

Asteroseismology of Massive Stars : Some Words of Caution

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Abstract. Although playing a key role in the understanding of the supernova phenomenon, the evolution of massive stars still suffers from uncertainties in their structure, even during their “quiet” main sequence phase and later on during their subgiant and helium burning phases. What is the extent of the mixed central region? In the local mixing length theory (LMLT) frame, are there structural differences using Schwarzschild or Ledoux convection criterion? Where are located the convective zone boundaries? Are there intermediate convection zones during MS and post-MS phase, and what is their extent and location? We discuss these points and show how asteroseismology could bring some light on these questions.

Keywords. stars: evolution, stars: interiors, stars: oscillations (including pulsations), stars: variables: massive stars, stars: mass loss,

1. Introduction

The key role played by asteroseismology in probing and understanding the stellar structure of massive stars is undeniable. Thanks to excited modes, in particular those propagating in the deep interior, the extent of the mixed central region can be constrained. This region consists of the fully mixed convective core surrounded by an “extra-mixed” region, either fully or partially mixed. The physical origin of this region can be rotation, overshooting... What asteroseismology will test is of course not the physics but the resulting chemical composition profile. In Sect. 2, we show how the extent of the extra-mixed region can only be reliably determined by asteroseismology provided some rather strong requirements are fulfilled not only on the number of well identified modes but also on the detailed elemental abundances of the observed star (Salmon 2014).

One of the big issues extensively discussed in this symposium is the treatment of convection in massive stars. However, most stellar evolution codes still compute convective regions in the frame of the local mixing length theory (LMLT) with either Ledoux or Schwarzschild criterion. We first show that whatever the adopted criterion, the extent of convective cores must be identical (see Sect. 3.1).

Asteroseismic analyses require fully consistent models, in particular models with correctly located convective boundaries, *i.e.* satisfying the convection criterion on its convective side. As shown in Gabriel et al. (2014), a departure from this requirement leads to too small convective cores and erroneous Brunt-Väisälä frequency distributions, with a possible misleading of the asteroseismic interpretation. This is discussed in Sect. 3.2.

In Sect. 3.3 we address the important point of the exact location and extent of convective shells in the vicinity of the hydrogen burning shell in supergiant B stars and

we discuss the different aspects of these shells resulting from the choice of Ledoux or Schwarzschild convection criterion. We raise some problems (semi-convection, overshooting, non-existence of a static solution) that can appear when a convective shell develops (Gabriel et al. 2014).

We then show in Sect. 4 how recent interesting asteroseismic analyses can help bring new constraints on these shells (Saio et al. 2006; Gautschy 2009; Godart et al. 2009, 2014; Saio et al. 2013; Georgy et al. 2014).

Sect. 5 addresses the problem of exciting β Cephei- and SPB-type modes in the Small Magellanic Cloud, with a metallicity so low that no such modes (only very few SPB-type) are indeed theoretically expected. This could be due to an underestimation of the Ni opacity in the “metal opacity bump” (Salmon et al. 2012).

2. Amount of extra-mixing in MS and core helium burning stars

In what follows we shall define the extra-mixing as an additional full mixing taking place on top of the convective core, resulting from various physical causes such as convective overshooting or penetration, rotation, semi-convection, diffusion... The extent of this extra-mixing region is referred to as a fraction α_{em} of the pressure scale height.

As was shown and discussed in session II of this symposium (Aerts 2014), several asteroseismic analyses of β Cephei stars have revealed quite a large range of values for this parameter α_{em} , from 0 to ~ 0.5 . The method used is a χ^2 minimisation of the differences between the observed frequencies and those found in a large grid of models with various stellar parameters, in particular various values of α_{em} . No direct relation between this latter parameter and another stellar property, such as the rotation velocity, seems to exist.

