MODELLING INTERMEDIATE MASS RED GIANTS

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ABSTRACT

Observations have shown that solar-like oscillations can be excited in red giant stars. Nevertheless, these stars are very different from main sequence stars. For instance, they present a great density contrast between a dense core and an extended envelope, they have a hydrogen-burning shell, and they are brighter which implies that they are expected to have larger amplitudes. Thus, they have proven to be worthy of asteroseismic investigation and, indeed, space missions as CoRoT have proposed to observe them. Therefore, being able to model red giants is important. When modelling red giants, one faces some extra difficulties which are not present or are not so prominent in main sequence stars modelling, such as the free parameters in the convection and in the semi-convection treatments. The non radial modes in red giants also behave differently from the non radial modes in main sequence stars. We will describe their main oscillatory properties and analyze their stability for the case of a 3 $M_\odot$ model in central He-burning phase. We conclude that the inertia of the modes plays the most important role in their stability.

Key words: Red giants; Non radial modes.

1. INTRODUCTION

There is a growing interest to consider red giants (RGs) as asteroseismology targets since recent observations have detected solar-like oscillations in these stars. A new era for RGs research has been born with space missions such as CoRoT [2, 28] and MOST [22]. These projects have included RGs in there observational programs to study them through asteroseismology as their amplitudes are expected to be large [9] and we know so few about their interiors. However, will asteroseismology allow us to pierce through their extended envelopes and help us to understand their internal structure?

RGs are evolved stars which have exhausted their hydrogen supply at the center. With its main energy supply gone the core contracts, compressing the layers surrounding the He core. The hydrogen starts burning in a shell outside the core, and the luminosity rises. In the meantime, the envelope expands, the convection penetrates deeply as the temperature drops. The star ends up lying on the right hand side of the HR diagram in a narrow band of temperature and broad band of luminosity. Therefore, RGs are extremely difficult to model since they can be in very different states of evolution and still be at the same place in the HR diagram. Intermediate mass RGs, for instance, can be found ascending the RG branch, or descending it after the onset of He-burning or ascending it once more during the central He-burning.

RGs have deep convective envelopes and very small cores that become convective once He starts burning in the core. When the convective core exceeds a certain size, a semi-convective region appears [7, 5, 6, 19, 23]. The size of this region varies with the RGs mass, being important in low- and intermediate mass stars. Understanding RGs is, therefore, understanding the physics behind convection and semi-convection.

The spacing between frequencies of p modes with same degree but different orders (the large separation) is essentially a measure of the mean stellar density. If high precision measurements of the interferometric radius are available, one can determine the stellar mass using the large separation outcome from observed mode frequencies [24, 18, 20]. For some RGs, radial modes have been reliably identified and large separations have been obtained [10, 4, 15] (see [3] for a review). Nevertheless, the possibility of observing non radial modes would put us a few steps further in understanding the structure of RGs. Different combinations of frequency spacings between modes of different degrees would allow us to access the intrinsic properties of their stellar interior [1, 21].

Theoretically, the internal structure of a RG is highly different from main sequence stars. Due to the highly condensed core and low-density envelope, the Brunt-Väisälä and the Lamb frequencies reach huge values near the center. Therefore, non radial modes are mostly mixed modes, which behave like g modes in the deep interior and as p modes in the convective envelope. Their eigenfunctions oscillate very rapidly in the inner layers and may cause a substantial damping. Non radial modes were predicted not be observed due to this mode damping [13, 25, 14]. However, recent observations of red giants suggest that non radial modes might be present in the collected data [17] reopening the question whether the non radial modes

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are excited in red giants or not.

In Section 1 we will describe the main characteristics of the non radial modes in our RG models, where we label the non radial modes into two types of modes. The first type which will be called modes of type (a) possess oscillatory properties like solar-like p modes, the second type labeled as modes of type (b) corresponding to a dense spectrum of non radial modes strongly trapped in the inner layers. A stability analysis of these non radial is described in Section 2.

2. NON RADIAL MODES IN RED GIANTS

The models shown in this paper were computed using ATON3 [27, 26]. Since He-burning is the longest phase in the intermediate mass RGs lifetime, our study is focused on this phase.

Figure 1 shows a density profile of a $3M_\odot$ RG model. For this model 20% of the stellar mass is concentrated in about 0.05% of the stellar radius. This kind of internal structure, i.e. a small highly condensed core, certainly affects the non radial oscillatory properties in a way that we don't see in main sequence stars.

