The CoRoT Legacy Book

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IV.1

Insights on the internal structure of stars as provided by seismology

Classical pulsators and Solar-like oscillations

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1. Introduction

One of the key objectives of the CoRoT mission relied on stellar seismology, as a tool to infer the physical mechanisms taking place in stellar interiors. Stellar pulsations can be split into two sub-classes; classical pulsations and solar-like pulsations. The first, thoroughly discussed in Sect. 2, are encountered in a wide variety of stars and mainly originate from thermal instabilities. Such oscillations have been observed for a long time from the ground and enabled us to unveil several fundamental physical questions such as stellar opacities (see for instance the reviews by Gautschy & Saio 1995, 1996; Samadi et al. 2015). However, by allowing us to measure micro-variability, CoRoT helped us to make a leap forward by providing access to the internal inner-most layers of a number of stars such as γ Doradus or β Cephei stars (Sects. 2.1 and 2.6). Moreover, it raised new questions about the nature of several type of pulsations as exemplified by the δ Scuti or Be stars (Sects. 2.2 and 2.7). As the nature of these oscillations is not always fully understood and is sometimes complexified by intricate combinations with rotation or magnetic fields, CoRoT's observations provided a large number of observational constraints that will certainly be breeding ground for future theoretical progress.

The second type of pulsations, called solar-like oscillations, concerns all stars that develop an outer convective envelope (so mainly low-mass stars) as the latter drives and damps these oscillations. This is addressed in Sect. 3. Indeed, prior to the CoRoT's launch, only a handful of targets were known to exhibit solar-like oscillations and their interpretation was quite thorny as ground-based observations do not allow for the necessary precision, duration, and duty-cycle. Only a few years after, the situation dramatically changed and several hundreds oscillating main-sequence stars and thousands of red-giant stars have been detected (Sect. 3.1). Thus, both the number and quality of the observations have been considerably improved and it is not much of a stretch to think that CoRoT enabled us to make a great leap forward. Analyzing light-curves of oscillating stars yields very precise oscillation frequencies intricately related to the internal structure of stars. The absolute values of oscillation frequencies bear a lot of information content on physical processes taking place in stars but previously out of reach (Sect. 3.2). For instance, specific frequency combinations enable us to isolate and probe localized regions of the star such as the interfaces between radiative and convective regions, allowing us to measure the extra-mixing related to penetration of convective elements (Sect. 3.3) or rotation (Sect. 3.5). Consequently, significant advances are now possible given this propitious context provided one brings together theoretical efforts and highly accurate observational constrains. CoRoT also opened new opportunities such as the precise and accurate characterization of planet-host stars (Sect. 3.5) and as such was the pathfinder for future missions such as PLATO (Rauer et al. 2014).

2. Classical pulsators (by A. Grotsch-Noels)

Classical pulsators cover nearly all the populated area of the Hertzsprung-Russell (HR) diagram. Figure IV.1.1 shows their location along the main sequence (MS) and in the classical instability strip (IS), defined by long-dashed cyan lines.

Although some pulsation properties were already known in the nineties, the amazing successes gathered by SOHO for the Sun (surface helium abundance, importance of diffusion, rotation profile…) were stimulating incentives to attempt at reaching similar goals in stars, despite enormous technical challenges. The aim was to detect extremely small light variations (down to one ppm) and to extract the frequencies responsible for these brightness fluctuations. To reach such performances, long observing times devoid of day/night alternations were required and space was thus the ideal asteroseismic laboratory. By revealing their microvariability, measuring their oscillations at the ppm level,

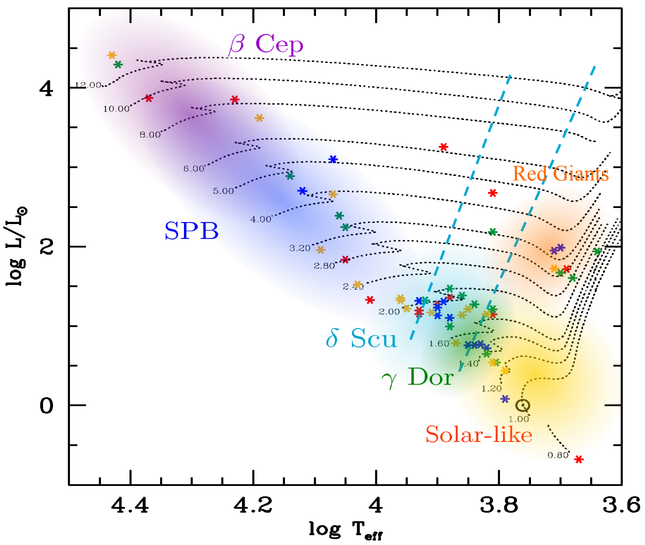

Fig. IV.1.1. Location of classical, solar-like and red giant pulsators in the HR diagram. Long dashed cyan lines show the Cepheids and RR Lyrae stars classical instability strip. Courtesy of A. Miglio.

CoRoT has provided a new vision of stars, never reached before by any ground-based observation.

Discoveries were indeed numerous. For classical pulsators let us cite just a few examples: the first detection of pre main sequence (PMS) γ Doradus variables (Zwintz et al. 2013, see Sect. 2.1), the discovery of hundreds of frequencies in δ Scuti stars (Poretti et al. 2009, see Sect. 2.2), the first detection of a deviation from a constant period spacing in gravity modes in a Slowly Pulsating B (SPB) star (Degroote et al. 2010a, see Sect. 2.5) and the spectacular time evolution of the frequency spectrum of a Be (emission lines B) star during an outburst (Huat et al. 2009, see Sect. 2.7), but also innovative probing in RR Lyrae stars (Poretti et al. 2010b, see Sect. 2.3), Cepheids (Poretti et al. 2014, see Sect. 2.4), OB stars (Degroote et al. 2010b, see Sects. 2.6 and 2.8), and sdB stars (Van Grootel et al. 2010, see Sect. 2.9). Interpreting those results opened new horizons in our vision of stars and galaxies. In the following sections we shall travel among the regions of the HR diagram populated by classical pulsators and we shall discuss these breakthrough contributions to stellar astrophysics, based on CoRoT's data.

2.1. A nursery for young γ Doradus stars

γ Doradus stars are pulsating in a high-order g-mode regime. They have periods similar to SPB stars (see Sect. 2.5), from 0.3 to 3 days. Their masses are however much smaller, about 1.4 to 2.1 $M_\odot$. These stars are cool enough to have a convective envelope. Most of the γ Doradus stars are indeed cooler than the red edge of the δ Scuti (or classical) Instability Strip. Their excitation mechanism is a modulation of the radiative flux at the base of the convective envelope, first proposed by Guzik et al. (2000) and later confirmed by Dupret et al. (2005) using a time-dependent convection (TDC) treatment involving the interaction of convection with pulsation. Because the depth of the convective envelope plays a major role in the driving mechanism, the theoretical predictions for the γ Dor instability strip are very sensitive to the mixing-length parameter used in the MLT treatment of convection and the observed location of its red edge is indeed a strong constraint on the mixing-length parameter.

These stars are of particular interest since their mass range covers the transition between a structure with a radiative core and a structure with a convective core, which can grow in mass during part of their main-sequence phase of evolution. The transition is due to the growing contribution of CNO cycle reactions to the total nuclear energy production. This constitutes a sharp transition in the chemical composition profile, which induces a very subtle signature in the gravity modes frequency spectrum. According to the asymptotic theory, periods of high-order (k) g-modes are regularly spaced with a spacing ($\Delta P = P_{k+1} - P_k$) decreasing as the degree of the modes increases. As the star evolves during MS, a higher and higher peak, starting at the limit of the fully mixed region, develops in the Brunt-Väisälä frequency distribution, as a result of the formation of the μ-gradient region. This sharp feature in the Brunt-Väisälä frequency shows up as a periodic component in the g-mode period spacing. The period spacing is no longer constant but it oscillates around a constant mean value. The non-rotating theory was extensively discussed in Miglio et al. (2008) for γ Doradus stars and SPB stars.

However, γ Doradus stars frequencies can be of the order or even higher than their rotation frequencies. Therefore, rotation has a non-negligible effect on their oscillation properties. Using the Traditional Approximation of Rotation (TAR), Bouabid et al. (2013) carried out a non-adiabatic analysis on a grid of models covering the γ Dor mass range. With this TAR approximation, the effect of the Coriolis force on the frequencies and the stability of high-order g-modes could be estimated. The effect of the Coriolis force depends on the type (prograde sectoral or not) of mode and increases with their periods. This analysis showed that the g-mode period spacing is no longer periodically oscillating around a constant value. The mean value between two consecutive period-spacing minima decreases with increasing period for non prograde sectoral modes and increases with the period for prograde sectoral modes. Moreover, the periodicity of the oscillation depends on the mode periods. For non prograde sectoral modes, the period interval between two consecutive period-spacing minima decreases with increasing period, while it is the contrary for prograde sectoral modes. However, the number of modes between two minima remains constant.