In an attempt to better understand the link between α_{em} and the fitting method, Salmon (2014) has realized a series of *hare-and-hound* exercises. Targets were computed with various choices of stellar parameters (M , R , X , Z , α_{em}) and different physical assumptions, such as the solar mixtures AGSS05 (Asplund et al. 2005) or GN93 (Grevesse & Noels 1993) and the opacities OPAL (Iglesias & Rogers 1996) or OP (Badnell et al. 2005). A set of non-adiabatic frequencies were computed for each target, to serve as “observed” frequencies. The grid of models used to minimize χ^2 for each target had fixed physical assumptions, *i.e.* AGSS05 for the solar mixture and OP for the opacities. Adiabatic frequencies were available for each model of the grid. We cite below some of the conclusions drawn from these exercises :

- If the physics is the same in the target and in the grid, five *well identified* (well known) observed frequencies are required to recover the stellar parameters, in particular α_{em} . With only three frequencies, the error on α_{em} can reach a factor two.
- If among those five frequencies, one of them is not correctly identified, the errors are as large as in the case where only three frequencies are observed. The minimum of χ^2 is however much larger than when a good solution is obtained.
- If the target is built with the solar mixture GN93 instead of that of the grid (AGSS05), a 50 % error is found on α_{em} . Here also the minimum of χ^2 presents a rather large value that could be used as an alarm criterion to detect an incorrect solution.

It should however be noted that, without asteroseismic data, the amount of extra-mixing in massive stars is impossible to obtain since there is a well-known degeneracy in M and α_{em} for a given set of T_{eff} and L . But we think useful to stress the importance of combining asteroseismic data with spectroscopic and photometric data in order to reach a higher level of constraints on the model. Moreover, “best” solutions obtained with a too large χ^2 should be regarded with caution.

3. Convection in LMLT frame

In this section, we would like to emphasize, and call attention on, some problems related to convective zones and, in particular to convective boundaries, which seem to be met in some stellar evolution codes. Since some codes, like the MESA code for instance (Paxton et al. 2013), are now being used on a larger and larger scale by the astrophysical community, extra care should be given to the outputs in order to help the developers to still increase the performances of the code. Another reason to be extremely careful is that an asteroseismic analysis requires a fully consistent model, at the risk of misinterpreting asteroseismic data if this exigence is not fully met.

3.1. Convection criterions

In spherically symmetric stars, the condition to define the boundary of a convective zone is (see Gabriel et al. 2014, and references therein)

$$V_r = 0 \quad (3.1)$$

where V_r is the radial component of the convection velocity. In the frame of the LMLT, this implies

$$L_{rad} = L(m) \text{ and } \nabla_{rad} = \nabla_{ad} \quad (3.2)$$

where L_{rad} is the radiative luminosity and $L(m)$, the total luminosity at mass fraction m ; ∇ stands for usual temperature gradient and the indices *rad* and *ad* refer to radiative and adiabatic. This is the so-called Schwarzschild criterion. Let us visualize a convective boundary as a two-sided spherical surface, with a “convective” and a “radiative” side. The condition 3.2 is obviously only meaningful in a convective region and thus it must be applied *on the convective side* of the boundary.

On the radiative side of the convective boundary, the situation is different since condition 3.2 becomes

$$L_{rad} = L(m) \text{ and } \nabla_{rad} = \text{ or } \neq \nabla_{ad} \quad (3.3)$$

depending on the presence, or not, of a discontinuity in chemical composition.

For a radiative layer to become convective, the Ledoux criterion¹ should be applied. For an equation of state $P = \mathcal{R}\rho T/\beta\mu$ with $\beta = P_g/P$ and μ , the mean molecular weight, it writes

$$\nabla_{rad} > \nabla_{ad} + \left(\frac{\beta}{4 - 3\beta} \right) \frac{d \ln \mu}{d \ln P} = \nabla_{Ldx} \quad (3.4)$$

If the physical conditions within a layer are such that ∇_{rad} is in between ∇_{ad} and ∇_{Ldx} , the layer is generally assumed to be semi-convective². In the absence of a special treatment of semi-convection in the code, such a layer will be assumed to be convective (radiative) if the Schwarzschild (Ledoux) criterion is adopted throughout the code. In MS massive stars for instance, the μ -gradient region is characterized by a quasi-equality of ∇_{rad} and ∇_{ad} . Small convective zones, leading to a step-like hydrogen profile, will generally appear with the Schwarzschild criterion while a smooth hydrogen profile is maintained throughout MS with the Ledoux criterion.

