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Open issues in probing interiors of solar-like oscillating main sequence stars:

2. Diversity in the HR diagram

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Abstract. We review some major open issues in the current modelling of low and intermediate mass, main sequence stars based on seismological studies. The solar case was discussed in a companion paper, here several issues specific to other stars than the Sun are illustrated with a few stars observed with CoRoT and expectations from Kepler data.

1. Introduction

After more than two decades of helioseismology, almost four years of asteroseismology with CoRoT (1) and almost two years of intensive asteroseismology with KEPLER (2), we review some current open issues about the internal structure of solar-like oscillating stars. We focus on low and intermediate mass, main sequence stars. We started with the Sun and stars that have a similar structure than the Sun in a companion paper. Here open issues not encountered with the Sun will be discussed and illustrated with a few individual stars observed by CoRoT and from ground. We end with a brief discussion about expectations from KEPLER data. For sake of shortness, we decided to include only unpublished figures and to cite published figures in the text. Several reviews exist on the topic, for instance (3), (4).

2. From the Sun to solar-like oscillating MS stars:

We focus on low and intermediate mass, main sequence stars that-is stars with masses up to $1.5 M_{\odot}$ corresponding to F, G, K spectral types. These stars have an external convective region and can oscillate like the Sun with high frequency p modes. For these stars, one encounters the same problems as for the Sun, namely surface effects when comparing absolute values of the frequencies. But although we refer to these stars as solar-like stars in the present framework for shortness, these stars can differ from the Sun by several aspects: mass, age, surface metallicity and helium abundances, initial conditions for the chemical abundances, the rotation and magnetic properties. For masses larger than about $1.2 M_{\odot}$, they have a convective

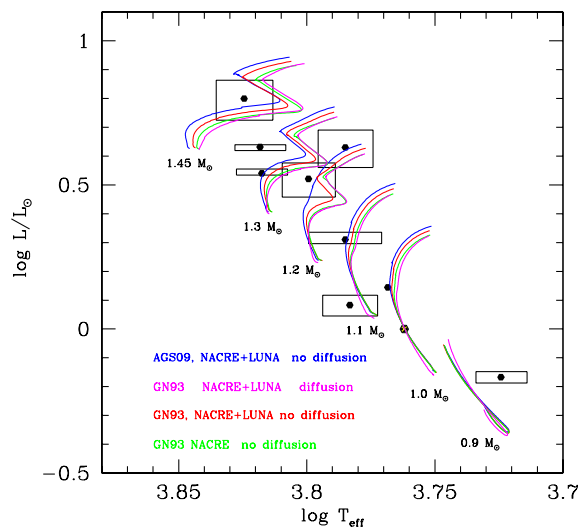


Figure 1. Evolutionary tracks of models built with several assumptions as indicated in the plot. All nuclear reaction rates are from NACRE except for the reaction $^{14}\text{N}(p, \gamma)^{15}\text{O}$ of the CNO cycle which is from LUNA when specified. The other nuclear rates are all from NACRE. The helium and metallicity are solar.

core unlike the Sun. These differences therefore lead to additional open questions about their modelling. The major problem concerns dynamical processes occurring inside stars that have a significant impact on the mean structure of the stars and their ages. In particular, the 3D multiscaled turbulent convective transport and related instabilities is taken into account by means of a 1D crude formulation that involves free parameters which cannot be derived from first principles. As a consequence they are calibrated with observations (the Sun, binaries) but these values have no predictive quality.

The input parameters such as mass, age, initial chemical composition $Y_0, (Z/X)_0$, rotation profile are usually not well known. A first order of magnitude for mass and age is obtained via the location of the star in the HR diagram based on photometric and spectroscopic information. Uncertainties on this location and the chemical abundances give rise to a large number of possible models which makes difficult to probe in detail the internal structure of the star. This number is significantly reduced when seismic diagnostics such as the large separation and the small spacings are used. However free parameters used to describe the convective transport and related instabilities increase the family of acceptable models. The resulting solution therefore remains input physics dependent.

2.1. Observational constraints and seismic diagnostics

Efforts are therefore currently put at obtaining seismic constraints that are discriminating and as model independent as possible. A first information that is looked for is the large separation, its mean value as well as its variation with frequency (5), (6). Other combinations of low degree mode frequencies are built to locate the base of the upper convective zone and obtain properties about He ionization regions (7); (8); (9); (10) and surface helium content (11). Theoretical developments are carried also out to devise diagnostics and appropriate methods to determine the age ((12) and references therein); to probe the core (13), (14), (15); (16); (9), (17) with specific attention to tiny convective core properties (18) of low mass stars using only low degree modes;

to investigate mixing beyond the convective core (19) or semiconvection (20). For instance, the spacing d_{01} is sensitive to convective core properties (21), (22); ; (23); (24). (24) shows the variations of the seismic quantity d_{01} with frequency over a large range of frequency for a model representing the star HD 203608. The slope of the observed d_{01} over the observed frequency range is directly related to the slow period of oscillation seen on the theoretical d_{01} that corresponds to a time scale related to the acoustic radius of core convective radius.