It was thus highly challenging to search for the presence of periodic components in the period spacing. The frequency resolution from a CoRoT long run was however too small to clearly reveal such components in period spacing for γ Dor stars. But CoRoT had opened up the way and in a recent paper (Van Reeth et al. 2015), 67 γ Dor stars observed by *Kepler* during 4 years were analyzed with unprecedented detail. Period spacing patterns could be found for 50 of them. Moreover, a strong correlation between the spectroscopic $v \sin i$ and the period spacings could be established, confirming the influence of rotation on γ Dor-type pulsations as proposed by Bouabid et al. (2013).

Although it is generally assumed that γ Dor stars are MS stars, some of them could also be PMS stars. Bouabid et al. (2011) derived the theoretical arguments, which could help distinguishing between these two possibilities. In particular, they computed the instability strip for PMS γ Dor stars and found that it covers the same effective temperature range as the MS γ Dor instability strip but the frequency domain of unstable modes in PMS models is greater than in MS models. Moreover, the differences between MS and PMS internal structures bear a signature in the average values of the period spacing, as well as in the dependence of the period spacing on the radial-order of the modes, opening the window to determination of the evolutionary phase of γ Dor stars from their pulsation properties.

During a 23-day observing run in March 2008, CoRoT observed 636 members of the young open cluster NGC 2264. The so-called Christmas tree cluster, is located in the constellation Monoceros relatively close to us at a distance of about 1800 light years. Its age is estimated to be between 3 and 8 million years. At such a young age, the cluster is an ideal target to investigate many different scientific questions connected to the formation of stars and early stellar evolution and in particular to search for γ Dor pulsators, which would definitely be PMS γ Dor stars. The CoRoT observations led to the discovery of two PMS γ Dor candidates, namely NGC 2264 VAS 20 and NGC 2264 VAS 87 (Zwintz et al. 2013). Moreover, the presence of hybrid δ Scuti/γ Doradus pulsations (showing at the same time gravity γ Dor and acoustic δ Scuti modes) was confirmed in members of NGC 2264.

High-precision light curves obtained from the CoRoT faint-field during LRa01 led to the detection of 418 γ Dor and 274 δ Sct/γ Dor hybrid candidates (Hareter 2012). The bona fide γ Dor are mostly concentrated at the cool border of the δ Sct strip. In contrast, the hybrids fill the whole δ Sct instability strip without a noticeable concentration.

Detection of transits in the faint-field allowed the discovery of γ Dor stars belonging to eclipsing binaries (see for instance Maceroni et al. 2013, see also Sect. 3, Part V, Chap. 3). In particular the eclipsing binary CID 100866999, observed during LRc01, showed large-amplitude hybrid γ Dor/δ Sct star with two clearly distinct frequency domains (Chapellier & Mathias 2013). The large number of detected frequencies led to a detailed analysis of the interaction between them. According to the model proposed by Kennedy et al. (1993) for the Sun, the low g-mode frequencies trapped in the stellar interior produce oscillatory perturbations of the p-mode cavities and are responsible for the formation of a pair of weak spectral sidelobes symmetrically located about the unperturbed p-mode frequency. A period spacing of 0.03493 d could also be derived for a family of $\ell = 1$ modes with a very small dispersion of about 0.002 d. Following the amplitudes of the periodic behavior of ΔP obtained in Miglio et al. (2008), such a constant period spacing would only be compatible with a quasi ZAMS (zero-age main-sequence) central hydrogen abundance.

2.2. A forest of pulsation modes in δ Scuti stars

δ Scuti stars are MS and close to MS stars in the mass range 1.5 to 2.5 $M_\odot$ for a solar chemical composition and 1 to 2 $M_\odot$ in low metallicity conditions. They are located in the lower part of the classical Instability Strip. They pulsate in radial and non-radial modes with periods between about 30 minutes to 8 hours. Their photometric amplitudes can be greater than 0.3 magnitude, in which case they belong to a subclass called HADS (High Amplitude Delta Scuti). However, the vast majority of all δ Scuti stars are small-amplitude variables, pulsating mainly with nonradial acoustic modes. The excitation mechanism of δ Scuti stars is the κ-mechanism acting mostly in the HeII ionization zone near 48000 K.

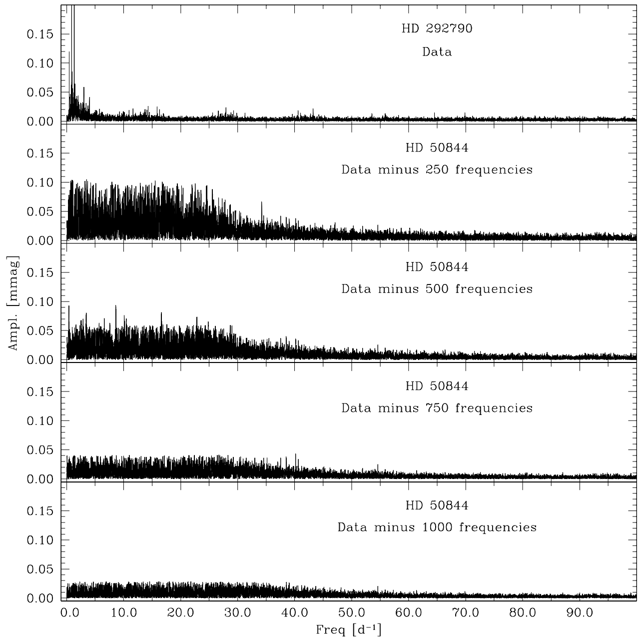

Fig. IV.1.2. The amplitude spectra of a comparison star, the rotational variable HD 292790, is shown in the top panel. The other 4 panels displays the richness of the spectra of the CoRoT δ Scuti star HD 50844. © Astronomische Nachrichten, 331, 1049.

Prior to the CoRoT launch, ground-based observations of δ Scuti stars enabled the detection of a multitude of low amplitude pulsation modes with, however, a big question mark as to their true nature as pulsation modes or their just belonging to the signal noise (Garrido & Poretti 2004). The first δ Scuti CoRoT target, observed during the Initial Run, brought an answer to that question. As can be seen in the spectra displayed on Fig. IV.1.2, hundreds of frequencies in the range 0−30 d^{-1} were indeed discovered in the analysis of the CoRoT time series on HD 50844, an evolved star located near the TAMS (terminal age main sequence) and slightly underabundant in heavy elements (Poretti et al. 2009, 2010a). The richness of δ Scuti spectra was thus confirmed. For the sake of mode identifications, the CoRoT data were complemented by ground-based high-resolution spectroscopy with FEROS, mounted on the ESO/MPI telescope at La Silla. It appeared that a large number of high degree (up to $\ell = 14$) modes were excited, which seems to imply that cancellation effects are not sufficient in removing the related flux variations at the CoRoT noise level. This analysis also revealed that the dominant frequency peak was associated with the fundamental radial mode.

Another interpretation for the presence of such a huge number of frequencies has been proposed, especially in order to refute the absence of cancellation effects in disk-integrated photometry. Instead of high-degree acoustic modes, most of the peaks in the Fourier spectra could result from non-white, frequency-dependent, granulation background noise. The less numerous remaining peaks would still be non-radial low degree p-modes (Kallinger & Matthews 2010). CoRoT targets HD 174936 and HD 50844 were tested for that purpose and granulation timescales where found to be consistent with those expected from stars with recognized surface granulation. However, another argument was put forward by Poretti et al. (2010a). They argued that the amplitude spectra of HD 171856, a non-variable star of the same spectral type as HD 50844, does not show any trace of granulation noise, which would plead for a high degree p-mode interpretation of the spectrum of HD 50844 if the surface conditions of both stars are really similar.

In the presence of such a high number of modes, a periodic pattern in the frequency spectra of the CoRoT target HD 174966 was searched for and a large frequency separation, $\Delta\nu$, could be extracted (García Hernández et al. 2013). The related mean density derived from a grid of model can thus reach a 6% level of accuracy. The CoRoT target CID 102749568 was also scrutinized for the possible presence of frequency patterns and distinct peaks in frequency spacings were obtained (Paparó et al. 2013). Combining CoRoT photometry with spectroscopy and stellar modeling, the physical stellar parameters were then derived while the observational mode identification could be confirmed, with the dominant mode being the first radial overtone.

