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PROBING CORE OVERSHOOTING USING SUBGIANT ASTEROSEISMOLOGY

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Abstract. Convective cores are the fuel reservoir of stars that are more massive than about $1.2\,M_\odot$. Their size therefore has a substantial influence on stellar evolution. However, several physical processes that remain poorly understood by theory can extend those convective cores. Observations are therefore required to help constrain them. We here show how we can use subgiant asteroseismology to indirectly constrain the main-sequence convective core extension. Indeed, subgiant stars exhibit mixed modes, whose dual nature as pressure and gravity modes allows us to probe the very core of the star. We therefore used the full Kepler data set to thoroughly model KIC10273246, using a method that we specifically tailored for subgiants. We obtained models that show a good statistical agreement with the observations, and found that adding overshooting significantly improves the quality of the seismic fit. We also found that having access to several g-dominated mixed modes provides a stronger constraint on the structure of the star, especially the Brunt-Väisälä frequency and the central density. This study paves the way of a more general study, which will include subgiants observed with Kepler and TESS.

Keywords: asteroseismology, convection, stars: evolution, stars: interiors, stars: individual: KIC10273246

1 Introduction

Convective cores are found in stars more massive than approximately $1.2\,M_\odot$ (e.g., Kippenhahn et al. 2012). As they are the fuel reservoirs of the star, their masses is of prime importance on stellar evolution: the bigger the core is, the more time the star spends on the main-sequence (MS). However, several physical processes are known to extend this core beyond the limit defined by the classical Schwarzschild (or Ledoux) criterion. Those can be, for instance, overshooting, rotational mixing or semi-convection. Unfortunately, those processes, and even more the way they interact are today poorly constrained by the theory. Therefore, one generally models the core extension, usually referred as *overshooting* regardless of the physical process, in a simplistic way. For instance, it is often modeled as a crude extension of the convective core, called step overshooting, on the distance $d_\mathrm{ov} = \alpha_\mathrm{ov} H_p$, H_p being the pressure scale length and α_ov a free parameter.

Historically, constraints on the core extension have been obtained through the study of color-magnitude diagrams of clusters (e.g., Maeder & Mermilliod 1981). More recently, the study of eclipsing binaries also allowed to put constraints on this parameter (e.g., Claret & Torres 2018).In all cases, overshooting appears to be required in order to correctly reproduce the observations.

Over the last decade, the rapid progress of observation asteroseismology allowed to directly probe inside of the stars. Thanks to the data of the space missions CoRoT (Baglin et al. 2006), *Kepler* (Borucki et al. 2010) and now TESS (Ricker et al. 2014), oscillations have been detected in thousands of stars, which allowed unprecedented exploration of the stellar structure. Once again, overshooting have been a necessary ingredient to correctly model solar-like oscillators (e.g. Deheuvels et al. 2016), more massive slowly-pulsating (SPB) stars (e.g. Pedersen et al. 2021) and γ Doradus (Mombarg et al. 2021).

Asteroseismology of post-main-sequence stars is another way to place constraints on the MS core. Once the central hydrogen is totally exhausted at the end of the MS, the core becomes radiative and contracts until the hydrogen-rich layers above become hot enough to start hydrogen burning. The resulting core structure is therefore highly dependent on the properties of the former convective core. Moreover, interestingly, the stars starts to exhibit mixed modes. Those modes, which have a gravity (g) nature in the core and a pressure (p)

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nature in the envelope, allow a very fine probing of the structure of the star. These features make subgiant interesting targets to investigate the properties on MS convective cores. Thus, Deheuvels & Michel (2011) succesffuly constrained $\alpha_{\rm ov}$ by seismically modeling a star observed by CoRoT. In the present work, published in Noll et al. (2021), we use the high quality sesmic data from *Kepler* to model a subgiant star.

2 Choice of the target and observational properties

2.1 Choice of the target

In this study, we chose to focus on KIC10273246, a subgiant star observed during a total duration of 978 days by *Kepler*. Such a long duration of observation allows a high precision of the frequencies. Moreover, this star exhibits several "g-dominated" modes, i.e. modes that are mainly of gravity nature. We thus expected to obtain more precise information on the core as most of the energy and probing capacities of such modes are located in the central region of the star. Finally, early seismic analyses of this star (Campante et al. 2011; Creevey et al. 2012) indicate that it is massive enough to have had a convective core during the MS.

