Seismic models of O and B stars with Kurucz's opacity data[★]

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ABSTRACT

Aims. We investigated seismic models of O and B stars calculated with the new Kurucz opacities implemented in the Opacity Project (OP) and Rogers & Iglesias OPAL opacity tables (OPAL).

Methods. We studied the problem using Dziembowski's computer codes for linear, nonadiabatic, and nonradial oscillations. We considered seismic models of main sequence (MS) stars for different chemical compositions of elements in the mass-range $9 \leq M \leq 70 M_{\odot}$.

Results. The new opacity bump at $\lg T \approx 5.06$ that occurs in Kurucz's data influences evolutionary tracks mainly for $M \geq 30 M_{\odot}$ and markedly changes the driving zone for pulsations of stars in the whole mass range studied. We obtained no unstable oscillation modes for models corresponding to the abundance parameter $Z \leq 0.013$ and only unstable low-frequency g -modes for $0.013 < Z \leq 0.021$.

Conclusions. The opacity bump at $\lg T \approx 5.3$ should be significantly larger than the opacity bump at $\lg T \approx 5.06$ to drive pulsations of B stars in low-degree p -modes. Models with an increased OPAL (or OP) opacity bump at $\lg T \approx 5.3$ by a factor of about 1.7 have sufficiently large driving zones to excite modes in the β Cephei frequency-domain for $0.003 \leq Z \leq 0.021$. These values of Z are in a good agreement with those derived spectroscopically for stars in the Galaxy and Magellanic Clouds.

Key words. asteroseismology – atomic data – stars: early-type – pulsars: general

1. Introduction

The opacity and equation of state (EOS) are important ingredients for modeling the structure, evolution, and pulsation of stars. Three sets of data are commonly used, including: Rogers & Iglesias OPAL results (OPAL), the Opacity Project (OP), and Kurucz's data. The OPAL data are based on an OPAL computing code developed by Rogers, et al. (cf. Rogers et al. 1988; Rogers & Iglesias 1992; Iglesias & Rogers 1996, and the OPAL website¹). The OP data were calculated by an international team led by Seaton (OP, cf. Seaton 1987; Seaton et al. 1994; Badnell et al. 2005, and the OP website²). Since 1970 the opacity data and EOS calculated by Kurucz are the basic tools when local thermodynamic equilibrium (LTE) atmosphere models are considered (cf. Kurucz 2005, 2011, and Kurucz's website³).

The atmosphere and envelope models calculated with the same OP data are reasonably close to each other at the optically thick layers (Cugier 2012). A simple fit of the atmosphere model (with the proper treatment of the transport of radiation energy) and envelope model, which is usually calculated with the diffusion approximation, at $\tau_R = 100$ is then justified. There are obstacles to this approach when atmosphere models calculated with the Kurucz's atomic data were fitted to the OPAL or OP internal models of early-type stars. This is explained by the current results of the Kurucz's (2011) project, which attempts to include

all spectral lines of atoms, revealing a large excess of opacity relative to the OPAL and OP data near $\lg T = 5.06$ (Cugier 2012).

The new opacity bump at $\lg T \approx 5.06$ should be considered, in addition to the already known four opacity maxima. The first two maxima (at $\lg T \approx 4.0$ and 4.7) are mainly due to hydrogen and helium (Seaton et al. 1994). The other two maxima (at $\lg T \approx 5.3$ and 6.3) are caused by heavier elements (metals). The maximum at $\lg T \approx 5.3$ is of particular importance for stellar pulsations of early-type stars and is produced by the iron-group elements, among which Fe dominates. The elements C, N, O, and Ne give an opacity enhancement at $\lg T \approx 5.1$ and form, with the iron-group elements, the fourth opacity maximum at $\lg T \approx 6.3$ clearly seen when the solar ($X = 0.70$ and $Z = 0.02$) abundance of elements was assumed by Seaton et al. (1994). The remaining elements considered in the OPAL and OP projects yield the largest contributions near $\lg T \approx 5.9$. As usual, X , Y , and Z parameters describe the mass abundances of hydrogen, helium, and metals, respectively.

In addition to atomic physics, the abundance of metals has an important influence on seismic models, especially for early-type stars, where the hydrogen and helium opacity bumps play a minor (if any) role. In the last two decades, one can observe that the metal abundance parameter Z derived from spectroscopic observations of stars decreased markedly. The present-day solar photospheric elemental abundances $Z/X = 0.0181$ given by Asplund et al. (2009) lead to $X = 0.7381$ and $Z = 0.0134$, assuming a seismic measurement of $Y = 0.2485$ (Basu & Antia 2004). Previously, the value of $Z/X = 0.0245$ was accepted following Grevesee & Noels (1993). Recently, Vorontsov et al. (2013) obtained $0.008 < Z < 0.013$ and $0.240 < Y < 0.255$ from the reanalysis of the solar p -modes measurements. The results depend mainly on a particular version

[★] Appendix A is available in electronic form at <http://www.aanda.org>

¹ <http://opalopacity.llnl.gov>

² <http://cdsweb.u-strasbg.fr/topbase>

³ <http://kurucz.harvard.edu>

of the EOS used. No unstable low-degree oscillation modes in the p -domain were obtained for models of B stars using Grevesse & Noels (1993) mixture of elements for $Z < 0.01$ (Pamyatnykh 1999; Miglio et al. 2007). If a small contribution of C, N, O, and Ne to Z as listed in Asplund et al. (2009), then $Z \geq 0.007$ is needed for excitation of p -modes in B stars (Salmon et al. 2012), because of the higher contribution of iron-group elements to Z . In this context, variable B stars observed in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) are interesting. Compilations of spectroscopic data listed in Brott et al. (2011) and Salmon et al. (2012) indicates that $Z = 0.0047\text{--}0.0060$ and $Z = 0.0021\text{--}0.0024$ for the LMC and SMC, respectively. Several candidates for β Cephei-type stars were, however, found by Pigulski & Kolaczowski (2002), Kolaczowski et al. (2004, 2006), Diago et al. (2008a,b), Karoff et al. (2008), and Pigulski & Pojmanski (2008).

The aim of this paper is to investigate the evolutionary and seismic models of stars, which are closely related via Kurucz's opacity data available for $T \leq 200$ kK. In Sect. 2, we briefly review oscillation spectra predicted for O and B type stars using the OPAL and OP data. The new opacity bump at $\lg T = 5.06$ is discussed in Sect. 3 for different abundances of elements. Examples of evolutionary tracks for stellar models calculated with Kurucz's opacity data are shown in Sect. 4. Seismic models are discussed in Sect. 5 and conclusions are described in Sect. 6.

2. Oscillation spectra of early-type stars

In this section, a few aspects of theoretical oscillation spectra related to observations of O- and B-type stars were briefly pointed out. This is well justified because the pulsational instability mechanism and theoretical oscillation spectra of B stars were already reviewed by Dziembowski & Pamyatnykh (1992), Gautschi & Saio (1993), Dziembowski et al. (1993), Moskalik (1995), Dupret (2001), and others. More recent investigations (e.g. Pamyatnykh 1999; Saio et al. 2000; Daszynska-Daszkiewicz et al. 2005; Miglio et al. 2007; Daszynska-Daszkiewicz & Walczak 2010; Salmon et al. 2012) lead to quantitatively different results when different abundances of elements were assumed, but the basic results for the chemical composition not far from $X \approx 0.70$ and $Z \approx 0.02$ are remarkably the same as obtained as early as the 1990s (Dziembowski 2009).

The radial and some nonradial modes are called p -modes because the restoring force for pulsations is predominantly the gas pressure. Nonradial modes may also be governed by buoyancy acting as restoring force, and these are called g -modes. These two kinds of modes are well separated in the frequency-domain for stellar models near the zero age main sequence (ZAMS). Nonradial modes may have also mixed character for evolved main sequence (MS) stars (Dziembowski & Pamyatnykh 1992; Balona & Dziembowski 1999). Those B stars with predominant variations in frequency domain characteristic of p -modes are called β Cephei-type stars, while those with variations in the frequency domain characteristic of g -modes are called SPB-type stars. A number of β Cephei stars, however, show low-frequency pulsations characteristic of SPB stars. They are known as β Cep/SPB hybrids (e.g. De Cat et al. 2007; Pigulski & Pojmanski 2008; Handler 2009; Balona et al. 2011; Degroote et al. 2012b; Pápics et al. 2012).

In addition, there are also f -modes (for $l \geq 2$) (e.g. Cox 1980; Saio & Cox 1980). In the frequency domain they are located between p - and g -modes for models near ZAMS. According to Balona & Dziembowski (1999), some high degree ($l \geq 12$) of unstable modes can be regarded

as f -modes when models far from ZAMS are considered. Daszynska-Daszkiewicz et al. (2006) suggested that high-frequency modes observed in FG Vir (a δ Scuti star) can be explained by f -modes.

