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Detailed Study of the Internal Structure of a Red-giant Star Observed with *Kepler*

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Abstract. We study the internal structure and evolutionary state of KIC 4351319, a red-giant star observed with the *Kepler* satellite. The use of 25 individual oscillation frequencies, together with the accurate atmospheric data provided by ground-based spectroscopic observations, allowed us to estimate the main parameters of this star with a level of precision without precedents for a red giant. In addition, the excellent quality of the observations enabled us to define the location of the base of the convective envelope and to learn about the internal rotation, the helium abundance, the surface effects and extra mixing effects such as diffusion and overshooting.

1. Introduction

Red giants are cool stars characterized by a small degenerate helium core and a deep convective envelope that can, like in the Sun, stochastically excite pressure modes of oscillations [for a review, see Christensen-Dalsgaard (2011)]. A solar-like oscillation pattern has been already revealed in more than two thousand G- and K-giant stars observed by the space missions CoRoT (De Ridder et al. 2009) and *Kepler* (Gilliland et al. 2010). In particular, the high-precision photometry by the NASA space mission *Kepler*, launched in March 2009 and designed to discover habitable earth-like planets around distant Sun-like stars (Borucki et al. 2010), extended the detection of solar-like oscillations from the red clump (e.g., Hekker et al. 2009) to the lower-luminosity region of the red-giant branch (e.g., Bedding et al. 2010), where stars are still burning H in the shell.

In this article we present the analysis of the red giant KIC 4351319 (TYC 3124-914-1) observed by the *Kepler* satellite. We derive the asteroseismic estimates of age, mass and radius and of other structural characteristics, making use of a set of 25 identified oscillation frequencies together with the accurate atmospheric parameters obtained by ground-based spectroscopy [for more details, see Di Mauro et al. (2011)]. The star selected for this study is of particular interest because its oscillation spectrum shows an excess of power centered at frequency $\sim 380\,\mu$Hz, which indicates that the star is well below the red clump in luminosity and is still ascending the red-giant branch. Its relatively high frequencies require *Kepler*'s short-cadence mode, which means that relatively few stars with these characteristics are being observed and KIC 4351319 therefore provides a very important opportunity to study this evolutionary phase.

2. Oscillation Frequencies in Red Giants

The properties of the solar-like oscillations can be described by adopting the asymptotic development (Tassoul 1980), which predicts that the spectra should be characterized by acoustic modes almost evenly spaced in frequency by large and small separations. The solar-like oscillation pattern, typical of main sequence stars, assumes in red-giant spectra a quite complicated appearance due to the presence of modes with frequencies shifted from the regular asymptotic spacing, the so-called 'mixed modes' (e.g., Christensen-Dalsgaard 2011). In the red giants most of the mixed modes have a much larger amplitude in the core than in the envelope, so we refer to them as mixed modes with gravity-dominated character because they behave like pure gravity modes penetrating deeply in the core and allowing to study the inner region.

Very recently, the quality of the *Kepler* observations led Beck et al. (2011) and Bedding et al. (2011) to establish a very important breakthrough on the possibility of measuring the period spacing of the mixed modes with gravity-dominated character in order to study the density contrast between the core region and the convective envelope. In particular, Bedding et al. (2011) found that measurements of the period spacings of the gravity-dominated mixed modes distinguish between the hydrogen- and helium-burning stages of evolution of the red giants. A similar approach to measure the period spacing of gravity modes was successfully applied by Mosser et al. (2011) to CoRoT red-giant observations.

The occurrence of mixed modes is then a strong indicator of the evolutionary state of a red giant and can provide estimates not only of mass and radius but also, with good accuracy, the age of the star.