2.2 Observational properties

The luminosity of the star have been extracted using Gaia DR2 data (Evans et al. 2018) combined with a spectral energy distribution (SED) fit. We obtained $L = 5.74 \pm 0.17\,L_{\odot}$. The effective temperature and metallicity, from the spectroscopic modeling of Creevey et al. (2012), are respectively $6150 \pm 100\,\mathrm{K}$ and $-0.13 \pm 0.13\,\mathrm{dex}$.

The oscillation frequencies have been extracted from the full *Kepler* light curve, following the method of Appourchaux et al. (2008). We obtained a large separation $\Delta\nu = 48.47 \pm 0.02\,\mu\mathrm{Hz}$ and a frequency of maximum power of the oscillations $\nu_{\rm max} = 843 \pm 20\,\mu\mathrm{Hz}$.

3 Modeling method

To model the star, we carried out a forward modeling (i.e. trying to reproduce the observations with models) using the MESA v10108 stellar evolution code (Paxton et al. 2015) coupled with the ADIPLS stellar oscillation code (Christensen-Dalsgaard 2008). Microscopic diffusion has been taken into account (Burgers 1969). Radiative accelerations have been neglected. Overshooting has been modeled as a *step overshooting* (i.e. crude extension of the core). The surface effects were corrected using the cubic term of the prescription of Ball & Gizon (2014). The free parameters were the mass M, the age, the initial helium composition Y, the initial metallicity [Fe/H], the mixing-length parameter $\alpha_{\rm conv}$ and the overshoot parameter $\alpha_{\rm ov}$. All the rest of the physics is detailed in Noll et al. (2021).

Subgiant stars are notoriously difficult to model. This is mainly due to the very fast evolution of the frequencies of the g-dominated modes, which are highly impacted by the steep increase in the central density. Reproducing such modes by using a grid of stellar evolution models therefore requires extremely small steps in mass and age. Interpolation within the grid of models could alleviate this issue, however, if interpolation in age is doable for modes with degrees less than 2 (Li et al. 2020), it is difficult across tracks. Finally, the highly non-linear behavior of mixed modes prevents us from directly using traditional iterative optimization techniques.

We therefore used a dedicated approach in Noll et al. (2021), which consists in a nested optimization. This method is composed of two steps, the first being embedded within the second. The first part only deals with the mass and age as free parameters, the rest of the parameters being fixed. One can show that, when all other input parameters are fixed, the optimal mass and age of a model can be found only by reproducing the large separation $\Delta\nu$ and the frequency of a g-dominated mode ν_g (Deheuvels & Michel 2011). This allows to "easily" handle these two otherwise tedious parameters. This dedicated approach is nested in a more general step, in which we handle the other parameters, namely the metallicity, mixing-length parameter, initial helium composition and overshoot. For those parameters, we used more general techniques such as an optimization using a Levenberg-Marquardt algorithm (Press et al. 1992) and a grid. The former allowed us to retrieve more precise parameters, while the latter allowed a better exploration of the space parameters and determination of the modeling uncertainties.

4 Results

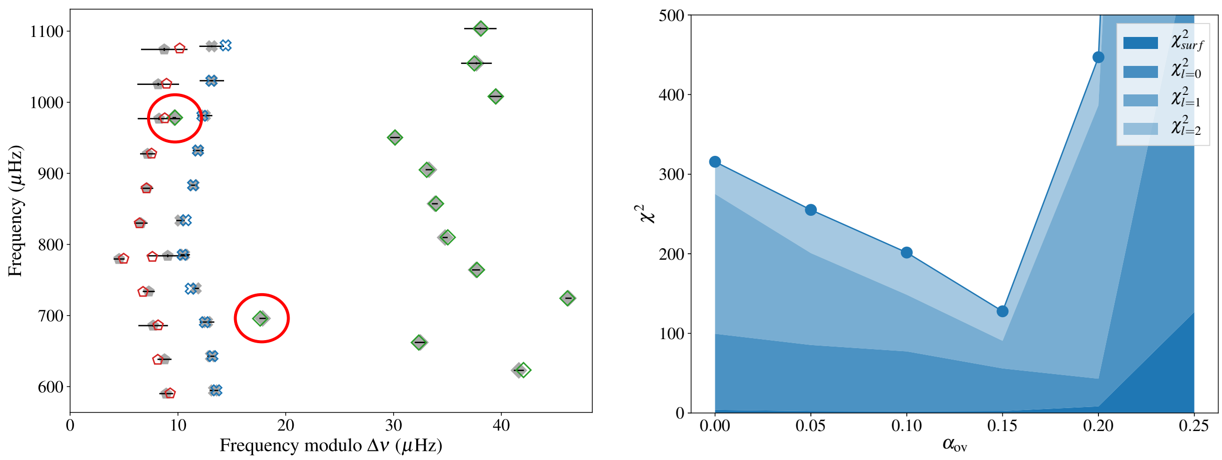

Fig. 1. Left: Echelle diagramme of the best model (in open symbols) and of the observations (in full symbols). Radial, dipolar and quadripolar frequencies are in blue, green and red, respectively. G-dominated modes are cercled in red. **Right:** χ^2 of the best models for every value of α_{ov}. The colored regions indicate the χ^2 contributions of surface observables and frequencies depending on their degrees.