The amplitude limit for ground-based observations are typically a few millimagnitudes. At this level, modes with the spherical harmonic degree $l \leq 2$ were usually considered because of large cancelation effects over the stellar disk for higher values of l . The dominant mode of oscillation (the mode with the highest amplitude) may be either the radial or nonradial mode in β Cephei stars (e.g. Cugier et al. 1994). An unprecedented level of precision, a few ppm, was recently achieved from space-based instruments aboard Convection Rotation and Planetary Transits (CoRoT, cf. Auvergne et al. 2009) and *Kepler* (cf. Gilliland et al. 2010) satellites. Balona et al. (2011) concluded that the frequency spectra are quite different from what is seen from ground-based observations. They suggest that pulsations with values of l as high as 20, or even higher, may be visible in *Kepler* photometry. Basic properties of such modes were discussed by Balona & Dziembowski (1999) and Dziembowski (2009). There are, however, also stars within the β Cephei and SPB instability strips with no detected variability at the level of a few ppm (Balona et al. 2011).

In the case of O-type stars, the linear, nonadiabatic theory predicts that two or three radial modes and a similar number of nonradial p -modes with low l -values are unstable using the OPAL and OP data for $X = 0.70$ and $Z = 0.02$ (e.g. Pamyatnykh 1999; Pamyatnykh & Ziomek 2007). The instability strip extends to masses well above $50 M_{\odot}$ for $l \leq 2$ (e.g. Moskalik 1995). Observations do not show, however, that variability with frequency characteristics for p -modes is a common feature in O stars (e.g. Balona 1992; Pigulski & Kolaczowski 1998). The β Cephei-type pulsations were, however, found in O-type stars (e.g. Walker et al. 2005; Pigulski & Pojmanski 2008), and oscillations with periods of the order of one day were commonly present, as was first predicted by Vogt & Penrod (1983) from observed variability of line profiles detected by Walker et al. (1979). CoRoT observations show further examples of the variability of O stars and several frequencies in light curves were found, which were not predicted to be unstable modes by the OPAL and OP seismic models (cf. Blomme et al. 2011; Briquet et al. 2011; Degroote et al. 2010; Mahy et al. 2011).

In summary, although the driving κ -mechanism of oscillations has been identified using the OPAL and OP data, there are still unsolved problems related to the identification and selection of oscillation modes for O and B stars. Consequently, our understanding of the observed oscillation spectra of early-type stars is not complete. Therefore, some numerical experiments with opacity in the driving zones for stellar pulsations were also made (e.g. Pamyatnykh et al. 2004; Zdravkov & Pamyatnykh 2008; Salmon et al. 2012). Some critical remarks regarding the atomic physics and accuracy of the OP data were given by Prandhan & Nahar (2009).

3. Kurucz's opacity data

Recently, Castelli & Kurucz (2003) and Meszaros et al. (2012) calculated two extensive grids of atmosphere models and Rosseland-mean opacities. The same Kurucz atom models were used, but data given by Grevesse & Sauval (1998) and Asplund et al. (2005) were assumed to be the solar elemental mixture, respectively. Both Castelli & Kurucz (CK)

Fig. 1. Rosseland-mean opacity κ_R [$\text{cm}^2 \text{g}^{-1}$] vs. $\lg T$ taken from the Castelli & Kurucz (2003) atmosphere models of $\lg g = 5.0$, $T_{\text{eff}} = 15\,000, 20\,000, 25\,000, 30\,000$ K (left panel) and $T_{\text{eff}} = 35\,000, 40\,000, 45\,000$ K (right panel) in comparison with envelope models calculated with the OPAL data. The atmosphere models corresponding to the microturbulent velocity $\xi = 0$ (taken from the Castelli website) were plotted as lines with pluses. Both the CK and OPAL models were calculated for $X = 0.7347$ and $Z = 0.0169$.

and Meszaros et al. (M) models (available from Castelli⁴ and ATLAS-APOGEE⁵ websites) reveal an excess of opacity at high optical depths in comparison with atmosphere and envelope models calculated with the OPAL and OP data. Examples are plotted in Fig. 1. The atmosphere models (shown as lines with pluses) ended at the Rosseland-mean optical depth equal to 100 and the opacity bump at $\lg T = 5.06$ can therefore be overlooked for $\lg T_{\text{eff}} < 4.7$. In the following, we used the Rosseland-mean opacities (CK, M, OPAL and OP) given in a tabular form. Details are provided in Appendix A.

First, we selected the OPAL and OP opacity data for a comparative study. In particular, we calculated the OPAL models (Nos. 1–8 in Table 1) for scaled metal abundances based on Grevesse & Noels (1993) data, while the chemical mixtures listed in Asplund et al. (2009) were used for OP models Nos. 9 and 10. In the last case, we selected the mean values of Y and Z from the best-fit solution ($Y = 0.25$, $Z = 0.008$) obtained by Vorontsov et al. (2013) for the SAHA-S3 EOS, using p -modes trapped in the upper half of the solar convective envelope, and ($Y = 0.245$, $Z = 0.010$) for p -modes trapped in deeper layers.

Next, we calculated the K-OPAL and K-OP models with hybrid CK/OPAL and M/OP opacity data, viz., for the CK or M opacity at outer stellar layers (up to $\lg T = 5.2$) implemented with the OPAL or OP data for $\lg T > 5.2$. Models calculated using the OPAL and CK/OPAL opacities can be regarded as representative for the aim of this paper because basic characteristics of the M/OP and CK/OP opacities are the same. Names of the K-OPAL models contain information about both sets of the opacity data used (Appendix A). Nuclear reaction rates and EOS were calculated for the initial (at ZAMS) chemical composition X and Z listed in Table 1. The K-OPAL models are divided into three groups explained in Sects. 3.1–3.3.

Table 1. Opacity data for stellar models analyzed.

Model No.	Name	X	Z
OPAL			
1	OPALz0266	0.7275	0.0266
2	OPALz0213	0.7315	0.0213
3	OPALz0169	0.7347	0.0169
4	OPALz0135	0.7373	0.0135
5	OPALz0108	0.7394	0.0108
6	OPALz00682	0.7423	0.00682
7	OPALz00542	0.7433	0.00542
8	OPALz00306	0.7451	0.00306
OP			
9	OPz0134	0.7381	0.0134
10	OPz009	0.7435	0.0090
K-OPAL/A			
11	CK-OPALp02z0266	0.7275	0.0266
12	CK-OPALp01z0213	0.7315	0.0213
13	CK-OPALp00z0169	0.7347	0.0169
14	CK-OPALm02z0108	0.7394	0.0108
15	CK-OPALm04z00682	0.7423	0.00682
16	CK-OPALm05z00542	0.7433	0.00542
17	CK-OPALm075z00306	0.7451	0.00306
K-OPAL/B			
18	CK-OPALm05z0266	0.7275	0.0266
19	CK-OPALm04z0266	0.7275	0.0266
20	CK-OPALm02z0266	0.7275	0.0266
21	CK-OPALp00z0266	0.7275	0.0266
22	CK-OPALm05z0169	0.7347	0.0169
23	CK-OPALm04z0169	0.7347	0.0169
24	CK-OPALm02z0169	0.7347	0.0169
K-OPAL/C			
25	Km02z0266	0.7394	0.0108
26	Km05z0169	0.7433	0.00542
27	Km075z0135	0.7451	0.00306

3.1. The K-OPAL/A opacity data

We built the K-OPAL/A models (Table 1) using the CK and OPAL opacity data selected for the same abundance parameters

⁴ <http://wwwuser.oat.ts.astro.it/castelli/>

⁵ <http://www.iac.es/proyecto/ATLAS-APOGEE/>

Fig. 2. Rosseland-mean opacities κ_R [$\text{cm}^2 \text{g}^{-1}$] vs. $\lg T$ for $\lg R = \lg \rho - 3 \lg T + 18 = -6.0, -5.0, -4.5$, and -4.0 . The OPAL (blue lines) and K-OPAL/A (red lines) data were plotted for $Z = 0.0266, 0.0168$ and 0.00542 , viz., opacity data Nos. 1, 3, 7, 11, 13, and 16 listed in Table 1 were displayed. The K-OPAL data with α -enhanced elements (*m05a* in Table A.1) were also plotted as green lines. (A color version of the figure is available online.)

of X and Z . In Fig. 2, we plotted examples of these hybrid opacities in comparison with the pure OPAL data for $Z = 0.00542, 0.0169$, and 0.0266 . As one can see, the CK Rosseland-mean opacities, κ_R^{CK} , differ markedly from the OPAL, κ_R^{OPAL} , opacities at $4.7 < \lg T < 5.2$. The opacity bump at $\lg T \approx 5.06$ dominates for $\lg R = \lg \rho - 3 \lg T + 18 < -5$ and its role decreases for higher densities, but is still important for subphotospheric layers of early-type stars ($\lg R \leq -3.5$). In this case, we see two opacity bumps (at $\lg T = 5.06$ and 5.3). The local minimum of the opacity occurs at $\lg T \approx 5.2$, where $\kappa_R^{\text{CK}} \approx \kappa_R^{\text{OPAL}}$. A deeper insight into why the local minimum of κ_R takes place at $\lg T \approx 5.2$ follows from an analysis of monochromatic opacities (Appendix A).

