Modeling pulsations in hot stars with winds

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Modeling pulsations in hot stars with winds

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Abstract. The interaction pulsation/mass loss takes different aspects. Pulsations can trigger mass loss as in LBVs and Miras; on the other hand, mass loss can modify the driving conditions within the stars. But the most spectacular aspect is the effect on stellar models which, in turn, opens a royal way to asteroseismology to test physical conditions inside massive stars, such as the extent of convective cores or the appearance of new driving mechanisms. We start with a discussion on MS stars and their strange mode instabilities. We then move on to the excitation of the LBV phenomenon. WR stars and the newly observed MOST period in WR123 are discussed in view of the power of asteroseismology. We then turn to B supergiants, in particular HD163899, and show how asteroseismology can really probe convection, semiconvection and mass loss.

1. Introduction

Mass loss is a common feature in massive stars (see for instance Chiosi and Maeder 1986). Pulsations are maybe less common but more and more observations as well as theoretical arguments seem to be in favor of a rather wide range of pulsations. The interaction between pulsation and mass loss is therefore a crucial problem which only begins to be addressed. This interaction can be seen from various angles. Can pulsations trigger mass loss as in Luminous Blue Variables for instance where some violent outbursts of mass loss are still not accounted for? Or, on the contrary, can mass loss affect the properties of pulsations, either directly through a leakage of energy which would soften the driving, or indirectly through the effects of mass loss on the stellar interior which in turn can modify the driving regions in their locations as well as in their importance? We shall review the successive phases of the evolution of a massive star and show how asteroseismology can help understand the internal structure of massive stars.

2. Massive Main Sequence Stars

The stability of massive MS stars has been extensively studied in the frame of the ε-mechanism which essentially affects the fundamental radial mode with generally a very small growth rate (Stothers and Simon 1969, Ziebarth 1970). Other types of instabilities, such as those driven by the κ-mechanism and those due to strange modes are however present and much more efficient. Figures 1 and 2 shows a modal diagram for the real and the imaginary parts of the radial non adiabatic eigenfrequencies for homogeneous massive MS models (Glatzel and Kiriakidis 1993a).

The fundamental radial mode and the first radial overtone show rather large instability ranges. Unstable fundamental modes are essentially driven by the ε-mechanism while first radial overtones have an additional driving region due to the κ-mechanism acting in the classical iron

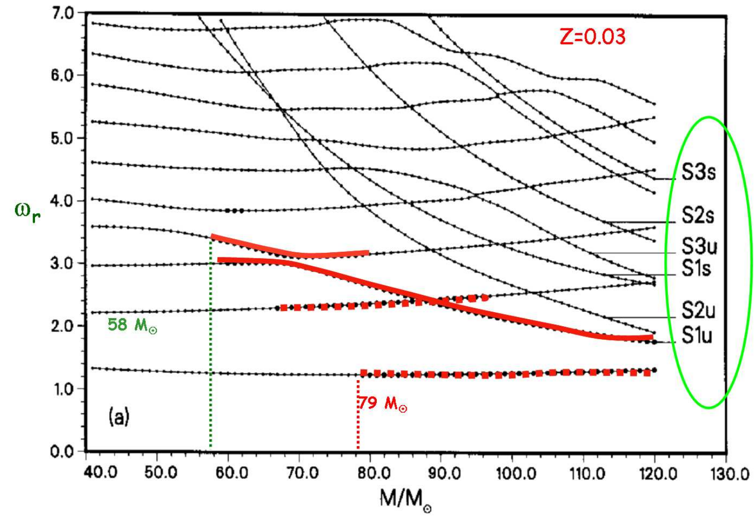

Figure 1. Real part of the radial mode eigenfrequencies for homogeneous MS models (after Glatzel and Kiriakidis 1993a). Curves in red show the unstable modes. Strange modes are labelled Sn in the green ellipse.

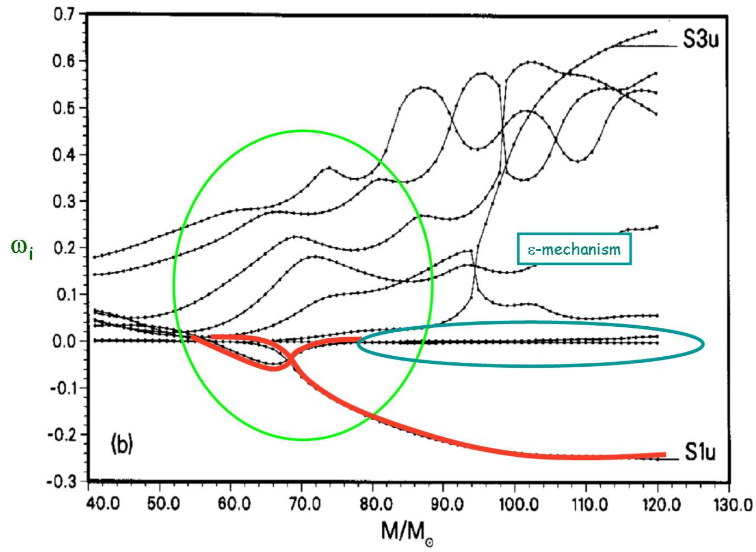

Figure 2. Same as figure 1 for the imaginary part of the eigenfrequencies (after Glatzel and Kiriakidis 1993a). The green circle shows the strong instabilities due to strange modes. Modes driven by the ε-mechanism are shown in the blue frame.