Notes:

¹ *Convection is the result of the non-linear development of the linear instability of dynamically unstable gravity modes, which is only the case if condition 3.4 is satisfied.*

² *Semi-convection is the result of the non-linear development of the linear vibrational instability of dynamically stable gravity modes.*

3.2. Location of convective boundaries

Whatever the convection criterion adopted in the code, the convective boundary is located by finding the zero of the function y , *i.e.*

$$\begin{aligned} y &= \nabla_{rad} - \nabla_{ad} = 0 \quad \text{or} \\ y &= \nabla_{rad} - \nabla_{Ldx} = 0 \end{aligned} \quad (3.5)$$

on the convective side of the boundary. However, a discontinuity in y may be present at the boundary. With the Schwarzschild criterion, this happens when the chemical composition is discontinuous, *i.e.* during the early MS phase of low mass stars ($\sim 1.1 - 1.6M_{\odot}$) when the convective core is growing in mass, and during core helium-burning phase. With the Ledoux criterion, this happens all the time since, except in homogeneous models, the μ -gradient is discontinuous at the boundary.

Finding the zero of a discontinuous function by interpolation or by locating a change of sign (or checking the sign layer by layer) leads to a infinity of solutions. Whatever the location of the discontinuity, *i.e.* the location of the boundary, the condition on the change of sign will be satisfied. However, the only acceptable solution in the frame of LMLT is the one for which $\nabla_{rad} = \nabla_{ad}$ on the convective side of the boundary. This indeed means that the radial convective velocity is zero and that the convective flux is accordingly zero at the boundary. This condition leads to $L_{rad} = L(m)$, which must be satisfied on both sides of the boundary. The way to proceed is to *extrapolate* from points located exclusively in the convective region (see the more complete discussion in Gabriel et al. 2014).

The extent of convective cores of MS massive stars should be exactly identical, whatever the adopted convection criterion, if an extrapolation procedure is applied. With an interpolation (or change of sign) scheme however, the mass extent can be very different. If, at a given iteration, the estimated convective boundary is smaller than the real boundary, such a scheme will not be able to move the estimated boundary outward since the condition 3.5 will appear to be satisfied. This (too small) location will be accepted by the code as the correct one since from one iteration to the next, it will not move anymore.

Fig. 1 illustrates this behavior in the case of a $16M_{\odot}$ MS star computed with the code CLÉS (Scufflaire et al. 2008) and the Ledoux criterion. The hydrogen profile is drawn in long dashed line, ∇_{rad} in full line, ∇_{ad} in dashed line and ∇_{Ldx} in dotted line. In the left (right) panel, the location of the convective core boundary has been obtained through an extrapolation (interpolation) scheme. One can easily see that the extent of the convective core (fully mixed region) is smaller when an interpolation scheme is used. At the end of MS, the difference can reach $\sim 25\%$ depending on the distribution of mesh points for instance. It is also very clear that the model displayed in the right panel is not coherent since at the convective boundary, condition 3.5 is in fact not satisfied. Moreover, on top of the too small convective core, a misidentified semi-convective region covering the whole μ -gradient region is found. This of course will lead to significantly different Brunt-Väisälä frequency distributions (see the behavior of ∇_{Ldx} in both panels).

Fig. 2 shows the helium profile (dotted line), ∇_{rad} (full line) and ∇_{ad} (dashed line) in a core helium-burning star of $8M_{\odot}$ computed with the code CLÉS and the Schwarzschild criterion. In the left (right) panel, the location of the convective core boundary results from an extrapolation (interpolation) scheme. The boundary of the convective core displayed in the left panel is fully consistent since it satisfies condition 3.5. A convective boundary similar to that displayed in the right panel of Fig. 2 was met and discussed by Castellani et al. (1971). With ∇_{rad} larger than ∇_{ad} at the boundary, V_r is not equal to 0 and L_{rad} is still smaller than $L(m)$ on the convective side of the boundary, while it must

