Calibrating Core Overshooting in Low-Mass Stars with *Kepler* Data

S. Deheuvels[1,2]

[1] *Université de Toulouse; UPS-OMP; IRAP; Toulouse, France*

[2] *CNRS; IRAP; 14, avenue Edouard Belin, F-31400 Toulouse, France*

Abstract. The extent of the chemically mixed regions associated with convective cores remains uncertain due to our poor understanding of the interface between convective and radiative zones (e.g. *overshooting*). This generates large uncertainties on stellar ages. So far, several studies have shown that convective cores must extend beyond the Schwarzschild boundary. However, very few constraints exist on the size of this extension and its dependency with stellar parameters. We used 3 years of high-precision photometric data from the *Kepler* satellite to investigate how stars whose mass lies around the limit for having a convective core ($M \sim 1.2\,M_\odot$) can contribute to the longstanding question of the size of convective cores. We constrained the amount of core overshooting in 14 targets and found a tendency of overshooting to increase with stellar mass in this mass range. These results will be presented in more details in a paper in preparation.

1. A seismic diagnostic for the core size

The boundary of the convective core generates a glitch in the sound speed velocity, to which acoustic waves are sensitive: it causes the mode frequencies to oscillate as a function of the radial order, with a period that is directly related to the depth of the glitch (Gough 1990). Thus, seismology can be used as a tool to measure the size of mixed cores. It has been shown that the small separations built with $l = 0$ and $l = 1$ modes are particularly sensitive to the core (Deheuvels et al. 2010; Silva Aguirre et al. 2011), and that their ratio to the large separations $\Delta\nu$ (hereafter referred to as r_{010}) are almost immune to the so-called near-surface effects (Roxburgh & Vorontsov 2003). Using this seismic diagnostic, a convective core could already be detected in a *Kepler* target with 9 months of data (Silva Aguirre et al. 2013). Now, with more than 3 years of *Kepler* data, more mode frequencies can be estimated with

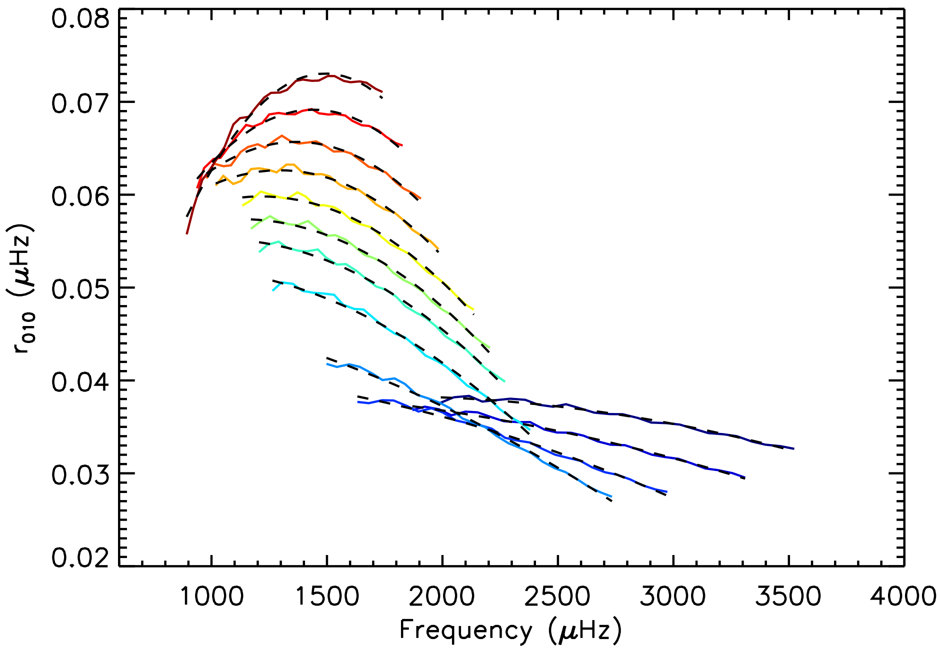

Figure .1: Variations in the ratio r_{010} around $\nu_{\max}$ as a function of frequency for models of 1.2 $M_{\odot}$ from the ZAMS (dark blue) to the beginning of the PoMS (dark red). The dashed lines correspond to fits of 2^{nd} order polynomials.

a better precision, and we can hope to bring constraints on the extension of the convective cores.

