Gravity-mode pulsations in subdwarf B stars: a critical test of stellar opacity

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ABSTRACT
The identification of non-radial g-mode oscillations as the cause of variability in cool subdwarf B stars (PG1716 variables) has been frustrated by a 5 000 K discrepancy between the observed and theoretical blue edge of the instability domain (Fontaine et al. 2003). A major component in the solution to this problem has been identified by (a) using updated OP instead of OPAL opacities and (b) considering an enhancement of nickel, in addition to that of iron, in the driving zone. The reason for this success is that, in OP, the “Fe-bump” contributions from iron and nickel occur at higher temperatures than in OPAL. As well as pointing to a solution of an important problem in stellar pulsation theory, this result provides a critical test for stellar opacities and the atomic physics used to compute them.

Key words: atomic processes, radiative transfer, stars: interiors, stars: oscillations, stars: horizontal branch, stars: early-type

1 INTRODUCTION
Jeffery & Said (2006) recently reviewed the excitation of pulsations in certain low-mass stars by so-called “Fe-bump instability”. This instability is caused by a significant contribution to stellar opacity from M-shell electrons in iron-group elements at temperatures around 200 000 K (Rogers & Iglesias 1992; The Opacity Project Team 1995). It provides the driving mechanism for radial pulsations in certain extreme helium stars (Saio 1993) and p-mode oscillations in hot subdwarf B stars (EC14026 variables: after prototype EC14026–2647 ≡ V361 Hya) (Charpinet et al. 1996, 1997; Kilkenny et al. 1997).

The Fe-bump opacity mechanism is effective in these stars because of an increase in the contrast between opacity due to iron-group elements and opacity from other sources. In the case of extreme helium stars, the background hydrogen opacity is suppressed. In the case of EC14026 stars, Jeffery & Said (2006) demonstrated that, for radial and non-radial p-mode oscillations, the observed boundaries of the instability strip can be explained only by increasing the iron abundance (X_{Fe}) without increasing the heavy element abundance (Z) as a whole. It was already well known that radiative forces act differentially on the ions in the stellar envelope such that substantial chemical gradients are established over a diffusion time scale \( \sim 10^5 \) y (Michaud et al. 1980). The consequent levitation and accumulation of iron in layers at around 200 000 K (Chaver, Fontaine & Wesemael 1992) enhances the Fe-bump opacity sufficiently to excite pulsations in about 10% of sdB stars within the EC14026 instability zone (Charpinet et al. 2001).

The discovery of oscillations with periods of a few hours in many cool sdB stars (PG1716 variables: after PG 1716+426) has presented a challenge to stellar pulsation theory (Green et al. 2003). While the radiatively-driven diffusion of iron can still operate in these stars, p-modes were reported to be stable in the chemically stratified models (Charpinet et al. 2001). On the other hand, non-radial g-modes of high radial order (\( k \geq 10 \)) and high spherical degree (\( l \geq 3 \)) were found to be unstable, but only in models of stars cooler than those in which variability has been detected (Fontaine et al. 2003).

Jeffery & Said (2006) found that, for homogeneous models of blue horizontal branch stars, non-radial g-modes of high radial order (\( k \geq 10 \)) and low spherical degree (\( l \geq 2 \)) could be excited even without any enhancement of the iron abundance, but only in a narrow range of effective temperature around 18 000 K. The width of the g-mode instability strip and the number of excited modes increases substantially with increasing iron abundance, but Jeffery & Said (2000) were unable to obtain unstable g-modes for \( T_{\text{eff}} > 24 000 \) K. Even these modes were only obtained with iron enhanced by a factor of twenty over a base.
The motivation for this work is the general result that the theoretical g-mode blue edge is some 5000 K cooler than the hottest known PG1716 variables, Balloon 090100001 and HS 0702+6043, which have $T_{\text{eff}} \sim 29 500$ K (Oreiro et al. 2003; Schuh et al. 2004). Efforts to reduce this difference by varying the helium and iron abundances, and the overall metallicity, were unsuccessful.

Subsequently the authors have considered what other mechanisms might contribute to the instability of g-modes in PG1716 stars. This paper describes the surprising results that the explanation lies in the atomic physics used to compute the stellar opacities (section 2) and that the theoretical blue-edge can be reconciled with observation by considering the individual rôles of other iron-group elements including nickel (section 3). The consequences for theoretical models of stellar interiors and the atomic processes to be found therein are briefly considered (section 4), before conclusions are drawn (section 5).

