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Introduction and overview of the thesis

1.1 Introduction

Stars represent the fundamental units of the observed universe, therefore understanding stellar structure and evolution plays a privileged role in astrophysics. Classical observations, however, provide information which is mainly confined to the superficial layers of stars and give no direct knowledge about their interior. The lack of information on stellar interiors is well expressed by a famous quote from the opening paragraph of Sir Arthur Eddington's book *The internal constitution of stars* (Eddington, 1926):

> At first sight it would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?

At that time Eddington considered that the only scientific mean to bore those *substantial barriers* and to investigate stellar interiors was an *analytical boring device*, i.e. theory (Eddington, 1920).

However, to be considered a reliable and trustworthy description of stars, a theory must pass observational tests. In fact Eddington himself, in a later book, *Stars and atoms* (Eddington, 1927), already indicated a *material appliance* that could provide theoretical models with observational tests:

> Ordinary stars must be viewed respectfully like objects in glass cases in museums; our fingers are itching to pinch them and test their resilience. Pulsating stars are like those fascinating models in the Science Museum provided with a button which can be pressed to set the machinery in motion. To be able to see the machinery of a star throbbing with activity is most instructive for the development of our knowledge.

Eighty years ago stellar pulsations were already indicated as a unique tool to test our understanding of stars! The goal of the observation and the study of stellar pulsation modes (asteroseismology) is indeed to disclose the information carried by the frequencies of oscillation. Each mode of oscillation sounds differently the inner regions of the star and represents then a unique tool to probe stellar interiors.

There are several beautiful examples on how the study of resonant oscillation modes gives us information otherwise inaccessible to any other probe (see e.g. the general introduction to asteroseismology by Kurtz, 2006). In geophysics, for instance, the study of seismic waves allows to infer the internal structure of the earth. Asteroseismology has a similar objective: to allow us to "see" inside stars and learn about their internal structure.

In the case of the Sun, a detailed picture of its internal structure was obtained thanks to helioseismology, the study of solar global oscillations. Since the first detection of the five-minutes oscillations in the Sun by Leighton et al. (1962), and their interpretation as global acoustic oscillation modes (Ulrich, 1970; Leibacher & Stein, 1970), helioseismology led to several major scientific results (see e.g. Christensen-Dalsgaard, 2002, for an exhaustive review). Helioseismology gave us access to the properties of the internal regions of the Sun, namely the sound-speed and density profile and the internal rotation rate. One of the most successful results was the precise determination of the depth of the solar convective envelope ($d_{\rm cz} = 0.287 \pm 0.003\, R_{\odot}$, Christensen-Dalsgaard et al. 1991) which allowed to show that the inclusion of helium settling in the theoretical models was needed to significantly reduce the sound speed differences between the Sun and the models (Christensen-Dalsgaard et al., 1993). This provided indeed a strong evidence of the importance of diffusion in stellar interiors.

Following the success of helioseismology, there have been major efforts to detect in other stars multiperiodic variations of luminosity/radial velocity that can be interpreted as global oscillation modes. In the last few years, in particular, large observational campaigns from ground (see Handler, 2006, for a recent review) as well as space-based observations such as MOST (Matthews, 1998) and WIRE (Buzasi, 2003) allowed to detect number of radial and non-radial oscillation frequencies in a large variety of stars along the Hertzsprung-Russel diagram. Moreover, the realisation of stabilized spectrographs to search for extra-solar planets allowed to reach a sufficient accuracy to detect small amplitude pulsations in solar-like stars (see e.g. the review by Bedding & Kjeldsen, 2007).

In the very near future, observational asteroseismology will take an even larger step forward: the long and uninterrupted photometric observations from space that are currently being gathered by CoRoT (Baglin et al., 2006) will allow to determine oscillation frequencies with unprecedented precision. A further advance in the observation of oscillations will result from the asteroseismic programme of the forthcoming Kepler space-mission (Christensen-Dalsgaard et al., 2007) and from ground- and space-based asteroseismology projects such as SIAMOIS (Mosser & The Siamois Team, 2007), SONG (Grundahl et al., 2006) and PLATO[1] (Roxburgh et al., 2007).