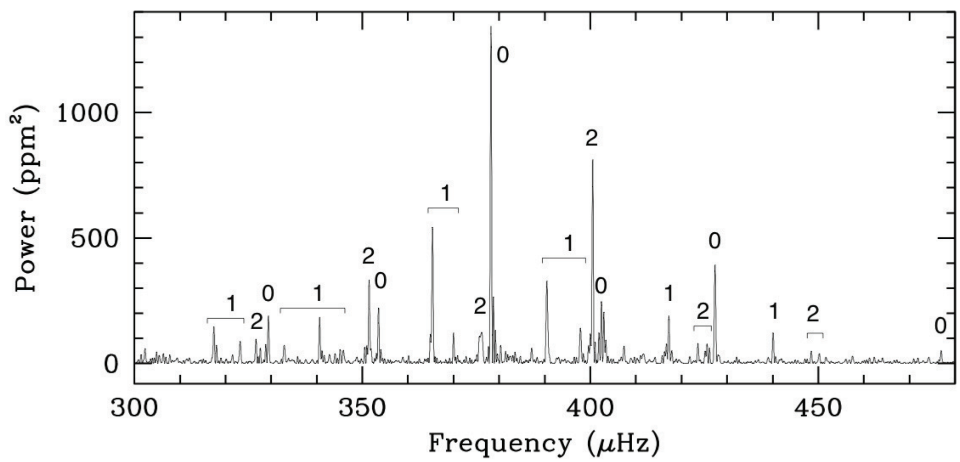

Figure 1. Fourier spectrum of KIC 4351319 in the region of the p-mode excess; the harmonic degrees of the excited modes are shown.

3. Oscillation Frequencies Observed in KIC 4351319

KIC 4351319 was observed for 30 consecutive days in short-cadence mode (integration time of ~1 min) by the *Kepler* satellite (Koch et al. 2010).

The analysis of the data allowed Di Mauro et al. (2011) to determine the large and small frequency separations, $\Delta\nu_0 = 24.6 \pm 0.2\,\mu$Hz and $\delta\nu_{02} = 2.2 \pm 0.3\,\mu$Hz respectively, the frequency of maximum oscillation power $\nu_{\max} = 386.5 \pm 4.0\,\mu$Hz and to identify 25 independent pulsation modes with degree $\ell = 0, 1, 2$ and frequencies between $300 - 500\,\mu$Hz. The resulting power spectrum with regularly spaced peaks is shown in Fig. 1, while the complete list of the individual observed frequencies is given by Di Mauro et al. (2011).

The relation between the large and small frequency separations, which provide asteroseismic inferences on the mass and the age of main-sequence and post-main-sequence solar-type stars (Christensen-Dalsgaard 1988), cannot be used as an unambiguous diagnostic tool for more evolved stars (e.g., Bedding 2011). However, the stellar mass and radius can be approximately derived, within 7% and 3% respectively (e.g., Kallinger et al. 2010), from measurements of the $\Delta\nu_0$ and $\nu_{\max}$, by using the scaling relations found by Kjeldsen & Bedding (1995) and Bedding & Kjeldsen (2003) for solar-like stars. In the case of KIC 4351319 we obtained the following rough estimate of the global parameters: a mass $M/M_\odot \simeq 1.35 \pm 0.09$ and a radius $R/R_\odot \simeq 3.44 \pm 0.08$.

3.1. Period Spacing of g-dominated Modes

In the attempt to measure the period spacing of mixed modes with g-dominated character, it has been noticed that this star is substantially less evolved than the red giants considered by Bedding et al. (2011) and Mosser et al. (2011), so its spectrum is not only rich in mixed modes with g-dominated character but also in mixed modes with p-dominated character like the subgiant stars. Thus, it becomes quite hard to measure a clear $\ell = 1$ g-dominated mode period spacing. However, it has been determined that the consecutive $\ell = 1$ g-dominated mixed modes have a period spacing in the range