2.2. CoRoT solar-like stars

Most CoRoT solar-like stars differ from the Sun either because they are more massive and faster rotators such as the F2 star HD181420 (25); (26) and the F5 star HD170987 (27) or because they are evolved and have an isothermal core such as the G0 star HD49385 (28),(29) or they have a mass similar to that of the Sun but differ in their metallicity such as HD49933 (30), HD 52265, or the young magnetic star HD 46375 (31). These stars can also differ significantly from the Sun by their level of magnetic activity and their magnetic cycles (32).

2.2.1. Which star for which diagnostic? Due to their differences, some of these stars are better suited to probe different physical processes.

Initial abundances and chemical mixture: Fig.1 shows some of these stars in a HR diagram together with evolutionary tracks of models built assuming no microscopic diffusion; nuclear reaction rates are from NACRE completed with recent LUNA determinations. Two mixtures have been used : AGS09 and GN93. The effect of changing the mixture has a clear impact on a star such that the F star HD181906 (33) which has a convective core in the first case and no convective core in the second case. As the existence of a convective core manifests itself with a large slope of d_{01} , this can be in principle determined with this seismic diagnostic.

Nuclear reaction rate:CNO cycle and $^{14}\text{N}(p,\gamma)^{15}\text{N}$ burning: The change from NACRE (34) to LUNA (35) reaction rate led to reduce the CNO cycle efficiency. As a result, the tracks for the most massive stars (i.e. with central temperature high enough for CNO to dominate) are slightly shifted upward. This of course coincides with stars having a convective core. For a $1.2M_{\odot}$ and $Z = 0.01$ model, the convective core is smaller at given mass and appears at higher mass (34).

Microscopic diffusion, surface helium abundance and initial metallicity: Due to gravitational settling and atomic diffusion in the radiative region below the convective envelope, the surface helium decreases with time. This decrease is larger for higher mass stars because the convective envelope is thinner. The decrease is also larger for lower metallic stars which are more compact and - due to smaller opacities and therefore smoother radiative temperature gradient- have also a thinner convective envelope. The disparition of helium in such thin convective zones is therefore very rapid. If microscopic diffusion acts alone, the envelope of HD49933 for instance would be fully depleted of helium. Mechanisms opposite to diffusion must therefore be at work such as turbulent diffusion and/or radiative acceleration, rotationally induced mixing and must therefore be included in the modelling.

2.2.2. Mode degree identification Seismic inferences assume that the modes are identified that is that the observed frequencies can be attributed to modes with given degree l and azimuthal number m values in a spherical harmonics description. However in some cases, the $l = 1$ split multiplets can be mistaken with overlapping $l = 0$ and $l = 2$ modes in the fitting process. Hence some ambiguity can exist in the determination of $l = 0$ and $l = 1$ ridges in an echelle diagram. This is particularly true for the hottest (F type) stars because of their large mode linewidths and their relatively fast rotation. Exemples are HD49933 (36), HD181420 (25) and HD181906 (33) for which 2 scenarii are proposed for the identification of the $l = 0$ and $l = 1$ modes. In one case, fitting the data imposes a quite large core overshoot whereas in the other case a usual intermediate core overshoot amount is sufficient. This ambiguity that exists when the data sets