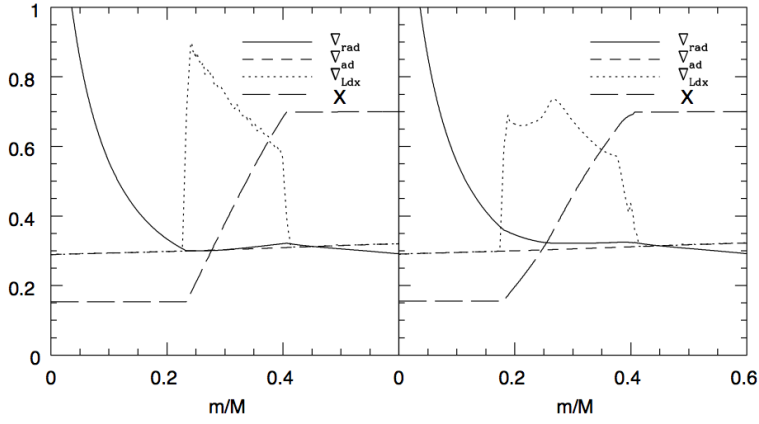


Figure 1. Hydrogen profile (long dashed line), radiative (full line), adiabatic (dashed line) and Ledoux (dotted line) temperature gradients, as a function of the fractional mass m/M , for an MS model of $16 M_{\odot}$, computed with an extrapolation scheme (left panel) and computed with an interpolation scheme (right panel), using in both cases the Ledoux criterion

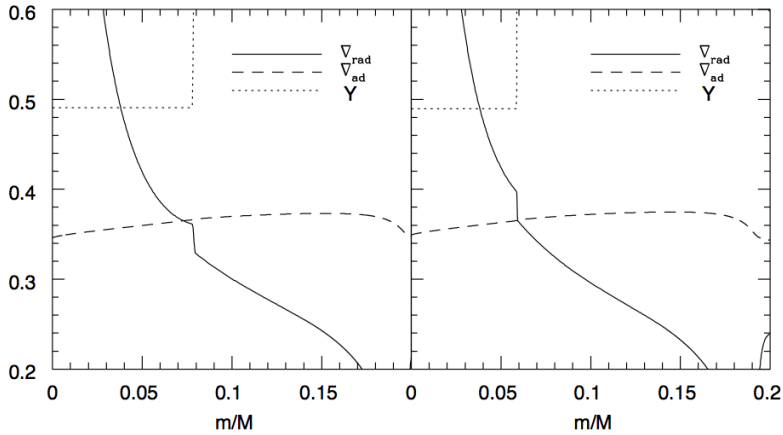


Figure 2. Helium profile (dotted line), radiative (full line), adiabatic (dashed line) temperature gradients, as a function of the fractional mass m/M , for a core helium-burning model of $8 M_{\odot}$, computed with an extrapolation scheme (left panel) and computed with an interpolation scheme (right panel), using in both cases the Schwarzschild criterion

obviously be equal to $L(m)$ on the radiative side. Indeed with the transformation of helium into carbon and oxygen, the discontinuity becomes larger and larger and Castellani et al. (1971) showed that an increase of the convective core mass was the only way out of such an unstable situation. This is indeed obtained when an extrapolation procedure from convective points only is implemented in the code.

It is clear that, with an underestimation of the extent of the convective core, the Brunt-Väisälä frequency distribution will be affected and as a result, the asteroseismic properties expected from core helium-burning stars will also be impacted.

3.3. Convective shells

If the Ledoux criterion predicts a convective shell in a μ -gradient region, the consistency of the model can be very difficult to achieve (see Sect. 7 in Gabriel et al. 2014). Fig.

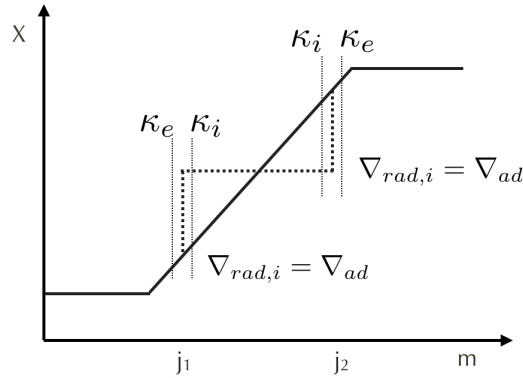


Figure 3. Schematic illustration of a convective shell developing in a μ -gradient region described by the hydrogen profile X as a function of m . κ stands for the opacity coefficient and the indices i and e refer to the inner and external sides of the convective boundaries

3 illustrates the change in the hydrogen profile arising from the occurrence of such a convective shell located in between mesh points j_1 and j_2 . The opacity is noted κ and the indices i and e refer to the inner and external sides of the convective boundaries. The main problems are listed below :

