Main-sequence instability strip for different opacities and heavy element abundances: a comparison with observations.

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Abstract. Updated theoretical instability domains are presented for \(\beta\) Cephei and SPB star models. Calculations were performed using new OP opacities for old (GN93) and new (A04) solar heavy element mixtures. The position of observed \(\beta\) Cephei and SPB variables in the HR and related diagrams is compared with theoretical domains for three heavy element mass fractions: \(Z = 0.020, 0.015\) and \(0.010\).

1. Introduction
A significant increase of the Rosseland mean opacity, \(\kappa_R\), near the temperatures of about 200,000 K (referred as metal opacity bump or as Z-bump), was provided by the OPAL opacity tables (Rogers & Iglesias \([1],[2]\)). This allowed to solve long-standing problem of the main sequence B-type pulsators, namely, \(\beta\) Cep and slowly pulsating B stars (SPB) (Cox \et\, \[3]\; Kiriakidis, El Eid & Glatzel \[4]\; Dziembowski, Moskalik & Pamyatnykh \[5]\; Dziembowski, Moskalik & Pamyatnykh \[6]\). Later, the Opacity Project (OP) (Seaton \et\, \[7]\) used an independent approach for calculating stellar opacities. OP opacities provided similar results to the OPAL opacities, with differences in some temperature-density regions. Effect of the differences on the \(\beta\) Cep and SPB instabilities was demonstrated by Pamyatnykh \et\, \[8]\ and Pamyatnykh \[9]\. Recently, the OP opacities have been updated, including data for inter-combination lines, improvements in the photoionization cross-sections and some other refinements (Seaton \[10]\, Badnell \et\, \[11]\). In Z-bump region, new OP opacities exceed the OPAL data by approximately 18\%. The effect of the new OP data on the excitation of pulsations in \(\beta\) Cep and SPB stars has been studied by Miglio, Montalban & Dupret \(\[12]\, \[13]\) and Pamyatnykh & Ziomek \[14]\.

Also recently, a significant revision of the solar chemical composition by Asplund \et\, \([15]\, \[16]\) led to decrease of the heavy element abundances (we refer to this composition as A04). Heavy element mixture A04 compared to the earlier GN93 mixture (Grevesse & Noels \[17]\), indicates a large decrease by \(\sim 40\%\) for the abundances of C, N, O, Ne, and smaller decrease by \(\sim 20\%\) for the abundances of Fe-group elements. This modification was due to the application of a time-dependent, 3D hydrodynamical model of the solar atmosphere, and also improved atomic and molecular data. Note that new solar CNO abundances agree with the spectroscopic measurements of the B-type stars in the solar environment (Turck-Chièze \et\, \[18]\; Cunha...
et al. [19]). As a result, the mass fraction of the heavy elements in the solar photosphere was decreased from \(Z = 0.017\) to \(Z = 0.012\) (Antia & Basu [20]).

Both new updates of the OP opacities and new data on the solar abundances have significant impact on the stellar models and their pulsations. We tested the effect of these modifications on the instability domains of the \(\beta\) Cep and SPB-type oscillators. We compared the results with the position of the observed stars in the HR and related diagrams for different heavy element mass fractions.

As an example, left panels in Fig. 1 show the opacity run inside a 12\(M_\odot\) star model, typical for the \(\beta\) Cep variables. Panels demonstrate the effect of (i) the opacity choice, (ii) the mixture choice and (iii) the choice of the heavy element mass fraction. The right panels show relative differences in the opacities.

![Figure 1](image_url)

Figure 1. Opacity run inside a typical \(\beta\) Cep-type model of a 12\(M_\odot\) star (left panels) and relative differences in the used opacities (right panels).

2. Instability domains in the HR and related diagrams

In our computations the domains of \(\beta\) Cep and SPB instability cover mass range approximately from 2.5 up to 40\(M_\odot\). We did not take into account the effects of mass loss and stellar rotation. The initial hydrogen abundance was chosen to be \(X = 0.70\). The calculations were performed with the updated OP opacities for the GN93 (old) and A04 (new) heavy element mixtures.
Theoretical instability domains were obtained for three different heavy element mass fractions: $Z = 0.020$, $Z = 0.015$ and $Z = 0.010$. For the $\beta$ Cep and SPB models we computed radial and non-radial oscillations of spherical harmonic degree $\ell \leq 2$. For comparison with the observations, we used data from catalogues of Stankov & Handler ([21], $\beta$ Cep) and De Cat et al. ([22], SPB). We chose stars with the available Hipparcos parallaxes. Photometric data in Strömgren and Geneva systems were taken from The General Catalogue of Photometric Data (http://obswww.unige.ch/gcpd/gcpd.html). The data were transformed to effective temperature and gravity using calibration due to Moon & Dworetsky [23] for Strömgren photometry (in practice, we used the program UVBYBETA written by T.T. Moon in 1985 and modified by R. Napiwotzki). For Geneva photometry, we used the program CALIB (G. Handler, private communication). In all our figures the positions of the observed stars were plotted using effective temperature obtained from Strömgren photometry (excluding Fig. 7). Theoretical instability domains were compared with the positions of the $\beta$ Cep and SPB variables in the HR, $\log g$–$\log T_{\text{eff}}$ and Period–$\log T_{\text{eff}}$ diagrams.

![Figure 2](image-url)

**Figure 2.** Theoretical $\beta$ Cep domain (left panel) and SPB domain (right panel) calculated with OP and OPAL opacities for GN93 mixture and $Z = 0.020$. For a comparison, the instability domain for OPAL, $Z = 0.010$ is shown. Evolutionary tracks for indicated values of mass (in solar units) are shown.