opacity bump. These instabilities are however rather weak. Much stronger instabilities with growth times of the order of the dynamical time-scale are associated with strange modes. The presence of strange modes has been extensively discussed but their nature remains unclear (Saio et al. 1998, Glatzel 1994 and references therein). The seemingly necessary condition for their presence in massive stars is a high Luminosity/Mass ratio which leads to a high radiation pressure and a density inversion as a result. Another important condition is the presence of a peak of opacity in the vicinity.

A strange mode behaviour in a modal diagram is sternly different from that of regular modes as can be seen in figure 1. Strange modes interact with regular modes either through an avoided crossing if the non adiabaticity is rather low or through a coalescence giving rise to a mode pairing with the appearance of two almost complex conjugate eigenfrequencies in case of extreme non adiabaticity. The imaginary part immediately becomes large (see figure 2) which means that strong instabilities are associated with strange modes.

As the mass increases, the non adiabatic conditions drastically changes and the adiabatic periods are no longer good approximations of the non adiabatic ones (see figure 3 adapted from Saio et al. 1998). Some strange modes have a counterpart in the regular adiabatic spectrum and the trapping occurs near an avoided crossing (see figure 1). For other strange modes, no adiabatic counterparts is found.

Some modes, radial but also non radial (Glatzel and Mehren 1996), become efficiently trapped in the density inversion region as can be seen in figure 4 (from Saio et al. 1998).

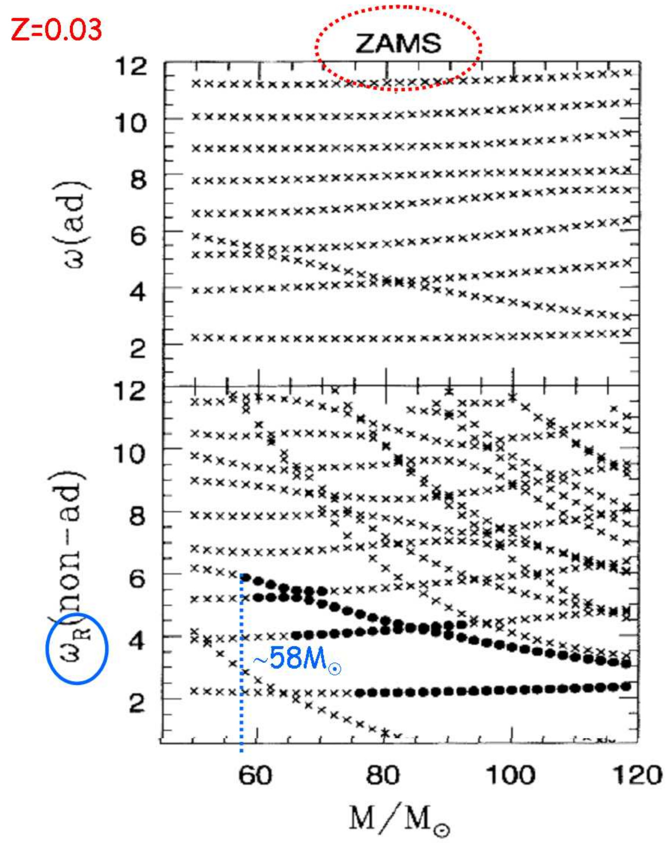

Figure 3. Modal diagrams showing the adiabatic frequencies, upper panel, and the real part of the non adiabatic frequencies for homogeneous MS models (from Saio et al. 1998). Unstable models are indicated by big dots.

The upper panel in figure 4 illustrates the trapping of a strange mode with a negligible contribution from the rest of the star. The total pulsation energy is thus very low compared to that of a regular mode (lower panel) which means a much higher imaginary part and a much larger growth rate for the strange mode pulsation.

Most strange modes are stable (see figures 1 and 2) on the ZAMS but as the star evolves, they become strongly unstable, especially if the metallicity is high (Kiriakidis et al. 1993).