## 2 STELLAR OPACITY

The motivation for this work is the general result that the position of an instability strip, i.e. the $T_{\text{eff}}$ range within which a star can be expected to pulsate, is dictated by the temperature of the opacity peak which provides the driving. In their original work, Jeffery & Saio (2006) considered variations in only helium ($Y$), all metals together ($Z_0$), and iron ($Z_{\text{Fe}}$) – the latter being the dominant element within the iron group by a large factor. However, if radiative acceleration acts on iron, it will also operate on other elements, particularly iron-group elements with electronic structures similar to that of iron.

Our first question was, therefore, whether an increased contribution of elements other than iron might alter the position (i.e. temperature) of the “Fe-bump”. This was addressed by obtaining tables of updated Rosseland mean opacities (Badnell et al. 2005) from the Opacity Project webserver for mixtures with $X = 0.7$, $Z_0 = 0.02$, but with elements chromium, manganese, iron and nickel individually enhanced by a factor $(f)$ of ten. Comparing these in the vicinity of the “Fe-bump”, it was evident that there are significant differences in the bump temperature for each element (Fig. 1). Considering the relative abundances of these elements (Table 1) and that we had simply multiplied by ten the default fraction of each element (as prescribed by the respective webservers), it was also apparent that nickel and chromium are highly effective absorbers. Significantly, the bump temperature of nickel is markedly higher than that of iron, whilst those of manganese and chromium are similar or lower. Therefore, we set out to investigate whether a nickel overabundance might drive g-mode pulsations at a higher $T_{\text{eff}}$ than iron.

Since our stellar structure code is designed to work with OPAL opacity tables, a new set of tables was obtained from the OPAL webserver with nickel enhanced by a factor $f_{\text{Ni}} = 20$, and other elements normal ($X = 0.70$, $Z_0 = 0.02$). A pulsation stability analysis was carried out for a series of zero-age horizontal-branch models, as described by Jeffery & Saio (2006). These new opacities had a negligible effect on the stability results, being essentially the same as for the mixture with $f_{\text{Ni}} = 1$ and $f_{\text{Fe}} = 20$.

The reason became apparent when the OPAL and OP opacities were compared. The peak temperatures of the bumps are significantly different in the two sets (cf. Figs. 1 and 10, Seaton & Badnell 2004). The Fe-bump occurs at a higher temperature in OP than in OPAL. The OPAL Ni-bump is at practically the same temperature as the OPAL Fe-bump (Fig. 2). It would be necessary to make the pulsation calculations using OP data.

This was achieved by obtaining single tables of Rosseland mean opacity from the OPAL webserver for mixtures $X = 0.70, 0.35, 0.10, 0.03, 0.0, Z_0 = 0.02$, and reformatting these to match the OPAL tables using the OP utility opfit (Seaton 1993). Type 2 OPAL tables were obtained from the OPAL webserver for the same standard mixtures, but including the 16 tables with enhanced C and O used to compute evolved stars as required by our codes. Both sets of tables were computed with elemental enhancements $f_{\text{Fe,Ni}} = (1, 1); (20, 1); (1, 20);$ and $(10, 10)$.

To use the OP tables within our codes, the OPAL tables were read in first. The OP tables were then read in to replace the corresponding tables with no enhanced C and O. This works because the interpolations required for modelling the H-rich layers of ZAHB stars make no use of the tables with enhanced C and O.

### 3 G-MODES IN BLUE HORIZONTAL-BRANCH STARS

As previously (Fontaine et al. 2003; Jeffery & Saio 2006), we have assumed that the PG1716 variables are extreme horizontal branch stars and have constructed series of “zero-age” horizontal-branch (ZAHB) models having a helium-burning core with a mass of $M_c$ and with a hydrogen-rich envelope with mass $M_e$ ranging from $3 \times 10^{-6}$ to 0.034 $M_\odot$. Here we have considered only the case of $M_e = 0.486$ $M_\odot$. The surface layers are characterized by mass fractions of hydrogen $X = 0.75$ and base metallicity $Z_0 = 0.02$, with iron and nickel enhanced by the pairs of $f_{\text{Fe}}, f_{\text{Ni}}$ given above.