2.3. A step forward in solving the Blazhko mystery in RR Lyrae stars

RR Lyrae stars were observed in the faint field of CoRoT with the aim of shedding some new light on the variability of these stars and especially of gathering new data to help solve the mystery of the Blazhko effect, which is a periodic modulation of the amplitudes and phases of the main pulsation mode. CoRoT data brought new evidence on a long term variation of the Blazhko period, which means that the Blazhko mechanism has now not only the requirement to explain the regular structures observed in the frequency spectra but it must also reproduce the long term variability observed by CoRoT.

Another important issue raised by CoRoT is the excitation of additional modes, preferentially the second overtone, leading to a regime of double-mode pulsation that may be part of the Blazhko phenomenon. Moreover significant peaks were present in V1127 Aql and CID 101128793 with the immediate inference of the presence of non-radial pulsations in horizontal branch stars (Poretti et al. 2010b).

A systematic analysis of CoRoT RR Lyrae stars was recently done aiming at detecting the presence of period doubling first observed in the *Kepler* RR Lyrae sample. This is a dynamical effect where a new limit cycle comes out from another limit cycle with a period twice as long as the preceding one. In the frequency domain a period doubling shows up as half-integer frequencies. As could be expected from the *Kepler* results, period doubling is an ephemeral phenomenon detectable only for short time intervals. It could result from complex interactions between radial and nonradial modes in RR Lyrae stars and be an important ingredient in the explanation of the Blazhko effect. The detailed asteroseismology of RR Lyrae stars is now within reach (Szabó et al. 2014).

2.4. A puzzling pulsation spectrum in a Cepheid

The faint CoRoT field led to another important discovery. CID 0223989566 was found to be a triple-mode Cepheid with the two largest amplitude modes being the first and second radial overtones while the faintest mode is either a radial mode or an isolated non-radial mode whose period is much longer that that of the first overtone mode. The period ratio between the first overtone and the longest period mode is quite unusual and makes CID 0223989566 a unique object in our Galaxy (Poretti et al. 2014).

2.5. An imprint of the hydrogen profile in slowly pulsating B stars

Slowly pulsating B (SPB) stars revealed to be important CoRoT targets (Degroote et al. 2010b). These are late to mid-type B stars showing a frequency spectrum dominated by high order gravity modes excited by the κ-mechanism at work in layers where partial ionization of iron group elements produces an opacity peak at a temperature of about 200 000 K. In addition the most evolved of these stars may present mixed modes i.e. modes with a g-character in deep layers and p-character in the envelope. The masses of SPB stars typically range from 2.5 to 8 $M_\odot$ and their periods cover a rather wide domain, from about a third of a day to several days (see for example Aerts et al. 2006b).

In this mass range, the main sequence phase is characterized by a convective core, in which all the H-burning CNO reactions take place, surrounded by a mostly radiative envelope except for tiny convective layers related to partial ionization of helium and/or iron group elements. Above the convective core where mixing of chemicals is instantaneous and efficient, some layers can be affected by partial or total mixing during the main sequence phase of evolution. The extent of this extra mixed zone as well as the mixing efficiency are, however, difficult to assess. This additional mixing has very important consequences since it involves longer time scales for nuclear burning phases and may in particular affect the value of the stellar mass at the transition between those stars which end up their life as white dwarfs and those which face a final supernova explosion. Physical reasons for this extra-mixing are various, either a mixing induced by internal rotation or a mixing resulting from convective bubbles crossing the convective core boundary to enter the radiative zone where they finally lose their identity (overshooting), or even some other poorly known processes.

As hydrogen is transformed into helium in the core, the opacity decreases and the convective core mass becomes smaller and smaller, leaving behind it a region of varying chemical composition, the so-called μ-gradient region. If the extra-mixing is assumed to produce an instantaneous mixing, the fully mixed region covers the convective core and the extra-mixing region. In that case, the μ-gradient region starts just on top of the fully mixed region and the μ-profile is sharp. On the other hand, if a diffusive approach is adopted to treat the extra-mixing, a non instantaneous mixing takes place and produces a smoother μ-profile.

Whatever the way the mixing is performed, the affected region is rather thin and constitutes a sharp transition region, which induces a periodic component in the g-mode

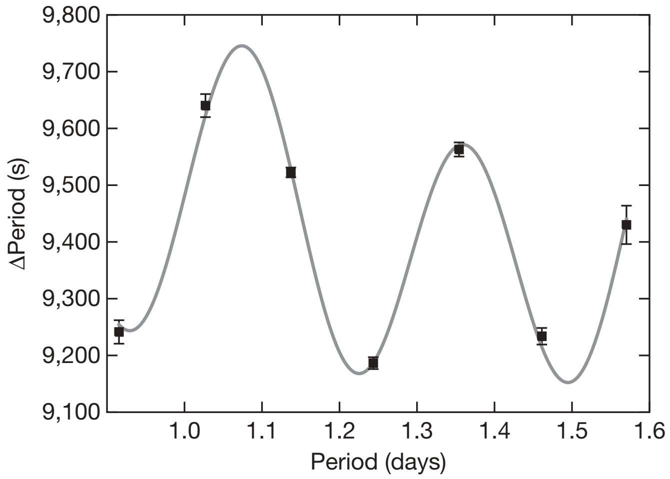

Fig. IV.1.3. Period spacing of g-modes in terms of the period of successive radial orders, observed in HD 50230. © Nature, 464, 259.

period spacing, as was shown by Miglio et al. (2008) (see also Sect. 2.1). A constant period spacing is indeed found in homogeneous ZAMS theoretical stellar models while periodic deviations from this constant value are seen in models affected by a sharp transition region. The period of the deviation, Δk, expressed in numbers of radial order k, can be written

$$\Delta k \simeq \Pi_\mu / \Pi_0 \quad (1)$$

where Π_μ^{-1} and Π_0^{-1} are respectively the buoyancy radius of the sharp transition and the total buoyancy radius ($\Pi_x^{-1} = \int_{x_0}^{x} \frac{|N|}{x'} \mathrm{d}x'$). Observing a periodic deviation from a constant value of the period spacing is thus a powerful tool to directly locate the μ-gradient region and probe stellar cores.

When a diffusive extra-mixing is adopted, the μ-gradient is smoother and so is the Brunt-Väisälä frequency. The period of the deviation remains similar but the amplitude of the oscillation is modulated by a factor $1/\mathrm{P_k}$ leading to an almost constant period spacing if the smoothing is effective enough. This would be the case for instance with a rotational extra-mixing.

This phenomenon has been detected in two hybrid B stars observed by CoRoT (showing at the same time acoustic β Cephei and gravity SPB modes): (1) HD 50230, a slow rotator, identified as a spectroscopic binary, for which an extra-mixing with a somewhat smooth shape is clearly required in the modeling (see Fig. IV.1.3 from Degroote et al. 2010a) (see also Degroote et al. 2012); and (2) HD 43317, a rapid rotator in which an almost constant period spacing is found (Pápics et al. 2012).

In the *Kepler* era new results are booming and a number of SPB stars are now analyzed. Among them, the cool SPB star KIC 10526294 is a very slow rotator (rotation period of 188 days) for which 19 consecutive g-modes were detected, showing an almost constant period spacing (Pápics et al. 2014a,b). With the *Kepler* SPB star KIC 7760680, as many as 36 consecutive g-modes have been extracted. This star has the potential to become the Rosetta Stone of SPB stars. The period spacing clearly shows a modulation related to a smooth extra-mixing as well as a decrease with the radial order associated with rotational effects (Pápics et al. 2015, see also Sect. 2.1).

One can say that CoRoT really opened up the way to a direct scrutiny of the internal structure of such stars bringing new and important constraints not only on the amount of extra-mixing but also on the efficiency of the mixing.

2.6. Probing the extra-mixing and the iron enrichment in β Cephei stars

β Cephei stars are early B-type stars covering a mass range from about 8 to 20 $M_\odot$. They present radial and non-radial pulsations with typical periods of the order of 2 to 8 hours. Their non-radial pulsation modes are low order g- and p-modes excited by the κ-mechanism acting in the iron group elements opacity peak at ~200 000 K. Most of them are slow to moderate rotators but still a significant fraction of them can reach rotation velocities of 50–100 $\mathrm{km\,s^{-1}}$ and even, for a few of them, 200–300 $\mathrm{km\,s^{-1}}$. Evidences of the presence of a magnetic field have also been detected in some of them.

Their internal structure is rather similar to that of SPB stars (see Sect. 2.5), with a convective core surrounded by a mostly radiative region, in which can be embedded a convective shell due to the iron opacity peak at ~200 000 K. The main difference from an SPB stellar structure comes from the fact that the radiative gradient in the layers adjacent to the convective core boundary is very close to the adiabatic gradient, which can induce a semi-convective region in the most massive β Cephei stars. Moreover those layers can be affected by overshooting from the convective core and/or by a rotational mixing. Indeed, the modeling of β Cephei stars does generally not take into account the structural changes due to rotation except in the form of this possible extra-mixing taking place in the layers surrounding the convective core. The μ-gradient profile outside the convective core is thus an open question since it depends on the presence and the efficiency of the extra-mixing.