- Two discontinuities arise except if the opacity, κ , is independent of the chemical composition. One of them will necessarily be such that $\kappa_e > \kappa_i$ and since $\nabla_{rad,i} = \nabla_{ad}$ on the inner side of both boundaries, $\nabla_{rad,e}$ will be greater than ∇_{ad} at the external side of either j_1 or j_2 . This means that a semi-convective region may develop either below j_1 or above j_2 .
- Since consistent boundaries imply $L_{rad} = L(m)$ on both sides, L_{rad} must necessarily decrease above j_1 and increase when reaching j_2 . This might not be the case except maybe in nuclear burning shells or in the vicinity of an opacity peak.
- When consistency is not met, one of the boundaries is such that $\nabla_{rad} > \nabla_{ad}$ and $V_r \neq 0$. An overshooting or undershooting will take place and the chemical composition will change inside the shell, which will move along the μ -gradient region.

Once more, the consistency should be checked at each convective boundary in order to correctly interpret the asteroseismic analyses.

4. Intermediate convective zones (ICZ) in B supergiants

As can be seen in the left panel of Fig. 1, MS models of massive stars are characterized by a near equality of ∇_{rad} and ∇_{ad} in the μ -gradient region. Once the H-burning shell develops, the rapid increase of $L(m)/m$ creates a region where $\nabla_{Ldx} > \nabla_{rad} > \nabla_{ad}$, *i.e.* a semi-convective zone, which is treated as convective if the Schwarzschild criterion is used. This intermediate convective zone (ICZ) overlaps the region of nuclear energy production.

Fig. 4 shows such an ICZ in a post-MS star of $16 M_{\odot}$ computed with CLÉS and the Schwarzschild criterion. The dashed line is the hydrogen profile, ∇_{rad} and ∇_{ad} are respectively drawn in black and gray full lines and the Brunt-Väisälä frequency (in log) is shown in dotted line.

The left panel illustrates a model computed without any extra-mixing nor any mass

loss. If an extra-mixing is added on top of the convective core during MS, the near equality of both temperature gradients is replaced by $\nabla_{rad} < \nabla_{ad}$ in the μ -gradient region and for large enough extra-mixing, the ICZ can become very small and be disconnected from the nuclear burning region. The middle panel of Fig.4 is an illustration of this influence of an extra-mixing ($\alpha_{em} = 0.2$). If the models are computed with mass loss, the near equality is also affected since the μ -profile is less steep and this lessens the increase of the opacity, leading to smaller values of ∇_{rad} . With a high enough mass loss rate, the ICZ does not appear, as can be seen in the right panel of Fig. 4 ($\dot{M} = 2 \cdot 10^{-7} M_{\odot}/yr$).

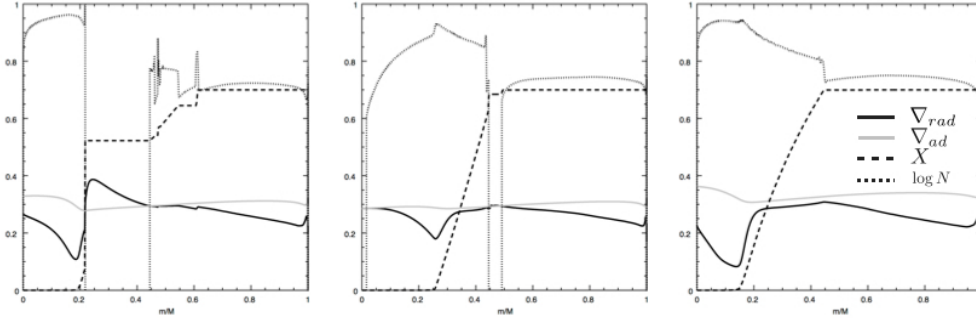


Figure 4. Hydrogen profile (dashed line), radiative (full line) and adiabatic (gray line) temperature gradients, and $\log N$ (dotted line) (N is the Brunt-Väisälä frequency) for a post-MS model of $16 M_{\odot}$ still quite close to the MS turn-off, computed with the Schwarzschild criterion. Left panel : no extra mixing, no mass loss. Middle panel : extra-mixing with $\alpha_{em} = 0.2$. Right panel : mass loss with $\dot{M} = 2 \cdot 10^{-7} M_{\odot}/yr$. The regions where N is equal to zero are convective