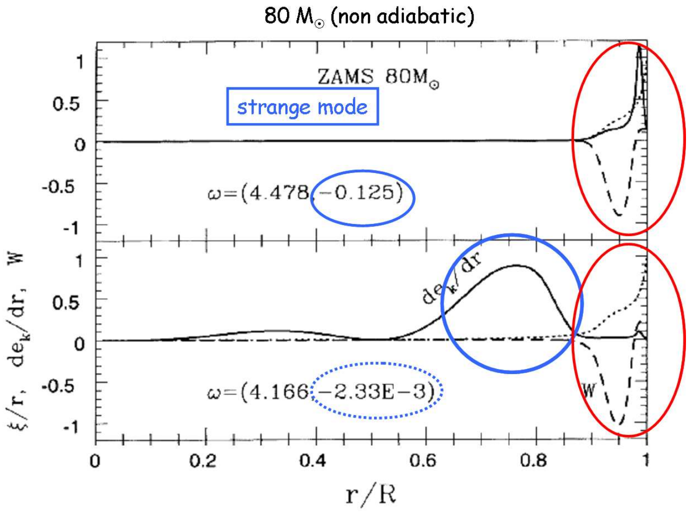

Figure 4. Displacement (dotted curves), pulsation energy distribution (full curve) and work integral (dashed curve) for a strange strongly unstable mode (upper panel) and for a regular unstable mode (lower panel) (from Saio et al. 1998). The red ellipses show similar behaviour in the trapping region while the energy distribution, highlighted in blue shows why the regular mode is less unstable (larger total pulsation energy) than the strange mode.

3. Luminous Blue Variable Stars

Luminous Blue Variable stars undergo so violent outburts of mass loss that a dynamical instability could be at the origin of the LBV phenomenon. The condition for a dynamical instability to appear is a high L/M ratio which means an important contribution of the radiation pressure and a Γ_1 value close to 4/3. Ionization zones (Fe, He, H) lead to an additional decrease in Γ_1 and a dynamical instability can occur. Stothers and Chin (1993) find such an instability but the required metallicity is rather high and the effective temperature at the onset of the instability is somewhat low compared to the Humphreys-Davidson limit (Humphreys and Davidson 1979) (see figure 5).

Another possible source of strong instabilities can be searched for in strange modes. Glatzel and Kiriakidis (1993b) have indeed found unstable strange modes which nicely cover the forbidden Humphreys-Davidson region (see figure 6). It is an interesting point to consider pulsations as a trigger to a violent mass loss event.

4. Wolf-Rayet Stars

After an LBV event, a single O star can become a Wolf-Rayet star (Chiosi and Maeder 1986) which essentially consists of a pure helium star whose mass largely exceeds the critical mass for He stars (Stothers and Chin 1993). Many attempts have been made in order to extract periodic signals out of WR light curves. Most often the proposed periods were short, of the order or less than the hour. It was thus tempting to attribute such periods to an instability of the fundamental radial mode driven by the ε-mechanism (Noels and Gabriel 1981). Blecha et al. (1992) obtained such an instability in pure helium models representing the structure of WNE stars. The growth times associated with the ε-mechanism are however generally very large compared to the evolution time. Stronger strange modes instabilities are found in pure helium stars as can be seen in figure 7 (Glatzel et al. 1993). The extreme non adiabatic conditions in such stars are favorable to a particularly clear mode pairing with nearly complex conjugate eigenvalues with large imaginary parts. This onset of the strange mode regime appear at the

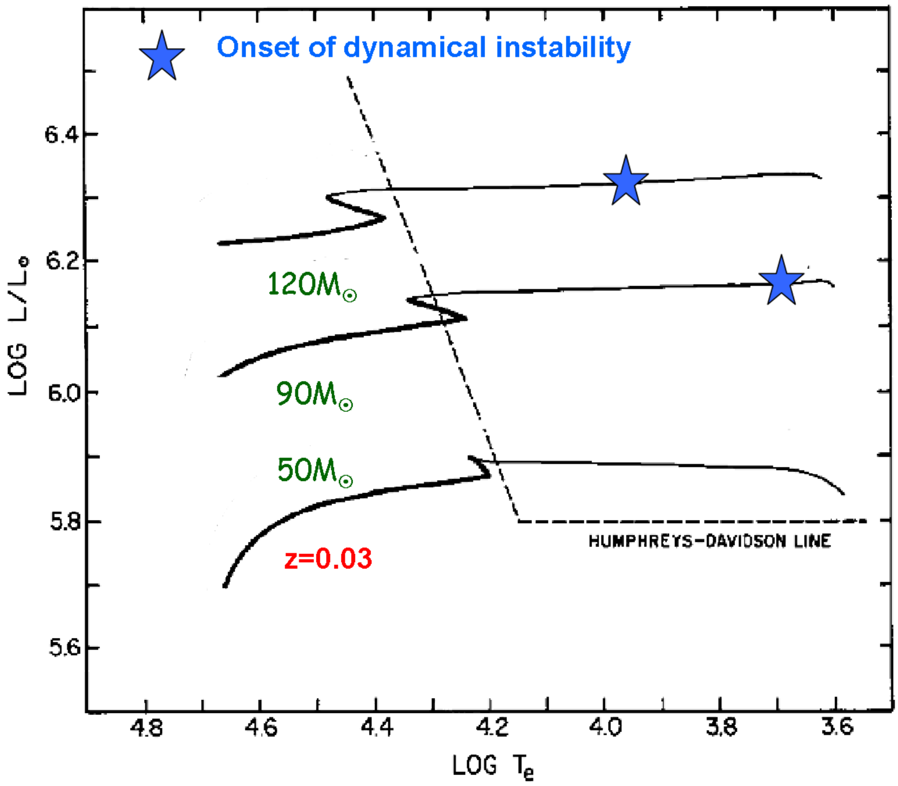

Figure 5. Evolutionary paths for stars of initial mass 60, 90 and 120 $M_{\odot}$ with Z=0.03. The blue stars mark the onset of the dynamical instability. Dashed lines show the Humphreys and Davidson limit (adapted from Stothers and Chin 1993).

coalescence of two regular modes when the stellar mass increases.

