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# Unveiling the internal structure of massive supergiants: HD 163899

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## Abstract

Supergiant massive stars are post-main sequence stars. During the H shell burning phase of evolution, they present a radiative core in which a strong damping prevents the pulsation modes from being excited. However Saio et al. (2006) have recently highlighted p and g pulsation modes in a post-main sequence star (HD 163899) observed by MOST. They suggest that the presence of an intermediate convective region (ICZ) at the top of the radiative core allows a partial or total reflexion of the mode. Through some numerical results achieved with CLES (Scuflaire et al. 2008) and MAD (Dupret et al. 2003) codes, we show that this scenario depends on the evolution stage of the star and on the considered mass loss rate and overshooting parameter.

Individual Objects: HD 163899

## Introduction

p and g mode pulsations have been detected in a B supergiant star observed by MOST: HD 163899 (B2 Ib/II Schmidt & Carruthers 1996). Lefever et al. 2007 have also suggested the presence of non-radial pulsations in a sample of B supergiants. At first sight this is quite unexpected. Indeed supergiant stars present a high density radiative helium core surrounded by a hydrogen rich envelope. A strong damping occurs if the modes propagate into the radiative core. In that case g-modes are not observed. However Saio et al. (2006) have shown that an intermediate convective zone (ICZ) at the top of the radiative core could prevent the propagation of g-modes into the core. The $\kappa$-mechanism due to the iron opacity bump at $\log T_{\rm eff} = 5.2$ is then sufficient to excite some g-modes. We show that mass loss and overshooting can prevent the formation of an ICZ and therefore the excitation of g-modes.

## Effect of mass loss

The presence of an ICZ during the post-main sequence (post-MS) phase is a result of the MS evolution (Dupret et al. 2009): a region where the neutrality of the temperature gradient is reached during the MS is needed for the formation of the ICZ. However, when taking mass loss into account, the central temperature and the radiation pressure increase less rapidly during central H-burning. As a result, the adiabatic temperature gradient decreases less and less with time as the mass loss rate increases. If a large enough mass loss rate is assumed during the MS, no region where $\nabla_{\rm rad} \cong \nabla_{\rm ad}$ is formed and no ICZ appears during the supergiant phase (Chiosi & Maeder 1986).

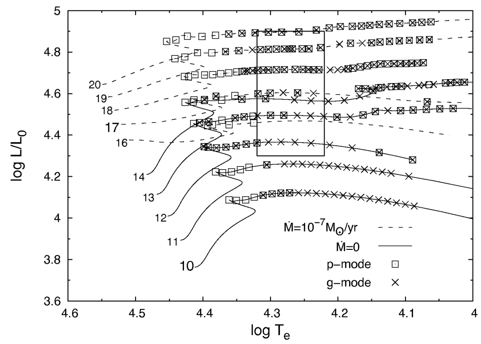


Figure 1: Evolutionary tracks computed without mass loss (10 to 14$M_\odot$) and with $\dot{M} = 10^{-7} M_\odot$/yr (16 to 20$M_\odot$) in the HR diagram. All sequences computed without mass loss present excited g-modes on the supergiant phase, but the sequences computed with mass loss present excited g-modes only for a mass higher or equal to 17$M_\odot$. The error box of the MOST star is also shown (Saio et al. 2006).

We adopted a mass loss rate of $10^{-7}$ $M_\odot$/yr to emphasize the effect of mass loss on the excitation of g-modes. According to Vinck et al. (2001) the mass loss rate should be between $10^{-9}$ and $10^{-7}$ $M_\odot$/yr, depending on the location of the star with respect to the bistability jump and on the mass of the star. We have computed evolutionary tracks with and without mass loss. Their location in the HR diagram is shown on fig. 1: tracks from 10 to 14$M_\odot$ (respectively tracks from 16 to 20$M_\odot$) are computed without (respectively with) mass loss. We performed nonadiabatic computations to determine whether unstable modes were present or not. On the one hand, for the sequences computed without mass loss, there are indeed excited g-modes during the supergiant phase for models within the error box for the MOST star (Saio et al. 2006). Even at 10$M_\odot$ the supergiant phase is characterized by excited g-modes. This is true for all higher masses. On the other hand, in the sequences computed with mass loss, we find excited g-modes only for stars more massive than about 17$M_\odot$. With an even higher mass loss rate, this value becomes larger and larger. The sequences without any excited g-modes are characterized by the absence of ICZ on the supergiant phase, due to the mass loss effect during the MS phase. Hence, all the modes enter the radiative core and suffer the strong radiative damping. The frequency distribution of the theoretical excited modes (fig. 2) is in good agreement with the observed frequencies.