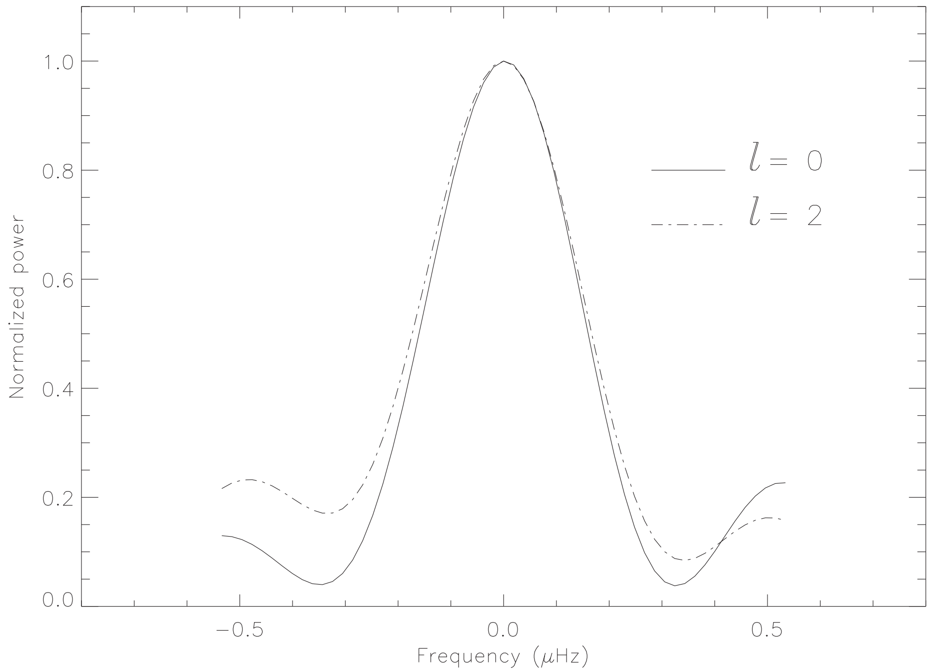

Figure 2. Summed power spectrum centred on retrieved frequencies of the $\ell = 0$ and $\ell = 2$ modes (with frequencies shifted to zero).

35–50 s, which is consistent with a hydrogen-shell-burning evolutionary phase (Bedding et al. 2011). This result is in good agreement with the value deduced by applying the method described by Mosser et al. (2011) who found a period spacing for this star of about 40 ± 4 s.

3.2. Internal Rotation

It can be estimated that the observed rotational velocity $v_e \sin i \simeq 6\,\mathrm{km\,s^{-1}}$ (Di Mauro et al. 2011), quite high for a red giant, might produce a rotational splitting of $\sim 0.8\,\mu$Hz for the modes of $\ell = 2$, $m = \pm 2$ in case of rigid rotation. Such a rotational splitting is about twice the value of the frequency resolution of the 30-d data set. To check for the signature of rotation, it was necessary to model the oscillation spectrum by adding rotational split components for $\ell = 1$ and $\ell = 2$ modes, following the approach of Gizon & Solanki (2003). The rotational frequency and the inclination angle were allowed to vary in the range between $0 - 3\,\mu$Hz and $0° - 90°$ respectively. A comparison of the global likelihoods of the two models (with and without rotation) indicates that the rotation-free model is about 70 times more likely than the model including rotation.

Moreover, we have looked for signature of rotation by comparing the linewidth of the $\ell = 2$ with that of the $\ell = 0$ modes. The summed power spectrum obtained by centering it on retrieved frequencies (Fig. 2) indicates that the linewidth of $\ell = 2$ is comparable to that of the $\ell = 0$ modes with no evidence for split components and tends to favour a slow rotation rate in this star.

4. Characterizing the Structure of KIC 4351319

In order to interpret the observed oscillation properties of KIC 4351319, we produced theoretical structure models satisfying the spectroscopic constraints with the use of the ASTEC evolution code (Christensen-Dalsgaard 2008). The assumed effective temperature, iron abundance and gravity were $T_{\rm eff} = 4700 \pm 50$ K, [Fe/H]= (0.23 ± 0.15) dex and $\log g = 3.3 \pm 0.1$ as determined by Di Mauro et al. (2011).

The models have been calculated with the OPAL 2005 equation of state (Rogers & Nayvonov 2002), OPAL opacities (Iglesias & Rogers 1996), and the NACRE nuclear reaction rates (Angulo et al. 1999). Convection was treated according to the mixing-length formalism (MLT) (Böhm-Vitense 1958). Additional evolutionary models were calculated by including overshoot beneath the convective envelope and turbulent diffusion from the convective envelope.