It would be extremely interesting to establish a relation between the extent of this extra-mixed zone and the rotation velocity and/or the magnetic field for these stars and CoRoT was the perfect laboratory for such a purpose. Although not the most favorite targets in the early days of the preparation of the CoRoT mission, it soon appeared that a lot of scientific returns could be expected from β Cephei stars (see the review by Degroote et al. 2010b). Ground-based asteroseismology had indeed already proven its ability to probe the rotation profile and the extent of the extra-mixed region in some β Cephei stars (see for example Aerts et al. 2003). However, it proved not obvious at all to derive a one-to-one extent of this extra-mixed zone (Goupil & Talon 2009). A rather large extent seems to be required to model θ Ophiuchi (Briquet et al. 2007) while a much smaller one is favored for HD 129929 (Dupret et al. 2004; Thoul et al. 2004), for β Canis Majoris (Mazumdar et al. 2006), for δ Ceti (Aerts et al. 2006a) and for 12 Lacertae (Dziembowski & Pamyatnykh 2008; Desmet et al. 2009). This extra-mixed zone could even be absent in the structure of the CoRoT target V1449 Aquilae (HD 180642, Aerts et al. 2011) (see also, for ν Eridani, Pamyatnykh et al. 2004; Ausseloos et al. 2004). One must

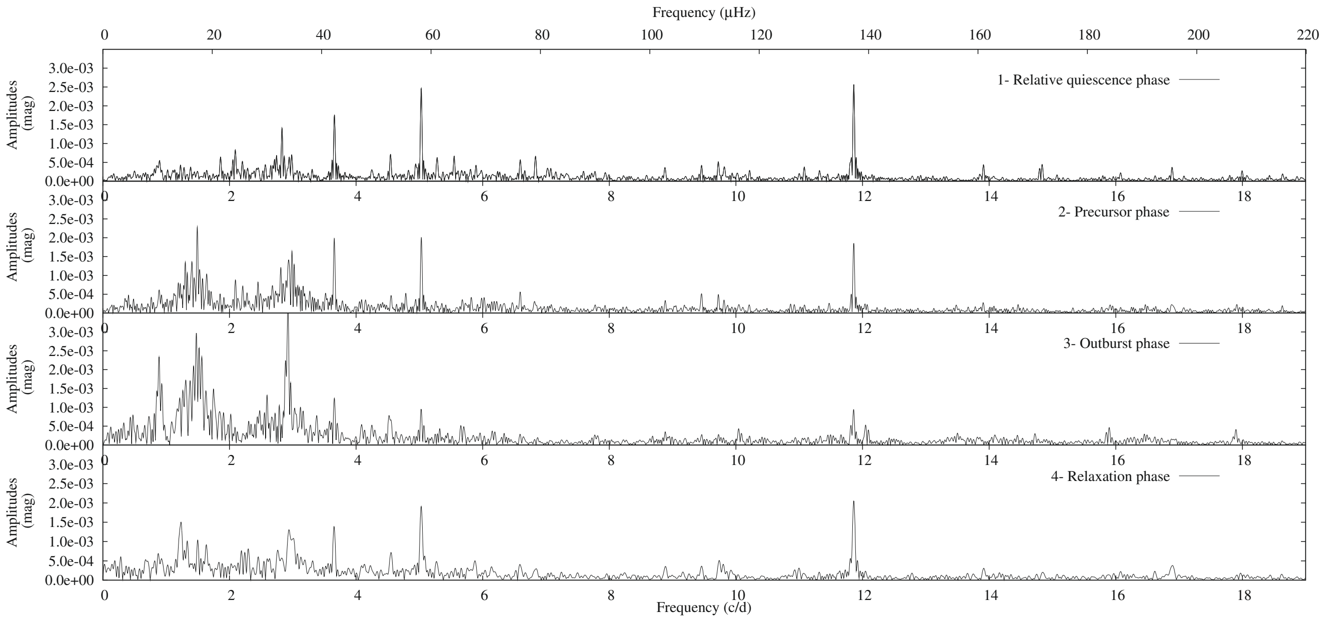

Fig. IV.1.4. Stochastically excited g-modes and acoustic p-modes in the spectrum of CoRoT Be star HD 49330 at quiescence, precursor, outburst, and relaxation phases (*from top to bottom panels*). From Huat et al. (2009) © A&A.

however proceed with caution in deriving asteroseismic constraints on extra-mixing since the results may depend on the number on well identified observed modes and on the assumptions made on the physics at work inside the star, such as the chemical mixture and the adopted extra-mixing processes for instance (Salmon 2014).

Magnetic fields could also play an important role in the asteroseismic inferences from β Cephei stars. Seismic analyses of V2052 Ophiuchi show that this star although rapidly rotating, which would favor extra-mixing, could be devoid of such a region. The magnetic field detected in this star could be the reason for this lack of extra-mixing (Briquet et al. 2012). Research is presently intensifying in order to detect and interpret magnetic stars in CoRoT (see for example Briquet et al. 2013) and *Kepler* (see the review by Neiner et al. 2015).

Moreover, some discrepancies with theoretical predictions appeared, especially in the analysis of hybrid β Cephei/SPB pulsators, since the excitation of low frequency modes was not accounted for by theory, and some iron enrichment in the excitation zone was proposed (see for example Miglio et al. 2007a; Dziembowski & Pamyatnykh 2008). The instability strips for SPB and β Cephei stars are indeed highly sensitive to the stellar metallicity since the operating κ-mechanism is related to the iron opacity peak (see for example Miglio et al. 2007b, and references therein). However it has been argued that, should an iron enrichment be the solution of the problem, chemically inhomogeneous HgMn stars would then present excited pulsation modes (Turcotte & Richard 2003). The seismic analysis of the CoRoT HgMn star HD 45975 seems to preclude any iron anomaly as the origin of the mode excitation since no pulsations were detected in this star (Morel et al. 2014).

Some SPB and β Cephei candidates have even been detected in the ultra low metallicity environment of the Magellanic Clouds, which is irreconcilable with theory. Instead of a chemical anomaly, an increased opacity could be the solution. A quest for a revision of opacity in conditions prevailing at the iron opacity bump, especially for the Ni opacity, has thus been advanced (Salmon et al. 2012) and new efforts are now being made in that direction (see for example Le Pennec & Turck-Chièze 2014).

An unexpected surprise came from V1449 Aql, which is a known large-amplitude β Cephei star. Solar-like oscillations (see Sect. 3) were indeed detected, which was a first in the asteroseismology of massive stars (Belkacem et al. 2009).

2.7. A live outburst in a Be star

In case of rapid rotation, especially when the rotation velocity is close to the break-up velocity, the structure and the evolution is deeply affected and hydro- and magnetohydrodynamical processes must enter the stellar modeling. The best laboratories for these processes are Be stars, which are rapidly rotating B stars surrounded by a gaseous disk formed of material ejected from the star, which is, in essence, the origin of the Be phenomenon. Asteroseismology of Be stars requires state-of-the-art modeling, including rotational effects, coupled with a pulsational analysis taking into account the Coriolis and the centrifugal accelerations.

Late Be type CoRoT targets HD 181231 and HD 175869 are very rapid rotators, about 20 times more rapid than the Sun. Their seismic analysis seems to require a centrally mixed zone about 20% larger than what is expected from convection only (Neiner et al. 2012). This already puts important constraints on the way hydro- and magnetohydrodynamical processes are implemented in the modeling.

But another CoRoT Be star, HD 49330, had a very exciting surprise in store. Observed by CoRoT during an outburst of matter towards its circumstellar disk, its frequency spectrum suffered drastic changes. Firstly dominated by acoustic modes the spectrum showed the appearance of gravity modes with amplitudes strictly in line with the outburst (Huat et al. 2009). Figure IV.1.4 shows the appearance and disappearance of stochastically excited g-modes in phase opposition with the acoustic p-modes present during the quiet phases. Such a link between the nature of the excited modes and a dynamical phenomenon is of course a gold mine in our quest for the understanding of the Be phenomenon. This was the first time that a clear evidence could link Be stars outbursts with their pulsations. An entirely new scenario was then proposed: the transport of angular momentum by waves or pulsation modes increases the stellar rotation and brings it to its critical value at the surface, leading to an ejection of matter into the circumstellar disk (see Neiner et al. 2013).