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Table 1. Assumed fraction of iron-group elements within the heavy element fraction $Z_0$: OPAL = Grevesse & Noels (1993), OP = $S92$ of Seaton et al. (1992).

| El | $Z$ | $Z_{el}/Z_0$ |
|----|----|-------------|
| Cr | 24 | 0.000329 0.000324 |
| Mn | 25 | 0.000170 0.00017 |
| Fe | 26 | 0.021877 0.02244 |
| Ni | 28 | 0.001293 0.00123 |

Table 2. Blue-edge ($\log T_{\text{eff}}/(K)$) of instability strip for g-modes in blue horizontal branch stars

| $f_{\text{Fe,Ni}}$ | OP | OPAL |
|-----------------|-----|------|
| $l$ 1 | 1,1 | 4.26 | 4.31 |
| $f_{\text{Fe}}$ | 20,1 | 4.36 | 4.41 |
| $f_{\text{Ni}}$ | 1,20 | 4.39 | 4.43 |
| $f_{\text{Fe}}$ | 10,10 | 4.38 | 4.43 |
| $f_{\text{Ni}}$ | 3 | 4.37 | 4.40 |
Jeffery & Saiio (2006) discuss variations with $X$ and $Z_0$, and $M_c$. In particular, varying $M_c$ has no effect on the stability of g-modes. They also found the only significant effect of evolution is that g-modes cease to be excited when the core becomes radiative at the end of core He-burning. Of course pulsation periods $P$ increase with radius $R$. Since $P \propto R^{3/2}$ or surface gravity $g^{-3/4}$, normal horizontal-branch evolution produces a period increase of $\sim 0.2$ dex in all modes.

The high-temperature end of this ZAHB sequence corresponds with the locus of the short-period EC14026 variables. PG1716 variables are to be found at lower temperatures, with $21000 \leq T_{\text{eff}}/K \leq 29000$ (Fontaine et al. 2003; Randall et al. 2006). The lower limit probably does not represent a formal red edge; horizontal branch stars at these temperatures are very scarce.

We have tested the stability of each of our horizontal-branch models for non-radial $p$- and g-modes with spherical degree $l = 1, \ldots, 4$. The frequency range considered is $0.2 \leq \omega \leq 20$, where $\omega$ is the angular frequency of pulsation normalized by $\sqrt{GM/R^3}$ with $G$ being the gravitational constant.

Fig. 3 compares the results for OP and OPAL with normal composition. With OP, unstable modes are obtained even for $l = 1$. In general, the number and the temperature range of unstable modes is increased with OP opacities. Fig. 4 compares the results for OP and OPAL with $f_{\text{Fe}, \text{Ni}} = (10, 10)$. For modes with $l = 3$, g-modes are excited up to $T_{\text{eff}}/K \lesssim 28000$ in OP models, but only to $T_{\text{eff}}/K \lesssim 25000$ in OPAL models. Although less likely to be observable, they are excited up to $T_{\text{eff}}/K \lesssim 29500$ for OP models with $l = 4$. In contrast, the position of the models on the HR diagram hardly changes with the choice of opacity table.

Table 2 compares the theoretical blue-edge of the g-mode instability strip for different enhancements of iron and nickel, for OP and OPAL models and for the three most observable modes, $l = 1, 2$ and 3.

It is clear that the use of OP opacities combined with the inclusion of excess nickel can shift the theoretical blue-edge of the g-mode instability strip significantly closer to the observed blue edge. This prompts us to believe that Fontaine et al. (2003) correctly identified the oscillations in PG1716 variables as opacity-driven g-modes, and that the discrepancy in the predicted and observed blue edges can be solved by invoking more accurate atomic physics in the calculation of stellar opacity, as well as considering atomic species other than iron.

