Ledoux’s convection criterion in evolution and asteroseismology of massive stars

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Abstract

Saio et al. (2006) have shown that the presence of an intermediate convective zone (ICZ) in post-main sequence models could prevent the propagation of g-modes in the radiative interior and hence avoid the corresponding radiative damping. The development of such a convective region highly depends on the structure of the star in the \( \mu \)-gradient region surrounding the convective core during the main sequence phase. In particular, the development of this ICZ depends on physical processes such as mass loss, overshooting (Chiosi & Maeder 1986, Chiosi et al. 1992, see also Godart et al., these proceedings) and convective instability criterion (Schwarzschild’s or Ledoux’s criteria). In this paper we study the consequences of adopting the Ledoux’s criterion on the evolution of the convective regions in massive stars (15 and 20 \( M_\odot \)), and on the pulsation spectrum of these new B-type variables (also called SPBsg).

Stellar models: evolution of convective regions during main sequence and post-main sequence phases

Stellar evolution models have been calculated with the CESAM code (Morel & Lebreton, 2008) for masses \( M = 15 \) and 20 \( M_\odot \), a solar chemical composition (\( Z/X = 0.0245, Y = 0.27 \)) without and with overshooting of convective zones (\( \alpha_{ov} = 0.2 H_p \)). For all these models, we calculated the pre-main sequence evolution. In models including overshooting, we assumed that \( \nabla = \nabla_{ad} \) in the overshoot region.

As the star evolves on the main sequence (MS), a gradient of chemical composition (\( \nabla_\mu \)) develops at the outer border of the convective core. In the context of Schwarzschild’s criterion (convective instability if \( \nabla_{rad} \geq \nabla_{ad} \)), the outwards increase of opacity leads to the formation of a region of semiconvective instability outside the convective core (CC) and therefore to the mixing of matter until the neutrality of gradients is reached (\( \nabla_{rad} = \nabla_{ad} \)). During the post-MS this region becomes an ICZ which develops as H starts burning in a shell in the \( \mu \)-gradient region.

When the Ledoux’s criterion for convection (convective instability if \( \nabla_{rad} \geq \nabla_{ad} + \frac{\beta}{\mu} \nabla_\mu \) where \( \beta \) is the ratio of the gas to the total pressure) is used instead of the Schwarzschild’s criterion, the role of \( \mu \)-gradients on the stability against convection is taken into account. Adopting the Ledoux’s criterion does not change the size of the CC during the MS. Nevertheless, in models based on Ledoux’s criterion, a convective region located outside the CC appears during the MS phase at the base of the homogeneous region at \( m/M = 0.45 \).
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Asteroseismology of post-MS B-type stars

We have investigated the seismic characteristics of our models according to the recipes described by Dupret et al. (these proceedings). Excitation and damping of p and g modes
highly depend on the location and thickness of the ICZ, hence on the change of luminosity as the star becomes cooler. In models computed with the Ledoux’s criterion, the $\mu$-gradient region located below the ICZ brings a large contribution to the Brunt-Väisälä frequency $N_{BV}$ which leads to strong damping of the modes. For instance, we find that at $\log T_{\text{eff}} = 4.27$ the kinetic energy of a $\ell = 1$ mode in the radiative core of post-MS models of $15 M_\odot$ is much higher than in $20 M_\odot$ models. As a consequence, the mode in the $15 M_\odot$ star is more damped in the radiative centre and its amplitude in the driving region at $\log T \sim 5.2$ is too low for the mode to be effectively excited.

The frequency range of excited modes and the $T_{\text{eff}}$ domain of the instability strip are shown in Fig.3.

Conclusions

In models computed with the Schwarzschild’s criterion, the ICZ which is closely related to the H-burning shell is located within the $\mu$-gradient region. In the ICZ, $N_{BV} = 0$ which corresponds to less radiative damping. On the other hand, in models computed with the Ledoux’s criterion, the ICZ is thin and is located at higher values of $\mu/M$, at the base of the homogeneous region and therefore $N_{BV}$ remains high in the $\mu$-gradient region which leads to more radiative damping. As a consequence more modes are excited in models computed with the Schwarzschild’s criterion than in models computed with the Ledoux’s one.

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