2.8. Unusual behaviours in O stars

A bunch of six O stars have been observed by CoRoT (Degroote et al. 2010b). Among them HD 46150 and HD 46223, members of the galactic cluster NGC 2264 (see Sect. 2.1) and HD 46966, member of the OB association Mon OB2, do not seem to pulsate, which is in agreement with stellar modeling of stars with similar global parameters. Their light curves seem to be dominated by red noise and clearly indicates a different origin than non-radial pulsations. The physical cause of this red noise is unclear, but it could be related to sub-surface convection, granulation, or stellar wind inhomogeneities (Blomme et al. 2011).

On the contrary, HD 46202 definitely shows β Cephei type modes. However, none of the observed modes are found theoretically excited, which is a recurrent problem in the upper part of the HR diagram (Briquet et al. 2011, see also Sect. 2.6).

The frequency spectrum of the Plaskett's star HD 47129 shows a peak with six harmonics with periods in the range 4h to 1d (Mahy et al. 2011). Plaskett's star is a non-eclipsing binary system composed of two massive O stars. The high rotation velocity of the secondary induces a large temperature gradient between the poles and the equator, making the determination of the spectral class ambiguous at least. Different physical origins for the observed frequencies have been looked at and the presence of non-radial pulsations seems to be the more plausible explanation. Although difficult to model given the uncertainties on the global parameters, it seems that the observed frequencies can be reproduced by radial and non-radial ($\ell = 1$) low-order modes.

CoRoT O star HD 46149 had another surprise in its basket. Solar-like oscillations (see Sect. 3) were indeed observed and their frequency range as well as their frequency spacings were found to be compatible with theoretical expectations (Degroote et al. 2010c).

2.9. Unraveling the helium burning core in sdB stars

Type-B subdwarfs (sdB) are located on the extreme horizontal branch in the HR diagram. With a very limited mass range, from 0.3 to 0.7 $M_\odot$, they are evolved stars, having undergone core hydrogen burning as well as the red giant phase. They are currently transforming helium into carbon and oxygen in a convective core surrounded by radiative quasi-pure helium layers and a very tiny hydrogen-rich envelope, whose mass is less than about 0.02 $M_\odot$. They have indeed been striped down through a process still under debate during an earlier phase of evolution, and as a result, they are hot and compact. With no hope of ascending the asymptotic giant branch they end up as cooling white dwarfs.

Among sdB stars, two classes of pulsators have been discovered. The short period pulsators, $sdBV_r$, are the hottest ones with $T_e \gtrsim 28\,000$ K, and periods covering a range of 100 to 600 s, typical of low-degree low-order p-modes. The long period sdB, $sdBV_s$, are cooler, with $T_e \lesssim 30\,000$ K, and periods of 1–2 h, attributed to low-degree mid-order gravity modes. The mode excitation results from the classical κ-mechanism acting in layers where partial ionization of iron group elements takes place. In order to enhance the efficiency of this exciting region, the competition between atomic diffusion and radiative levitation is assumed to increase the local content of iron group elements (Charpinet et al. 1997).

The hot long period sdB KPD 0629–0016 was selected as the CoRoT primary target in SRa03. The analysis revealed a large number of g-modes, with 17 clearly identified and 7 more candidates. The oscillations cover a range of 90–400 μHz with a dominant peak at 205.29 μHz (P = 1.353 h) (Charpinet et al. 2010). It was the very first time that the frequencies of such a large number of oscillation modes were reliably measured in an sdB pulsator, showing the power of CoRoT over ground-based observations in the asteroseismology of sdB stars.

A forward modeling approach has been carried out by Van Grootel et al. (2010). This means that a grid of theoretical sdB models, with known g-mode frequencies, was used with the aim of matching simultaneously the observed independent frequencies. This method has the advantage of delivering at the same time the structural stellar parameters and the identification of the modes. The derived global parameters are typical of a hot sdB star (see Table 2 in Van Grootel et al. 2010) but more importantly, the characteristics of the helium burning core were ascertained, thanks to the g-modes power to probe the very deep layers of the star. This core has a mass including 46 % of the total mass, probably indicating than an additional mixing must be invoked in the layers surrounding the purely convective core.

3. Solar-like oscillations (by S. Deheuvels)

In the Sun, oscillation modes are stochastically excited by turbulent motions in the outer convective envelope. In principle, similar oscillations are expected in all stars that possess a convective envelope, which is the case of low-mass ($M \leqslant 1.5\ M_\odot$) main-sequence stars, but also of red giants. The detection and precise characterization of solar-like oscillations in stars other than the Sun had been longed for by the stellar physics community for decades, owing mainly to the impressive results provided by helioseismology. The modes excited by convection in solar-like pulsators are high-order[1] acoustic modes. They nearly follow asymptotic relations (Tassoul 1980) and are thus roughly equally spaced in frequency by the so-called large separation $\Delta\nu$. This makes

[1] Except for stars at the tip of the red giant branch.

it much easier to identify the observed modes, which is a prerequisite for exploiting them to probe the internal structure of stars.

Before the launch of CoRoT, solar-like oscillations had been detected in only a handful of main-sequence stars from the ground, and the interpretation of their oscillation spectra was hampered by the short duration of the observations and the strong aliasing due to the low duty-cycle. The long duration (observing runs ranging from 20 to 170 days) and the very high duty cycle (close to 90%) of CoRoT observations were particularly well suited for detecting and characterizing solar-like oscillations, and the first detections lived up to the expectations (Michel et al. 2008).

The detection of solar-like oscillations with CoRoT was expected mainly for low-mass main-sequence stars and subgiants. Less expected was the impressive richness of this class of pulsators, which was revealed by CoRoT observations. Solar-like oscillations were indeed clearly detected in hundreds of red giants, and very interestingly also in massive main-sequence stars. We here give a brief overview of these successes.

3.1. A profusion of pulsating solar-like stars across the HR diagram

3.1.1. Main-sequence solar-like pulsators

Over all, oscillations were unambiguously detected in 12 main-sequence solar-like pulsators with CoRoT observations, which produced oscillation spectra of unprecedented frequency resolution. The quality of CoRoT seismic data is well illustrated by the échelle diagram[2] of the CoRoT target HD 49385 shown in Fig. IV.1.5, in which the identification of $\ell = 0$, 1, and 2 modes is visually clear.

The extraction of the mode parameters (now commonly referred to as peak-bagging) for the first CoRoT targets has paved the way for all subsequent analyses of this type. Methods based on maximum-likelihood estimation (MLE) were adapted from helioseismology (e.g. Appourchaux et al. 2008). These methods are now commonly used, in particular for solar-like pulsators observed with the *Kepler* satellite, and they were progressively improved to the point of being nearly automated today. The first CoRoT targets (HD 49933, Appourchaux et al. 2008 and HD 181420, Barban et al. 2009), which were chosen as F-type stars owing to the expectedly high amplitudes of their oscillation modes, clearly showed that the analysis of solar-like oscillation spectra is not always as straightforward as in the solar case. The mode amplitudes revealed comparable to expectations, but their lifetimes were shorter by a factor three, which complicated the identification of the modes. Bayesian methods, consisting of adding well-chosen prior information to the MLE procedures, combined with Markov chain Monte Carlo techniques helped solve this identification problem (Benomar et al. 2009a,b; Gaulme et al. 2009). Dedicated techniques using the autocorrelation of the time series were also established to

[2] An echelle diagrams is built by chopping the oscillation spectrum in sections $\Delta\nu$-wide, which are then piled up onto one another. This has the advantage of lining up modes of like degree in ridges.

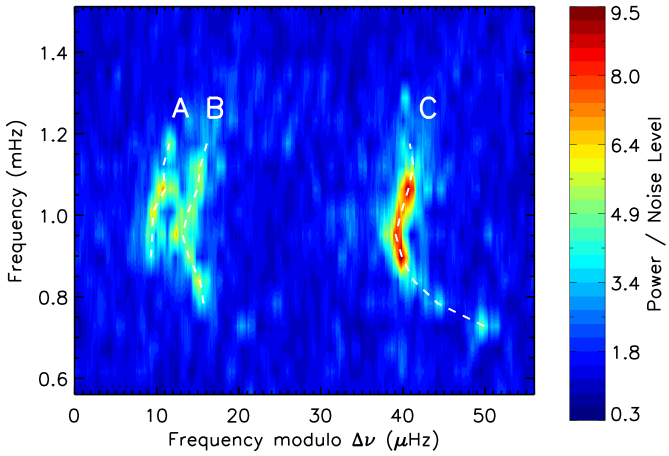

Fig. IV.1.5. Echelle diagram of the oscillation spectrum of CoRoT solar-like pulsator HD 49385. Three ridges appear, corresponding to $\ell = 0$, 1, and 2 (labelled as B, C, and A, respectively). Figure taken from Deheuvels et al. (2010) © A&A.

estimate global seismic parameters (such as the large separation and the frequency of maximum power of the oscillations $\nu_{\max}$, see Sect. 2, Part V, Chap. 2) in the case of lower signal-to-noise-ratio oscillations (Mosser et al. 2009; Mosser & Appourchaux 2009; García et al. 2009).