While recent advances in the observational side of asteroseismology will soon allow the determination of precise oscillation frequencies in different stars, we have to face a new challenge: can we infer the internal structure of other stars with the same level of detail as we know the Sun? Do we expect to get the same information on their internal structure as in the solar case? While the answer is negative in general, this does not imply that the scientific achievements we expect to get from seismology of other stars will necessarily be minor compared to those

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[1] `http://www.lesia.obspm.fr/~catala/plato_web.html`

of helioseismology. There are of course limiting factors for asteroseismology that should not be overlooked. Asteroseismology has, however, two main prerogatives:

- *the variety of pulsating stars*, which means the opportunity to test our models under physical conditions that can be significantly different than in the Sun,

- *the diversity of the oscillation modes excited in pulsating stars along the HR diagram.* In addition to high-order pressure modes observed in solar-like stars, asteroseismology will benefit from the information provided by other types of pulsations that probe different regions of the star. In the case of main-sequence pulsators, for instance, low-order pressure modes are detected in δ Scuti and β Cephei stars. Moreover, the detection of gravity modes and modes of mixed pressure-gravity character provides the exciting possibility to probe in detail the core structure of stars. These modes are observed in several classes of pulsators on or near the main sequence, in particular mixed modes are expected to appear in the spectrum of solar-like oscillations in subgiant stars, whereas low-order g modes are detected in δ Scuti and β Cephei stars. Finally, the variability observed in γ Doradus and Slowly Pulsating B stars is attributed to high-order gravity modes.

1.1.1 The goals of asteroseismology

The information that can be gathered from the oscillation frequencies strongly depends on the number of available observational constraints, on the precision of asteroseismic data and on the structure of the star itself (and thus on its seismic properties). For simplification, we can however regroup the potential achievements of seismology in two broad categories:

- Seismology helps determining with precision *global parameters of stars* (e.g. age, radius, mass) by adding strong constraints to the available observational data (such as luminosity, effective temperature and chemical composition). Binary stars are evidently the most favorable cases since the orbital parameters increase furthermore the number of observational constraints. A precise determination of global parameters for a large number of stars will give us a more detailed picture of the evolution of stars and stellar populations, and thus improve our knowledge of the chemical evolution of the galaxy.

  A further interesting application, in the case of solar-like oscillations, is the combined study of exoplanets and their parent stars (see e.g the review by Charbonneau et al., 2007). The observation of the so-called large frequency separation in the parent star allows to put tight constraints on its radius and thus on the radius of the planet detected by a photometric transit. Similarly, an estimate of the mass of the star allows to better constrain the orbital parameters of the planet and its mass (see e.g. Stello et al., 2007).

- If adding precision to the determination of global parameters is certainly an interesting application, we have to keep in mind that the determination of parameters relies on the stellar models we use to compute oscillation frequencies. Rather than assuming models right and deriving parameters, asteroseismolgy can lead to major scientific achievements by supplying observational evidence to prove our models wrong and/or inaccurate. This brings to the second, ambitious objective of asteroseismology: to *use stars as laboratories* to test physical inputs of the models. This, on the one hand, would add accuracy and not only precision to the determination of global parameters and, on the other hand, it would allow a deeper knowledge of physics in the conditions reached in the stellar interiors.

Which are the ways to proceed in order to reach these ambitious objectives? Let us have a closer view on the strategies that can be adopted to infer properties of stars from the observation of their pulsation modes.

1.2 Strategies for asteroseismic inferences

The link between the observation of oscillation frequencies in stars and the final goal of asteroseismology, which is to learn about stellar interiors, is not straightforward. We here describe some of the strategies adopted by asteroseismologists to process this information: this is by no means intended to be a comprehensive review of all the approaches, we rather try to highlight the main scientific questions that motivated this thesis.

