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SEISMIC INFERENCE ON THE CORE OF THE SUBGIANT HD 49385 VIA MIXED MODES

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Abstract. We report the detection of mixed modes in the oscillation spectrum of the CoRoT target HD 49385. We propose a new grid-search method specifically designed to handle stars with mixed modes, which we apply to HD 49385.

Keywords: Stars: oscillations, Stars: interiors, Stars: evolution, Stars: individual: HD 49385

1 Introduction

As a star evolves, the density in the core keeps increasing, which causes the frequencies of gravity modes (g modes) to increase. They eventually become of the same order of magnitude as pressure modes (p modes). When the frequency of a g mode becomes close to that of a p mode of same degree ℓ, the two modes undergo an *avoided crossing* at the end of which they have exchanged natures. During this process, the modes have a *mixed* character: they behave as g modes in the core and as p modes near the surface. These mixed modes have a very high potential for core diagnostics because they are sensitive to the core while having much higher amplitudes than pure g modes, which are still impossible to detect in solar-like pulsators. Their existence in stars has been theoretically known since Osaki (1975) discovered them in stellar evolution models. However, until very recently, the quality of the observed oscillation spectra was too low to detect and fully exploit mixed modes. The development of space missions CoRoT and Kepler has opened new opportunities.

We here report the detection of mixed modes in the oscillation spectrum of the CoRoT target HD 49385. We then propose a new approach to grid-search modeling specifically designed to handle stars with mixed modes, which we apply to HD 49385.

2 Detection of an $\ell = 1$ avoided crossing in the spectrum of HD 49385

The star HD 49385 is a solar-like pulsator, which was observed with the CoRoT satellite over a period of 137 days with a duty cycle close to 90%. Its oscillation spectrum was analyzed by Deheuvels et al. (2010) who unambiguously identified modes of degrees $\ell = 0, 1$, and 2 over nine radial orders. The authors estimated the frequencies of these modes by fitting Lorentzian profiles to the power spectrum. The mode frequencies are plotted in Fig. 1 in the traditionally used *échelle diagram*. This representation makes use of the fact that in solar-like pulsators, p modes of consecutive orders are spaced by the *large separation* $\Delta\nu$, which is roughly constant with frequency. To build an échelle diagram, the oscillation spectrum is divided in $\Delta\nu$-wide sections, which are then piled up onto one another. That way, modes of similar degree form vertical ridges, as can be seen in Fig. 1. Deheuvels et al. (2010) identified several unaccounted for features in this diagram. First, the curvature of the $\ell = 1$ ridge unexpectedly differs from that of the $\ell = 0$ ridge at low frequency. Then, several modes were detected outside the identified ridges.

Deheuvels & Michel (2010) investigated the possibility that these peculiar features might be caused by mixed modes. They proposed a toy model, which demonstrated that $\ell = 1$ avoided crossings induce a specific distortion of the $\ell = 1$ ridge that is very comparable to the one that we observe in the spectrum of HD 49385. They then found a post-main-sequence (PoMS) model with an $\ell = 1$ avoided crossing that reproduces both the spectroscopic constraints and the observed shape of the $\ell = 1$ ridge in the échelle diagram (model plotted in red in Fig. 1). This enabled them to establish the firm detection of $\ell = 1$ mixed modes in the oscillation spectrum of HD 49385, as well as the PoMS status of the star.

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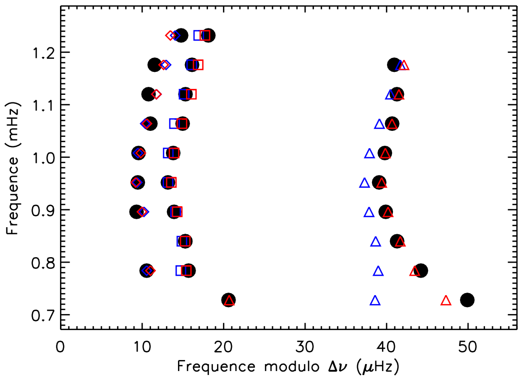

Fig. 1. Échelle diagram of the oscillation spectrum of HD 49385, folded with a large separation of $\Delta\nu = 56.3\,\mu$Hz. The frequencies of a MS model (blue) and a PoMS model (red) have been overplotted (see text for a description of the models). Squares represent $\ell = 0$ modes, triangles $\ell = 1$ modes and diamonds $\ell = 2$ modes.

3 A new approach to grid-search modeling for stars with mixed modes

We now present a thorough modeling of HD 49385, trying to fit stellar models to the properties of the observed avoided crossing. It is the first time such a study is attempted. The main difficulty we encountered is that avoided crossings occur on a very short timescale (typically of the order of 1 Myr or less) compared to the stellar evolution timescale. Applying a traditional grid-search method with a time step of the order of the avoided crossing timescale is infeasible, because it would require the computation of a tremendously large number of models. On the other hand, with a larger time step, the probability of finding models that correctly reproduce the frequency of the avoided crossing is very low and we therefore miss the best-fit models.