3.1.2. Subgiants

After the end of the main sequence, the frequencies of g modes increase owing to core contraction, and they become of the same order of magnitude as those of p modes. This gives rise to so-called mixed modes, which behave both as p-modes in the envelope and as g-modes in the core. Such modes have a unique potential for seismic diagnostics since the detection of pure g modes in solar-like stars remains out of reach (Appourchaux et al. 2010). The theoretical existence of mixed modes had been known for long (Dziembowski 1971; Scuflaire 1974; Aizenman et al. 1977), but they had not been unambiguously detected in solar-like pulsators, until CoRoT observations showed evidence of their presence in the oscillation spectrum of the target HD 49385 (Deheuvels & Michel 2010). The bending in the $\ell = 1$ ridge that can be seen in the low-frequency part of the échelle diagram (Fig. IV.1.5) is a typical signature of mixed modes in subgiants. These modes made it possible to establish the subgiant status of the star and opened the interesting opportunity to probe the structure of its core (see Sect. 3.3). Since then, mixed modes produced remarkable diagnostics about stellar interiors, especially with the detection of such modes in red giants. The potential of mixed modes has now been further exploited using the data from *Kepler*, and provided novel constraints on the internal rotation of subgiants (Deheuvels et al. 2012, 2014) and red giants (Beck et al. 2012; Mosser et al. 2012).

3.1.3. Red giants

As extensively discussed in Sect. 2, Part V, Chap. 2, before the launch of CoRoT, radial solar-like oscillations had been detected in red giants (Frandsen et al. 2002), but it remained uncertain whether non-radial modes could be detected in red giants. They were thought to be damped far more strongly than radial modes (Dziembowski et al. 2001), and first observations led to think that they might indeed have very short lifetimes, which would blur the oscillation spectra of giants (Stello et al. 2006). This was contradicted thanks to CoRoT observations with the detection of long-lived non-radial mixed modes in hundreds of red giants (De Ridder et al. 2009). These detections were understood with the theoretical computation of expected amplitudes and lifetimes of mixed modes in red giants by Dupret et al. (2009). This has opened a novel and very rich field in asteroseismology, and the seismology of red giants has produced major progress in stellar evolution (see Sect. 2, Part V, Chap. 2) and in galactic stellar population studies (see Sect. 3, Part V, Chap. 2).

3.1.4. Massive stars

As mentioned in Sects. 2.6 and 2.8, it had been suggested before that the thin convective region caused by the ionization of iron in massive stars could stochastically excite oscillations in a way similar to the solar convective envelope. The signature of such oscillations was found for the first time in a 10-$M_\odot$ β Cephei star observed with CoRoT (Belkacem et al. 2009). Similar modes were later detected in a CoRoT O-type star (Degroote et al. 2010c). These detections open interesting opportunities to better understand stars in this mass range and to learn more about the excitation mechanisms in solar-like pulsators.

3.2. Seismic modeling of CoRoT solar-like pulsator

The unprecedentedly long duration of CoRoT observations yielded estimates of the frequencies of solar-like oscillation modes with a typical precision of a few tenths of μHz. These new observables were used as precious additional constraints to model stellar interiors. The exploitation of CoRoT data has led to the development of new methods to model stars using asteroseismic constraints, and to improve existing methods.

The seismic data provided by CoRoT and now also by *Kepler* have been used to provide estimates of the most fundamental stellar parameters of the observed solar-like pulsators, such as their masses, radii, and ages. For this purpose, two different approaches were followed. The first one uses global parameters (the mean large separation of acoustic modes $\Delta\nu$ and the frequency $\nu_{\max}$ of maximum power of the oscillations) as seismic constraints, and yields estimates of stellar parameters by interpolating through large grids of stellar models (Chaplin et al. 2014). The advantages of this technique are its quickness, which makes it an interesting tool for ensemble asteroseismology (see Sect. 2, Part V, Chap. 2) and its applicability to low signal-to-noise targets, where individual modes cannot be detected, but powerful methods have been proposed to estimate global seismic parameters (Roxburgh 2009; Mosser & Appourchaux 2009). This approach was successfully applied to several CoRoT targets (Mosser et al. 2009; García et al. 2009; Gaulme et al. 2010). The second approach consists in performing a detailed modeling of specific targets using the properties of individual oscillations modes (either their frequencies of combinations of them), which is now referred to as "à la carte" or "boutique" modeling. This alternative approach is more time-consuming but obviously much more precise. Using the CoRoT target HD 52265 as a test-case, Lebreton et al. (2014) performed a very detailed study of these two approaches, and showed how asteroseismology improves the precision achieved on stellar parameter determination. For this specific target, they obtained age, mass, and radius estimates with uncertainties of ∼10%, 7%, and 3%, respectively, taking into account observational errors and current state-of-the-art model uncertainties. This work will undoubtedly serve as a reference for future asteroseismic modeling of solar-like pulsators.

For low signal-to-noise targets, an interesting approach has been suggested by Ozel et al. (2013), which consists in searching for a well-constrained stellar twin, i.e. a star whose stellar parameters are well-known and which shares similar surface and global seismic parameters with the studied target. A differential modeling can then be led to estimate differences in fundamental stellar parameters between the star and its well-characterized stellar twin. This approach was successfully applied to CoRoT target HD 175272, which was found to be a stellar twin of another CoRoT target HD 181420 (Ozel et al. 2013).

Another challenge was the seismic modeling of subgiants using the properties of mixed modes, whose large potential for seismic diagnostic of stellar interiors has already been mentioned. The timescale over which the frequencies of mixed modes are modified in these stars is small compared to the evolution timescale, which makes the usual approaches to seismic modeling (computation of grids of models or automatic optimization procedures) generally inefficient. Deheuvels & Michel (2011) proposed an alternate approach consisting in a two-step procedure, which was successfully applied to the CoRoT subgiant HD 49385, and was later adapted to red giants (Deheuvels et al. 2012).

The precise measurement of oscillation mode frequencies in stars of diverse masses and evolutionary stages combined with the improvement of seismic modeling techniques has given the opportunity to better understand certain physical processes which so far hindered our progresses in the modeling of stellar evolution. We now describe the main advances produced by CoRoT data.

3.3. Mixing beyond convective cores and envelopes

Several processes are expected to extend the size of convective regions beyond the Schwarzschild frontier (overshooting, rotational mixing,...), but since we lack a realistic description of these mechanisms, the actual size of convective zones remains uncertain. This generates in particular large uncertainties in our determination of stellar ages for stars that have a convective core because this core plays the role of a reservoir for nuclear reactions. Observational constraints on the size of convective regions are therefore crucial.

3.3.1. Core overshoot

The CoRoT satellite was well suited for obtaining such constraints. The boundary of the mixed region associated to the convective core generates variations in the sound speed profile on length scales shorter than the wavelength of acoustic modes. This introduces an additional oscillatory signal in the mode frequencies, which conveys information about the size of the mixed core. For the main-sequence solar-like pulsator HD 49933, Goupil et al. (2011) found that an extension of the mixed core produced by standard models (without overshooting nor rotational mixing) over a distance of 0.25 to 0.3 H_P is required to reproduce the observed frequency separation $\delta\nu_{01}$. By adding rotational mixing, they showed that it cannot account in itself for such a large extension, and that core overshooting should be responsible for an extension of the mixed core over about 0.2 H_P. On the other hand, Escobar et al. (2012) found that no extra-mixing beyond the convective core is required for the main-sequence star HD 52265.

Another powerful seismic diagnostic for the extent of convective cores is given by mixed modes in subgiants. Indeed, the coupling between p- and g-modes is linked to the Brunt-Väisälä profile in the core, which retains information about the size of the convective core at the end of the main sequence, provided the star is not too evolved (Deheuvels & Michel 2010). The detection of mixed modes in the subgiant HD 49385 offered a great opportunity to use such a diagnostic. Deheuvels & Michel (2011) found that models with a convective core that is extended over a distance of 0.18 and 0.2 H_P reproduce the frequencies of observed mixed modes at closest, but they could not exclude the case of a very small overshoot below 0.05 H_P.

The measurement of the size of the mixed core in stars with different masses, chemical composition, and evolutionary stages offers the opportunity to calibrate the extension of convective cores as a function of stellar parameters. By complementing results from CoRoT and using *Kepler* data, Deheuvels et al. (2016) recently proposed such a calibration with stellar mass for the evolution codes CESAM2K and MESA. This should decrease the uncertainties on stellar ages, especially for stars near the end of the main sequence (see Lebreton et al. 2014). On the longer term, we expect these measurements to provide constraints to theoretical models of the different processes that can extend convective cores.