Longer periods, of the order of a few hours, were also suggested (see for instance Rauw et al. 1996 and references therein) with a possible link to non radial oscillations (Noels and Scuflaire 1986, Scuflaire and Noels 1986). A major event has been the recent discovery by MOST satellite of such a period, 9.8hr, in WR123 (Lefèvre et al. 2005). Such an increase of the period range needs an increase in the model radii and the best way to achieve this is to add a non zero hydrogen envelope on top of the pure helium star. Dorfi et al. (2006) have indeed obtained a very tempting solution from 22 to 27 $M_{\odot}$ models with hydrogen-rich envelope (X=0.35). From their radiation-hydrodynamic simulations, a non linear saturation occurs after about 28 days only. This necessity of a hydrogen-rich envelope seems however in contradiction with the spectroscopic analysis of Crowther et al. (1995) in which they find for WN123 a very low hydrogen abundance with H/He smaller than 0.1.

Another solution has been proposed by Townsend and MacDonald (2006). Their idea is to search for a g-mode instability driven by the κ-mechanism acting in a “deep opacity bump” (DOB) located at $\log T \sim 6 - 6.3$ (see figure 8). Evolving a star with an initial mass of 100 $M_{\odot}$ up to the WR phase, they find unstable g-modes in the required range (see figure 9 and 10). This course of reasoning shows that asteroseismology plays an inspirational role in deriving the internal structure of pulsating stars.

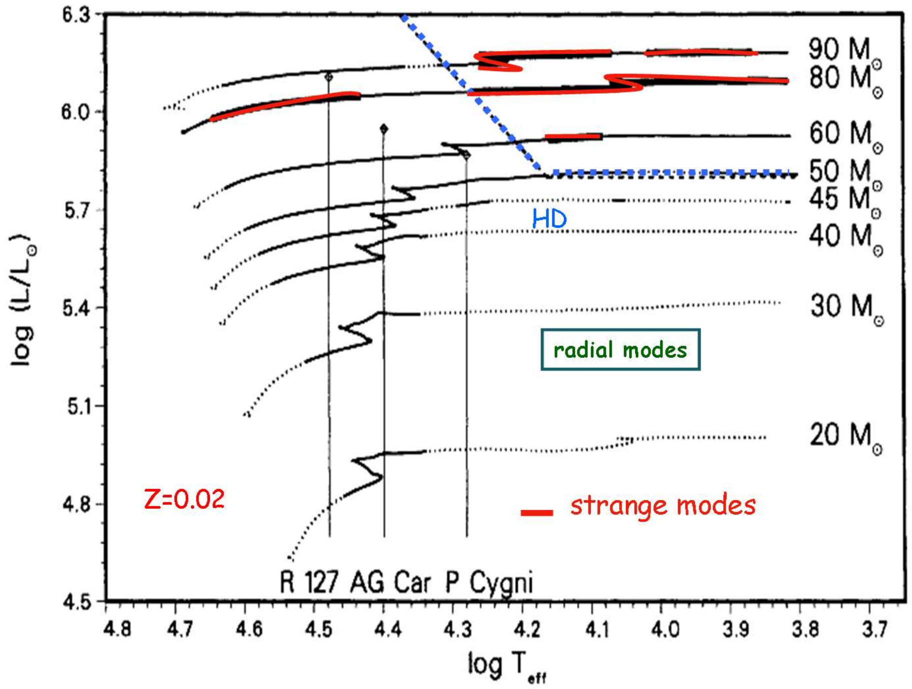

Figure 6. Evolutionary paths for massive stars with Z = 0.02. Full curves shows the instability of regular modes and red full curves mark unstable strange modes. Dashed lines show the Humphreys and Davidson limit (adapted from Kiriakidis, Fricke and Glatzel 1993).

5. B Supergiants

The presence of periodic signals in B supergiants is a rather long-standing observational problem (see for instance Burki 1978, Lovy et al. 1984, Kaufer et al. 1997, Waelkens at al. 1998). Evidence of g-mode instability has recently been advanced by Lefever et al. (2007) from a photometric and spectroscopic analysis of 28 B supergiants, and the first space detection of p- and g-modes in HD 163899 was achieved by MOST satellite (Saio et al. 2006). These authors have computed supergiant models for a mass range from 12 to 20 $M_{\odot}$ and they have shown that excited p-modes but also g-modes were indeed numerous in these models. Figure 11 clearly shows the transition between SPB and β Cephei stars, with a rich g-mode domain near 7 $M_{\odot}$, typical of SPBs, followed by a p- and g-mode regime and then a pure p-mode excitation in MS models as the mass increases, from values typical of β Cephei to more massive O stars.

