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Conclusions and future prospects

The work presented in this thesis deals with different strategies adopted in asteroseismology. We here present a brief summary and outline future prospects for each topic addressed in the chapters describing our results (Chap. 4-7).

Inferences from excitation: β Cephei and SPB stars

Recent studies have shown that current models fail to reproduce the instability of the observed modes in some of the best studied β Cep stars (Ausseloos et al., 2004; Pamyatnykh et al., 2004; Handler et al., 2006; Kołaczkowski et al., 2006) as well as the pulsation of B-type stars in low-metallicity environments (see e.g. Kołaczkowski et al., 2006).

Since the theoretical predictions of excitation of pulsations in B stars are largely determined by the behaviour of the opacity in the driving region of the modes, in Chap. 4 we addressed the following questions: which are the current uncertainties on opacity calculations and on the metal mixture adopted in standard stellar models? Do they affect the theoretical predictions of excited pulsation modes in β Cep and SPB stars?

In the driving region of the modes ($\log T \simeq 5.3$) we noticed that differences in opacity up to $\sim 50\%$ can be induced by the choice between OPAL (Iglesias & Rogers, 1996) and OP (Badnell et al., 2005) opacity tables, and between two different metal mixtures (Grevesse & Noels 1993 and Asplund et al. 2005).

We find a significant effect on the excitation of pulsation modes. Compared to results obtained with OPAL and Grevesse & Noels (1993), if we consider OP opacities and Asplund et al. (2005) metal mixture, we find that:

- the blue border of the SPB instability strip is displaced towards higher effective temperatures, leading to a larger number of models being hybrid SPB-β Cephei pulsators;

- higher overtone p-modes are excited in β Cephei models and unstable modes are found in a larger number of models with lower metallicities, in particular β Cephei pulsations are also found in models with Z=0.01.

These findings help solving the discrepancies between theoretical predictions and observations of β Cep in low-metallicity environments, and the detection of a large domain of excited modes detected in some β Cep and hybrid SPB-β Cep pulsators.

A thorough comparison between observations and models computed with OP–AGS05 opacities is currently ongoing and is of course part of our future projects. First encouraging results have recently been obtained in the modelling of the β Cep star θ Ophiuchi (Briquet et al., 2007b), where OP opacities with AGS05 metal mixture successfully explain the excitation of the observed pulsation modes, whereas the commonly adopted OPAL–GN93 fail. A similar case is that of the β Cep HD

180642 (a COROT primary target) where a preliminary modelling shows that the excitation of the dominant observed mode (identified as a radial mode) can be recovered when using OP–AGS05 opacities (see Aerts et al. 2007). The modelling of other β Cephei stars, such as ν Eri and 12 Lac is still needed to determine if the discrepancies between "standard" models and observations can be explained adopting the new OP opacities and AGS05 metal mixture.

Inferences on stellar cores through gravity modes

In Chap. 5 we analyzed in detail the properties of gravity modes in main-sequence stars. In analogy with the works on white dwarfs by Brassard et al. (1992) and Montgomery et al. (2003), we showed that

- in the case of main sequence stars analytical approximations can be used to directly relate the deviations from a uniform period spacing to the detailed properties of the μ-gradient region that develops near the energy generating core.

We find that a simple approximation of g-modes periods, based on the variational principle of stellar oscillations, is sufficient to explain the appearance of sinusoidal components in the period spacing. The periodicity and amplitude of such component are related, respectively, to the location and sharpness of the μ gradient.

We investigated the properties of high-order gravity modes for stellar models in a mass domain between 1 and 10 $M_{\odot}$, and the effects of the stellar mass, evolutionary state, and extra-mixing processes (overshooting, diffusion, turbulent mixing) on the properties of the period spacing. In particular, we find that

- for models typical of SPB stars, a chemical mixing that could likely be induced by the slow rotation observed in these stars, is able to significantly change the g-mode spectra of the equilibrium model.

These results are relevant for the asteroseismology of both γ Dor and SPB stars. Depending on the mixing processes acting near the centre, deviations from the constant period spacing predicted by first-order asymptotic approximation can be significant and should not be ignored when developing tools for the seismic modelling of these pulsators.

As we also discussed in Chap. 5 even though a frequency resolution sufficient to resolve closely spaced periods will be provided by the forthcoming space-based observations with CoRoT, an asteroseismic inference on the internal structure of these stars will only be possible for stars with very slow rotation rates, and with reliably identified pulsation modes. *Once these conditions are fulfilled, we will be able to access the wealth of information on internal mixing which, as shown in* *this work, is carried by the periods of high-order gravity modes in main-sequence objects.*

In the second part of Chap. 5 we have extended our analysis of the effects of extra-mixing processes to low-order gravity modes and mixed modes. We find that

- turbulent mixing leaves a signature in the oscillation spectrum which differs from that of overshooting, and which can be related to the detailed properties of the sharp variation in $\boldsymbol{N}$ due to the different mixing processes considered.

In β Cephei stars, we find that the turbulent mixing induced by the typical rotation rates observed in these stars affects the frequency difference between non-radial modes of consecutive frequency.

These findings could have important effects on the seismic modelling of the best studied β Cep pulsators (e.g. ν Eri). We consider the modelling of β Cep pulsators including the effects of turbulent mixing near the core, one of the highest-priority projects in our future plans.

Inferences from solar-like oscillations in visual binaries

In Chap. 6 and 7 we discussed how the combination of classical constraints and of solar-like oscillations makes the visual binary systems α Cen and 12 Böotis valuable laboratories to test stellar models.