3.2. The K-OPAL/B opacity data

We considered K-OPAL/B models to study how the relative strength of the opacity bumps at $\lg T = 5.06$ and 5.3 influences seismic models of early-type stars. They are basically the OPAL models for $Z = 0.0266$ and $Z = 0.0169$ at all stellar layers, with the exception that $\kappa_R = \max(\kappa_R^{\text{CK}}, \kappa_R^{\text{OPAL}})$ was selected near the opacity bump at $\lg T \approx 5.06$ (models Nos. 18–24 in Table 1). Further details were provided in Appendix A.

3.3. The K-OPAL/C opacity data

We also searched K-OPAL/C models with enhanced opacities at $\lg T > 5.2$ (opacity data Nos. 25–27 in Table 1) motivated mainly by Pradhan & Nahar (2009) who suggested that the missing opacity in the OP data may lie in an energy range from a

few eV to few hundreds of eV, depending on the element and ionization stage. In the case of No. 25, we used EOS and nuclear reaction rates for the initial chemical composition of $X = 0.7394$, $Y = 0.2498$, and $Z = 0.0108$. We assumed the CK opacity data (*m02*, $Z = 0.0108$) at $\lg T < 5.2$, but the OPAL data for $Z = 0.0266$ at $\lg T > 5.2$. The models Nos. 26 and 27 were constructed for $Z = 0.00542$ and 0.00306 with enhanced opacities (OPAL: $Z = 0.0169$ and 0.0135) at $\lg T > 5.2$, respectively. The above described approach leads to an increase of the opacity bump at $\lg T = 5.3$ by a factor of about 1.7 for all K-OPAL/C models listed in Table 1. The CK/OP Rosseland-mean opacities calculated from OP monochromatic cross-sections increased by factors of 1–5 at $\lg T > 5.2$ shown with similar results (Cugier 2014).

4. The K-OPAL models of early-type stars

We note first that it is sufficient to consider κ_R for stellar evolution models, while the derivatives of the opacity over temperature and density are necessary for seismic models of stars discussed in Sect. 5. In some computing codes for stellar evolution, the opacity derivatives are also used, but only in the convergence process. The original OPAL opacity data (Iglesias & Rogers 1996) contain tables of $\kappa_R(T, \rho, X, Y, Z)$. In particular, temperature is in the range $\lg T = 3.75$ – 8.7 with steps of 0.05 dex. (for $\lg T = 3.75$ – 6.0), and 0.1 dex. (for $\lg T = 6.0$ – 8.1), and 0.2 dex. (for $\lg T = 8.1$ – 8.7), while density ρ , expressed by the parameter of $\lg R$, is in the range $\lg R = -8.0$ – -1.0 with a step of 0.5 dex, respectively. These data were extended toward lower

Fig. 3. H-R diagram for OPAL (blue lines) and K-OPAL (black lines) models of $M = 70, 60, 50, 40, 35, 30$, and $20 M_{\odot}$ calculated with the initial chemical composition $X = 0.7347$ and $Z = 0.0169$. No mass loss and no core overshooting were included in the calculations. $L_{\odot}$ means the solar luminosity and $M_{\odot}$ solar mass. (A color version of the figure is available online.)

temperatures using molecular and grain opacities calculated by Alexander & Ferguson (1994).

The above described opacity data are sometimes interpolated for a denser grid of parameters by decreasing steps in $\lg T$ and $\lg R$ by a factor N . The purpose of this is to allow further linear interpolation in the opacity tables by computing codes for modeling stellar evolution to save computing time. This approach is justified for calculations of evolutionary tracks of stars, but the accuracy of seismic models may be decreased. In particular, we found that this linear interpolation influences the net pulsational energy gain during one cycle of some oscillation modes even for $N = 5$, and thereby affects their stability properties. A better approach (adopted in this paper) is to use, e.g., $N = 2$ with a more accurate interpolation procedure in the computing code for modeling stellar structure.

Now we calculate stellar models with the OPAL and CK/OPAL opacity data. Examples are shown in Fig. 3, where we plotted the Hertzsprung-Russel (H-R) diagram for the models of $M = 20\text{--}70 M_{\odot}$, calculated assuming the initial abundance parameters equal to $X = 0.7347$ and $Z = 0.0169$ (opacity data Nos. 3 and 13 in Table 1). The evolutionary tracks are shown from ZAMS to the moment when the central temperature reaches the value of $\lg T_c = 8.0$, just before helium ignition in the stellar core. We did not assume any mass loss, rotation or core overshooting. This means that the models reveal only differences in the opacity data used. The ZAMS, terminal age main sequence (TAMS), and the end of the MS overall contraction phase are seen for all tracks. Clearly, the K-OPAL/A models show a very broad band of the MS phase of evolution for $M > 20 M_{\odot}$. This is caused by a high gradient of radiation pressure at optically thick regions, $\lg T \approx 5.06$, where the CK Rosseland-mean opacities approach maximum (see Sect. 3). Consequently, this leads to an increase in the stellar radius. The deeper layers are almost the same in the both cases, however, because of the same (OPAL) opacities assumed there.

Figures 4–5 show the H-R diagram for OPAL and K-OPAL models of 40 and $12 M_{\odot}$ calculated with different chemical compositions. In the case of $M = 40 M_{\odot}$ (Fig. 4), one can see that the above mentioned effect of the gradient of radiation pressure near $\lg T = 5.06$ is important even for $Z = 0.00542$,

but $Z < 0.0108$ is sufficient to prevent MS stellar evolution to a very low effective temperature of approximately $\lg T_{\text{eff}} < 4.4$. Mass loss is another important reason that can markedly change evolutionary tracks of massive stars. In the models presented here, we took the mixing of elements into account, but only within the range of the convective core with the boundary determined by the Schwarzschild criterion. The effect of the initial chemical composition remains important for $M \leq 20 M_{\odot}$ (Fig. 5), but the differences between the OPAL and K-OPAL/A evolutionary tracks are small for a given stellar mass at least up to the moment of helium ignition in the stellar core. The K-OPAL/C models of No. 25 with enhanced opacities at $\lg T > 5.2$ show a bit lower luminosity on the H-R diagram. Here, we also plot models of No. 25 for $M = 13 M_{\odot}$. This evolutionary track is not far from that calculated for $M = 12 M_{\odot}$ models of Nos. 5 and 14, shown in Fig. 5, with the exception of higher luminosity by about 0.05 dex.

5. Seismic models

The basic physical assumptions remain the same as those used in the well-known Dziembowski's (1977) computing code for linear and nonadiabatic stellar oscillations. Both radial and nonradial oscillations were considered. In this paper, we used a computing code based on the PERIBC and PIGMOD codes elaborated by Dziembowski (2000, priv. comm., cf. also Balona & Dziembowski 1999). In these codes, outer layers were treated in the full nonadiabatic approach, while deeper layers in quasadiabatic approximation. We refer the readers to Dziembowski (1977), where both approaches were described in detail.

The calculated seismic models were examined with review propagation diagrams, oscillation energy, E , work integrals, W , and eigenfunctions of oscillation modes. All first order perturbed quantities were assumed to be proportional to $Y_l^m e^{i\omega t}$. The period, Π , and frequency, ν , of oscillation is given by $\Pi = \frac{2\pi}{\text{Re}(\omega)} = \frac{1}{\nu}$, while the imaginary part of ω gives the excitation rate. The dimensionless frequency, σ , is defined as $\sigma = \omega(4\pi G \langle \rho \rangle)^{-1/2}$, where $\langle \rho \rangle$ is the mean density of the star and G is the gravitational constant. The propagation diagrams for the oscillation modes involve the Brunt-Väisälä (N)

Fig. 4. H-R diagram for OPAL and K-OPAL models of $M = 40 M_{\odot}$ calculated with different initial chemical compositions. The evolutionary tracks were numbered according to the opacity data listed in Table 1. (A color version of the figure is available online.)

Fig. 5. Same as Fig. 4, but for $M = 12 M_{\odot}$. The evolutionary track for $M = 13 M_{\odot}$ (only for the opacity data No. 25; violet line) was also plotted. (A color version of the figure is available online.)

and Lamb (L_l) frequencies (e.g. Cox 1980). The g -modes propagate in the regions where $\nu^2 < N^2, L_l^2$, while the p -modes propagate in the regions where $\nu^2 > N^2, L_l^2$. The remaining regions are called evanescent zones. The properties of the basic eigenfunctions, kinetic energy distributions and work integrals for models of B stars were already discussed by Dziembowski & Pamyatnykh (1992), Dziembowski et al. (1993), Pamyatnykh (1999), Dziembowski (2009), Dupret (2001), and others. The proper behavior of the Rosseland-mean opacity and eigenfunctions are necessary, but not sufficient conditions for the κ -mechanism to work. The other requirement is that the thermal timescale of the driving zone is comparable or longer than the period of oscillation considered (cf. papers cited above). A mode is unstable when the cumulative work integral, W , is positive.