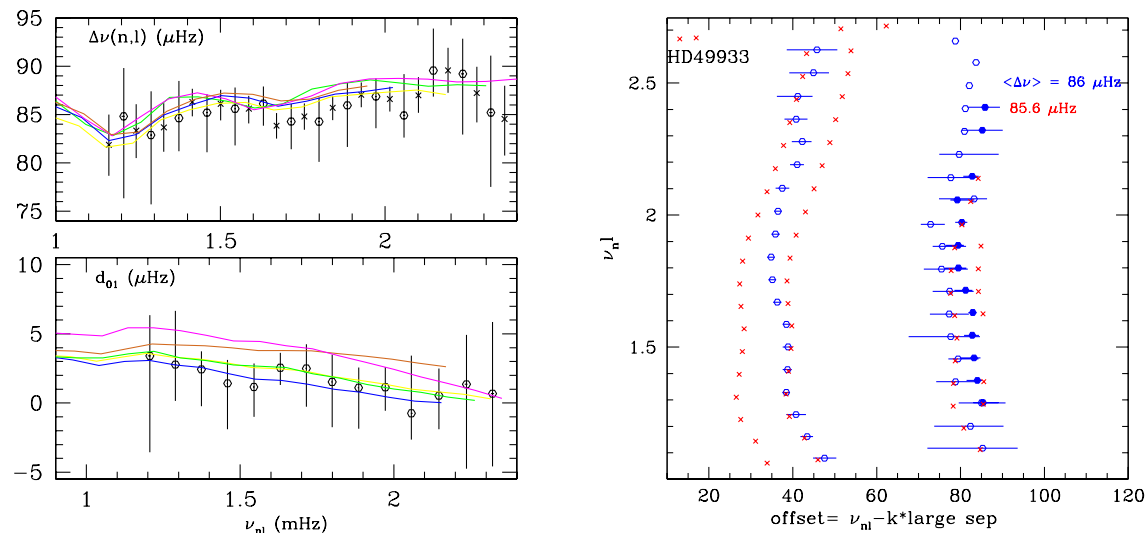


Figure 2. (Left top:) Large separation $\Delta\nu_{n,l}$ in function of the frequency $\nu_{n,l}$ and **(left bottom:)** the small spacings $d_{01} = \nu_{n,0} - (\nu_{n,1} + \nu_{n-1,1})/2$ and $d_{10} = -\nu_{n,1} + (\nu_{n+1,0} + \nu_{n,0})/2$ in function of the frequency $\nu_{n,0}$ for HD49933. Data (open circles and crosses) are from (38). Models (solid curves) are built assuming AGS05, no diffusion; $\alpha_{cgm} = 0.6$, $\alpha_{ov} = 0.27$ (magenta); AGS05, diffusion, $\alpha_{cgm} = 0.6$, $\alpha_{ov} = 0.21$, $Y = 0.27$, $Z/X = 0.0079$ (yellow) AGS09, diffusion (green); AGS05, diffusion, $\alpha_{ov} = 0.2$, rotationally induced transport (blue); AGS05, diffusion, $\alpha_{ov} = 0.$, rotationally induced transport, $Y = 0.27$, $\alpha_{cgm} = 0.6$ (chocolate). **(Right:)** Echelle diagram for HD49933. Blue dots represent the observations and red ones the model.

are too short can be lifted when using sophisticated data analysis treatments (37), (38), (39), (5). To lift the ambiguity in mode identification when it exists, (40) have proposed to use scaling relations (ν and $\Delta\nu$ scale as $\langle \Delta\nu \rangle$) to build scaled echelle diagrams with reference to a star similar to the studied one. The authors tested this procedure with two sets of twin stars Sun and 18 Sco - τ Ceti and α Cen B and used it to determine the most probable scenario for two CoRoT stars HD181420 and HD181906 using HD49933 as the reference star. This scaling procedure has then been recently used on the ground based observed star, HD203608 (41). Indeed for this F8V star, two possible scenarii have been found with again important consequences on conclusions that can be drawn from the mode identification (28); (24). Echelle diagrams built assuming the scaling according to (40) coincide with the observed echelle diagram in the case of one of the two possible scenarii and definitely rejects the alternative scenario (41). This scenario favours a mild overshoot and the survival of convective core despite the small mass and old age of the star due its low metallicity (29). Mode identification based on scaling relations therefore appears as a potential interesting method that must nevertheless be studied further on theoretical ground before it can be used as a proper decision method.

2.2.3. HD49933: a low metallicity star With 180 days of observation with CoRoT, all seismic data analyses agree to provide the same scenario for the $l = 0, 1$ mode identification for this star (30). Seismic modelling of HD49933 illustrates the difficulty one encounters because of the degeneracy in input parameter space composed of mass, age, $(Z/X)_0$, Y_0 , α_{cgm} , α_{ov} , initial rotation and transport coefficients. The free parameters α_{cgm} , α_{ov} represent the convective mixing length for the adopted CGM formulation (42) and the convective core overshoot

parameter respectively. All models discussed below are calibrated so that the mean large separation $\langle \Delta\nu \rangle$ and the mean small spacings d_{01}, d_{10} agree with the observations as well as the observed location in a HR diagram. This lifts only partially the degeneracy. The phase of oscillation of the large separation is found to be quite sensitive to values of α_{cgm} and Y_0 and therefore such a constraint must be added in the minimisation process to reduce the number of acceptable models although this has not been done here. Individual frequencies have not been fitted (see below). The surface metallicity of the star is taken in the observed range $[Fe/H] = -0.4 \pm 0.1$, significantly lower than the Sun (43).