Figure 3 shows a series of evolutionary tracks obtained for different masses and fixed initial composition. The location of KIC 4351319 in the H-R diagram identifies the star as being in the post-main-sequence phase of evolution, beginning its ascent of the red-giant branch. It has a small, degenerate helium core, having exhausted its central hydrogen, and it is in the shell-hydrogen-burning phase, with a very deep convective zone, extending from the base located at about $r_{\rm b_{cz}} \simeq 0.23\,R$ to the photosphere.

Among all the possible models, we selected a few (see Table 1) able to reproduce the set of the observed frequencies and the observed values of the large and small separations. Our computations show that the age of KIC 4351319 is 5.6 ± 0.4 Gyr, with a mass $M = 1.30{\pm}0.03\,M_\odot$, a radius $R = 3.37{\pm}0.03\,R_\odot$ and a luminosity $L = 5.1{\pm}0.2\,L_\odot$. The values of mass and radius obtained by fitting the individual frequencies are better constrained than those obtained by using the global parameters (see Sect. 3).

Table 1. Age, luminosity L, effective temperature $T_{\rm eff}$, surface radius R, gravity g, location $r_{\rm b_{cz}}$ of the base of the convective envelope in units of R, occurrence of extra mixing effects for a set of models of KIC 4351319 calculated with mass $M = 1.32\,M_\odot$, initial hydrogen abundance $X_0 = 0.7$ and surface metallicity $Z_{\rm s} = 0.03$.

Model	age (Gyr)	$L/L_\odot$	$T_{\rm eff}$ (K)	$R/R_\odot$	$\log g$	$r_{\rm b_{cz}}/R$	Extra mixing effect
1	5.29	5.25	4752	3.39	3.50	0.23	No
2	5.28	5.23	4747	3.39	3.50	0.23	turb. diffusion
3	5.27	5.28	4761	3.38	3.50	0.23	overshooting

A detailed comparison between the theoretical oscillation spectra and the observed data is provided in the échelle diagram of Fig. 4. The size of the symbols is proportional to the theoretical oscillation amplitudes of p-modes, relative to the amplitudes of radial modes with the same frequency. We find a very good agreement between observed and theoretical frequencies. In particular, we are able to fit all the $\ell = 1$ mixed modes.

The results show that the observed modes are $\ell = 0$ pure acoustic modes, and $\ell = 1$ and $\ell = 2$ mixed modes. Several mixed modes have pressure-dominated character with an inertia so low as to propagate up to the surface and appear to behave like solar-like oscillations. Very few mixed modes, with a quite high inertia, have gravity-dominated character and appear to depart strongly from the regular solar-like pattern.

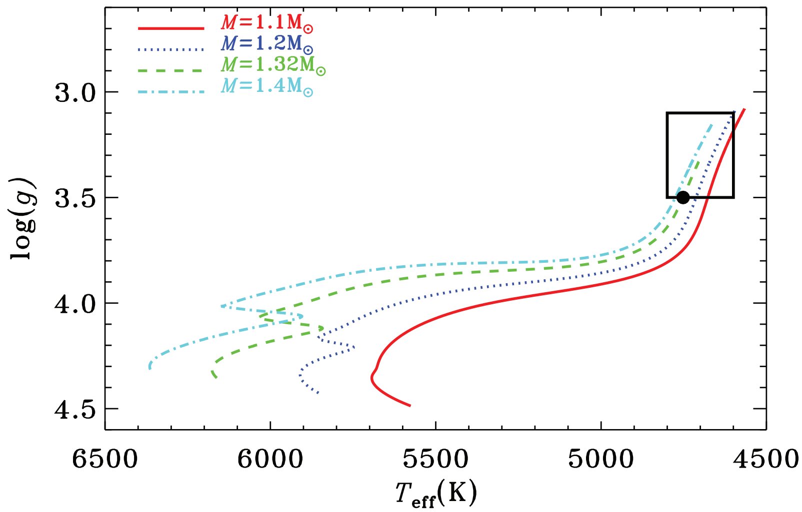

Figure 3. Evolutionary tracks plotted in the H-R diagram calculated for increasing values of the mass, while all the other parameters are fixed. The metallicity is $Z = 0.03$, the initial hydrogen abundance $X_0 = 0.7$. Here no additional effects are included. The rectangle defines the two-sigma error box for the observed gravity and effective temperature for KIC 4351319. The bullet indicates the position of Model 1 of Table 1.