Figure 12 shows the comparison of the observed frequencies with the theoretical frequencies. As the mass increases, the agreement gets better and better but the evolutionary tracks come out of the error box at about 18 $M_{\odot}$. A model of about 15 $M_{\odot}$ seems indeed a good compromise. The simultaneous presence of p- and g-modes in MS models of B stars is however very sensitive to the opacity and the chemical composition (Pamyatnykh 1999, Pamyatnykh and Ziomek 2007, Miglio et al. 2007a 2007b) and we infer that this might also be the case for post MS models.

A B supergiant is however not a good candidate for housing unstable g-modes since its radiative core, where the Lamb and Brunt-Väisälä frequencies are extremely large, exerts a strong radiative damping. The reason for the excitation of g-modes is the presence of a fully convective intermediate zone (FCZ) located near the hydrogen burning shell (Saio et al. 2006). This shell can indeed prevent g-modes from entering the radiative core and, without the strong radiative damping, they can be excited by a normal κ mechanism in the classical Fe opacity

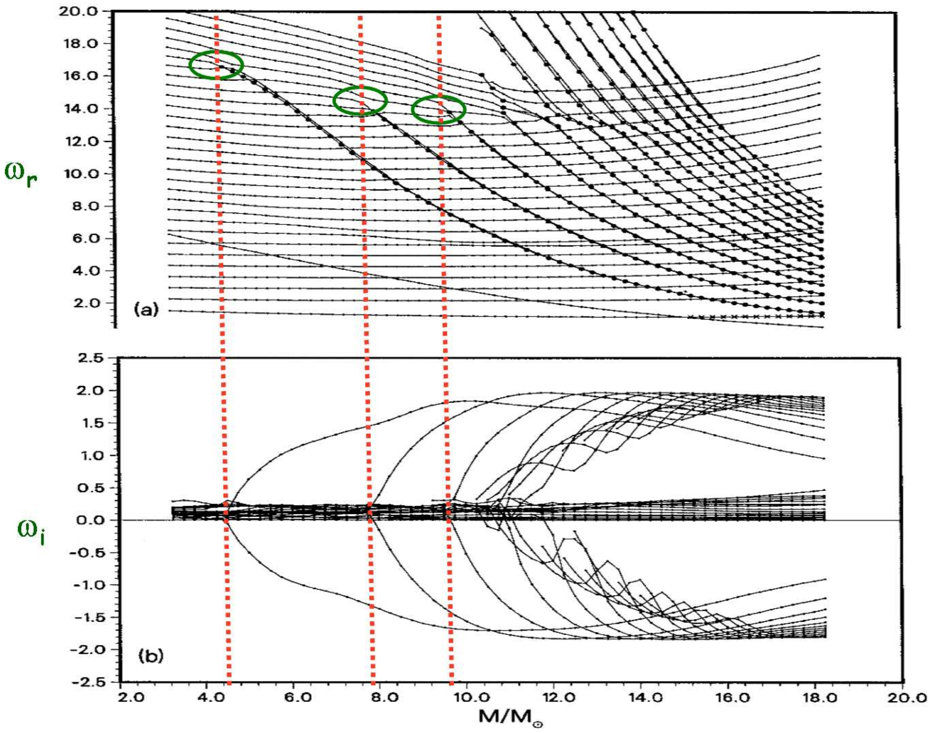

Figure 7. Real (upper panel) and imaginary (lower panel) parts of the eigenfrequencies for pure helium stars (after Glatzel, Kiriakidis and Fricke 1993). Green ellipses emphasize the coalescence of modes and red dashed lines show that a coalescence of the real parts coincides with the occurence of nearly complex conjugate eigenfrequencies.

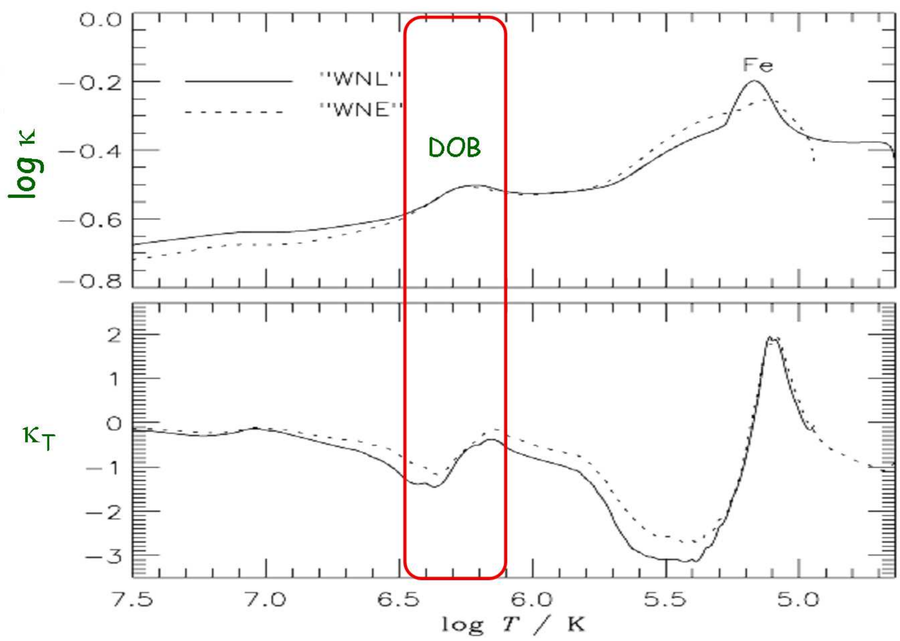

Figure 8. Opacity and its temperature derivative as a function of temperature (from Townsend and MacDonald 2006). The "deep opacity bump" (DOB) is emphasized by the red box.