Fig.2 compares the mean large separation and the small spacings $d_{01}, d_{1,0}$ for models built assuming either AGS05 or AGS09 mixtures and various assumptions about microscopic diffusion, rotationally induced transport, convective core overshoot as listed in the caption. All models are computed with CESAM2k (44). Models including rotationally induced transport of angular momentum as implemented by J. Marques in the code CESTAM (a modified version of cesam2k) have been computed assuming no loss of angular momentum. The initial angular rotation on the PMS has been set in order to fit the observed rotation period of the star, $P = 3.4$ days at the age of HD49933. Details on the modelling of this star will be published elsewhere.

For all these different assumptions, one can find a mass and age that fit the mean large separation oscillation by adjusting α_{cgm} and Y_0 although this has not been done yet for our rotating models. The mass is found in the range 1.05-1.18 M_\odot and the age in the range 2900-3900 Myr depending on the assumptions in the physical description and the chemical abundances. As a result of these various calculations, we find that a) when the AGS05 mixture is assumed, it is difficult to find a model satisfying all the observational constraints when $(Z/X)_0$ is on the smaller part of the authorized interval. This is less the case with the less extreme AGS09 mixture. It is important to stress that the star being metallic deficient compared with the Sun, the above mixtures taken from the Sun might not well be suited; b) because this star is low metallic, its thin convective envelope is rapidly devoid of helium when microscopic diffusion is included if one starts with solar initial helium abundance when one assumes AGS05 mixture. One then needs to start with a large initial helium abundance Y_0 or one must include some turbulence in the radiative zone. Starting then with a large $Y_0 = 0.35$, one still obtains a small $Y_{surf} = 0.10$ value for HD49933. One obtains a less extreme surface helium abundance $Y_s = 0.18$ when using the less extreme AGS09 mixture; c) without including microscopic diffusion nor rotationally induced transport, no model fits d_{01} for an overshoot smaller than $0.25 - 0.3 H_p$ whatever the mixture; d) for AGS05 mixture, when diffusion is included with or without rotationally induced transport, some intermediate amount of overshoot ($\approx 0.2 H_p$) still remains necessary. As a conclusion, microscopic diffusion and rotationally induced transport as modelled here are not enough to render count of the slope of d_{01} variation with AGS05. One needs to include also some amount of convective core overshoot as a proxy for true overshoot and/or additional mixing process.

Absolute frequencies and echelle diagram The echelle diagram displayed in Fig.2 shows a systematic shift between the observed and theoretical $l = 1$ ridges roughly independent of the frequency when the mean separation is taken to be the same in building the observed and theoretical echelle diagrams. This discrepancy comes from the fact that absolute values of the frequencies have not been included in the optimisation procedure to find an optimal model. Increasing slightly the mean separation for building the echelle diagram for the model enables to perfectly match the low frequency part of the observed ridge as seen in Fig.2. The deviation of the theoretical ridge with the observed ones remains at high frequencies and might reflect surface effects that are not properly taken into account in the numerical frequencies.

2.2.4. HD181420: a fast rotator Analyses of the light curve of this star has been performed by (25) and (39) who found two possible scenarii for the mode identification. Results based on a Bayesian approach favors scenario 1 Benomar (2010, priv.com). This is also the conclusion of

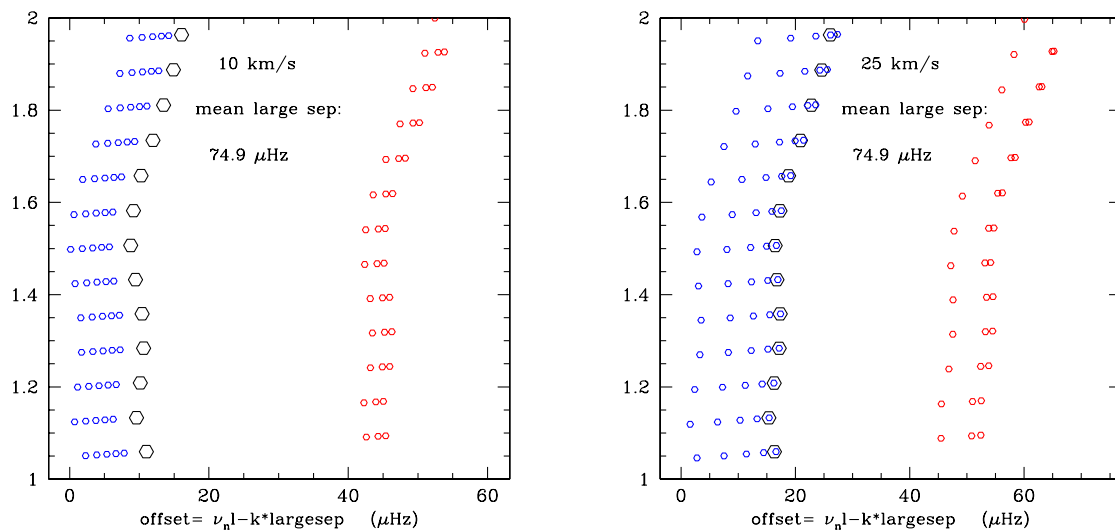


Figure 3. Echelle diagrams for a model of HD181420: rotational velocities $v = 10$ km/s (**left**) and 25 km/s (**right**) are assumed when computing the frequencies. From left to right in each panel, ridges for $l = 2, 0, 1$ respectively appear.