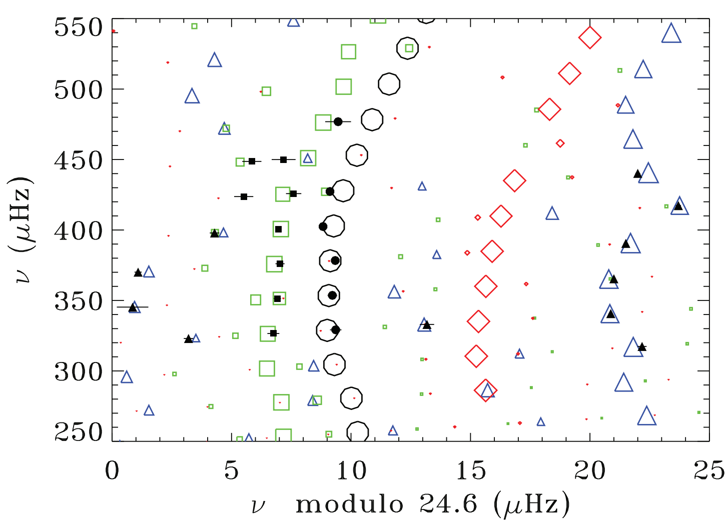

Figure 4. Échelle diagram based on observed and computed frequencies, plotted with $\Delta\nu = 24.6\,\mu$Hz, and showing results for Model 1 of Table 1. The open symbols represent computed frequencies, while the filled symbols represent the observed frequencies of Di Mauro et al. (2011). Circles are used for modes with $\ell = 0$, triangles for $\ell = 1$, squares for $\ell = 2$, diamonds for $\ell = 3$. The size of the open symbols indicates the relative surface amplitude of oscillation of the modes.

In order to reproduce the observed modes, we did not correct the frequencies for the surface effects as suggested by Kjeldsen et al. (2008). This might indicate that the treatment of non-adiabatic effects or other near-surface problems in cool stars is less crucial than for subgiant stars.

4.1. Sharp Features inside Red giants

It is known that sharp variations localized at a certain acoustic depth in the structure of pulsating stars produce a distinctive quasi-periodic signal in the frequencies of oscillation. The characteristics of such a signal are related to the location and thermodynamic properties of the layer where the sharp variation occurs. In main-sequence stars the signals coming from different sharp features in the interior overlap, generating a complex behaviour (Mazumdar & Antia 2001); on the contrary in the red giants sharp features are well separated and observed modes probe different internal regions according to their gravity or pressure dominating character.

We have considered the possibility of isolating the signal coming from the base of the convective envelope by looking at the observed modes which penetrate deeply inside the star, namely the g-dominated mixed modes. This can be studied by comparing models modified by adding turbulent diffusion or overshooting at the base of the convective envelope. The upper panel of Fig. 5, obtained for three models of this star (see Table 1), shows that the presence of additional mixing effects modifies the profile of the sharp feature occurring at the base of the convective envelope in the internal content of hydrogen. The results show that the inclusion of turbulent diffusion, or overshooting, below the convective envelope produces displacements only in the $\ell = 1$ and $\ell = 2$ g-dominated mixed modes, while all the other frequencies are not modified, as shown in the lower panel of Fig. 5. Thus, although we have not observed high-order g-modes, we can use the g-dominated mixed modes to probe qualitatively the deep interior of a red-giant star. However, it is impossible to distinguish the effect on the frequencies due to diffusion from that of overshooting.