In the case of $l = 1$ p_1 - and g_1 -modes, the kinetic energy density have two maxima, one in the region of gravity wave

propagation and other one in the region of acoustic wave propagation. For higher overtones, the number of nodes, n , equals to the number of maxima in the kinetic energy distribution.

5.1. The OPAL models

Figure 6 shows frequencies ν [c/d] of unstable modes for stellar models calculated for $M = 12 M_{\odot}$ at the moment when the central hydrogen content was decreased to $X_c = 0.24$. The number of a model describes the opacity data used (Table 1). The low-degree modes ($l = 0, 1$, and 2) were marked individually, while the modes with $3 \leq l \leq 10$ are shown as small (black) points. The fundamental and first overtone radial, and three $l = 1$, and three $l = 2$ nonradial modes were unstable for the OPAL models Nos. 1–3. In addition, a high number of $3 \leq l \leq 10$ modes were also unstable, especially in the g -mode frequency domain.

Fig. 6. Frequencies ν [c/d] of unstable modes ($l \leq 10$) for the OPAL, OP, and K-OPAL models of $M = 12 M_{\odot}$ with the central hydrogen content $X_c = 0.24$. The models were numbered according to the opacity data used (Table 1). Symbols are explained in the *right hand panel*. (A color version of the figure is available online.)

Table 2. Frequencies (σ, ν) of unstable modes of $l = 0-3$ for OPAL, OP, and K-OPAL seismic models of an evolved $M = 40 M_{\odot}$ star calculated with the opacity data Nos. 3, 9, 10, 13, 20, 24, and 25 shown in Table 1.

l	OPAL No. 3 (σ, ν [c/d])	OP No. 9 (σ, ν [c/d])	OP No. 10 (σ, ν [c/d])	K-OPAL/A No. 13 (σ, ν [c/d])	K-OPAL/B No. 20 (σ, ν [c/d])	K-OPAL/B No. 24 (σ, ν [c/d])	K-OPAL/C No. 25 (σ, ν [c/d])
0	(1.966, 2.643)	(1.903, 2.761)	(1.824, 2.909)	—	—	—	—
0	(2.269, 3.050)	(2.299, 3.335)	—	—	—	—	—
1	(1.769, 2.379)	(1.669, 2.422)	(1.574, 2.510)	—	—	—	—
1	(2.214, 2.976)	(2.200, 3.191)	(2.145, 3.421)	—	—	—	—
1	(2.328, 3.129)	(2.344, 3.401)	—	—	—	—	—
2	(2.056, 2.764)	(2.002, 2.905)	(1.925, 3.070)	—	(0.620, 0.509)	(0.529, 0.556)	(0.543, 0.553)
2	(2.286, 3.073)	(2.316, 3.360)	—	—	(0.624, 0.512)	—	(0.576, 0.585)
3	(1.741, 2.341)	—	(2.049, 3.268)	(0.722, 0.772)	—	(0.689, 0.724)	(0.753, 0.766)
3	(2.147, 2.887)	—	—	(1.271, 1.360)	—	(0.737, 0.774)	(0.757, 0.770)
3	(2.313, 3.109)	—	—	(1.363, 1.459)	—	(1.295, 1.361)	—
3	—	—	—	—	—	(1.387, 1.457)	—
$\lg T_{\text{eff}}$	4.534	4.544	4.557	4.499	4.462	4.498	4.489
$\lg L/L_{\odot}$	5.544	5.540	5.538	5.535	5.541	5.544	5.527
X_c	0.254	0.257	0.263	0.263	0.247	0.254	0.259

An increase in the Z-parameter leads to a higher radiation pressure, larger stellar radius and lower frequencies of the modes. Note also that the oscillation spectra have a hybrid character, but g -modes with $l \geq 4$ (model No. 1), $l \geq 5$ (model No. 2), and $l \geq 6$ (model No. 3) were unstable in the low-frequency domain ($\nu < 3$ [c/d]). In the case of model No. 4, only modes with $l \geq 3$ are unstable in the whole frequency domain studied in this paper. A lack of data for OPAL models Nos. 5–8 ($Z \leq 0.0108$) in Fig. 6 means that ($l \leq 10, 0.2 \leq \sigma \leq 6$) modes were stable.

Frequencies of all unstable $l \leq 3$ modes are shown in the second column of Table 2 for a model of $M = 40 M_{\odot}$, $X_c \approx 0.25$, and $Z = 0.0169$. They are p - and low-order ($n \leq 4$) g -modes of the mixed character.

5.2. The OP models

The OP models Nos. 9 and 10, plotted in Fig. 6, illustrate how Asplund et al. (2009) solar abundances of metals implemented with helioseismic measurements, of Y in Basu & Antia (2004), and Y and Z in Vorontsov et al. (2013), change the oscillation spectra of unstable modes for models of early-type stars. Note that the OPAL models were stable for $Z < 0.0108$. Now, the evolved MS models with lower abundances of C, N, O, and Ne elements accompanied by higher contribution of iron group elements to $Z = 0.009$ show unstable modes including low-degree modes in the β Cephei frequency domain. In Table 2, we also show frequencies of all unstable $l \leq 3$ modes for the OP models of $M = 40 M_{\odot}$ and $X_c \approx 0.26$.

Fig. 7. Differential work integrals, Rosseland-mean opacities and their derivatives over temperature of $l = 1$ modes were plotted for the OPAL (opacity data No. 3), K-OPAL/A (No. 13), and K-OPAL/B (No. 20) models of $M = 12 M_{\odot}$ ($X_c \approx 0.24$). For better visibility, κ_R and κ_T were multiplied by factors equal to 10 and 8, respectively. The numbers shown on the *top of the panels* (1, 1.92) mean $l = 1$ and $\sigma = 1.92$, etc. (A color version of the figure is available online.)

Fig. 8. Same as Fig. 7, but for models of $M = 40 M_{\odot}$ ($X_c \approx 0.26$) calculated with the opacity data Nos. 3, 13, and 24, respectively. (A color version of the figure is available online.)

5.3. The K-OPAL/A models

According to Sect. 4, MS evolutionary tracks for models of $M \leq 20 M_{\odot}$ calculated with the OPAL and K-OPAL/A opacity data are almost the same. However, the additional opacity bump at $\lg T \approx 5.06$, which occurs at the K-OPAL/A models, markedly changes the driving zone for stellar pulsations. Consequently, low-degree oscillation p -modes were stable (Fig. 6) and only g -modes ($l \geq 8$) were unstable with the exception of two $l = 2$ modes at model No. 11. Again, the

lack of the models Nos. 14–17 means that ($l \leq 10, 0.2 \leq \sigma \leq 5$) modes were stable. In inner zones, the propagation diagrams and oscillation energy distributions for the K-OPAL/A models are basically the same as for the OPAL models. The luminosity, f , pressure, p , and radial displacement y -eigenfunctions of unstable modes were similar, but not identical, to those discussed in Cugier et al. (1994). The opacity bump at $\lg T = 5.06$ has a minor influence on these functions for models of B stars.

Figure 7 shows a comparison of the differential work integrals, $\frac{dW}{d\lg T}$, for two modes of $l = 1$ calculated for the OPAL (with

Fig. 9. Examples of the luminosity $f = f_R + if_I$ and radial displacement $y = y_R + iy_I$ eigenfunctions for unstable modes of seismic models of $M = 40 M_\odot$ ($X_c \approx 0.26$) calculated with the opacity data Nos. 3, 13, and 24, respectively. κ_R and κ_T were also plotted. (A color version of the figure is available online.)

the opacity data No. 3, Fig. 7a) and K-OPAL/A (No. 13, Fig. 7b) models of $M = 12 M_\odot$. The local κ -driving is sufficient for the OPAL model, but is much less efficient and cannot overcome the radiative damping for the K-OPAL/A model. In the case of low-degree ($l \leq 2$) g -modes, the driving is too weak, even for the OPAL model.

The above discussion concerns a model of $M = 12 M_\odot$ with $X_c \approx 0.25$, but the basic results have a more general character. Low-degree p -modes were stable for the K-OPAL/A models with $Z \leq 0.0213$ shown in Table 1, as well as for other stellar masses corresponding to β Cephei stars.