3.3.2. Envelope overshoot

Overshooting below convective envelopes has a less direct impact on stellar evolution than core overshooting, but it can help us understand this theoretically challenging phenomenon. The abrupt transition between convective and radiative energy transport induces a glitch in the sound speed profile, which causes acoustic modes to oscillate as a function of frequency. The period of this oscillation yields an estimate of the depth of the boundary of the convective envelope (BCE). Such a measurement has been tried for HD 49933 by Mazumdar et al. (2012), who obtained rather loose constraints on the depth of the BCE. Using a similar diagnostic, Lebreton & Goupil (2012) were able to show that the convective envelope of the CoRoT solar-like pulsator HD 52265 is extended over a distance of 0.95 H_P compared to the classical Schwarzschild boundary. By comparison, Christensen-Dalsgaard et al. (2011) showed that an overshooting over a distance of 0.37 H_P is needed at the base of the convective envelope of the Sun. The difference between the overshooting distances of the two stars might be linked to the fact that HD 52265 has roughly twice the abundance of heavy elements of the Sun.

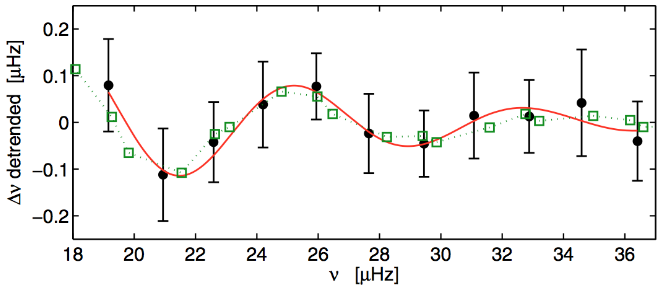

Fig. IV.1.6. Detection of an oscillatory trend in the large separations $\Delta\nu(\nu)$ of a CoRoT red giant, which is produced by the second helium ionization zone. Figure taken from Miglio et al. (2010) © A&A.

3.4. Structure of outer convective layers

The structure of the outer convective zones of Sun-like stars remains a source of uncertainty in our modeling and understanding of these stars. It constitutes a poorly determined transition zone between what is seen from the star at the surface and the internal part that we "interpolate" with theoretical models, structurally and chemically speaking. The seismic observations of CoRoT have provided additional constraints that will help us to better understand these regions.

3.4.1. Helium ionization zones

Similarly to the effect of the BCE, the second helium ionization zone (HIZ) produces an oscillatory behavior in the mode frequencies because of the bump that it creates in the first adiabatic exponent Γ_1. The signature of the HIZ has been detected in the second differences of the main-sequence pulsator HD 49933 (Mazumdar et al. 2012) and in the large separations of a bright red giant (Miglio et al. 2010), as can be seen on Fig. IV.1.6. The period of the oscillation provides a model-independent estimate on the depth of the HIZ, which can be confronted to stellar models. But also, the amplitude of the oscillation is directly related to the helium abundance in the envelope, which could thus be estimated in the future for CoRoT targets using methods that were applied to the Sun (Monteiro & Thompson 1998; Basu et al. 2004) and recently successfully adapted to a *Kepler* target (Verma et al. 2014). This opportunity is interesting because the current uncertainty on the initial helium abundance in stars[3] limits the precision to which stellar masses can be estimated, owing to the well-known correlation between helium abundance and stellar mass (e.g. Lebreton et al. 2014).

3.4.2. Mode amplitudes and widths

The amplitudes and lifetimes of solar-like pulsations depend on the driving and damping of these modes, i.e. on

[3] The helium abundance in the envelope is hard to estimate from spectroscopy because useful lines of helium are generally absent in the spectra of cool stars.

the properties of convection in the outer envelope (see Samadi et al. 2015 for a comprehensive review). The seismic data obtained with CoRoT enabled us for the first time to measure the amplitudes and line-widths of individual modes in stars other than the Sun. These measurements made it possible to test models of excitation and damping of acoustic modes by turbulent convection.

Theoretical models predict mode amplitudes to scale with $(L/M)^s$, where s ranges from 0.7 to 1.5. CoRoT observations were found to be in agreement with this scaling and favor values of s in the lower end of this interval (Baudin et al. 2011). By combining seismic estimates of the mode widths of HD 49933 from CoRoT data (Benomar et al. 2009b) with theoretical mode excitation rates for this star, Samadi et al. (2010b,a) derived expected mode amplitudes for this star[4]. They showed that the effects of metallicity must be taken into account, and in doing so they found an agreement with the observed mode amplitudes of HD 49933 within 1-σ errors, except at higher frequencies, which might reveal some deficiencies in the modeling of mode excitation.

The detection of oscillations in thousands of red giants with CoRoT and *Kepler* gave the opportunity to test whether or not the amplitude scaling relations can be extended to the red giant branch. Baudin et al. (2011) extracted mode amplitudes for several hundreds of CoRoT red giants. Samadi et al. (2012) showed that for red giants stars, non-adiabatic effects need to be taken into account when converting velocity amplitudes that are predicted from 3D simulations into intensity amplitudes. Even then, the predicted mode amplitudes for red giants were found to be underestimated by about 40%. Solving this discrepancy will require a better knowledge of the depth at which the mode inertia need to be computed and a more realistic treatment of the interaction between convection and pulsations and more precisely a non-adiabatic treatment of mode compressibility (Samadi et al. 2012).

Baudin et al. (2011) also extracted the mode linewidths for the solar-like pulsators observed by CoRoT. They found that the mode linewidths of main sequence pulsators vary very sharply with the star's temperature ($\Gamma \propto T_{\rm eff}^m$ with $m = 16.2 \pm 2$), which was later confirmed by Appourchaux et al. (2012) with *Kepler* data and is now understood as a consequence of the compensation between the work integral and mode inertia in the damping rates (Belkacem et al. 2012). This sheds new light on the unexpectedly large width of the modes of F stars such as HD 49933 (Appourchaux et al. 2008). According to Baudin et al. (2011), this scaling relation does not extend to red giants *Kepler* data, which would suggest a possible change in the regime responsible for mode damping between main-sequence and red-giant stars (Corsaro et al. 2015). Belkacem et al. (2012) however performed fully non-adiabatic calculations with the MAD code (Dupret 2001) including time-dependent convection, and they were able to reproduce the observed mode linewidths of both *Kepler* main sequence stars and CoRoT red giants (see Fig. IV.1.7) with the same physical background. This brings an interesting validation to the theoretical computation of mode damping rates, and suggests that a similar damping mechanism operates in main-sequence stars and in red giants. *Kepler* observations, which are longer than those of CoRoT, should yield mode linewidths for red giants higher on the RGB ($T_{\rm eff} < 4200$ K), which will make it possible to further test our damping rate models.

[4] These calculations provided predictions for the surface velocity amplitudes of the mode that needed to be converted into intensity amplitudes using the method of Michel et al. (2009) in order to be compared to the observed amplitudes.

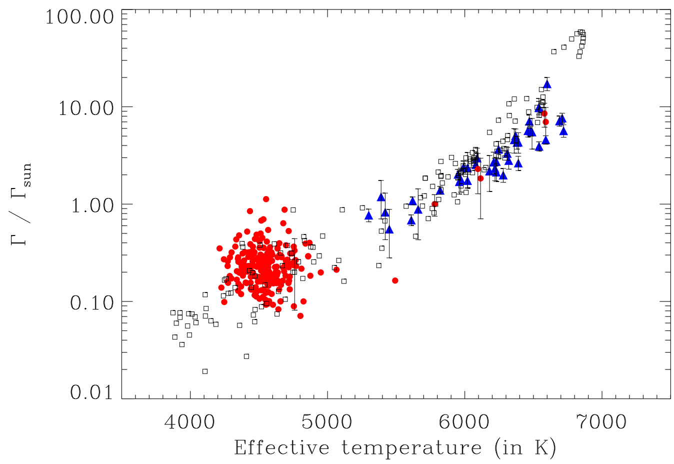

Fig. IV.1.7. Mode linewidths of stochastically-excited modes measured for CoRoT red giants (red circles) and *Kepler* main-sequence stars (blue triangles) plotted versus $T_{\rm eff}$. The mode widths predicted from non-adiabatic calculations (black symbols) show a remarkable agreement with observations. Figure taken from Belkacem et al. 2012).