Sources of sharp variations are also the regions of rapid variation in the first adiabatic exponent Γ_1, such as the one that occurs in the region of the second ionization of helium. The behaviour of Γ_1, shown in the upper panel of Fig. 6 as function of the acoustic radius $t = \int_0^{r_1} [c(r)]^{-1} \mathrm{d}r$, indicates that in the models of KIC 4351319 the second helium ionization zone occurs at about $t_{\mathrm{He\,II}}/T \simeq 0.7$, while the base of the convective envelope is located at $t_{\mathrm{b_{cz}}}/T \simeq 0.08$, too deep to produce a signal detectable as solar-like frequencies (Miglio et al. 2010). As shown in the lower panel of Fig. 6, this sharp variation produces a weak oscillatory signal in the calculated frequencies of those acoustic modes which follow closely the asymptotic law, namely the radial modes and the nonradial modes with very low inertia.

The properties of the helium ionization zone, once determined from the oscillation frequencies, may be used to constrain the structure of the star, in particular the envelope helium abundance.

5. Conclusions

Detailed modelling, matching both the asteroseismic and spectroscopic constraints, allowed us to determine the main parameters of KIC 4351319 with an unprecedented level of precision for a red-giant star, with uncertainties of 2% for mass, 7% for age,

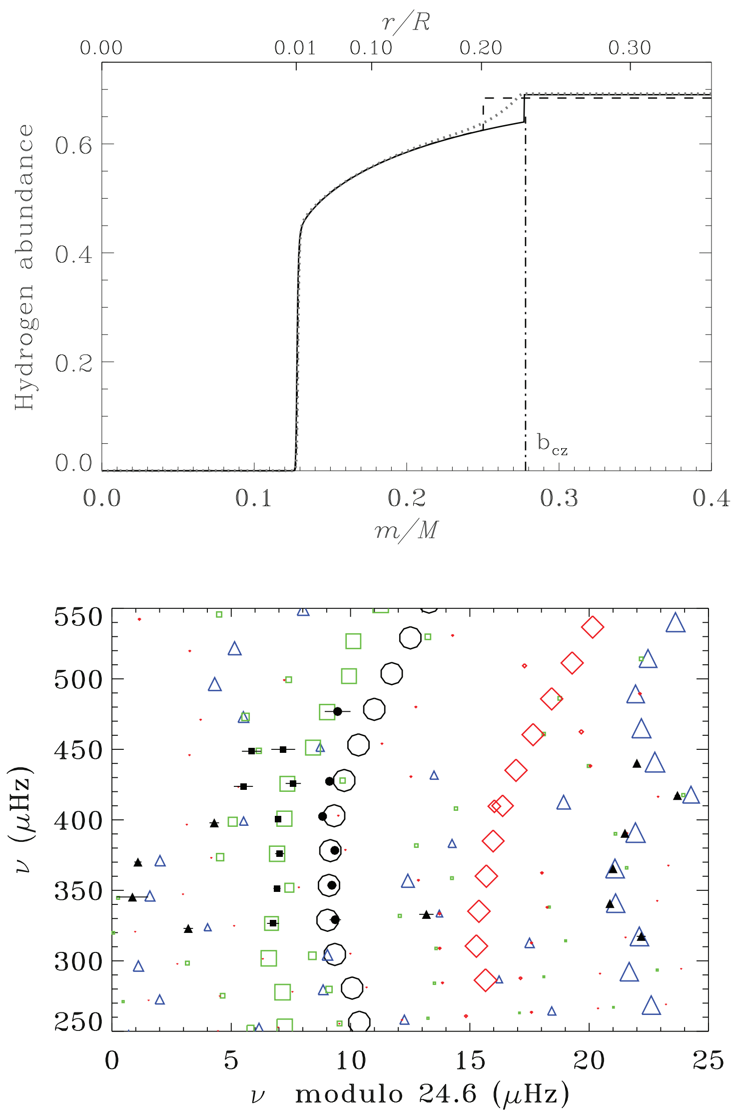

Figure 5. Upper panel: hydrogen content for models of Table 1. The solid, the dotted and the dashed lines indicate respectively Model 1 with no additional effects, Model 2 with inclusion of turbulent diffusion and Model 3 with overshooting from the convective envelope. The base of the convective envelope is shown by the dot-dashed line. Lower panel: échelle diagram showing computed frequencies for Model 2 of Table 1, plotted with $\Delta\nu = 24.6\,\mu$Hz. Symbols are like Fig. 4.