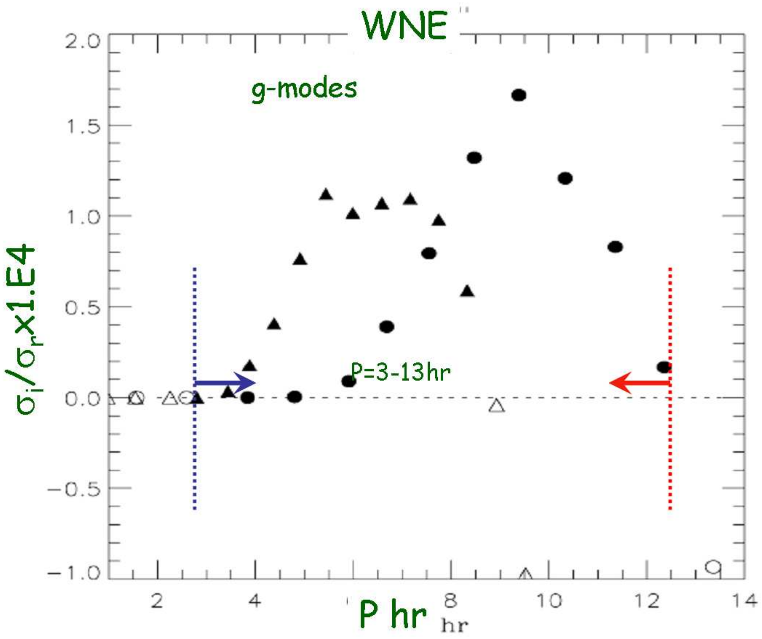

Figure 9. Normalized growth rates for l=1 (circles) and l=2 (triangles) g-modes for a WNL model (after Townsend and MacDonald 2006). Full symbols mark instability. The period range of unstable modes is emphasized by dotted lines.

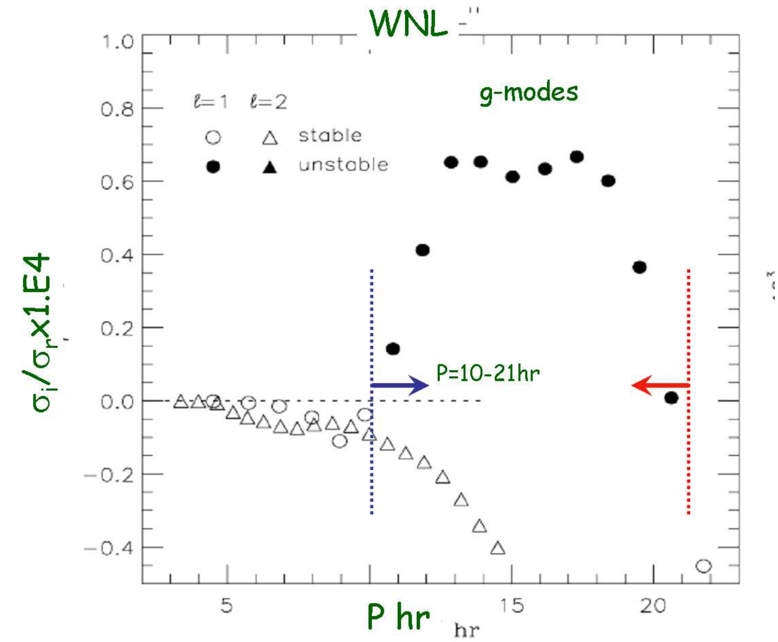

Figure 10. Same as figure 9 for a WNE model (after Townsend and MacDonald 2006)