## Effect of overshooting

An enlargement of the mixed core makes the star more luminous. It also increases the core H burning lifetime while, in the HR diagram, the MS track reaches lower effective temperature values. When assuming a large enough overshooting during MS, the zone where $\nabla_{\rm rad} \cong \nabla_{\rm ad}$ does not exist especially if the radiative gradient is assumed in the overshooting region and this can prevent the formation of an ICZ during the post-MS phase. No g-modes are thus found to be excited. We have checked the presence of an ICZ by progressively increasing the overshooting parameter (fig. 3) from one evolutionary sequence to the next. For a model of 12$M_\odot$ the ICZ is well-developed for a moderate amount of overshooting $\alpha_{\rm ov} = 0.2$, it is much smaller for 0.3 and it completely disappears for $\alpha_{\rm ov} = 0.4$. From preliminary computations the extent of the ICZ is not very different if the adiabatic temperature gradient is chosen in

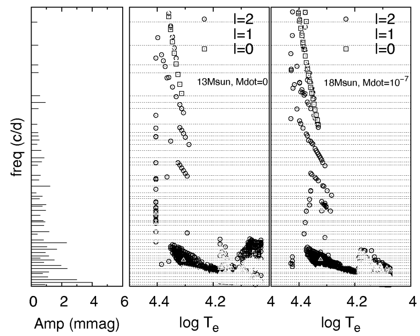


Figure 2: Frequency distribution of excited p and g-modes for supergiant models of 13$M_\odot$ computed without mass loss (middle panel) and 18$M_\odot$, computed with $\dot{M} = 10^{-7} M_\odot$/yr (right panel). The observed frequency of MOST are also shown (left panel) from Saio et al. 2006.

the overshooting region.

However, another possibility to solve the problem of the presence of excited g-modes would be to bring MS evolutionary tracks into the error box of HD 163899. This can be achieved by including larger overshooting in MS models. We have computed evolutionary tracks with different overshooting parameters, ranging from $\alpha_{\rm ov} = 0.2$ to 0.5 (fig. 4). MS evolutionary tracks cross the error box for an overshooting parameter equal to or larger than 0.3. Since MS massive stars present a convective core surrounded by a radiative envelope, the Brunt-Väisälä frequency is therefore zero in the core and no damping can occur. The $\kappa$-mechanism in the superficial layers excites p and g-modes. We performed nonadiabatic computations which revealed excited g-modes in all the sequences. The spectrum of the theoretical excited modes is shown on fig. 5 for $\alpha_{\rm ov} = 0.4$ and 0.5 during the MS (decreasing effective temperatures) and near the turn off (increasing effective temperatures). The agreement in the mode spectrum is however not as good as it was for the 'true' supergiant model.

## Conclusions

The presence of excited g-modes in B supergiant stars depends on physical processes during the MS: we have shown that large amounts of either overshooting or mass loss affect the formation of an ICZ and therefore can prevent the excitation of g-modes. The supergiant star could also be helium burning, but in that case again, as long as the ICZ is present, there should be excited g-modes. Another phenomenon which affects the formation of the ICZ is the convective criterion which can be either the Schwarzschild or the Ledoux's criterion (Lebreton et al. 2009). In a future work we shall extend this preliminary analysis in order to define an instability strip depending on those physical aspects and compare it to the observations. In this confrontation process, it is clear that asteroseismology of massive supergiant stars can give us a better understanding on the physical processes not only during the supergiant phase but also during the MS phase.