The K-OPAL/A model of an $M = 40 M_\odot$ star at the moment when the central hydrogen abundance decreases from $X = 0.7347$ to $X_c \approx 0.26$ shows almost the same value of luminosity as the OPAL model, but markedly lower effective temperature. This reflects the fact that the stellar interior was the same, but stellar radius was larger, as discussed in Sect. 4. Now, unlike the OPAL model, the $l \leq 2$ modes were stable (Table 2), but unstable $l = 3$ g_7 - and g_4 -modes. Figure 8 shows the differential work integrals of two $l = 1$ modes for the OPAL (panel a) and K-OPAL/A (panel b) models. The former modes mimic the behavior of unstable modes already discussed for less massive stars. In the case of the K-OPAL/A model, the driving zone was markedly changed by the two-peak structure of κ_R . The driving corresponding to the opacity bump at $\lg T = 5.3$ was very weak because of the local plateau in κ_R near $\lg T \approx 5.2$ ($r/R \approx 0.8$). Consequently, $l \leq 2$ modes were stable despite an additional driving in outer layers ($r/R \approx 0.92$) due to the opacity bump at $\lg T = 5.06$. The driving was more effective for $l = 3$ (panel b) and three unstable modes were found (Table 2). In Fig. 9, examples of the luminosity f - and radial displacement y -eigenfunctions were plotted for unstable modes. Again, the OPAL modes mimic the behavior of the OPAL modes calculated for less massive stars (cf. Fig. 9a and Cugier et al. 1994), while the K-OPAL/A eigenfunctions are markedly influenced by the opacity bump at $\lg T = 5.06$ (Fig. 9b).

5.4. The K-OPAL/B models

Frequencies of unstable K-OPAL/B modes calculated for seismic models with opacity data Nos. 18–24 were plotted in the right hand panel of Fig. 6. Clearly, the oscillation frequencies are determined by the structure of the stellar interior, while the outer layers control the stability of the modes. No unstable modes were found for $\nu \geq 2.6$ [c/d] if large opacity took place at $\lg T = 5.06$. In the case of smaller opacity, as in model No. 21, only $l \geq 2$ modes were unstable. For a very small opacity bump at $\lg T = 5.06$ (as in model No. 18) we have a seismic model not far from the OPAL model for $Z = 0.0266$. The models calculated with the opacity data Nos. 22–24 show further evidence that differences between opacity bumps at $\lg T = 5.06$ and 5.3 should be sufficiently large to obtain unstable p -modes. The other condition is that the opacity bump at $\lg T = 5.3$ must be large enough to drive pulsations of β Cephei stars.

Figures 7c and 8c show examples of the differential work integrals of unstable modes for the K-OPAL/B models of $M = 12$ and $40 M_\odot$ stars, respectively. Unstable modes were also shown in Table 2 for $M = 40 M_\odot$. The differential work integrals (plotted in Fig. 8c) and the f - and y -eigenfunctions (plotted in Fig. 9c) are quantitatively the same as mentioned above for the K-OPAL/A model No. 13, shown in Figs. 8b and 9b.

5.5. The K-OPAL/C models

Figure 10 shows the K-OPAL/C models (cf. Sect. 3) for $M = 9$ – $12 M_\odot$. Here, we examined seismic models with the central abundance of hydrogen equal to $X_c = 0.70, 0.5, 0.24$, and 0.006 . The initial chemical composition of elements ($X = 0.7394$ and $Z = 0.0108$) and the opacity data No. 25 were selected. As one can see from Fig. 10a, models located very close to ZAMS ($X_c = 0.70$) show a hybrid character of oscillation spectra. In the high-frequency domain, only f -modes ($l \geq 2, n = 0$) were unstable, but the fundamental radial mode

Fig. 10. Same as Fig. 6, but opacity data No. 25 (Table 1) were used. Models of $M = 9$ (No. 25.1), 10 (No. 25.2), 11 (No. 25.3), and $12 M_{\odot}$ (No. 25.4) are shown for $X_c = 0.70, 0.50, 0.24$, and 0.006 . (A color version of the figure is available online.)

Table 3. Frequencies (σ, ν [c/d]) of unstable f-modes for K-OPAL/C seismic models near ZAMS calculated with the opacity data No. 25 (cf. Table 1).

l	$M = 9 M_{\odot}$ (σ, ν)	$M = 10 M_{\odot}$ (σ, ν)	$M = 11 M_{\odot}$ (σ, ν)	$M = 12 M_{\odot}$ (σ, ν)
2	(1.818, 10.728)	–	–	–
3	(1.945, 11.482)	–	–	–
4	(1.994, 11.769)	(1.985, 11.297)	–	–
5	(2.037, 12.024)	(2.032, 11.562)	–	–
6	(2.086, 12.313)	(2.083, 11.856)	–	–
7	(2.143, 12.648)	(2.142, 12.190)	(2.142, 11.792)	–
8	(2.206, 13.019)	(2.206, 12.554)	(2.207, 12.149)	–
9	(2.272, 13.411)	(2.273, 12.935)	(2.274, 12.520)	(2.280, 11.197)
10	(2.339, 13.809)	(2.341, 13.322)	(2.342, 12.896)	(2.349, 11.535)
11	–	(2.409, 13.707)	(2.410, 13.270)	(2.417, 11.870)
12	–	(2.475, 14.086)	(2.477, 13.639)	(2.484, 12.200)
13	–	(2.540, 14.458)	(2.543, 14.001)	–
14	–	–	(2.607, 14.353)	–
$\lg T_{\text{eff}}$	4.352	4.377	4.399	4.413
$\lg L/L_{\odot}$	3.531	3.682	3.816	3.963
X_c	0.70	0.70	0.70	0.65

($l = 0, \sigma = 1.886, \nu = 11.13$ [c/d]) for $M = 9 M_{\odot}$. Table 3 shows frequencies of all unstable f-modes for $M = 9$ – $12 M_{\odot}$.

In more advanced evolutionary models ($X_c = 0.50$, Fig. 10b), low-degree p -modes ($l \leq 2$) were unstable in the high-frequency domain, including the fundamental radial mode. For $X_c = 0.25$, the radial modes were stable in the model $M = 9 M_{\odot}$, but unstable for higher masses. Near the end of MS phase of evolution ($X_c = 0.006$) only $l \geq 2$ modes remained unstable in the high-frequency domain. In this case, g -modes of $l = 2$ were also unstable ($\nu \approx 0.5$ [c/d]) for $M = 9 M_{\odot}$ (Fig. 10d).

Next, we examined whenever an increase of the OPAL opacity bump at $\lg T \approx 5.3$ by a factor of 1.7 (cf. Sect. 3.3) was

sufficient to drive pulsations of B stars in the Magellanic Clouds. For this purpose we calculated the K-OPAL/C models with the opacity data Nos. 26 and 27. The models of No. 26 show unstable low-degree modes in the p -mode frequency domain. The seismic models of No. 27 ($Z \approx 0.00306$) show unstable modes for $M \leq 11 M_{\odot}$. In particular, we found unstable modes of $l = 3$ – 7 for $M = 10 M_{\odot}$ in the frequency domain $5.1 \leq \nu \leq 6.9$ [c/d] and $l \geq 8$ modes in $2.2 \leq \nu \leq 3.0$ [c/d].

We plotted examples of the differential work integrals for the K-OPAL/C models of $M = 10, 12$, and $40 M_{\odot}$ in Figs. 11 and 12. Again, the driving zone of the model of $40 M_{\odot}$ has two well separated components, shown in Fig. 12b, for unstable modes

Fig. 11. Differential work integrals, κ_R and κ_T were plotted. Panel **a**) shows unstable f-modes ($l = 9$ $n = 0$ and $l = 10$, $n = 0$) for $M = 12 M_\odot$ and $X_c \approx 0.65$ (opacity data No. 25). Panel **b**) shows unstable $l = 1$ modes for $M = 12 M_\odot$ and $X_c = 0.25$ (opacity data No. 25). Panel **c**) shows unstable $l = 3$ and $l = 4$ modes for $M = 10 M_\odot$ and $X_c \approx 0.26$ (opacity data No. 27). (A color version of the figure is available online.)

Fig. 12. Same as Fig. 7, but for models of $M = 40 M_\odot$ and $X_c \approx 0.25$ calculated with opacity data Nos. 20 and 25. (A color version of the figure is available online.)

of $l = 2$ ($\sigma = 0.54$ and 0.58 ; cf. Table 2). Note also, that the differential work integrals are almost the same for unstable g_8 - and g_9 -modes plotted in Figs. 12a and c. Similar behavior was seen for less massive models (cf. Figs. 7c and 11b). This indicates that the results depend mainly on the opacity data used, but not on EOS for the hybrid K-OPAL (K-OP) models of early-type stars.

6. Conclusions

The present-day results of the Kurucz (2011) opacity project to include all spectral lines of elements are the basic ingredients for the new atmosphere models calculated by Castelli & Kurucz (2003) and Meszaros et al. (2012). According to Kurucz⁶, much

⁶ A lecture given at the Astronomical Institute of the Wroclaw University, 2013.

more complete atom models than used so far should increase opacities elsewhere, not only in models of stellar atmospheres. The main motivation for this paper was to investigate seismic models, which are closely related to the new atmosphere models calculated based on the Kurucz's opacity data.