2. Testing the diagnostic

We built a grid of models with three main objectives: (1) to assess the efficiency of the seismic diagnostic given by r_{010} ratios, (2) to determine criteria to select the most promising *Kepler* targets, and (3) to interpret these data by confronting them to the grid of models and obtain constraints on the amount of core overshooting. This grid was computed using the stellar evolution code CESAM2K, with masses ranging from 0.9 to 1.5 $M_{\odot}$, metallicities from -0.4 to 0.4 dex, and initial helium abundance from 0.26 to 0.30. Core overshooting was included as a simple extension of the homogeneous convective core over a distance $\alpha_{\mathrm{ov}}H_p$, where H_p is the pressure scale height and α_{ov} the overshoot parameter. Models were computed for values of α_{ov} ranging from 0 to 0.2.

It should be noted that the period of the oscillation caused by the glitch at the boundary of the core is longer than the frequency range of the observed modes, so only a fraction of the oscillation can be observed, and the r_{010} ratios can generally be well approximated by 2^{nd}-order polynomials (see Fig. .1). We thus fitted polynomials of the type $\sum_{k=0}^{2} a_k\nu^k$ to the r_{010} ratios of each model and used the parameters a_k to study the core properties.

For observed stars, we have access to a precise estimate of the large separation $\Delta\nu$, so it is instructive to show models of the grid at a fixed $\Delta\nu$ in the (a_1, a_0) plane. Examples are shown in Fig. .2. This figure clearly shows that constraints can be obtained on

– the evolutionary status: main sequence (MS) and post main sequence (PoMS) models are well separated in the (a_1, a_0) plane
– the existence or absence of a convective core
– the size of the convective core if it exists

even when the effects of metallicity on the size of the core are taken into account. Such constraints can be obtained only if the star is evolved enough so that the edge of the convective core has had time to build up a μ-gradient, but not too evolved so that the $l = 1$ modes do not yet have a *mixed* behavior (this corresponds approximately to $60\,\mu\text{Hz} \lesssim \Delta\nu \lesssim 110\,\mu\text{Hz}$).

3. Selection and analysis of *Kepler* targets

We used the criteria derived from our grid of models to select among solar-like pulsators observed with *Kepler*. We thus obtained a set of 24 targets, with masses ranging from 0.9 to 1.4 $M_\odot$. We used a maximum likelihood estimation (MLE) method to extract the frequencies of the $l = 0$ and $l = 1$ modes from the power spectra of these stars. We then fitted 2$^{\text{nd}}$-order polynomial to the observed r_{010} ratios. We took into account the high level of correlation between the observables.

4. Measuring the extension of convective cores

For each *Kepler* target, we selected the models of our grid that reproduce the observed large separation $\Delta\nu$, surface metallicity, and seismic mass, and we compared their location in the (a_1, a_0) plane to the one obtained from the observations (yellow stars in Fig. .2).

The evolutionary status of the stars can be unambiguously established in most cases: 12 stars of the sample are found to be in the MS (e.g. Fig. .2a), 10 stars in the PoMS (e.g. Fig. .2b), and for only 2 stars of the sample, the evolutionary status remains ambiguous.

Among the MS stars, a convective core was detected in 8 targets (e.g. Fig. .2a). As predicted by the grid of models, the position in the (a_0, a_1) plane of the stars that have a convective core provides an estimate of the amount of core overshooting. Interestingly, the 8 stars draw a *very consistent picture of the extension of convective cores in low-mass stars*:

– All the targets require an extension of the mixed core over at least a small fraction of H_p.
– All the targets are inconsistent with an overshoot parameter above $\alpha_{\text{ov}} = 0.2$.

By performing optimizations using the Levenberg-Marquardt algorithm, we obtained more precise estimates of the amount of overshooting for the stars that have a convective core, as well as better estimates of the stellar mass. Fig. .3 represents the obtained values of α_{ov} as a function of the best-fit mass, which suggest that core overshooting increases with stellar mass.