1.2.1 Inferences from excitation

Why does a star pulsate? Which are the physical mechanisms responsible for the excitation of the observed oscillation modes? Answering these questions allows us to test the physical properties of the region that contributes the most to the excitation (or damping) of the modes. If we consider different classes of pulsating stars along the main sequence, we find a variety of excitation mechanisms that represent a source of information on distinct physical assumptions we include in our models.

For instance, the amplitudes, lifetimes and the frequency domain of the observed stochastically excited *solar-like oscillations* depend on the physical properties of the near-surface convective layers (see e.g. Samadi et al., 2007; Houdek, 2007; Carrier et al., 2007).

The role of convection in the driving of oscillation modes is also crucial in the case of γ *Dor stars* in which the instability of high-order g modes is attributed to the "convective blocking" (Guzik et al., 2000; Warner et al., 2003; Dupret et al., 2004). In these stars the transition region of oscillation modes of the observed periods is located near the bottom of the convective envelope (CE). The radiative luminosity has a sudden drop at the base of the CE and, at the hot phase of the pulsation cycle, energy cannot be transported by radiation in the convective zone. As the convective timescale at the bottom of the CE is longer than the periods of oscillation, the convective flux cannot adapt immediately to the changes due to oscillations: the energy is periodically blocked and transformed in mechanical work, providing a source of excitation for the oscillations. For this mechanism to be effective in these stars, and to excite the observed range of frequencies, the base of the convective envelope in the models needs to be located in a well defined temperature range ($T_{\rm bce} \sim 2{-}4.8{\times}10^5$ K, see Guzik et al. 2000). This represents a valuable constraint to current stellar models since the depth of the convective zone is sensitive to different theoretical prescription of convective transport and to other physical processes such as microscopic diffusion (see Montalbán et al., 2007a).

As a further example we shall consider δ *Scuti stars*, where the instability of low-order p and g modes is explained via the κ-γ mechanism acting in the HeII ionization region. While the location of the theoretical blue edge of the instability strip is mainly dependent on the helium abundance (see e.g. Pamyatnykh, 2000), in stars near the red edge, convection plays an important role in the stabilisation of pulsation modes. In order to reproduce the observed location of the cool border of the instability strip it is necessary to introduce in the models a treatment of the interaction between convection and pulsation (Houdek, 2000; Xiong & Deng, 2001; Dupret et al., 2004).

Not all the excitation mechanisms in main-sequence stars are sensitive to the treatment of convection (and to its uncertainties). This is the case for pulsating B stars. The driving of oscillation modes in β *Cephei* and *Slowly Pulsating B* stars is due to the κ mechanism acting in the so-called "metal opacity bump" (see Sec. 3.7). We should nonetheless recall that the envelope of these stars is not entirely radiative: thin convective zones appear in the helium ionization regions and in the metal opacity bump layers in models of $M \gtrsim 10$ M$_\odot$. However, in such near-surface regions, convection transports only a negligible fraction of the luminosity and does not affect the excitation and damping of modes. This makes the comparison between observed an theoretically predicted instability domains for main-sequence B stars a precious opportunity to probe stellar opacity. In this context, recent observational studies have shown that current models fail to reproduce the instability of the observed modes in some of the best studied β Cep stars as well as the pulsation of B-type stars in low-metallicity environments (Ausseloos et al., 2004; Pamyatnykh et al., 2004; Handler et al., 2006; Kołaczkowski et al., 2006). While an increase of the opacity in stellar models near the "metal opacity bump" is likely to be the solution to this discrepancy, the physical reason why standard models underestimate opacity in the driving region is still a matter of debate. For instance, Pamyatnykh et al. (2004) suggested as a possible solution a local increase, induced by radiative levitation, of Fe-group elements in the driving region of the modes. We think that a more detailed study on the uncertainties in the opacity used in standard stellar models is needed to try to solve this challenging discrepancy. This is the reason why in Chap. 4 we analyze how the current uncertainties in the adopted metal mixture and in opacity computations (see Sec. 2.3.3) affect the theoretical instability domains of main-sequence B stars.