We thus adapted the grid-of-model approach to the special case of stars with mixed modes. The method is described in detail in Deheuvels et al. (2011) but we here give a brief overview of how it works. As the star evolves from the MS to the PoMS, the most central regions keep contracting. As a result, the frequencies of g modes monotonically increase because of the growing central density. Therefore, for a given physics, there exists *only one age* for which the frequency of the observed avoided crossing $\nu_{\rm cross}$ is reproduced. The location in the HR diagram of the models which verify this condition is represented by the red dashed line in Fig. 2. But also, as the star evolves, the outer layers expend and the radius increases, which causes the large separation to monotonically decrease. Hence, there is *only one age* for which the models reproduce the observed large separation $\Delta\nu$. The models that verify this second condition are located on the blue dashed line in Fig. 2. From Fig. 2, it is obvious that, for a given physics, there is *only one stellar mass* for which both the frequency of the avoided crossing and the large separation match the observations. We therefore proposed to reduce the dimensions of the model space by eliminating the mass and age from the set of free parameters, these two quantities being each time determined by $\Delta\nu$ and $\nu_{\rm cross}$. Since the age is no longer a free parameter of the fit, this approach solves the problem of the definition of a time step for the grid of models.

4 Application to the case of HD 49385

We applied the method presented in Sect. 3 to the case of HD 49385. The properties of our models are described in Deheuvels et al. (2011). We computed two grids of models, one assuming the mixture of Grevesse & Noels (1993) (furhter noted GN93) and the other the more recent mixture of Asplund et al. (2005) (further noted AGS05). We varied the values of the mixing length parameter $\alpha_{\rm conv}$, the helium abundance Y_0, the metallicity (Z/X) and the amount of overshooting $\alpha_{\rm ov}$. For each point in the grids, an optimization was performed to determine the stellar mass and age that fit $\Delta\nu$ and $\nu_{\rm cross}$ simultaneously (for details on this optimization, see Deheuvels et al. 2011). We then computed a χ^2 function to estimate the agreement between the models and the observations (both spectroscopic and seismic).

We showed that by using this technique, we were able to constrain the stellar mass, radius, and age very tightly: we obtained $M = 1.25 \pm 0.05\,M_\odot$ (precision of 4%), $R = 1.94 \pm 0.03\,R_\odot$ (precision of 1.5%), and $\tau = 5.02 \pm 0.26$ Gyr (precision of 5%) for HD 49385. Interestingly, we also managed to obtain valuable

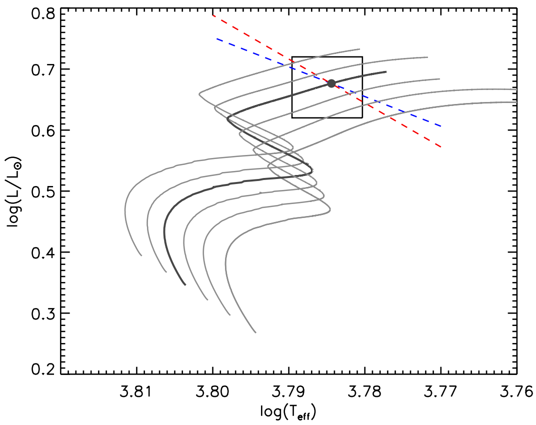

Fig. 2. Evolutionary tracks in the HR diagram of models with masses ranging from 1.2 $M_\odot$ to 1.3 $M_\odot$, for a given physics. The box corresponds to the observational values of the effective temperature and luminosity of the star within 1-σ error bars. The dashed lines indicate the location of models which reproduce the observed values of the large separation (blue) and the frequency of the avoided crossing (red). The model for which both conditions are verified is plotted in dark grey.

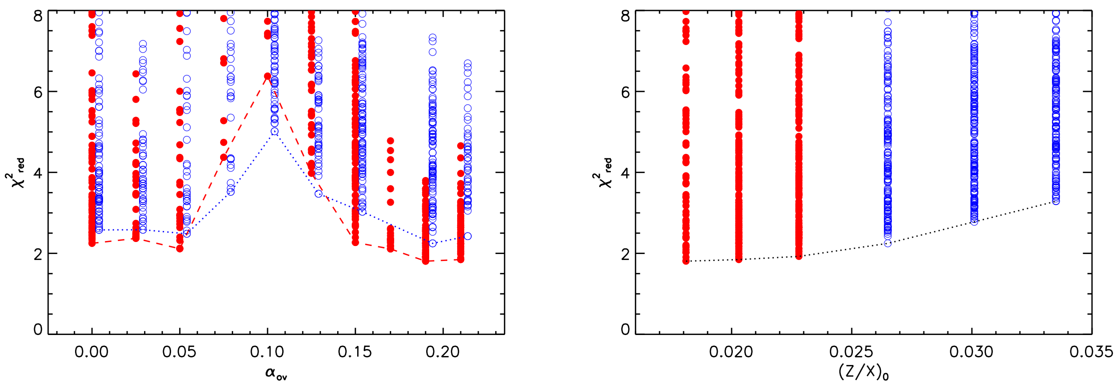

Fig. 3. Left: Values of the χ^2 function for the models computed with the mixture of GN93 (blue empty circles) and that of AGS05 (red filled circles) as a function of the amount of overshooting. The best-fit models for each value of $\alpha_{\rm ov}$ have been linked. **Right:** Same as the left panel, representing the values of the χ^2 function as a function of metallicity.