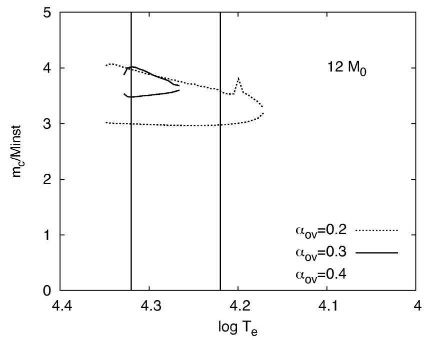


Figure 3: Evolution of the mass extension of the ICZ ($m_c/M$inst: ratio of the mass of the convective zone to the instantaneous mass of the star) during the supergiant phase (effective temperature decreasing on x-axis) for a 12M$_\odot$ star. For a moderate amount of overshooting 0.2, the ICZ is well-developed, it is much smaller for 0.3 and it disappears for 0.4.

## References


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## DISCUSSION

**Shibahashi:** Is the presence and/or extent of the intermediate convective zone dependent on the treatment of semi-convection?

**Godart:** Yes. We have no numerical treatment of the semiconvection in our evolutionary code, but with the Schwarzschild's criterion, small ICZs appear and disappear during the main sequence. So a partial mixing occurs at the top of the convective core and finally we do have a region where the temperature gradients ($\nabla_{rad}$ and $\nabla_{ad}$) are really close to each other.

**Noels:** I would like to comment on the mass loss rate adopted in this analysis. Mélanie chose indeed a too high value for $\dot{M}$ to show that this can make the ICZ disappear. But that's good news since excited g-modes are observed in that part of the HRD! That means that the ICZ is indeed present. This is a nice asteroseismic constraint on the mass loss rate.

**Meynet:** Could HD 163899 be on a blue loop after having evolved into a red supergiant stage? In that case, the star would have a helium convective core.

**Godart:** It certainly could be, either coming back from the red or having started burning helium in the blue. We are currently investigating this aspect.

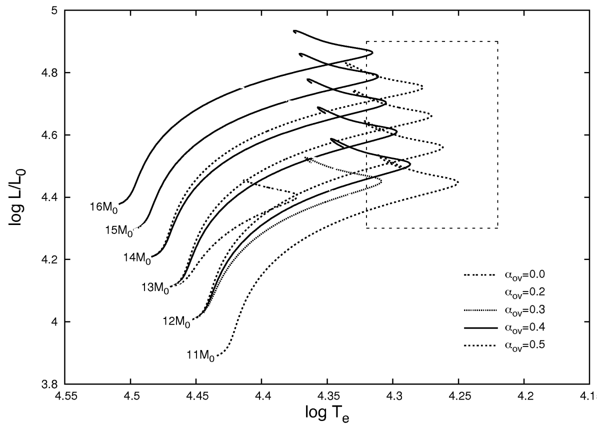


Figure 4: Main sequence evolutionary tracks computed with different overshooting parameters ranging from $\alpha_{ov} = 0.2$ to 0.5. The black box is the error box of HD 163899. Main sequence evolutionary tracks with at least $\alpha_{ov} = 0.3$ cross this error box.

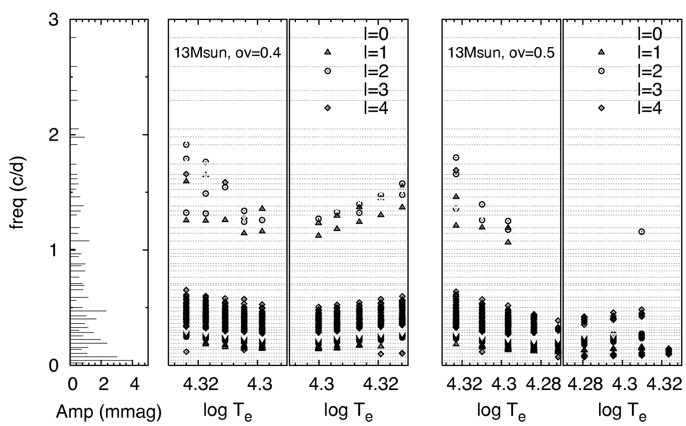


Figure 5: Frequency distribution of the excited p and g-modes during the MS (decreasing $T_{\rm eff}$) and near the turn off (increasing $T_{\rm eff}$) for $13M_\odot$ models computed with $\alpha_{ov} = 0.4$ (middle panels) and 0.5 (right panels). The agreement between the observed frequencies (left panel) and the theoretical mode spectrum is not as good as it was for the supergiant models.