α Centauri AB

From the observational standpoint, α Cen is a very well constrained system, thanks to the availability of interferometric, seismic constraints, and to a precise determination of the luminosities, masses (bracketing the mass of the Sun, $M_{\rm A} = 1.105$ and $M_{\rm B} = 0.934\ {\rm M}_{\odot}$) and chemical composition.

As described in Chap. 6, when confronted with the problem of modelling the α Centauri binary system including all available constraints, the usefulness of an objective and efficient procedure to fit stellar models to observations becomes clear. We therefore implemented a Levenberg-Marquardt minimisation algorithm to derive the fundamental parameters of the system, and to analyse the dependence of these parameters on the chosen observables, on their uncertainties, and on the "physics" used in stellar modelling. By performing and comparing several calibrations, we were able to find

- a robust determination of the global parameters,
- an indication of the dependence of the mixing-length parameter on the HR diagram location,

and showed how the so-called “surface effects” on the oscillation frequencies can affect a widely used seismic indicator such as the large frequency separation.

The available seismic data are not in favour of a convective core in α Cen A, moreover, the overshooting parameter needed for a convective core to persist after the PMS ($\alpha_{\rm OV} = 0.2$), appears to be too large for a model of the mass and chemical composition of α Cen A (see e.g. Demarque et al., 2004). This conclusion is also strengthened by the comparison with the latest seismic observational data. The effects on the oscillation frequencies of the uncertainty on other physical processes and inputs included in stellar models (such as diffusion, equation of state, etc), were also studied, though no direct inference could be made due to the quality of the current asteroseismic constraints.

In fact, such a study on a specific target makes clear that the asteroseismic inference on the internal structure of this type of stars is currently limited by the poor frequency resolution of single-site, ground-based observations.

The seismology of α Cen is therefore just at its infancy and its future is bright, provided that precise observational seismic data become available. A higher quality set of data will soon be provided by the ongoing combination of Bouchy & Carrier (2002) and Bedding et al. (2004) observational data (Bedding, private communication). Hopefully, in the near future, significantly more precise oscillation frequencies will be determined by long and uninterrupted observations with the project SIAMOIS (Mosser & The Siamois Team, 2007) and with SONG (Grundahl et al., 2006), a global network of small telescopes primarily dedicated to asteroseismology.

12 Böotis AB

While the study of α Centauri provides a test of our knowledge of stellar structure in physical conditions that are slightly different from the Sun, the observation of solar-like oscillations in the binary system 12 Boötis ($\rm M_A = 1.416$ and $\rm M_B = 1.374\ M_\odot$) will be a relevant step in understanding the structure of intermediate-mass stars. In Chap. 7 we presented a detailed modelling of the binary system 12 Boötis by fitting the available observational constraints: effective temperatures, luminosities, chemical composition, and high precision masses of both components.

As result of different calibrations of 12 Boo we find:

- a set of possible theoretical scenarios where the secondary component is still on the main sequence, whereas the primary has already left it,
- that the precise evolutionary state of 12 Boo B, however, may vary from the second overall contraction, to a thick-shell-H-burning phase by changing the overshooting parameter $\boldsymbol{\alpha}_{\rm OV}$ in the range 0.23–0.06. These values slightly decrease (by 0.02) if microscopic diffusion is included in stellar modelling.

Other central mixing processes, such as diffusive overshooting, and a turbulent mixing lead to similar results. For each transport process we find a possible range of values of the parameters describing the efficiency of the extra mixing that places 12 Boo B in the MS and 12 Boo A between the second gravitational contraction and the sub-giant phase. Our analysis also shows that

- solutions with both components on the main sequence can be found only by assuming an efficiency of the extra-mixing process larger in the primary component than in the secondary.

In order to discriminate among these scenarios, additional and independent observational constraints are needed: these can be provided by solar-like oscillations, that are expected to be excited in both components of the system. *A precise knowledge of the frequencies of solar-like oscillations in the primary component coupled to the precise knowledge of the masses, would allow a robust inference on the evolutionary state of the system and, therefore, on the required amount of extra-mixing in the core*.

A further result of this detailed study is that, for a model in a given evolutionary state, the chemical composition profile near the core depends on the physical process responsible for the extra-mixing. This affects the behaviour of the Brunt-Väisälä frequency and hence the frequency of modes of mixed pressure- and gravity- character. *Information on the mixing process taking place in the stellar centre could be inferred from the frequencies of mixed modes*.

Thanks to the strong scientific motivations resulting from this study, a collaboration between several researchers and institutes (Liège, Leuven, Roma, Genève, Nice) has been set up to prepare a joint proposal for a spectroscopic campaign to observe solar-like oscillations in 12 Boötis. The realisation of the SONG project (Grundahl et al., 2006) would also give the opportunity for a long-term monitoring of this most promising target.

As a spur to future research in asteroseismology we would like to end this thesis with another quote from Sir Arthur Eddington (Eddington, 1920):

> In ancient days two aviators procured to themselves wings. Dædalus flew safely through the middle air across the sea, and was duly honoured on his landing. Young Icarus soared upwards towards the Sun till the wax melted which bound his wings, and his flight ended in fiasco. In weighing their achievements perhaps there is something to be said for Icarus. The classic authorities tell us that he was only "doing a stunt", but I prefer to think him as the man who certainly

brought to light a constructional defect in the flying-machines of his day. So, too, in Science.

Cautious Dædalus will apply his theories where he feels most confident they will safely go; but by his excess of caution their hidden weaknesses cannot be brought to light. Icarus will strain his theories to the breaking-point limit till the weak joints gape. For a spectacular stunt? Perhaps partly; he is often very human. But if he is not yet destined to reach the Sun and solve for all time the riddle of its constitution, yet he may hope to learn from his journey some hints to build a better machine.