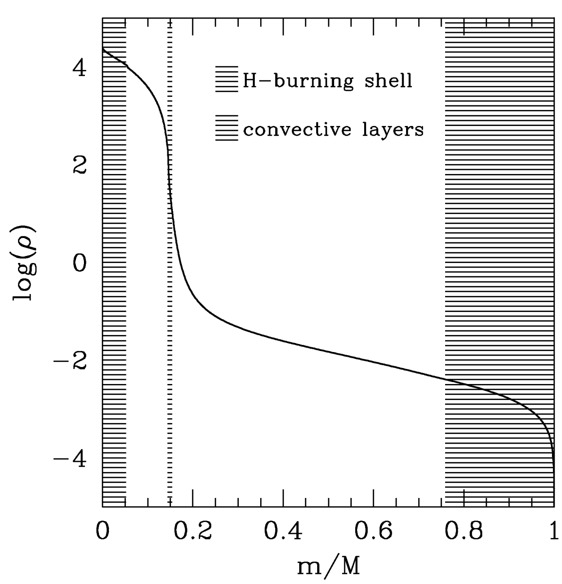

Figure 1. Density profile of a $3\ M_\odot$ *red giant. Dark-cyan horizontal lined pattern indicates the location and extension of the convective layers, brown horizontal lined pattern indicates the location and extension of the H-burning shell.*

The Brunt-Väisälä and Lamb frequencies are shown in Figure 2 and as aforementioned both frequencies reach high values in the inner layers. The extra spikes are due to the chemical composition gradients outside the convective core and the hydrogen-burning shell. The cut-off frequency calculated for this model is about 120 μHz. We can see in Figure 2 that modes below this frequency have nodes in acoustic p mode cavity and in the g mode cavity. These non radial modes have, therefore, a mixed character.

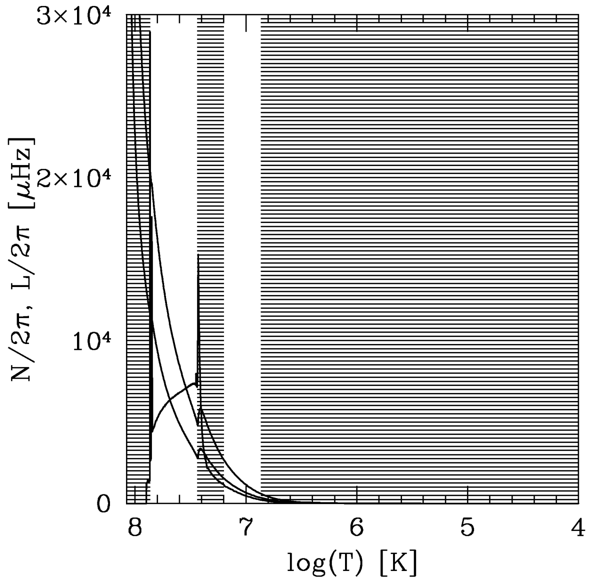

Figure 2. Brunt-Väisälä and Lamb frequencies. The horizontal lined patterns have the same meaning as in Figure 1. The red curve corresponds to the Brunt-Väisälä frequency and the dark-magenta and magenta curves to the Lamb frequency for $l = 1, 2$*, respectively.*

We followed the evolution of these modes for $l = 1, 2$ during the central He-burning by computing the dimensionless frequency, ω, as a function of the central He content, $Y_{\rm C}$, as shown in Figure 3. The color gradient is scaled according to the inertia ratio between non radial and radial modes as given by the following relation:

$$\frac{A_{n,l}}{A_0(\nu_{n,l})} = \sqrt{\frac{E_0(\nu_{n,l})}{E_{n,l}}} \tag{1}$$

with,

$$E = E(M) = \int_0^M |\delta r|^2 dm \tag{2}$$

In our notations, A is the amplitude, E is the inertia, n the order and l the degree of the mode. A_0 and E_0 are obtained by interpolating the amplitude and the inertia of the radial mode in terms of frequency. When one looks at Figure 3 we notice that the mode frequency spectra are very dense and there are modes with lower inertia which follow an asymptotic behavior as solar-like p modes. Thus, we might classify the modes into two different types:

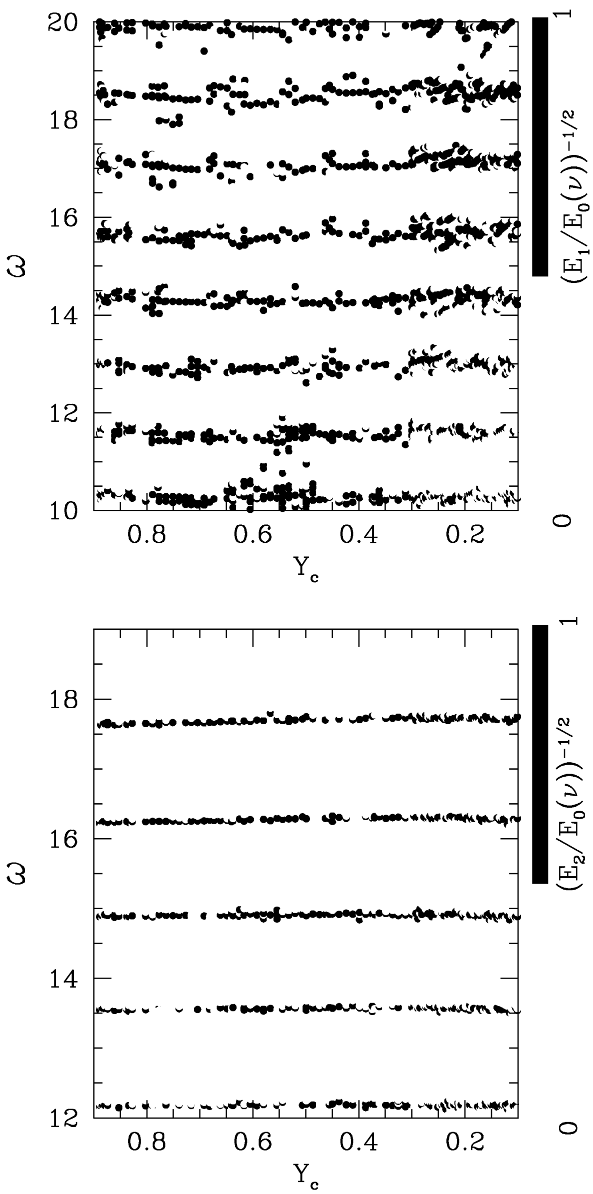

Figure 3. Non radial modes evolution. This figure shows the dimensionless frequency, ω, as a function of the central He content, Y_c. The color spectrum is scaled to the inertia ratio between non radial and radial modes (see Equation 1). Top: $l = 1$, bottom: $l = 2$.

a) Modes for which the surface inertia is comparable to the radial modes inertia and which have same properties as solar-like p modes. These modes are trapped mainly in the envelope.

b) Modes for which the surface inertia is much higher than the radial mode inertia. These modes are strongly trapped in the interior.

According to Equation 1 type (a) modes should have nearly the same amplitudes as radial modes. However, this equation assumes that energy input and the damping rate are independent of the degree, which is not exactly the case in here. We will see in Section 3 that the inertia of the non radial modes is very different and depends on the degree. Similar results have been found for ξ Hydrae models [8].

3. NON-RADIAL MODES STABILITY

Last section's results can be obtained using an adiabatic oscillation code. However, to have information about the stellar layers where modes are excited or damped one needs to evaluate the work integral, i.e. the increase of the total energy over one period of oscillation. This requires non adiabatic calculations.

We have used the non adiabatic oscillation code MAD [11] to study the stability of the modes. The non adiabatic code MAD uses a set of free parameters for the perturbation of the energy closure equation and non-local treatment [12, 16]. We have set these parameters to be the same as those found for the Sun. We are aware that different sets of free parameters might lead to different results and that maybe the parameters set for the sun might not be adequated for a RG. For instance, with different set of parameters, a mode can be stable or unstable. Nevertheless, some physical aspects such as the differences between radial and non radial modes that take place in the very deep layers of the star are not affected by these parameters. Hence, these uncertainties do not affects the main lines of our discussion.

Using MAD dimensionless formalism we define:

$$W(m) = \frac{R^3}{2GM\Re(\omega)} \frac{\int_0^m \Im(\frac{\delta\rho^*}{\rho}\frac{P}{\rho})dm}{E} \qquad (3)$$

in such a way that $W(M) = \eta$, where η is the dimensionless damping rate. Thus, here $W(m)$ is a measure of the dimensionless damping rate across the star.

Figure 4 shows that W obtained for the a radial mode, $l = 0$ and non radial modes, $l = 1$, of type (a) and type (b) with theoretical frequencies of 89.966, 93.563, and 93.636 μHz, and with lifetimes of 8.662, 12.653, and 26.980 days, respectively.

The driving and damping mechanisms as they appear in the numerator of Equation 3 are essentially the same for radial and non radial modes of type (a) and (b). The decrease of W towards the surface indicates that the main effect is a damping of the modes, as expected in solar-like oscillations. The numerator of Equation 3 is not much affected by the degree l of the mode, but the mode inertia which appears in the denominator depends strongly on the modes. This can be seen in Figure 5, which shows how the inertia function, $E(m)$, of the modes becomes very large, specially for the non radial modes which are trapped in that region.