1.2.2 Inferences on stellar cores through gravity modes

Besides understanding the mechanisms that excite pulsations, the ultimate goal of asteroseismology is to make use of the frequencies of global oscillation modes to infer properties of the internal structure of stars. It was indeed the success of helioseismology in constraining properties of the solar structure through the study of global oscillation modes, that triggered the development of asteroseismology. One of the main factors that contributed to the growth of helioseismology was certainly a deep theoretical understanding of the properties of high order pressure modes. This led to an effective exploitation of the information carried by the observed frequencies through the development of analysis tools adapted to the observed oscillation modes (see e.g. the review by Christensen-Dalsgaard, 2002).

In the case of solar-like oscillations in other stars, analysis tools used in the interpretation of the pulsation spectra are in turn suggested by the profound theoretical knowledge of the properties of solar global oscillations. For example, in addition to the basic asymptotic large and small frequency spacings (Sec. 3.6.2), local information on abrupt changes in the stellar structure (on scales smaller or of the same order as the wavelength of the modes), can be gathered from periodic deviations from the simple frequency spectrum predicted by the asymptotic approximation. These signatures bear information on the location of the *boundary of the convective envelope* (see e.g. Monteiro et al., 2000; Ballot et al., 2004) and on the *envelope helium abundance* (see e.g. Monteiro & Thompson, 1998; Perez Hernandez & Christensen-Dalsgaard, 1998; Miglio et al., 2003; Basu et al., 2004; Verner et al., 2006; Houdek & Gough, 2007). Moreover, inversion procedures to reconstruct the *internal rotation profile* (e.g. Lochard et al., 2005) as well as the *core-structure* of solar-type stars (see e.g. Roxburgh & Vorontsov, 2002a,b; Basu et al., 2002; Roxburgh & Vorontsov, 2003a) were also adapted from helioseismology, and promise to provide detailed information on stellar interiors once precise frequencies of solar-like oscillations will be available.

Contrarily to case of high-order p modes, the properties of gravity modes in main-sequence stars have been less extensively studied in the literature. The analyses based on the first order asymptotic approximation of gravity modes (that will be described in Sec. 3.6.3) in particular, neglect the information provided by deviations from the asymptotic solution. The latter, in analogy with the case of pressure modes, give information on localized sharp transitions in the stellar structure. We believe that a more detailed theoretical analysis of gravity modes is needed for the interpretation of the observed high-order gravity modes in γ Dor and SPB stars, as well as for a deeper understanding on how the detailed properties of stellar cores affect low-order g modes and mixed modes, with possible applications to the seismic analysis of β Cephei, δ Scuti stars and subgiants stars showing solar-like oscillations.

We thus decided to investigate in more detail the properties of gravity modes in main-sequence stars. Our analysis, presented in Chap. 5, is inspired by the seminal works by Berthomieu & Provost (1988) and Dziembowski et al. (1993) and by the detailed study of high-order g modes in the case of white dwarfs seismology (see e.g. Brassard et al., 1992). We analyze how the detailed shape of the chemical composition gradient that develops near the edge of the convective core perturbs the spectrum of g modes. We also discuss extra mixing processes acting near the core (e.g. turbulent mixing, overshooting) in search for observable effects on the oscillation frequencies.