When the Ledoux criterion is used, the semi-convective zone is treated as radiative and the ICZ is limited to the base of the homogeneous hydrogen-rich envelope. This is illustrated in the left panel of Fig. 5. For the reasons discussed here above, the ICZ becomes smaller when an extra-mixing is added during MS (middle panel, $\alpha_{em} = 0.2$), and it disappears when a rather high mass loss rate is applied (right panel, $\dot{M} = 2 \cdot 10^{-7} M_{\odot}/yr$). With the Ledoux criterion, whatever the extent of the ICZ, its location is disconnected from the nuclear burning region.

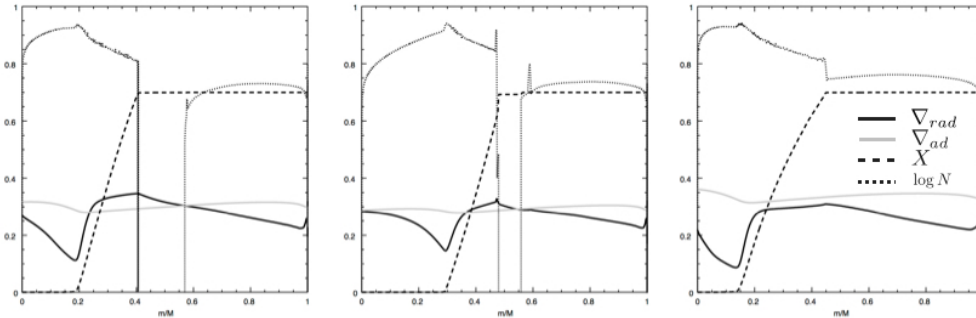


Figure 5. Hydrogen profile (dashed line), radiative (full line) and adiabatic (gray line) temperature gradients, and $\log N$ (dotted line) (N is the Brunt-Väisälä frequency) for a post-MS model of $16 M_{\odot}$ still quite close to the MS turn-off, computed with the Ledoux criterion. Left panel : no extra mixing, no mass loss. Middle panel : extra-mixing with $\alpha_{em} = 0.3$. Right panel : mass loss with $\dot{M} = 2 \cdot 10^{-7} M_{\odot}/yr$. The regions where N is equal to zero are convective

The importance of an ICZ in post-MS stars has been emphasized by the discovery of excited g-modes in a B supergiant observed by the MOST satellite (Saio et al. 2006). The role played by the ICZ is that of a barrier preventing g-modes from entering a very stabilizing helium core. The huge density in the central layers of such post-MS stars is indeed responsible for a strong radiative damping and in a star devoid of an ICZ, no g-modes can be excited (see also Gautschy 2009; Godart et al. 2009). The effects of extra-mixing and mass loss have been investigated and thoroughly discussed by Godart et al. (2009) (see also Godart et al. 2014, and references therein).

Radial pulsations observed in α Cygni variables are also good indicators of the presence of an ICZ. As discussed in Saio et al. (2013), a high value of L/M is required in order to obtain excited radial modes with periods compatible with those observed in α Cygni stars. Such high L/M can only be met in massive stars coming back from the red supergiant (RSG) stage, after a heavy mass loss undergone as a RSG. Moreover for two stars, Rigel and Deneb, the superficial N/C and N/O ratios show nitrogen and oxygen enrichments typical of CNO burning. With models computed with the Schwarzschild criterion, Saio et al. (2013) obtained far too strong such enrichments, resulting from the overlap of the ICZ and the H-burning shell. More recently, Georgy et al. (2014) computed similar models with the Ledoux criterion and showed that, with the disconnection of the ICZ and the H-burning shell, the enrichments were much closer to the observations.

The *power of asteroseismology* is here clearly seen in those two examples :

- One single g-mode observed in a B supergiant star is a signature of an ICZ and therefore brings constraints on the amount of extra-mixing and mass loss.
- The detection of radial modes, coupled with a detailed spectroscopic analysis, in an α Cygni variable star, not only lifts the degeneracy between supergiant models crossing the Hertzsprung-Russell diagram from blue to red and vice-versa but also imposes constraints on the location and mass extent of the ICZ.