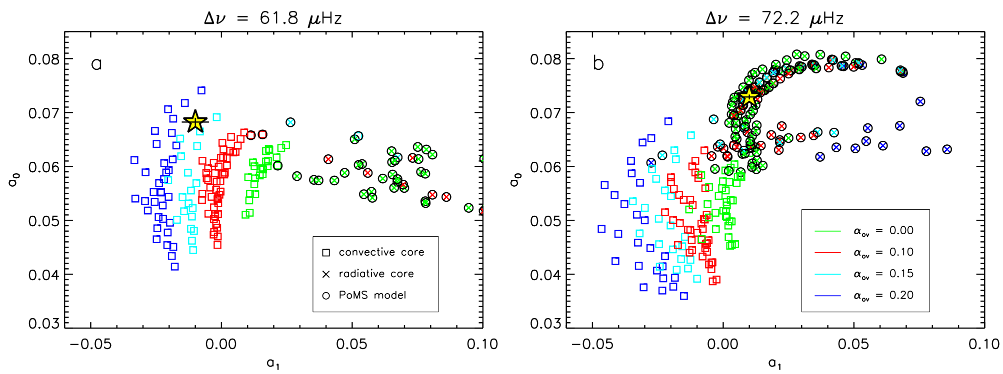

Figure .2: Location of two stars of the sample in the (a_1, a_0) plane (star symbols and black error bars). Models that reproduce the observed large separation, the spectroscopic estimate of metallicity, and the seismic mass are overplotted.

Information about core overshooting can also be drawn from stars that have no convective core but lie just below the mass limit for having one. Indeed, above a certain amount of core overshooting, the models all develop a convective core and the profile of the r_{010} becomes at odds with the observations. We thus obtained an upper limit of $\alpha_{\rm ov} < 0.2$ for 6 stars of the sample (see Fig. .3).

5. Conclusion

By analyzing the seismic data of 24 low-mass *Kepler* targets, we detected convective cores in 8 of them and were able to measure the extension of these cores beyond the Schwarzschild boundary. We showed that this extension is smaller than the commonly adopted value of $d_{\rm ov} = 0.2\, H_p$ for the 14 targets where it could be constrained. We also found that the amount of core overshooting increases with stellar mass. We intend to study how our conclusions are modified if core overshooting is described in a more complex way (e.g. as a diffusive process).

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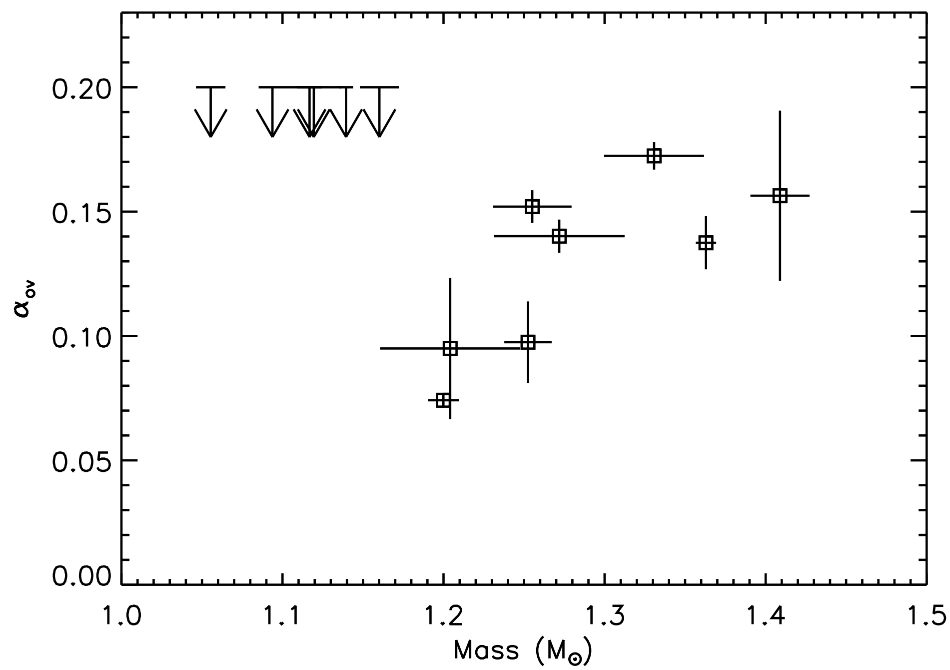

Figure .3: Amount of core overshooting found for the stars of the sample that have a convective core as a function of the fitted stellar mass. The vertical arrows indicate upper limits of α_{ov}.