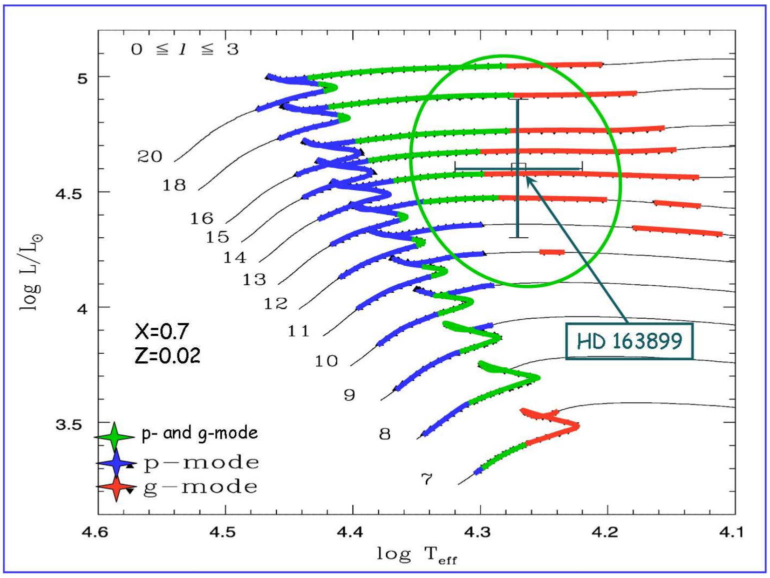

Figure 11. Evolutionary paths for stars of 7 to 20 $M_{\odot}$. Blue, red and green parts indicate respectively p-mode instability, g-mode instability and p- and g-mode instability (from Saio et al. 2006)

bump (see also Noels and Scuflaire 1986). Figure 13 shows the Brunt-Väisälä and the Lamb frequency and emphasizes the barrier exerted by the convective shell in which g-modes are evanescent and thus can be reflected and prevented from entering the radiative damping core. This is clearly seen in figure 14 where the kinetic energy distribution is shown for a damped and an excited g-mode. The convective shell acts as a mirror for the excited g-mode and its kinetic energy is orders of magnitude smaller than that of the damped non reflected g-mode.

The occurence of a fully convective zone in a post MS supergiant is extremely sensitive to the past history of the star. It results from a semiconvection episode during main sequence which tends to establish a nearly adiabatic temperature gradient in the μ-gradient zone. As soon as these layers start burning hydrogen in the post MS phase, they become convective and g-modes can be excited. When mass loss is taken into account, convective cores are smaller and recedes much quickly during the MS phase, preventing semiconvection to develop (Chiosi and Nasi 1974). The result is the absence of a fully convective zone in the post MS phase. A high enough mass loss rate can indeed make it impossible for g-modes to be excited (Godart et al. 2007). This is a very strong asteroseismology test since even a single g-mode in a B supergiant signs the presence of a semiconvection in MS B stars.

6. Conclusions

Stellar modeling is slowly leaving its infancy. Although tremendous progress has been made over the last decades, many unsolved, or still in debate, problems remain, even for massive MS models. What is the criterion for convection, Ledoux or Schwarzschild? What is the neutrality condition in a semiconvective zone? What is the amount of overshooting? Is it overshooting or convective penetration? Is mass loss treated in a coherent way? What are the structural effects of rotational mixing? Asteroseismology is due to answer some of these questions. Some striking results from the interpretation of MOST data, such as the structure of WR123 or the even more powerful probing of a fully convective zone near the hydrogen shell burning in HD 163899, have already clearly demonstrated this point. The coming years, with the accepted and proposed missions CoRoT, KEPLER, Siamois, SONG, and PLATO, will no doubt be extremely rich in

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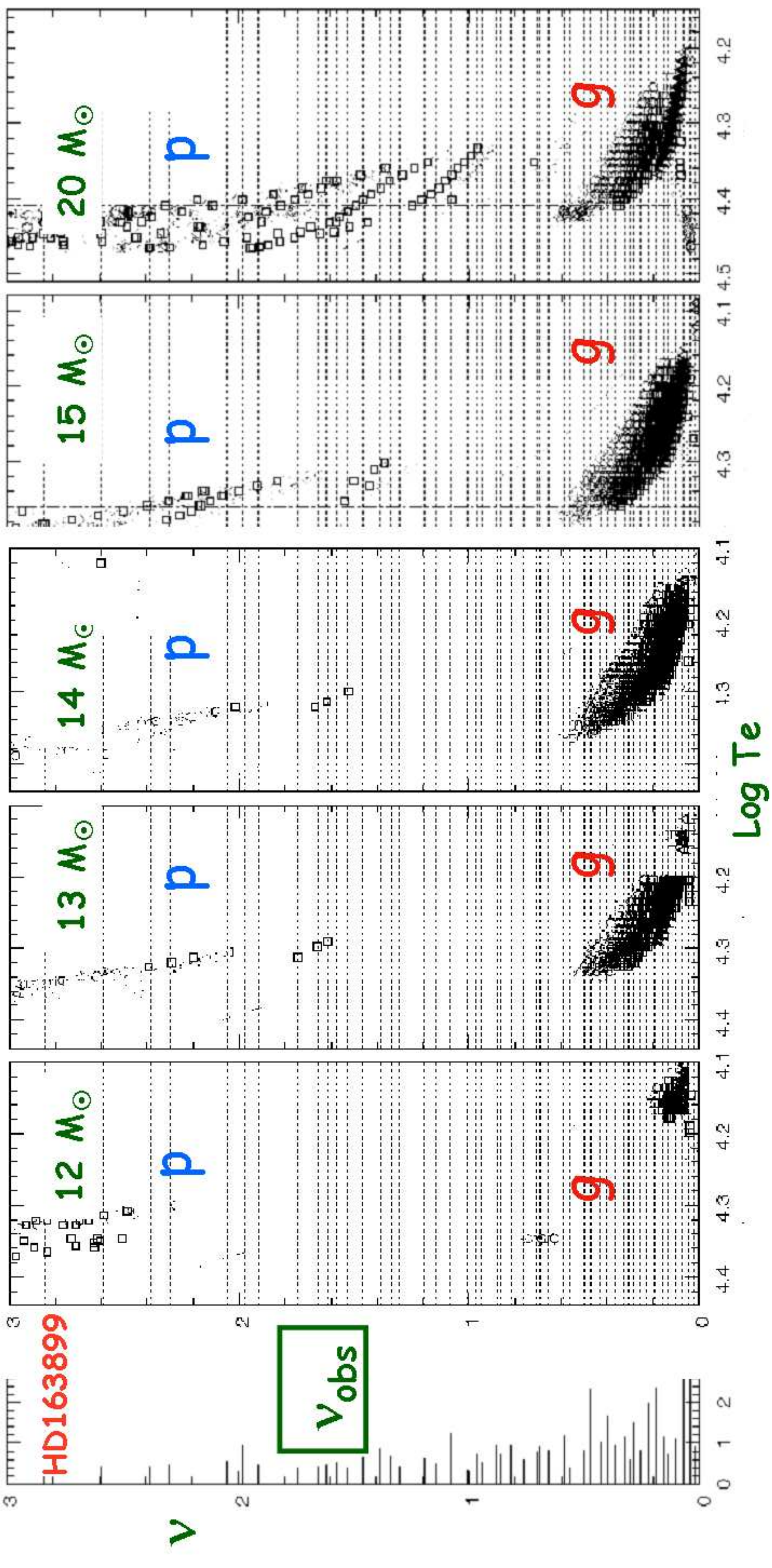