5. Opacity in the metal opacity bump

Since the excitation mechanism in β Cephei and SPB stars is the κ -mechanism acting in the metal opacity bump at $T \simeq 2 \cdot 10^5 K$, it is no surprise that metallicity plays a keyrole in the extension of their instability strips in the Hertzsprung-Russell diagram. It was indeed shown by Miglio et al. (2007) that at $Z = 0.005$ the instability strip for β Cephei stars does no longer exist while a very narrow strip still remains for SPB stars. Those results actually predict that no β Cephei and very few SPB stars should be expected in the Magellanic Clouds.

Challenging observations of such stars in the Small Magellanic Cloud (SMC) have however been presented by Karoff et al. (2008); Diago et al. (2008); Kourniotis et al. (2014). The possible explanations for this apparent contradiction have been investigated by Salmon et al. (2012) who concluded their analysis by suggesting that *the current opacity data are underestimating the stellar opacity due to nickel by a factor ~ 2 (in the metal opacity bump)*. This has indeed been an additional incentive element to proceed to new revisions of the stellar opacities. Recent comparisons between different opacity codes presented by Turck-Chièze & Gilles (2013) are very encouraging since they evoke a possible increase of the nickel opacity in the metal opacity bump by a factor similar to that proposed by Salmon et al. (2012).

This is not the first time that variable stars have demanded a revision in opacity data. Simon (1982)'s plea was followed by a successful update, which turned out to be the key factor in explaining the excitation mechanism in β Cephei stars. As for now, the

OP, OPAC and OPAL teams are undertaking new opacity computations, especially in physical conditions typical of B-type and solar-like stars.

6. Conclusions

Asteroseismology is definitely a powerful tool to bring some light on some unsolved problems affecting the structure and evolution of massive stars. However, we have tried with a few selected examples to call attention on some aspects of stellar modeling as well as asteroseismic analyses, which could lead to misinterpretations of seismic data :

- Our *first word of caution* relates to the asteroseismic estimation of the extent of extra-mixing on top of the convective core in β Cephei stars. Although not sufficient the following requirements must be met in order to have a really reliable determination :

- at least 4-5 *well identified* frequencies must be observed;
- the metallicity, and more precisely the detailed elemental abundances, should be known.

- Our *second word of caution* sets in the LMLT frame of convection. For a theoretically asteroseismic analysis to be reliable, fully consistent models are absolutely required. This implies that :

- the condition on convective neutrality defining the boundary of a convective region must be applied on the *convective side* of the boundary;
- when this boundary is affected by a discontinuity in the chemical composition (Schwarzschild criterion) or in the μ -gradient (Ledoux criterion), the location of the boundary must result from an *extrapolation* from convective points only;
- the boundaries of each intermediate convective zones should systematically be checked for consistency.

- Our *third word of caution* addresses the physical data entering stellar model computations. It certainly is another success of asteroseismology to have been at the origin of a new, and still in progress, opacity revision. This stresses the necessity to be open-minded to all the tools available in order to unveil the physical processes inside massive stars, *i.e.* not only asteroseismology but also spectroscopy and photometry for detailed elemental abundances and global stellar properties, as well as the most updated physical data related to nuclear reactions and opacities.

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Discussion

C. AERTS: Just a general remark for the majority of the audience about the hare-and-hound exercises : you should also compare the uncertainty on the model parameters (M , X , Z , α_{em}) between the case where you have only T_{eff} and $\log g$, with errors of 1000K and 0.2 dex, and the case where you also have a few identified modes, including, or not, a misidentification and/or wrong input physics.

A. NOELS: I fully agree that most of the time, the addition of 4 or 5 well identified modes will highly increase the level of constraints on the theoretical model best fitting the observed star. This is indeed the power of asteroseismology to probe deep inside the star, down to the centrally mixed region. This lifts the well-known degeneracy of possible M and α_{em} for a given set of T_{eff} and L . However, I want to call attention on a possible misinterpretation of asteroseismic data if the physics is not the same in the grid and in the observed target. It is of course impossible to check all the possible differences but an extra care should be given to the detailed chemical composition. This is indeed, in my opinion, an *important word of caution* : to increase the relevance and the power of asteroseismic analyses, all the tools should enter the game, and among them, detailed spectroscopic and photometric analyses definitely play key roles.