(40) using scaling properties. Focusing then on scenario 1, one reproduces the large separation and the small spacing d_{01} with a $1.36M_{\odot}$ stellar model assuming a core overshoot of $0.2H_p$ as well as with a $1.37M_{\odot}$ stellar model assuming no overshoot, everything else being the same in particular microscopic diffusion and rotation are not included (45). A secondary oscillation component is seen in the observed large separation that is not reproduced by any models (45), Michel (2010 priv.com). The 'period' of this oscillation corresponds to the base of the convective zone of the above models, but the reality of this secondary component is not confirmed (26), Mosser (2010, priv. comm). This star is a 'rapid' rotator compared to the Sun. Indeed with a radius $R = 1.66R_{\odot}$ and the observed mean rotational splitting $\nu_{split} = (3. \pm 1)\mu Hz$ (25), one obtains a rotational velocity $v = 21.97.3$ km/s that corresponds to a ratio of the centrifugal to the gravitational accelerations of $\epsilon = \Omega^2/(GM/R^3) = 320\epsilon_{\odot}$! Perturbation methods to compute the effect of rotation on the frequencies nevertheless remain valid for this rotation rate (46). The non-spherically centrifugal distortion causes asymmetries of split multiplets that are seen in echelle diagrams already for $v = 10$ km/s at high frequency (Fig.3, frequencies including rotating effects have been performed with the WarM oscillation code). Assuming a uniform rotation velocity of 25 km/s, the $m = 2$ components of the $l = 2$ modes coincide with the $l = 0$ mode for the lowest frequencies whereas at high frequencies both $m = 1$ and $m = 2$ components are mixed with the $l = 0$ frequency. Asymmetries increase with frequency and are therefore larger at high frequencies where they contribute to surface effects! The difference between the rotation frequency measured at low frequency in a power spectrum (47) and the mean splitting (25) is found to be compatible with a latitudinal dependence of the surface rotation of the star (Ouazzani, 2010 priv. com).

2.2.5. HD49385: an evolved star The light curve of this star has been analysed by (48) and (29). (29) clearly put in evidence the existence of an $l = 1$ avoided crossing and showed that it produces a characteristic distortion of the $l = 1$ ridge in the neighbour of this mode in an echelle diagram. A clear explanation of the deformation of the ridge by the presence of an avoided crossing for a $l = 1$ mode has been provided by (48). The distortion is caused by the

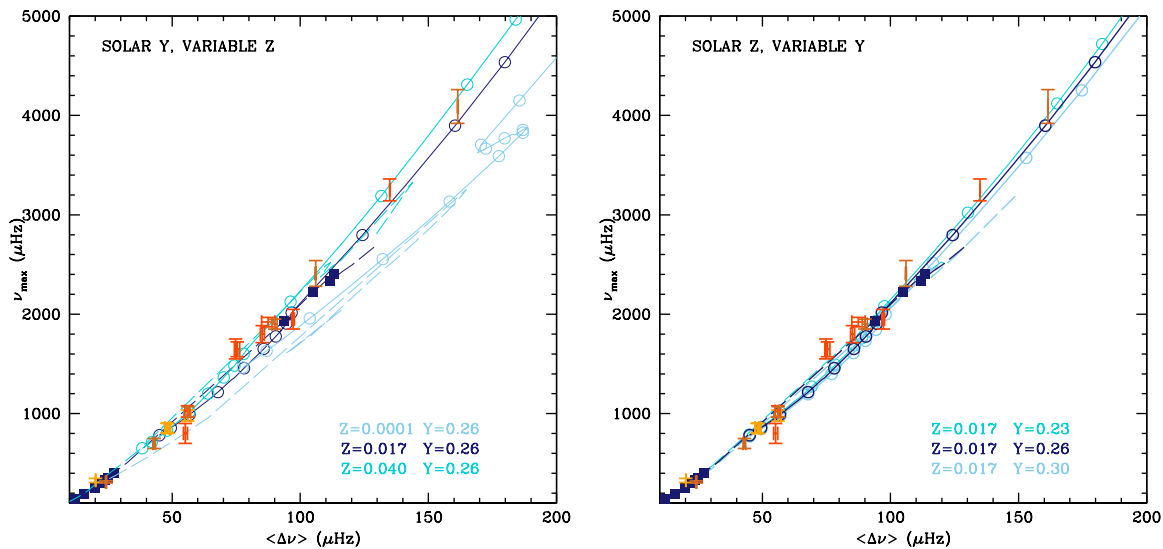


Figure 4. Frequency ν_{max} in function of the mean large separation $\langle \Delta\nu \rangle$. Models (solid curves) have been computed with cesam2k code. Scaling laws are computed according to (49) and (50). Data for a few ground based observed stars and some CoRoT targets plotted with their errors bars represented by crosses.