First, we present further evidence that Kurucz's more detailed atom models lead to a large excess of opacity at $\lg T \approx 5.06$ in comparison with the OPAL (and OP) data. This new opacity bump has only a minor counterpart in the OPAL and OP data (Sect. 1).

We calculated the OPAL, OP, K-OPAL, and K-OP models (Sect. 4) for stellar masses $M = 9\text{--}70 M_{\odot}$ from ZAMS to the moment short before helium ignition in the stellar core. We did not assume any mass loss, rotation, or core overshooting. However, we considered different chemical compositions following Castelli & Kurucz (2003) and Meszaros et al. (2012) atmosphere models as well as recent helioseismic measurements of Y and Z made by Vorontsov et al. (2013). The K-OPAL (K-OP) models mean that hybrid CK/OPAL (CK/OP) opacity data were used, viz., the Castelli & Kurucz or Meszaros et al. data at outer layers (up to $\lg T \approx 5.2$) and the OPAL (OP) data at $\lg T > 5.2$. The evolutionary tracks for the K-OPAL (K-OP) models differ markedly from the OPAL (OP) models for $M \geq 30 M_{\odot}$. The effect was caused by the high gradient of radiation pressure near $\lg T = 5.06$. This influences the K-OPAL (K-OP) models of stellar structure at outer layers and thereby stellar radius. Near TAMS, the models $M \geq 50 M_{\odot}$ show very low values of $\lg T_{\text{eff}} \ll 4.4$, even for $Z \approx 0.0107$. Probably, mass loss at sufficiently high rates is able to end the MS phase of evolution of these stars with higher surface temperature. Note, that TAMS is located near $\lg T_{\text{eff}} \approx 4.4$ for all OPAL (OP) models of massive stars considered. In the case of $9 \leq M \leq 20 M_{\odot}$, K-OPAL (K-OP) evolutionary tracks are almost the same as for the OPAL (OP) models for a given chemical composition. Now the gradient of radiation pressure at $\lg T \approx 5.06$ is well below the local gravity acceleration.

Next, we examined (Sect. 5) seismic models considering oscillation modes for the spherical harmonic degree $l \leq 20$ and dimensionless frequencies $0.2 \leq \sigma \leq 6$. The frequencies of modes are determined by stellar regions where the kinetic energy of the oscillation is high, viz., in the inner layers of early-type stars investigated. This means that the models with the same opacities in these layers show similar frequencies. If the abundance parameter $Z \approx 0.009$ is as low as preferred by recent helioseismic measurements (Vorontsov et al. 2013) then the OPAL and OP models of early-type stars were stable for the Grevesse & Noels (1993) mixture. The OP models were, however, unstable in low-degree modes using Asplund et al. (2009) mixture of elements.

We found that the new opacity bump at $\lg T = 5.06$ has important consequences for seismology even for stellar models with almost the same evolutionary tracks as the OPAL (OP) models. In particular, we obtain no unstable high-frequency modes for the K-OPAL/A (K-OP/A) models with masses $10 \leq M \leq 20 M_{\odot}$ for $Z \leq 0.0213$. In the case of O stars, the K-OPAL (K-OP) models show unstable nonradial modes, but only in the low-frequency domain. Such models fit better observed frequencies reported by Blomme et al. (2011) and Mahy et al. (2011). The OPAL and OP models predict unstable modes (Table 3) in the frequency domain not seen in the CoRoT observations of the investigated O stars.

The opacity bump at $\lg T = 5.3$ must be markedly larger than the new opacity bump at $\lg T = 5.06$ to drive pulsations of B stars in p -modes. An increase of the current OPAL

(OP) opacities by a factor of about 1.7 at $\lg T \approx 5.3$ is needed to sufficiently develop large driving zones to excite p -modes at K-OPAL (K-OP) models. The same factor, 1.7, is large enough to obtain unstable modes for $Z = 0.0054$ and 0.003. These values of Z are not far from the spectroscopic measurements for the Magellanic Clouds.

An increase of the opacity bumps at $\lg T \approx 5.3$ and 6.3 was already postulated by Pamyatnykh et al. (2004) and Zdravkov & Pamyatnykh (2008) to explain observed oscillation spectra in β Cephei stars. In this paper, we suggest that the opacity bump at $\lg T \geq 5.3$ may be markedly underestimated as a result of atom models used in the OPAL and OP projects. The diffusion of some elements, because of high radiation pressure near $\lg T \approx 5.06$, may also be important for asteroseismology of O and B stars. In this context, we note that opacities caused by the α -rich elements (O, Ne, Mg, Na, Si, S, Ar, Ca, and Ti) may play some role. For high abundances of these elements at stellar layers near $\lg T = 5.06$, the κ -mechanism is not expected to be efficient to drive instability in B stars. If a contribution of these elements is smaller (as in Asplund et al. 2009, mixture), then the driving zone for stellar pulsations is more extended. This means that the factor of 1.7 can be regarded as an upper limit.

Finally, we would like to point out that there are several points that were crudely approximated. Some of them result from the present lack of sufficient atomic data (e.g. Pradhan & Nahar 2009). However, the current OPAL and OP opacities, which include the old Kurucz's atomic data for Fe I–IV (Badnell et al. 2005), could also be upgraded, using the new Kurucz data for metals at higher ionization stages. In addition, the Rosseland-mean opacities are sensitive to pressure-broadening parameters of bound-bound transitions, especially at metallic opacity bumps. Relatively little is known about how this affects seismic models of stars (Appendix A).

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Appendix A: Details about Kurucz's and K-OPAL opacity data

The Rosseland-mean opacities calculated by Castelli & Kurucz are available in tabular form for different metallicities and microturbulent velocities $\xi = 0, 1, 2, 4$, and 8 km s^{-1} . Following Kurucz, the data (Table A.1) were named using the scheme, which describes abundances of metals relative to the solar abundances listed in Grevesse & Sauval (1998). In particular, $p15$ corresponds to enhanced abundances of metals by $[m/H] = \lg(m/H) - \lg(m/H)_\odot = +1.5$ dex, the solar chemical composition ($[m/H] = +0.0$) is denoted as $p00$, and $[m/H] = -4.0$ as $m40$. The X , Y , and Z abundance parameters and the mass abundances of oxygen (Z_O) and iron (Z_{Fe}) were also shown in Table A.1. The opacity data Nos. 1–22 have the same relative abundances of metals taken from Grevesse & Sauval (1998), while data Nos. 23–35 have enhanced abundances of O, Ne, Mg, Si, S, Ar, Ca, and Ti by +0.4 dex. These elements are produced by stellar nucleosyntheses in the α -process. The last two rows in Table A.1 show the abundance parameters listed in Asplund et al. (2005) and Asplund et al. (2009).

The CK Rosseland-mean opacities, κ_R^{CK} , were tabulated for $3.3 \leq \lg T \leq 5.3$ and $-4.0 \leq \lg P_g \leq 8.0$, where P_g is the gas pressure in the cgs units. Figure A.1 shows $\lg \kappa_R^{CK}$ as a function of $\lg T$ for $\lg P_g = 2, 4, 6$, and 8 , and $\xi = 0$. In each panel, the top line corresponds to $X = 0.4786$ and $Z = 0.3596$, while the bottom line to $X = 0.7474$ and $Z = 1.49 \times 10^{-7}$ (Table A.1). Clearly, the opacity bump at $\lg T \approx 5.06$ is caused by metals and can be explained by much more detailed atom models of the new Kurucz data. The opacities with enhanced abundances of the α -rich elements (O, Ne, Mg, Si, S, Ar, Ca, and Ti) by +0.4 dex. were plotted in Fig. A.2. These elements participate in the opacity bump at $\lg T \approx 5.06$ in addition to other heavy elements (cf. also Fig. 2, where the data of $m05$ and $m05a$ were plotted).

Recently, an extensive grid of atmosphere models, as well as the Rosseland-mean opacities, κ_R^M , were recalculated by Meszaros et al. (2012) for scaled solar abundances of metals given by Asplund et al. (2005). Examples are shown in Table A.2 and Fig. A.3. The data were named using the Kurucz scheme for the scaled metal (m) abundances composed with a standard/nonstandard content of C (c) and O (o).

We would like to note that Castelli & Kurucz's mixture of elements has higher values of Z and Z_O than those of Asplund et al. (2009), but the same abundance of Fe. The Meszaros et al. data (M) have lower Z - and Z_{Fe} -values. In addition, the helium abundance of the CK and M standard (solar) mixtures is not far from the helioseismological value $Y = 0.2485$ given by Basu & Antia (2004). This helium abundance was adopted by Grevesse & Sauval (1998), Asplund et al. (2005) and Asplund et al. (2009). The CK and M elemental mixtures have $Y = 0.1635$ – 0.2526 (Tables A.1 and A.2).