### 2.1. The effect of the opacity choice

In Fig. 2 we show the domains computed with OPAL and OP opacity tables in the HR diagram for $\beta$ Cep and SPB-type pulsations. The evolutionary tracks and the instability domains were calculated for GN93 mixture with the heavy element mass fraction $Z = 0.020$. The OPAL instability domains for $Z = 0.010$ are plotted too. Compared to OPAL, OP opacities provide considerably larger $\beta$ Cep instability domain and extends the SPB domain to higher luminosities and higher masses continuously (see also Pamyatnykh [9]). Results indicate that the use of the new OP opacities give significant effect on the theoretical instability domains.
Figure 3. Theoretical β Cep (left panel) and SPB (right panel) domains calculated with OP opacities for the mixtures A04 and GN93, Z = 0.020.

2.2. The effect of the mixture choice
Using A04 mixture, compared to the GN93 mixture, results in somewhat larger instability domains. The main-sequence theoretical instability strips are shown in Fig. 3 for heavy element mass fraction Z = 0.020. The effect of the mixture choice between of the GN93 and A04 is less significant than the effect of the opacity choice between OPAL and OP data.

2.3. The effect of the choice of the heavy element mass fraction
For the OPAL opacities, the instability domains for Z = 0.010 (dotted lines in Fig. 2) are small, especially, for β Cep-type pulsations. In contrast, using OP opacities for A04 mixture results in considerably larger β Cep and SPB instability regions for this value of Z. In Fig. 4 we show a comparison of the positions of the observed β Cep and SPB stars with the theoretical instability domains for Z = 0.020 and Z = 0.010. In Fig. 5 log g–log T_{eff} diagrams are presented. Values of the effective temperature and gravity are obtained from photometric calibration. For Z = 0.020, almost all observed stars are located inside the instability domains. For most of the the stars, this is also true for Z = 0.010.

Our additional computations, not presented here, with the OP, A04 data for Z = 0.015 give instability domains which are very similar to those calculated with OP, GN93 data for Z = 0.020.

The discovery of the β Cep and SPB stars in Large and Small Magellanic Clouds (Kołaczkowski et al. [24]) shows that even for Z < 0.010 pulsations of these types can be excited. The driving mechanism in the Z-bump region is very sensitive to the abundance of the Fe-group elements. Following suggestions by Cox et al. [3] and Pamyatnykh et al. [25], Miglio et al. [26] studied the effect of an iron enhancement in the metal opacity bump at fixed heavy element mass fraction, which may explain the oscillations for smaller Z values.

3. Periods of unstable modes. Hybrid stars
In our sample of the observed β Cephei and SPB stars most of them are multi-periodic. In Fig. 6, the observed periods are compared with the periods of unstable modes. Four stars (γ Peg, ν Eri, 53 Ari and 12 Lac) show both β Cep and SPB-type pulsations. However, for 53 Ari the lowest
Figure 4. Theoretical $\beta$ Cep (left panel) and SPB (right panel) domains calculated with OP opacities for the mixture A04 and heavy element abundances $Z = 0.020$ and $Z = 0.010$. Observed $\beta$ Cep and SPB stars are taken from Stankov & Handler [21] and De Cat et al. [22], respectively. Error bars for luminosity were estimated from the parallax errors. The errors in log $T_{\text{eff}}$ were adopted to be 0.02.

Figure 5. log $g$-log $T_{\text{eff}}$ diagrams for $\beta$ Cep and SPB stars calculated with OP opacities for the mixture A04 for $Z = 0.020$ (left panel) and $Z = 0.010$ (right panel), with observed stars. The error bars on the left side indicate accuracy for each star position. For the log $T_{\text{eff}}$ and log $g$ we used values 0.02 and 0.2 respectively.

frequency of 1.32663 c/d, which was discovered by De Cat et al. [22] is not predicted for models compatible with the position of this star in the HR diagram. The authors classified this star tentatively as a hybrid. This frequency couldn’t be related to the rotation frequency nor to binary motion. In Fig. 7 this star is located just under ZAMS line close to the position of the ZAMS $7 M_{\odot}$ model (empty circle). The other three stars exhibit clear hybrid $\beta$ Cep/SPB-type behaviour. HR diagram in Fig. 7 shows the instability domains calculated for A04 solar mixture...
Figure 6. Observed periods of \( \beta \) Cep and SPB stars versus periods of unstable modes for two solar compositions: GN93, \( Z = 0.020 \) (left panel) and A04, \( Z = 0.010 \) (right panel). Theoretical instability domains were calculated for \( \ell = 0, 1, 2 \) (\( \beta \) Cep domain) and \( \ell = 1, 2 \) (SPB domain).

Figure 7. Observed \( \beta \) Cep and SPB stars in the theoretical HR diagram. The instability domains have been computed with the OP opacities for A04 mixture and \( Z = 0.015 \). Three hybrid stars, \( \gamma \) Peg, \( \nu \) Eri and 12 Lac, are marked explicitly.
and \( Z = 0.015 \). The positions of the three hybrid stars are close to the regions where mixed \( \beta \) Cep/SPB-type pulsations are expected.

Stars \( \nu \) Eri and 12 Lac have rich spectra of observed frequencies and they are well studied (Jerzykiewicz et al. [27] and Handler et al. [28], respectively). In the case of \( \gamma \) Peg there are four observed frequencies: two of \( \beta \) Cep-type and two of SPB-type. Unfortunately, there is no mode identification. Our preliminary results show the instability in both observed frequency regions. A future mode identification will constrain models of this star.

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