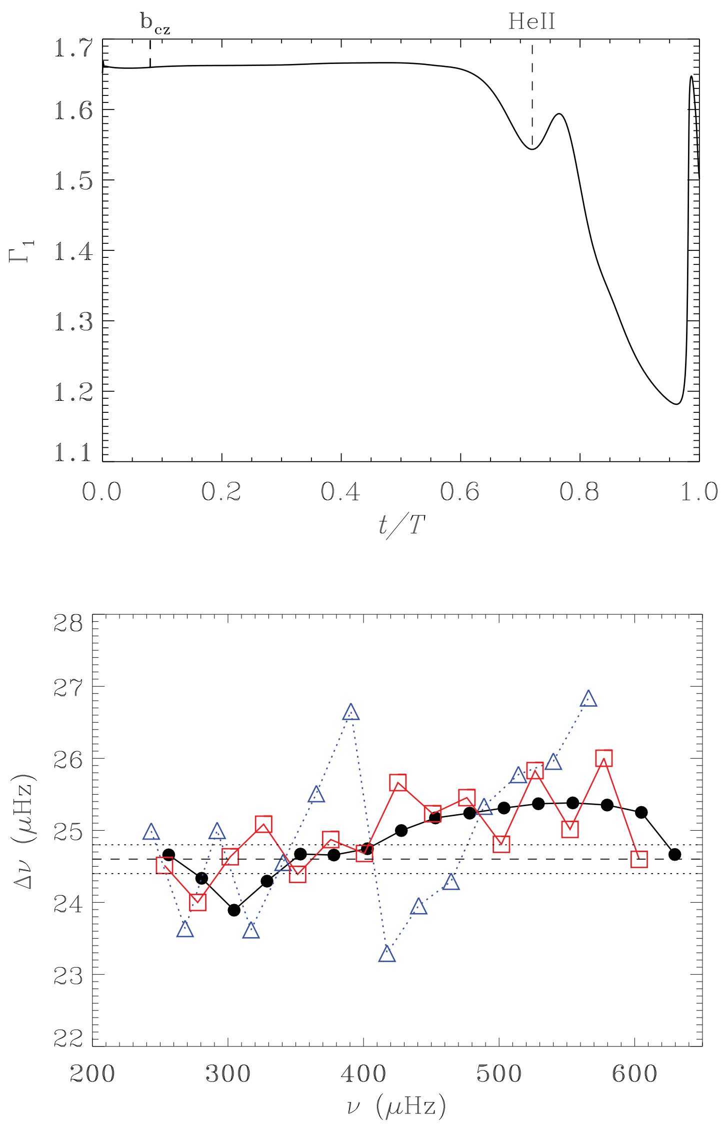

Figure 6. Upper panel: first adiabatic exponent as function of the acoustic radius, in units of the surface value T, for Model 1 of Table 1. The region where helium undergoes its second ionization and the location of the base of the convective envelope are indicated. Lower panel: small oscillations in the large frequency separation for solar-like modes of $\ell = 0$ (black dots), $\ell = 1$ (blue triangles) and $\ell = 2$ (red squares) as calculated for Model 1 of Table 1. Observed large separation and its uncertainty $\Delta\nu_0 = 24.6 \pm 0.2\ \mu$Hz are indicated by dashed line and dotted lines respectively.

1% for radius, and 4% for luminosity. We have demonstrated that observations of accurate oscillation frequencies enable a detailed study of the interior of the red giants. In particular, the conditions of the core can be probed by using the gravity-dominated mixed modes, while the conditions in the convective envelope can be studied by using the pressure-dominated mixed modes.

We conclude that the observation of individual oscillation modes represents a powerful tool for understanding several important questions about the red-giant evolutionary phase related to the determination of the stellar age, the abundance of the elements, the equation of state, the non-adiabatic effects, the internal rotation and the extra mixing effects.

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