The basic elements of this solution are that (i) the opacity peaks due to iron and nickel occur at a higher temperature in OP than in OPAL, (ii) the OP nickel peak occurs at a higher temperature than the OP iron peak, (iii) at these temperatures nickel is a more efficient absorber than iron (per ion), and (iv) radiative acceleration will force it to accumulate in the Ni-bump region in exactly the same way as iron.
4.4 4.3 4.2 4.1

Figure 3. Periods of modes due to Fe-bump instability for ZAHB stars with $M_c = 0.486 M_\odot$, $X = 0.75$, $Z_0 = 0.02$, and $M_e = \text{increasing from left to right. The top row shows models computed with OPAL opacities, the bottom row with OP opacities. Stable modes are marked as (blue) dots, unstable modes are marked as filled (red) circles.}$

4 ATOMIC PHYSICS

It should, perhaps, have been no surprise that the introduction of OP opacities would shift the instability blue edge. A more modest shift in the blue edge for high-order g-modes in slowly pulsating B stars was obtained by Pamyatnykh (1999). Since then, extensive work on the contribution of inner-shell electrons to the OP calculations, has brought the OP opacities into “much closer agreement with those from OPAL” (Badnell & Seaton 2004; Badnell et al. 2005).

Directed at obtaining good atomic data for very large numbers of atomic transitions, OPAL uses single-configuration wavefunctions with one-electron orbitals (Rogers & Iglesias 1992). OP originally obtained most of its atomic data using the R-matrix method to evaluate multi-electron wavefunctions, resulting in more accurate atomic data, but for fewer and simpler transitions (The Opacity Project Team 1995, 1997). Prompted by substantial differences between the first OP results and OPAL, primarily at high temperature and densities, the introduction of configuration-interaction codes enabled OP to include many more bound states and radiative transition probabilities, as well as auto-ionization probabilities and photoionization cross-sections (Seaton 2005).

For many astrophysical situations, OP and OPAL opacities appear to be in closer agreement with one another (< 5%) (Seaton 2005) than with observation. For example, helioseismology results currently require an increase of $\sim 20\%$ in opacity below the base of the solar convective zone (Bahcall et al. 2005). While the results presented here do not directly suggest a solution to the solar opacity problem, they do indicate that improvements in the treatment of atomic processes used in the calculation of stellar opacities can still have substantial consequences for calculations of pulsation stability. These are especially important when amplified by radiatively-driven diffusion of elements into layers of high specific opacity, as in the outer layers of many early-type stars. In turn, these will impact on elemental stratification, on stellar radii, on boundaries of pulsational stability, and on pulsation periods derived for use in asteroseismology.

5 CONCLUSION

We have analyzed the stability of models of hot zero-age horizontal-branch stars to nonradial g-mode oscillations. We have tested and confirmed the hypothesis that elements other than iron can raise the temperature of the so-called “Fe-bump” in opacity at around 200 000 K. In doing so we have discovered that, within this “Fe-bump”, recently updated OP opacity tables provide more opacity at significantly higher temperatures than the OPAL tables. The higher temperature Fe- and Ni-bumps in the OP tables have been combined with a tenfold enhancement of both nickel and iron abundances in the driving zone. This provides sufficient opacity at the right temperatures to shift the theo-
Figure 4. As Fig. 3 for models with iron and nickel both enhanced by a factor 10. PG1716-type variability has been observed for stars in the range $4.32 \lesssim \log T_{\text{eff}}/K \lesssim 4.47$ with periods $3.41 \lesssim \log P/s \lesssim 3.95$.

retical g-mode blue-edge to within 1000 K of the observed blue-edge for PG1716 stars. Given the approximate nature of our own calculations and the likely remaining uncertainties in the atomic physics, we conclude that, by modifying the driving mechanism identified by Fontaine et al. (2003), the discrepancy in the predicted and observed blue edges for PG1716 variables can be solved.

In reaching this conclusion, we have demonstrated that g-mode pulsations in PG1716 stars provide a critical test of stellar opacity, substantially preferring the updated OP calculations to OPAL. Future work should include an investigation of the use of OP opacities in models for EC14026 variables and OP radiative accelerations in self-consistent models of chemical diffusion in extreme horizontal-branch stars, as well as the influence of important opacity providers other than iron and nickel (e.g. chromium, manganese, vanadium). Detailed work for asteroseismological analyses will need to consider a wide range of additional physics, including the effects of evolution and time-dependent diffusion theory and core mass on predicted periods.

ACKNOWLEDGMENT

Travel support for this collaborative project was provided through PPARC grant PPA/G/S/2002/00546. This work has made extensive use of of the OP and OPAL web servers.

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