fact that the modes propagate as p mode in a surface cavity and as g mode in a central cavity. For each mode, both cavities are separated by an evanescent region which acts as a coupling between the two regions. The magnitude of the ridge deformation is related to the properties of the evanescent region. The deformation of the ridge is then fitted to constrain the stellar model. A model satisfying all the constraints simultaneously then is difficult to obtain. Only a change in the chemical mixture from AGS05 to AGS09 is able to affect the evanescent region so as to provide a correct ridge deformation (41).

3. Kepler data and ensemble seismic investigations

The seismic part of the space mission Kepler produces seismic data for a huge number of stars for which stellar parameters are in general not well known. Ensemble investigations to derive stellar masses and radii then rely on scaling seismic properties (51). Fig.4 shows ν_{max} (frequency at maximum oscillation power in a power spectrum) in function of the mean large separation $\langle \Delta\nu \rangle$ for series of stellar models (open circles) assuming different chemical compositions along evolutionary tracks from ZAMS (top right corner) to TAMS (down left corner). Data for a few ground based observed stars are overplotted as well as CoRoT targets. Due to NASA data policy, Kepler data are not shown. The error bars indicate that one cannot distinguish between metallicities $Z = 0.017$ and $Z = 0.04$ (with $Y = 0.26$) for instance, nor between $Y = 0.23$ and $Y = 0.30$ ($Z = 0.017$). This leads to small uncertainties on masses and radii derived from these scalings. This is a crucial issue for the ESA project PLATO (52) that aims at detecting and studying earth-type exoplanets and therefore requires the determination of stellar masses of exoplanet host stars with an accuracy of about 10-15%. This means that it will be mandatory to determine the metallicity and helium abundances Z/X and Y by other means; for instance Z/X by spectroscopy and Y by the properties of the frequency dependence of the large separation. Another important issue is to establish the physical origin of the ν_{max} scaling which so far has only been conjectured (53) but has been validated with observations (50). A better understanding of this origin could provide the explicit dependence of the scaling relations

on metallicity and chemical composition, rotation etc ...

4. Conclusion:

With the wealth of data from CoRoT and Kepler, we are confronted with seismological studies of a rich variety of low, and intermediate mass, main sequence stars that differ from the Sun in their stellar parameters and internal structure. Although this will enrich considerably our understanding of stellar physics and evolution, this also generates several difficulties not encountered with the Sun. Some were expected such as inaccurate determination of stellar parameters, degeneracy in parameter space and resulting non unicity of stellar models but some other problems were not really expected such as ambiguities in the mode identification due to broad linewidths and fast rotation (compared to the Sun) for F stars. So as far as probing internal structure by means of seismology of solar-like stars is concerned, we are therefore still at the beginning of the learning phase. Significant advances in stellar physics and solid conclusions about the open issues discussed in the present paper will require homogeneous detailed seismic studies for a larger number of individual stars that has been done so far. New roads also develop such as ensemble studies and scaling procedures and additional observational seismic constraints start to exist such as accurate mode amplitudes and linewidths and their variations with frequency that were not available from ground. Eventually studying a star and its planets as a global system is certainly the issue that must be addressed in the future. In that framework, the perspective offered by the ESA project PLATO which has precisely this aim is a strong motivation for the seismic community to pursue its efforts and in turn PLATO will grandly benefit from all the forthcoming advances in the field.