Figure 12. Comparison of observed (horizontal lines) and theoretical p- and g-mode frequencies for models ranging from 12 to 20 $M_\odot$ (from Saio et al. 2006).

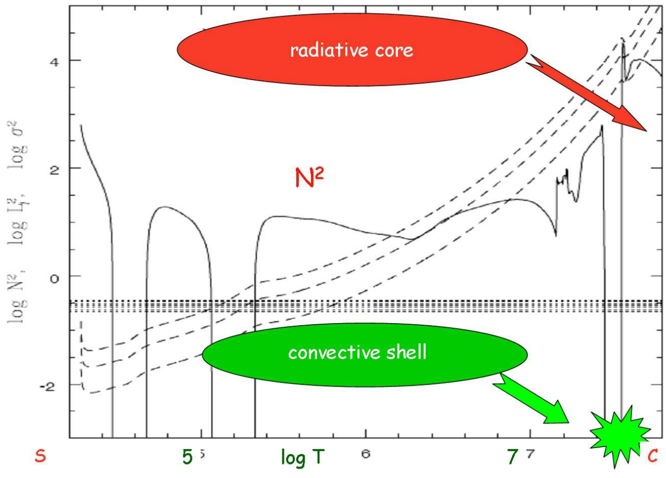

Figure 13. Brunt-Väisälä (full curve) and Lamb (dashed curves) frequencies in a 15 $M_{\odot}$ supergiant model. The horizontal dotted lines show the l=2 g-modes excited in that model. The radiative core (red) and the fully convective zone (green) are emphasized (from Saio et al. 2006).

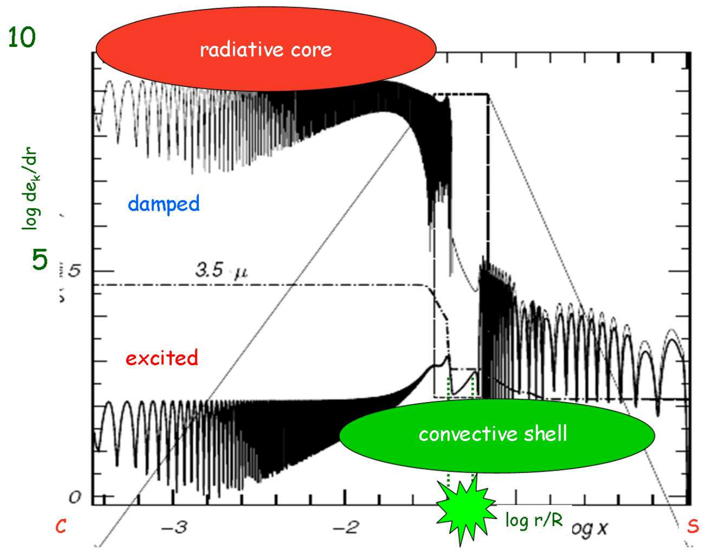

Figure 14. Kinetic energy distribution in a damped (upper curve) and an excited (lower curve) g-mode. The radiative core (red) and the fully convective zone (green) are emphasized (from Saio et al. 2006).

shedding some light on the structure and the evolution of massive stars.

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