4.1 General characteristics of the models

Using the nested optimization, we managed to obtain statistically satisfactory models of KIC10273246. Indeed, the best model, with $\alpha_{\text{ov}} = 0.15$, has a reduced χ^2 of 3.2. We found the following characteristics : $M = 1.223 \pm 0.03\, M_{\odot}$, $R = 2.110 \pm 0.021\, R_{\odot}$, Age $= 3.89 \pm 0.25$ Gyr, [Fe/H] $= -0.073 \pm 0.01$, $\alpha_{\text{conv}} = 1.739 \pm 0.089$ and $Y = 0.28 \pm 0.02$. Moreover, its luminosity and effective temperature are within the observational uncertainties. One can see in the left panel of Fig. 1 the échelle diagram of the best model, and the observations with the 3-σ uncertainties representend with black bars. It appears indeed that all the frequencies are well reproduced, even the g-dominated ones (circled in red) despite their high sensitivity to the age and mass of the model.

4.2 Constraints on α_{ov}

The right panel of Fig. 1 represents the χ^2 of the best models, for every value of α_{ov}. We can see that adding overshooting significantly improves the quality of the fit, with a χ^2 difference between the models without and with $\alpha_{\text{ov}} = 0.15$ of 188. Modeling KIC10273246 therefore allowed us to constrain α_{ov}. One can also notice on this plot the colored regions below the curve, which represent the contributions of the frequencies to the total χ^2 according to their degree. We can see that the dipolar modes play a crucial role to favor models with overshoot. Indeed, g-dominated modes are mainly dipolar for such stars. So, this confirms the high probing potential of such modes.

Finally, we notice that a high overshoot $\alpha_{\text{ov}} \geq 0.2$ strongly worsens the quality of the fit. This may be explained by the tight constraint on the central density ρ_c due to the g-dominated modes, as explained more in depth in Noll et al. (2021).

4.3 Constraints on the internal structure

We also investigated in Noll et al. (2021) the constraints that can be obtained from the mixed modes on the internal structure of the star. In particular, as KIC10273246 exhibits two g-dominated modes contrary to HD49385 which was studied in Deheuvels & Michel (2011). We showed that a second g-dominated mode allows to put strong constraints on the Brunt-Väisälä profile and especially on the part that is dominated by the chemical gradient in the H-burning shell. As this region is highly sensitive to the former MS core, subgiants with several g-dominated modes are therefore interesting targets to constrain overshoot.

5 Discussion and conclusion

During this detailed study of KIC10273246, we also tested the impact of the microscopic diffusion on the seismic modeling. Indeed, adding diffusion or not is a tricky question for stars in this mass range, as it may be competed by radiative accelerations in the envelope during the main sequence (Deal et al. 2018). We observed that adding microscopic diffusion allows to significantly improve the diffusion, as it indeed reduces the χ^2 by 71. We also observed no difference between the best model computed with and without radiative accelerations.

Additionally, a strong degeneracy between initial helium abundance Y and stellar mass M has been found during the modeling of the star. This degeneracy is the main contributor to the uncertainties on the stellar parameters. The mass-helium degeneracy, already known in main sequence (e.g., Lebreton & Goupil 2014), is therefore not lifted during the subgiant phase, in agreement with Li et al. (2020) .

Finally, the detection of a g-dominated quadrupolar mode which is split by rotation allowed us to constrain the core rotation of the star. Thus, we obtained a splitting of $0.53 \pm 0.03\,\mu$Hz. This value, close to the surface rotational modulation (around $0.5\,\mu$Hz, Campante et al. 2011), would indicate a low radial differential rotation, in agreement with Deheuvels et al. (2020).

In conclusion, this study showed the high interest that could represent the seismic study of subgiants to constrain the amount of overshooting in main-sequence convective cores. In the future, a similar method will be applied to other subgiant stars observed by *Kepler* (Noll et al., in prep.).

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