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References

- [1] Baglin A, Auvergne M, Barge P, Deleuil M, Catala C, Michel E, Weiss W and The COROT Team 2006 *ESA Special Publication (ESA Special Publication vol 1306)* ed M Fridlund, A Baglin, J Lochard, & L Conroy p 33
- [2] Borucki W J, Koch D G, Lissauer J, Basri G, Brown T, Caldwell D A, Jenkins J M, Caldwell J J, Christensen-Dalsgaard J, Cochran W D, Dunham E W, Gautier T N, Geary J C, Latham D, Sasselov D, Gilliland R L, Howell S, Monet D G and Batalha N 2007 *Transiting Extrapolar Planets Workshop (Astronomical Society of the Pacific Conference Series vol 366)* ed C Afonso, D Wel Drake, & T Henning p 309
- [3] Christensen-Dalsgaard J 2009 *ArXiv e-prints (Preprint 0912.1405)*
- [4] Christensen-Dalsgaard J and Houdek G 2010 *Ast. Sp. Sci* **328** 51–66
- [5] Mosser B and Appourchaux T 2009 *Astr. Astroph* **508** 877–887
- [6] Roxburgh I W 2009 *Astr. Astroph* **506** 435–444
- [7] Monteiro M J P F G, Christensen-Dalsgaard J and Thompson M J 2000 *MNRAS* **316** 165–172
- [8] Mazumdar A and Antia H M 2001 *Astr. Astroph* **368** L8–L12
- [9] Mazumdar A and Antia H M 2001 *Astr. Astroph* **377** 192–205

- [10] Mazumdar A and Michel E 2010 *ArXiv e-prints (Preprint 1004.2739)*
- [11] Basu S, Mazumdar A, Antia H M and Demarque P 2004 *MNRAS* **350** 277–286
- [12] Houdek G and Gough D O 2009 *Communications in Asteroseismology* **159** 27–29
- [13] Provost J, Mosser B and Berthomieu G 1993 *Astr. Astroph* **274** 595–611
- [14] Roxburgh I W and Vorontsov S V 1999 *Stellar Structure: Theory and Test of Connective Energy Transport (Astronomical Society of the Pacific Conference Series vol 173)* ed A Gimenez, E F Guinan, & B Montesinos p 257
- [15] Roxburgh I W and Vorontsov S V 2002 *Stellar Structure and Habitable Planet Finding (ESA Special Publication vol 485)* ed B Battrick, F Favata, I W Roxburgh, & D Galadi pp 349–351
- [16] Roxburgh I W and Vorontsov S V 2004 *Stellar Structure and Habitable Planet Finding (ESA Special Publication vol 538)* ed F Favata, S Aigrain, & A Wilson pp 403–406
- [17] Mazumdar A, Basu S, Collier B L and Demarque P 2006 *Proceedings of SOHO 18/GONG 2006/HELAS I, Beyond the spherical Sun (ESA Special Publication vol 624)*
- [18] Cunha M S and Brandão I M 2010 *ArXiv e-prints (Preprint 1008.1299)*
- [19] Popielski B L and Dziembowski W A 2005 *Acta Ast.* **55** 177–193
- [20] Silva Aguirre V, Ballot J, Serenelli A and Weiss A 2010 *Ast. Sp. Sci* **328** 129–133
- [21] Provost J, Berthomieu G, Bigot L and Morel P 2005 *Astr. Astroph* **432** 225–233
- [22] Miglio A and Montalbán J 2005 *Astr. Astroph* **441** 615–629
- [23] Roxburgh I W and Vorontsov S V 2007 *MNRAS* **379** 801–806
- [24] Deheuvels S, Michel E, Goupil M J, Marques J P, Mosser B, Dupret M A, Lebreton Y, Pichon B and Morel P 2010 *Astr. Astroph* **514** A31
- [25] Barban C, Deheuvels S, Baudin F, Appourchaux T, Auvergne M, Ballot J, Boumier P, Chaplin W J, García R A, Gaulme P, Michel E, Mosser B, Régulo C, Roxburgh I W, Verner G, Baglin A, Catala C, Samadi R, Bruntt H, Elsworth Y and Mathur S 2009 *Astr. Astroph* **506** 51–56
- [26] Benomar O 2010 *PhD thesis*
- [27] Mathur S, García R A, Catala C, Bruntt H, Mosser B, Appourchaux T, Ballot J, Creevey O L, Gaulme P, Hekker S, Huber D, Karoff C, Piau L, Régulo C, Roxburgh I W, Salabert D, Verner G A, Auvergne M, Baglin A, Chaplin W J, Elsworth Y, Michel E, Samadi R, Sato K and Stello D 2010 *Astr. Astroph* **518** A53
- [28] Mosser B, Deheuvels S, Michel E, Thévenin F, Dupret M A, Samadi R, Barban C and Goupil M J 2008 *Astr. Astroph* **488** 635–642
- [29] Deheuvels S, Bruntt H, Michel E, Barban C, Verner G, Régulo C, Mosser B, Mathur S, Gaulme P, Garcia R A, Boumier P, Appourchaux T, Samadi R, Catala C, Baudin F, Baglin A, Auvergne M, Roxburgh I W and Pérez Hernández F 2010 *Astr. Astroph* **515** A87
- [30] Benomar O 2010 *Astronomische Nachrichten, HELA IV proceedings* ed T Roca Cortés, P Pallé, S Jiménez Reyes,
- [31] Gaulme P, Deheuvels S, Weiss W W, Mosser B, Moutou C, Bruntt H, Donati J, Vannier M, Guillot T, Appourchaux T, Michel E, Auvergne M, Samadi R, Baudin F, Catala C and Baglin A 2010 *ArXiv e-prints (Preprint 1011.2671)*
- [32] García R A, Mathur S, Salabert D, Ballot J, Régulo C, Metcalfe T S and Baglin A 2010 *Science* **329** 1032–