The CK and M atmosphere models are available from Castelli and ATLAS-APOGEE websites (Sect. 3), respectively. The older models, available from Kurucz website, were calculated for older opacity distribution functions (ODF) with about 58 million lines of atoms and molecules in total. Despite this, according to Kurucz (2011), the line opacity was underestimated because not enough lines were included in calculations.

According to Kurucz (2012, priv. comm.), the CK opacities are less reliable for $\lg T \geq 5.2$. The K-OPAL models were therefore calculated using the CK (or M) opacities for $\lg T < 5.2$ and the OPAL (or OP) data for higher temperatures. We adjusted these two kinds of Rosseland-mean

opacities at $\lg T = 5.2$, assuming $\lg \kappa_R^{K-OPAL \text{ (or K-OP)}}(5.2, P_g) = [\lg \kappa_R^{CK \text{ (or M)}}(5.175, P_g) + \lg \kappa_R^{OPAL \text{ (or OP)}}(5.225, P_g)]/2$. The opacity data are usually included as tables of $\kappa_R(\lg T, \lg R)$ (the OPAL format) in computing codes for modeling stellar structure, where $\lg R = \lg \rho - 3 \lg T + 18$. We attempted to achieve good accuracy in the transformation of κ_R from $(\lg T, \lg P_g)$ to $(\lg T, \lg R)$ variables. First, we solved the EOS with a Kurucz's computing code to find out gas densities, ρ , for each pair of $(\lg T, \lg P_g)$. Next, we interpolated the opacity data to $(\lg T, \lg R)$ -points. In addition to κ_R , the derivatives of the Rosseland-mean opacities over temperature and density were calculated numerically with two methods. In the first method, having already calculated tables of $\kappa_R(\lg T, \lg \rho)$, we used Kurucz's (1970) differentiation procedure to obtain $\kappa_\rho = (\frac{\partial \ln \kappa_R}{\partial \ln \rho})_T$ and $(\frac{\partial \ln \kappa_R}{\partial \ln T})_{P_g}$. Next, we used the thermodynamic identity for

$$\kappa_T = \left(\frac{\partial \ln \kappa_R}{\partial \ln T} \right)_\rho = \left(\frac{\partial \ln \kappa_R}{\partial \ln T} \right)_{P_g} - \frac{\left(\frac{\partial \ln \kappa_R}{\partial \ln P_g} \right)_T \left(\frac{\partial \ln \rho}{\partial \ln T} \right)_{P_g}}{\left(\frac{\partial \ln \rho}{\partial \ln P_g} \right)_T}. \quad (\text{A.1})$$

Again, the CK (or M) and OPAL (or OP) derivatives were adjusted at $\lg T = 5.2$. In the second method, we started from $\kappa_R(\lg T, \lg R)$ and ran Seaton's (1993) bicubic interpolation procedure, which involves 16 neighborhood points as well as the derivatives of κ_R over temperature and density. Both methods yield similar results, although the second method reveals a little bit more regular behavior of the derivatives because of the higher number of data points involved in the procedure. In the rest of this paper we used data obtained from the second method. No additional smoothing procedure was ran.

The K-OPAL opacity data discussed in Sect. 3 show two opacity bumps at $\lg T = 5.06$ and 5.3 . Examples of the hybrid opacities, κ_R were plotted in Fig. 2 and their derivatives over density, $(\kappa_\rho)_T$, and temperature $(\kappa_T)_\rho$, in Figs. A.4 and A.5, respectively. The local minimum of the opacity at $\lg T = 5.2$ plays a crucial role in the K-OPAL seismic models of B stars as discussed in Sect. 5. A deeper insight into the problem follows from an analysis of the OP monochromatic opacities. Figure A.6 shows contributions of different elements to the total opacity (yellow lines) for $\lg T = 4.8, 5.0$, and 5.3 , and $\lg N_e = 16$. The black lines display opacity caused by H, He, Fe, and electron scattering (σ_e), while cross-sections of Fe are shown as violet lines. In Fig. A.6, the monochromatic cross-sections, $\sigma(u)$ are given in atomic units, where $u = \frac{h\nu}{kT}$. The Rosseland-mean opacity per unit mass is then

$$\kappa_R = \frac{\sigma_R}{\mu}, \quad (\text{A.2})$$

where

$$\frac{1}{\sigma_R} = \int_0^\infty \frac{1}{\sigma(u)} F(u) du, \quad (\text{A.3})$$

$$F(u) = \frac{15}{\pi^4} u^4 e^{-u} / [1 - e^{-u}]^2 \quad (\text{A.4})$$

and μ is the mean atomic weight. The smooth red lines in Fig. A.6, corresponding to $\lg F(u) + C$, display that a spectral region near $u = 3.83$ contributes mostly to the Rosseland-mean opacity. The constant C was introduced for better visibility of the Rosseland-mean weighting function (corrected for stimulated emission), $F(u)$. In the cases of $\lg T = 4.8$ and 5.0 , the Fe-curtain (violet lines in Fig. A.6) is located well below opacity caused by H, He, and σ_e at spectral region near $u \approx 3.83$.

Fig. A.1. Rosseland-mean opacities $\lg \kappa_R [\text{cm}^2 \text{g}^{-1}]$ calculated by Castelli & Kurucz for different chemical composition of elements and $\xi = 0$. The data plotted for the gas pressure, $\lg P_g = 2, 4, 6$, and 8 (in cgs units) were taken from the Castelli website on 2012. Black lines show opacity data Nos. 1–9 listed in Table A.1, while blue lines display opacity data Nos. 10–22.

Fig. A.2. Same as Fig. A.1, but the Rosseland-mean opacities $\lg \kappa_R [\text{cm}^2 \text{g}^{-1}]$ calculated by Castelli & Kurucz for enhanced abundances of O, Ne, Mg, Si, S, Ar, Ca, and Ti elements by +0.4 dex, viz., opacity data Nos. 23–35 listed in Table A.1 were plotted.

Fig. A.3. Examples of the Rosseland-mean opacities $\lg \kappa_R [\text{cm}^2 \text{g}^{-1}]$ calculated by Meszaros et al. for different chemical composition of elements and $\xi = 2 \text{ km s}^{-1}$ (Table A.2). The data plotted for the gas pressure, $\lg P_g = 2, 4, 6$, and 8 (in cgs units) were taken from the ATLAS-APOGEE website on 2013.

Fig. A.4. Derivatives of the Rosseland-mean opacities over density $\kappa_\rho = (\frac{\ln \kappa_R}{\ln \rho})_T$ vs. $\lg T$ for $\lg R = \lg \rho - 3 \lg T + 18 = -6.0, -5.0, -4.5$, and -4.0 . The OPAL (blue lines) and K-OPAL/A (red lines) data were plotted for $Z = 0.0266, 0.169, 0.00542$, viz., opacity data No. 1, 3, 7, 11, 13, and 16 listed in Table 1 are shown. The K-OPAL/A data with α -enhanced elements (*m05a* in Table A.1) were also plotted as green lines.

Fig. A.5. Same as Fig. A.4, but for $\kappa_T = \left(\frac{\partial \ln \kappa_R}{\partial \ln T} \right)_\rho$ vs. $\lg T$.

Fig. A.6. OP monochromatic cross-sections $\lg \sigma$ (in atomic units) vs. $u = \frac{h\nu}{kT}$ for $\lg N_e = 16$ and $\lg T = 4.8, 5.0, 5.2$, and 5.3 . The yellow lines show the total opacity produced by all elements considered in the OP project, the black lines display opacity caused by H, He, Fe, and σ_e , while the violet lines correspond to Fe. The Rosseland-mean weighting function is also plotted as smooth lines. The brown line in the two lowest panels correspond to H, He, and σ_e .

Table A.1. Castelli & Kurucz (2003) opacity data and atmosphere models available from Castelli website.

