 is reflected in wider instability strips, in the excitation of higher overtones in β Cep models and in a significantly larger number of β Cep pulsators for $Z = 0.01$ (see Figs 4e and f).

Computations for the lower metallicity corresponding to SMC ($Z = 0.005$) show that none of the different OP/OPAL and GN93/AGS05 + Ne evolutionary tracks for masses up to 12 $\mathrm{M}_{\odot}$ predict β Cep pulsators, whereas we find SPB-type modes excited when considering OP with AGS05 + Ne.

6 CONCLUSIONS

We have shown that the current uncertainties on opacity calculations and on the solar metal mixture adopted in standard stellar models, have a considerable effect on the excitation of pulsations in β Cep and SPB stars. Compared to models computed with OPAL opacities and GN93 metal mixture, we find that with OP opacities high-order g-modes are predicted to be excited in hotter stars and that higher overtones are excited if the AGS05 + Ne metal mixture is considered. For low metallicities, such as $Z = 0.01$, a larger number of models with excited modes is also found. These findings could help solving, at least partly, the discrepancies between theoretical predictions and observations of β Cep in low-metallicity environments and of a large domain of excited modes detected in some β Cep and hybrid SPB–β Cep pulsators. The detailed modelling of single stars, such as ν Eri, is however beyond the scope of this Letter and will be addressed in a forthcoming paper.

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