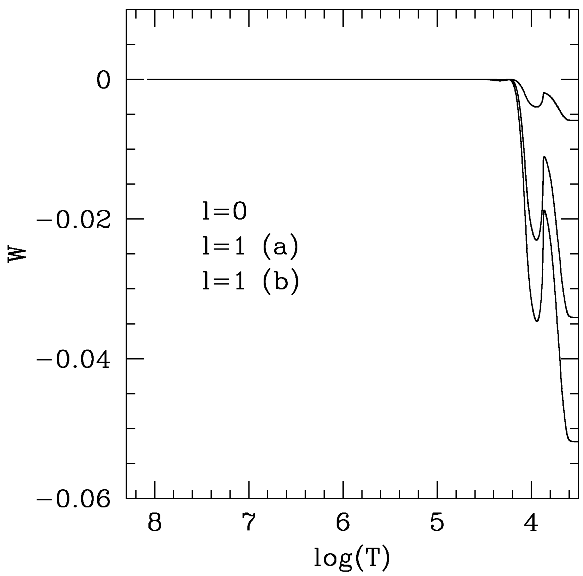

Figure 4. Comparison between the W obtained for a radial mode and for the two types of non radial modes, corresponding to the theoretical frequencies 89.966, 93.563 and 93.636 μHz, respectively.

The predicted lifetimes of non radial modes of type (a) are about the same order as radial modes, around 4 to 15 days, while the non radial modes of type (b) sometimes reach lifetimes up to 1000 days.

4. CONCLUSIONS

Some non radial modes have inertia comparable to radial modes that behave as p modes and are stable according to our modeling and set of free parameters. We compared the eigenfunction of radial modes to that of non radial modes and we see that the difference between the modes is mainly due to the mode inertia. The study presented here is not sufficient to draw conclusions about the possible stochastical excitation of these modes. The stochastical excitation is bound to the dynamics of the convection and its interaction with pulsations. This interaction convection-pulsation is not yet well known in RGs. So far we have been guided by the knowledge gained from studying the Sun to extrapolate the intrinsic physics of non radial modes in RGs. If non radial modes are indeed excited it would offer to a new way of looking at RGs, we could pierce them and see what is inside.

If one plans to observe red giants and study them in terms of asteroseismology, some work will have to be done. Improvements in the treatment of the convection and semi-convection are necessary, since the red giant phase is very sensitive to it. A comparison between the available stellar evolution codes focused on red giant modeling would also be important.

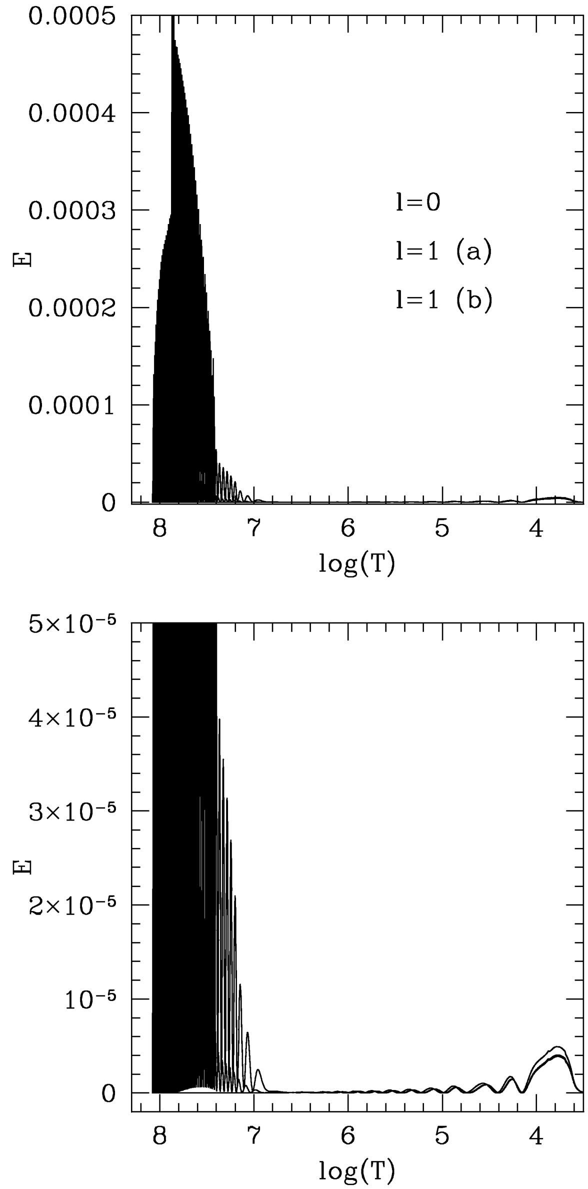

Figure 5. Comparison between the inertia function of the radial and non radial modes.

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