No.	Name	[m/H] [dex]	X	Y	Z	Z _O	Z _{Fe}	
1	p15	+1.5	0.4836	0.1635	0.3529	0.1641	0.02680	
2	p10	+1.0	0.6375	0.2154	0.1471	0.0684	0.01117	
3	p075	+0.75	0.6813	0.2303	0.0884	0.0411	0.00671	
4	p05	+0.5	0.7087	0.2395	0.0517	0.0241	0.00393	x
5	p04	+0.4	0.7164	0.2421	0.0415	0.0193	0.00315	
6	p03	+0.3	0.7225	0.2442	0.0333	0.0155	0.00253	
7	p02	+0.2	0.7275	0.2459	0.0266	0.0124	0.00202	x
8	p01	+0.1	0.7315	0.2472	0.0213	0.00988	0.00161	
9	p00	+0.0	0.7347	0.2483	0.0169	0.00788	0.00129	x
10	m01	-0.1	0.7373	0.2492	0.0135	0.00628	0.00103	
11	m02	-0.2	0.7394	0.2499	0.0108	0.00501	8.17×10^{-4}	
12	m03	-0.3	0.7410	0.2504	0.00857	0.00398	6.51×10^{-4}	
13	m04	-0.4	0.7423	0.2509	0.00682	0.00317	5.18×10^{-4}	
14	m05	-0.5	0.7433	0.2512	0.00542	0.00252	4.12×10^{-4}	x
15	m075	-0.75	0.7451	0.2518	0.00306	0.00142	2.32×10^{-4}	
16	m10	-1.0	0.7461	0.2522	0.00172	8.01×10^{-4}	1.31×10^{-4}	x
17	m15	-1.5	0.7470	0.2525	5.45×10^{-4}	2.53×10^{-4}	4.14×10^{-4}	x
18	m20	-2.0	0.7473	0.2526	1.72×10^{-4}	8.02×10^{-5}	1.31×10^{-5}	x
19	m25	-2.5	0.7474	0.2526	5.43×10^{-5}	2.54×10^{-5}	4.14×10^{-6}	x
20	m30	-3.0	0.7474	0.2526	1.74×10^{-5}	8.02×10^{-6}	1.31×10^{-6}	
21	m35	-3.5	0.7474	0.2526	5.28×10^{-6}	2.54×10^{-6}	4.14×10^{-7}	
22	m40	-4.0	0.7474	0.2526	1.64×10^{-6}	8.02×10^{-7}	1.31×10^{-7}	x
23	p05a	+0.5	0.6725	0.2273	0.1003	0.0572	0.00373	x
24	p02a	+0.2	0.7079	0.2392	0.05289	0.0301	0.00197	x
25	p00a	+0.0	0.7220	0.2440	0.03404	0.0193	0.00126	x
26	m05a	-0.5	0.7392	0.2498	0.01102	0.00624	4.10×10^{-4}	x
27	m10a	-1.0	0.7448	0.2517	0.00351	0.00199	1.30×10^{-4}	x
28	m15a	-1.5	0.7466	0.2523	0.00113	6.30×10^{-4}	4.14×10^{-5}	x
29	m20a	-2.0	0.7471	0.2525	3.52×10^{-4}	1.99×10^{-4}	1.31×10^{-5}	x
30	m25a	-2.5	0.7473	0.2526	1.11×10^{-4}	6.30×10^{-5}	4.14×10^{-6}	x
31	m30a	-3.0	0.7474	0.2526	3.52×10^{-5}	1.99×10^{-5}	1.31×10^{-6}	
32	m35a	-3.5	0.7474	0.2526	1.11×10^{-5}	6.30×10^{-6}	4.14×10^{-7}	
33	m40a	-4.0	0.7474	0.2526	3.52×10^{-6}	1.99×10^{-6}	1.31×10^{-7}	x
34	m45a	-4.5	0.7474	0.2526	1.11×10^{-6}	6.30×10^{-7}	4.14×10^{-8}	
35	m55a	-5.5	0.7474	0.2526	1.52×10^{-7}	6.30×10^{-8}	4.11×10^{-9}	
36	AGS05		0.7392	0.2486	0.0122	0.00536	0.00115	
	AGSS09		0.7381	0.2485	0.0134	0.00573	0.00129	

Table A.2. Examples of Meszaros et al. (2012) opacity data available from ATLAS-APOGEE website.

Nos.	Name	X	Y	Z	Z _O	Z _{Fe}
1	Mmp00cp00op00	0.7383	0.2495	0.0122	0.00536	0.00115
2	Mmp00cp00op03	0.7344	0.2482	0.0174	0.0106	0.00115
3	Mmp00cp05om05	0.7375	0.2493	0.0132	0.00169	0.00115
4	Mmp00cp05op10	0.7012	0.2370	0.0618	0.0509	0.00109
5	Mmp00cm10om10	0.7433	0.2512	0.00548	0.000539	0.00116

Note that the contribution of metals other than Fe is significant at $\lg T = 5.0$. This is the reason why the new Kurucz data were able to change the Rosseland-mean opacity mostly near $\lg T = 5.06$. The Fe-curtain dominates at $\lg T = 5.3$ (Fig. A.6). Now, the OP (and OPAL) opacity is caused mostly by very many lines due to Fe in electron configurations of the type $3s^x 3p^y 3d^z$ and $3s^x 3p^y 3d^z nl$, (Iglesias et al. 1990; Lynas-Gray et al. 1995; Seaton et al. 1994). As one can see, the synthetic Fe cross-section is located above the total cross-sections caused by H, He, and σ_e (a brown line) near $u \approx 3.83$ (and $u \geq 7$). This changes quickly depending on the temperature. At $\lg T = 5.2$, the Fe-curtain is also

seen, but its maximum is shifted to $u \approx 5$. Similarly, the maximum is located at $u \approx 2.3$ for $\lg T = 5.5$. As a result, the OP (and OPAL) opacity bump at $\lg T = 5.3$ is narrow and the K-OP (and K-OPAL) data have a two-peak structure of κ_R with the additional opacity bump at $\lg T = 5.06$.

As mentioned in Sect. 3.2, the K-OPAL/B models were designed to study how the relative strength of the opacity bumps at $\lg T = 5.06$ and 5.3 influence seismic models of early-type stars. They are basically the OPAL models for $Z = 0.0264$ and $Z = 0.0168$, but $\kappa_R = \max(\kappa_R^{\text{CK}}, \kappa_R^{\text{OPAL}})$ was selected near the opacity bump at $\lg T \approx 5.06$. The CK opacity data of

Fig. A.7. Derivatives of the Rosseland-mean opacities over temperature $\kappa_T = \left(\frac{\ln \kappa_R}{\ln T} \right)_\rho$ vs. $\lg T$ for $\lg R = -6.0, -5.0, -4.5$, and -4.0 . The K-OPAL/B data (Nos. 18–20 in Table 1) were compared with the OPAL (No. 1) and K-OPAL/A (No. 11) data.

m075, m05, m04, m02, and *p00* were considered. Figures A.7 show κ_R and κ_T for models of Nos. 18–20 (Table 1) in comparison with the OPAL (No. 1) and K-OPAL/A data (No. 11).

Relatively little is known about the sensitivity of the OP and OPAL data to the pressure-broadening parameters for spectral lines. There is little sensitivity at high densities, where the lines become very broad and give a quascontinuum, or at very low densities, where the profiles are mainly determined by Doppler broadening and radiation damping. At intermediate densities, like $\lg N_e = 15.5$ and $\lg T = 5.2$ ($\lg R = -5.8$) discussed by Seaton et al. (1994), an increase of the pressure broadening parameters of Fe lines by a factor of 2 results in an increase in the Rosseland-mean opacity by 33 per cent for the solar mix of elements. The opacity is much lower when only doppler broadening of lines is assumed (Rogers & Iglesias 1992).

In addition, including more electron configurations and many more line transitions, as in Kurucz (2011), would probably also increase opacity at $\lg T > 5.2$. Another potentially important reason why the OP (and OPAL) opacities should be upgraded is related to autoionizing transitions. In the OP project, these transitions were treated as resonances in photoionization cross-sections (Bautista 1997). To make the problem tractable, each *LS*-term was represented by only one level with its average energy. The splitting of spectroscopic *LS* terms

into individual levels may be necessary for final calculations of photoionization cross-sections with resonance structures. This is suggested by Kurucz's treatment of autoionizing transitions (Castelli & Kurucz 2004) and by recent results published by Nahar et al. (2011), which include the fine structure explicitly for Fe XVII. Similarly, the new effective cross-sections with photoexcitation-of-core (PEC) resonances for O III and Fe XXI are much higher, up to two orders of magnitude, than in the OP data (Fig. 1 in Pradhan & Nahar 2009). The missing opacity in the OP data may lie in an energy range from a few eV to few hundreds of eV, depending on the element and ionization stage. Therefore, we also searched K-OPAL/C (and K-OP/C) models (with opacity data Nos. 23–25) with enhanced opacities at $\lg T > 5.2$. In the case of No. 23, EOS and nuclear reaction rates were calculated for the initial (at ZAMS) chemical composition of $X = 0.7394$, $Y = 0.2499$, and $Z = 0.0107$. The CK opacity data corresponding to $Z = 0.0107$ were assumed at $\lg T < 5.2$, but the OPAL opacities corresponding to $Z = 0.0264$ at $\lg T > 5.2$. Similarly, models of Nos. 24 and 25, were calculated for $Z = 0.00537$ and 0.00303 with enhanced opacities at $\lg T > 5.2$ (OPAL: $Z = 0.0168$ and 0.0134), respectively.

Examples of κ_R and κ_T are shown in Figs. 11 and 12 (Sect. 5), where differential work integrals were plotted for the K-OPAL models.