information about several physical processes that remain theoretically uncertain.

4.1 Constraints on the amount of core overshooting

In stars that have a convective core, the distance over which convective elements penetrate in the radiative region owing to inertia, known as *core overshooting*, is difficult to predict theoretically. This can result in an uncertainty in the stellar ages of up to 30% (Michel et al. 2006). For HD 49385, we showed that the amount of overshooting had to be either very small (distance of penetration lower than 0.05 H_P, where H_P is the pressure scale height) or moderate (about 0.2 H_P). This can be clearly seen in Fig. 3. The existence of two minima in Fig. 3 is explained in Deheuvels et al. (2011).

4.2 Constraints on the abundance in heavy elements

The abundance in heavy elements at the surface of the Sun, which had been estimated to about $(Z/X) = 0.0245$ by GN93, has recently been revised by AGS05, who found a much lower value — $(Z/X) = 0.0165$. However, this new value is in disagreement with helioseismology (see Basu & Antia 2008 for a review) and the solar metallicity still remains uncertain. This generates large uncertainties in stellar structure, e.g. in the determination of radiative opacities and the efficiency of nuclear reactions. Because of the degeneracy of stellar models, it is very hard to constrain the value of (Z/X) in stars, even with the help of seismology. For HD 49385, we showed that the abundances of AGS05 are in closer agreement with the observations than those of GN93 (see Fig. 3).

4.3 Constraints on the efficiency of convection

Since we are still lacking a proper treatment of convection in stars, stellar models usually resort to the simplistic mixing length theory, and use a solar calibrated value for the mixing length parameter $\alpha_{\rm conv}$. In the case of HD 49385, no satisfactory model can be found if we use $\alpha_\odot$. Using the full-spectrum theory (FST) proposed by Canuto et al. (1996), the best-fit models are obtained for a mixing length parameter of $\alpha_{\rm conv} = 0.55 \pm 0.04$, whereas a calibration for the Sun gives $\alpha_\odot = 0.64$. It is interesting to note that Piau et al. (2011) also found sub-solar mixing length parameters for subgiants using a different approach.

5 Why are the stellar parameters so well-constrained in HD 49385?

Given that it is usually very hard to obtain information about the physical processes that we mentioned above with regular main sequence stars, one might wonder why it is possible for HD 49385. This is of course linked with the detection of mixed modes, and it was investigated in details in Deheuvels et al. (2011). There are mainly two reasons. First, the frequency of the observed avoided crossing reduces the dimensions of the model space, as shown in Sect. 3, which lifts some degeneracies between the models. Secondly, the intensity of the distortion in the $\ell = 1$ ridge that we mentioned in Sect. 2 depends on the strength of the coupling between the p-mode cavity and the g-mode cavity in the star. We have shown in Deheuvels et al. (2011) that this coupling is tightly related to the stellar mass. This provides an additional constraint, which we have proven to be crucial to discriminate between the different models.

6 Conclusions

We have performed a thorough modeling of HD 49385, trying to fully exploit the potential of the detection of $\ell =$ 1 mixed modes in the oscillation spectrum of the star. For this purpose, we have developed a new optimization method specifically suited to model stars with mixed modes. We then successfully applied it to HD 49385. We obtained very precise values of the stellar mass ($M = 1.25 \pm 0.05\, M_\odot$), radius ($R = 1.94 \pm 0.03\, R_\odot$), and age ($\tau = 5.02 \pm 0.26$ Gyr) for the star. We also showed that the recently revised abundances of AGS05 offer a closer agreement with the observations than those of GN93. We had to invoke sub-solar values of the mixing length parameter ($\alpha_{\rm conv} = 0.55 \pm 0.04$). We found two families of solution with either a very small amount of core overshooting ($\alpha_{\rm ov} < 0.05$) or a moderate one ($\alpha_{\rm ov} = 0.19 \pm 0.01$).

This study confirms to a large degree that stars with mixed modes have a very high potential in terms of asteroseismic diagnostics. We note that the space mission Kepler has already claimed the detection of mixed modes in several solar-like pulsators (Chaplin et al. 2010) and it will be very interesting to apply the method that we proposed here to these targets.

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