1.2.3 Inferences from solar-like oscillations in visual binaries

Theoretical studies demonstrating that stellar oscillation frequencies (and their excitation) are sensitive probes of the internal structure provide indeed a strong scientific motivation for the development of asteroseismology. This alone however, is a necessary but not sufficient requirement to ensure the success of asteroseismic inferences. Which are the limiting factors for asteroseismology? Which are the number and precision of the oscillation frequencies needed for seismic inferences? How much of the information on the stellar structure carried by the frequencies can be disentangled from the uncertainties in other stellar parameters? These are questions of no simple and general answer, and are beyond the competence of this thesis; we shall therefore restrict this type of analysis to a particular domain of pulsations: solar-like oscillations in stars on or near the main sequence.

As we discussed in Sec. 1.1.1, the goal of asteroseismology is not only the determination of global parameters of stars, but also to use stars as laboratories to test physical inputs of the models. This second objective is the one that mainly attracted our interest and, as explained in the following, it needs favourable conditions to be reached. Besides the need of a precise determination of the oscillation frequencies, the availability of additional non-seismic constraints in the modelling is obviously very valuable to constrain a larger number of model parameters (see e.g. Brown et al., 1994; Creevey et al., 2007).

Binary stars are known to provide additional constraints to the modelling and have been widely used in the literature as stringent tests for theoretical models (see e.g. Maceroni, 2006, for an overview). When modelling a binary system, we assume for both components a common initial chemical composition and the same age. Moreover, in the favourable case of visual binaries, the masses of the components are also determined. We thus further concentrate our interest on visual binaries with solar-like pulsating components, and we analyze in detail two cases: α Centauri and 12 Böotis.

The visual binary system α Centauri is amongst the promising targets in this context. Besides the availability of precise luminosities, masses ($M_{\mathrm{A}} = 1.105$ and $M_{\mathrm{B}} = 0.934\ \mathrm{M}_{\odot}$) and chemical composition for both components, interferometric and seismic constraints have recently been obtained for this system. The linear radii of both α Cen A and B are known with high precision thanks to the combination of a precise parallax (Söderhjelm, 1999) and angular diameters measured with the interferometer VINCI (Kervella et al., 2003). Moreover solar-like oscillations have been detected first in α Cen A by Bouchy & Carrier (2002), and then in component B by Carrier & Bourban (2003). Additional detections of oscillations in both components were later provided also by Bedding et al. (2004); Kjeldsen et al. (2005); Fletcher et al. (2006) and Bazot et al. (2007). The numerous and precise available observational constraints make α Cen AB a suitable target to test models of stellar structure and evolutions in conditions that are slightly different than those in the Sun. This is the reason why in Chap. 6 we present a thorough modelling of this system. The aim of this work is not just to derive the fundamental parameters of α CenA+B, but also to analyze the dependence of these parameters on the observables, on their uncertainty, on the different physics used in stellar modelling, and to investigate the capability of solar-like oscillations to constrain the properties of this system.

A most promising target for seismology that could represent a relevant step in understanding the structure of intermediate-mass stars is the binary system 12 Boötis. 12 Boo is a double-lined spectroscopic binary whose orbit has been resolved by interferometry: this allowed the determination of the masses of both components ($M_{\mathrm{A}} = 1.416$ and $M_{\mathrm{B}} = 1.374\ \mathrm{M}_{\odot}$) with a relative precision of about 0.3 % (Boden et al., 2005; Tomkin & Fekel, 2006). Although the masses of the components are very similar, their different luminosities, when compared to theoretical predictions, suggest that the secondary component is still in the central-hydrogen burning phase, while the primary is more evolved and burning hydrogen in a shell. As presented by Boden et al. (2005), however, this conclusion is highly dependent on the models and deserves further investigation. A detailed modelling of the system is reported in Chap. 7, where we study the capability of solar-like oscillations to distinguish between theoretical models obtained by including different mixing processes in the core.

The analysis of these binary systems represent a clear example of the potential of seismology to go beyond the determination of global parameters of stars and to allow inferences on the internal structure, provided that, as discussed in Chap. 6 and 7, the oscillation frequencies are determined with a sufficient precision.