- [33] García R A, Régulo C, Samadi R, Ballot J, Barban C, Benomar O, Chaplin W J, Gaulme P, Appourchaux T, Mathur S, Mosser B, Toutain T, Verner G A, Auvergne M, Baglin A, Baudin F, Boumier P, Bruntt H, Catala C, Deheuvels S, Elsworth Y, Jiménez-Reyes S J, Michel E, Pérez Hernández F, Roxburgh I W and Salabert D 2009 *Astr. Astroph* **506** 41–50
- [34] Angulo C, Arnould M, Rayet M and et al 1999 *Nuclear Physics A* **656** 3–183
- [35] Formicola A, Imbriani G, Costantini H, Angulo C, Bemmerer D, Bonetti R, Brogгинi C, Corvisiero P, Cruz J, Descouvemont P, Fülöp Z, Gervino G, Guglielmetti A, Gustavino C, Gyürky G, Jesus A P, Junker M, Lemut A, Menegazzo R, Prati P, Roca V, Rolfs C, Romano M, Rossi Alvarez C, Schümann F, Somorjai E, Straniero O, Strieder F, Terrasi F, Trautvetter H P, Vomiero A and Zavatarelli S 2004 *Physics Letters B* **591** 61–68
- [36] Appourchaux T, Michel E, Auvergne M, Baglin A, Toutain T, Baudin F, Benomar O, Chaplin W J, Deheuvels S, Samadi R, Verner G A, Boumier P, García R A, Mosser B, Hulot J, Ballot J, Barban C, Elsworth Y, Jiménez-Reyes S J, Kjeldsen H, Régulo C and Roxburgh I W 2008 *Astr. Astroph* **488** 705–714
- [37] Benomar O, Appourchaux T and Baudin F 2009 *Astr. Astroph* **506** 15–32
- [38] Benomar O, Baudin F, Campante T L, Chaplin W J, García R A, Gaulme P, Toutain T, Verner G A, Appourchaux T, Ballot J, Barban C, Elsworth Y, Mathur S, Mosser B, Régulo C, Roxburgh I W, Auvergne M, Baglin A, Catala C, Michel E and Samadi R 2009 *Astr. Astroph* **507** L13–L16
- [39] Gaulme P, Appourchaux T and Boumier P 2009 *Astr. Astroph* **506** 7–14
- [40] Bedding T R and Kjeldsen H 2010 *Communications in Asteroseismology* **161** 3–15
- [41] Deheuvels S 2010 *PhD thesis*
- [42] Canuto V M, Goldman I and Mazzitelli I 1996 *ApJ* **473** 550
- [43] Bruntt H 2009 *Astr. Astroph* **506** 235–244
- [44] Morel P and Lebreton Y 2008 *Ast. Sp. Sci* **316** 61–73
- [45] Goupil M e a *HELAS Workshop on ‘New insights into the Sun’* ed M Cunha, M Thompson
- [46] Suárez J C, Goupil M J, Reese D R, Samadi R, Lignières F, Rieutord M and Lochar J 2010 *ApJ* **721** 537–546
- [47] Mosser B 2010 *ArXiv e-prints (Preprint 1006.5530)*
- [48] Deheuvels S and Michel E 2010 *ArXiv e-prints (Preprint 1006.3178)*
- [49] Kjeldsen H and Bedding T R 1995 *Astr. Astroph* **293** 87–106
- [50] Bedding T R and Kjeldsen H 2003 *PACA* **20** 203–212 (*Preprint arXiv:astro-ph/0305425*)
- [51] Chaplin W J, Appourchaux T, Elsworth Y and et al 2010 *ApJ Lett.* **713** L169–L175
- [52] Catala C, Arentoft T, Fridlund M, Lindberg R, Mas-Hesse J M, Micela G, Pollacco D, Poretti E, Rauer H, Roxburgh I, Stankov A and Udry S 2010 *Astronomical Society of the Pacific Conference Series (Astronomical Society of the Pacific Conference Series vol 430)* ed V Coudé Du Foresto, D M Gelino, & I Ribas p 260
- [53] Brown T M, Gilliland R L, Noyes R W and Ramsey L W 1991 *ApJ* **368** 599–609