3.4.3. Near-surface effects

The structure of super-adiabatic outer layers in the convective envelope remains poorly understood because convective transport is inefficient in this region, which makes the mixing length theory inappropriate. This is currently a major problem for seismology because the frequencies of individual modes depend on the structure of the super-adiabatic layers. Empirical corrections of these so-called near-surface effects have been proposed (Kjeldsen et al. 2008; Ball & Gizon 2014) but a better understanding of the super-adiabatic layer is needed to solve this problem. The combination of the recent progress in the 3D hydrodynamical modeling of stellar atmospheres to the precise 1D modeling of stellar interiors thanks to CoRoT seismic data provides ways testing existing empirical corrections and to propose alternative more realistic corrections (Sonoi et al. 2015).

3.5. Stellar rotation from seismology

Reaching a better understanding of the effects of rotation on stellar structure and evolution was one of the main objectives of the CoRoT mission. Helioseismology has shown that the radiative interior of the Sun rotates as a solid-body down to about 30% of the solar radius (Schou et al. 1998; Chaplin et al. 1999), which brought evidence that an additional transport of angular momentum occurs inside the Sun. The origin of this transport, which could be wave-driven or have a magnetic origin, remains unknown.

Rotation is known to lift the degeneracy between modes of same radial order and angular degree but different azimuthal orders. The intensity of this rotational splitting provides an average of the rotation rate in the cavity in which the waves propagate. By observing stars almost continuously over periods of several months, the CoRoT satellite made it possible to reach the level of precision required to measure the splitting of modes caused by rotation. Note that in order to obtain localized information about the internal rotation profile, one needs to measure the splittings of modes that probe significantly different regions inside the star. This could be achieved for the Sun, because higher-degree modes could be detected. Since the surface of solar-like pulsators other than the Sun cannot be resolved, the contribution from higher-degree modes cancels out owing to disk-averaging. As a consequence, it was not expected that CoRoT observations of main sequence stars could produce inversions of the internal rotation like obtained for the Sun. However, important information could be derived about the rotation of solar-like stars.

For solar-like pulsators observed by CoRoT, the rotational splitting is comparable to the mode width, which complicated its extraction from oscillation spectra. Estimating the splittings of individual modes is still out of reach, but an average splitting for all detected modes was successfully measured for HD 49933 (Appourchaux et al. 2008; Benomar et al. 2009b; Benomar et al. 2015), HD 181420 (Barban et al. 2009), and HD 52265 (Gizon et al. 2013), and ambiguity still remains for HD 49385 (Deheuvels et al. 2010) and HD 43587 (Boumier et al. 2014). The measurement of an average splitting is relevant since all the p-modes that are detected in solar-like pulsators probe roughly the same regions and therefore are expected to be split approximately the same way by rotation. The observed modes are mainly sensitive to the rotation in the superficial layers, but also to a lesser extent to the rotation in the radiative interior.

It is well known that low-mass stars are braked during the main sequence because they lose angular momentum through a magnetized wind generated by the convective envelope. Having access to precise and reliable rotation periods for stars whose mass and age can also be constrained by seismology, as is the case for the aforementioned CoRoT targets, will give precious observational constraints to calibrate theoretical relations of angular momentum loss (e.g. Kawaler 1988), which will be helpful for gyrochronology.

Interesting information can also be drawn on differential rotation by confronting seismic data, which provide an estimate of the rotation rate in the cavity probed by the observed modes, to other measurements of the surface rotation rate. The case of the CoRoT target HD 52265, a K-type solar-like pulsator hosting a planetary companion, is illustrative in that sense. Beside the measurement of the average rotational splittings of acoustic modes, the surface rotation rate was estimated:

- by photometry: the signature of starspot modulation was found in the CoRoT lightcurve of the star (Ballot et al. 2011);
- by combining the spectroscopic $v \sin i$ to the radius of the star obtained from the seismic modeling (Escobar et al. 2012), and its inclination angle i from seismology (Gizon et al. 2013).

Interestingly, these three measurements agree remarkably well, as shown by Fig. IV.1.8. It is important to stress that

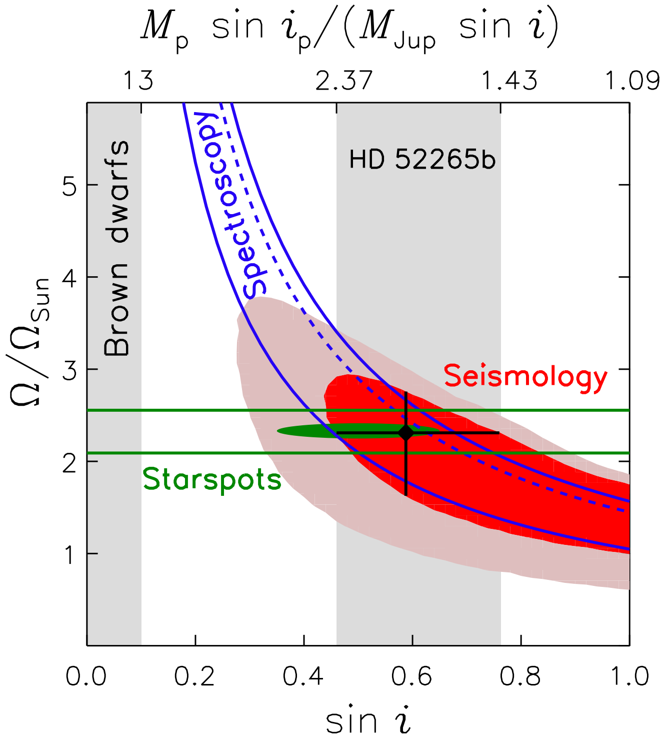

Fig. IV.1.8. Constraints on the surface rotation of HD 52265 from seismology (black diamond with 1σ error bars), from spectroscopy (blue lines) and from the modulation of the lightcurve caused by star spots (horizontal green lines). © Proceedings of the National Academy of Science, 110, 13267.

the rotational splittings of p modes are also sensitive to the rotation in the interior of the star, and in particular in the radiative region, so the agreement between seismic rotation rate and surface rotation rate from photometry and spectroscopy gives an upper bound to the amount of radial differential rotation that exists inside the star.

This point was recently quantified by Benomar et al. (2015) who confronted the average rotation seen by acoustic modes to the photometric and spectroscopic estimates of the surface rotation rates in CoRoT and *Kepler* targets. They found good agreements between these quantities and concluded that the difference in the rotation rates between the radiative interior and the surface is no more than a factor two in most of the main-sequence stars, regardless of their age. This strengthens the hypothesis conveyed by helioseismology that the rotation profiles of solar-like stars are made nearly rigid by an efficient angular momentum transport, the origin of which remains to establish.

It was also proposed to interpret the difference between the mean rotation obtained through seismology and the photometric estimate of the surface rotation as the result of a latitudinal gradient of rotation in the envelope (Ouazzani & Goupil 2012). Provided this effect can be separated from that of a potential radial gradient of rotation in the interior, this would yield interesting constraints on the latitudinal rotation profile near the surface. Note also that the latitudinal dependence of the modes differs for modes of different angular degree and if the rotational splittings of $\ell = 1$ and $\ell = 2$ modes could be estimated separately, one could also obtain constraints on the latitudinal rotation profile. This has however not been managed so far.

Since then, rotational splittings could be measured in the mixed modes of red giants using the longer datasets of the *Kepler* mission. This gave evidence for differential rotation in these stars, the core spinning faster than the envelope (Beck et al. 2012). The mean core rotation rate measured in subgiants (Deheuvels et al. 2012, 2014) and red giants (Mosser et al. 2012; Deheuvels et al. 2015) with *Kepler* data was found to be several orders of magnitude lower than predicted by rotationally-induced mechanisms of angular momentum transport, which showed that an additional efficient redistribution of angular momentum occurs in the radiative interiors of these stars.

3.6. Asteroseismology of planet hosts

The CoRoT mission has marked the beginning of the contribution of asteroseismology to the study of the evolution of exoplanetary systems. The determination of the properties of detected exoplanets is usually limited by the imprecise knowledge of the host star's properties. In particular, the mean density of detected planets, which is crucial to determine the planet's internal composition, is foremost dependent on the stellar mass and radius estimates. One key contribution from asteroseismology is that it can provide a better characterization of the host star. This was illustrated in the case of HD 52265 which hosts a hot Jupiter: the analysis of the acoustic modes provided an estimate of the stellar inclination angle (Gizon et al. 2013). In the case of the Saturn-like planet host HD 46375, the analysis of the faint solar-like oscillations of the star provided an estimate of the large separation of acoustic modes, which was sufficient to improve the mass estimate of the planet by a factor two (Gaulme et al. 2010). In the wake of these first successes, seismic estimates of the properties of 33 planet-candidate host stars were obtained using *Kepler* data (Silva Aguirre et al. 2015), and the PLATO mission, selected by ESA, will detect solar-like oscillations in tens of thousands main-sequence stars, including numerous planet hosts.

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