Modelling solar-like oscillators

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Abstract. The computation of models of stars for which solar-like oscillations have been observed is discussed. After a brief introduction on the observations of solar-like oscillations, the modelling of isolated stars and of stars belonging to a binary system is presented with specific examples of recent theoretical calibrations. Finally the input physics introduced in stellar evolution codes for the computation of solar-type stars is discussed with a peculiar emphasis on the modelling of rotation for these stars.

1. Introduction: observations of solar-like oscillations
The observation of oscillation frequencies in the Sun and their comparison with theoretical calculations has led to significant revisions of solar models. These results as well as the need to constrain the input physics included in the stellar evolution codes stimulated various attempts to detect a similar signal on other stars. These past years, the spectrographs developed for extra-solar planet search have finally achieved the accuracy needed to make these detections. While solar-like oscillations have been detected for a handful of solar-type stars, individual p-mode frequencies have only been identified for a few of these stars: α Cen A [1–3], α Cen B [4; 5], Procyon A [6; 7], η Bootis [8; 9], µ Arae [10], β Virginis [11], β Hydri [12] and ν Indi [13; 14]. Individual frequencies have also been identified in giant stars like ε Ophiuchi [15; 16] and ξ Hydræ [17]. From a theoretical point of view, these seismic targets can be divided into two groups: single stars and stars which belong to binary systems. The modelling of single stars is first described in Sect. 2, while theoretical analyses of binary stars are presented in Sect. 3. The modelling of rotation for solar-type stars is briefly discussed in Sect. 4, while the conclusion is given in Sect. 5.

2. Modelling of single stars
The characteristics of a standard stellar model depend on five modelling parameters: the mass M of the star, its age, the mixing-length parameter α ≡ l/Hρ for convection and two parameters describing the initial chemical composition of the star. For these two parameters, the initial helium abundance Yl and the initial ratio between the mass fraction of heavy elements and hydrogen (Z/X)l can be chosen. The latter ratio is directly related to the abundance ratio [Fe/H]
assuming that log\( \left( \frac{Z}{X} \right) \) \( \cong \) [Fe/H] + log\( \left( \frac{Z}{X} \right) \odot \). When rotation is included in the computation, another modelling parameter must be added: the initial rotational velocity of the model. All the observational constraints available for a given star are then used in order to determine the value of these modelling parameters. For an isolated star, the non-asteroseismic observational constraints typically include its luminosity, effective temperature, and surface metallicity. In some cases, an interferometric determination of the stellar angular diameter is available leading to a precise determination of the radius which constitutes an important additional measurement in order to be able to accurately constrain the mass of an isolated star. When rotational effects are included in the computation, the value of the surface rotational velocity of the star is used in order to constrain the initial rotational velocity of the model. In addition to these classical observational constraints, asteroseismic measurements are used for the determination of the modelling parameters. These seismological observations consist of characteristic frequency spacings such as the large and small separations as well as of individual frequencies of the oscillation modes.

The small number of non-asteroseismic observational constraints available for a single star is usually insufficient to accurately determine all the global stellar parameters and to really test the underlying physics. An illustrative example is the modelling of the star \( \beta \) Virginis for which we find that, because of the limited number of non-asteroseismic observational constraints, two distinct solutions are able to reproduce all existing observations well: a main–sequence model or a post-main-sequence model [18]. Due to different masses, these two solutions also exhibit a difference in radius in order to have the same mean density and to reproduce thereby the observed value of the asteroseismic large separation (see Fig. 1). Thus, we see that an accurate independent determination of the radius of \( \beta \) Virginis can discriminate between these two solutions in order to accurately determine its global parameters as well as its evolutionary state. In the case of single stars, we therefore conclude that interferometric measurements of angular diameters will be very valuable to constrain the several free parameters of the models. This illustrates the complementarity between different observational techniques and in particular between asteroseismic and interferometric measurements.

More accurate determinations of individual oscillation frequencies can also provide the necessary constraints to unambiguously determine the global parameters of a single star and test the input physics of the models. In the case of \( \beta \) Virginis, we indeed notice that the small separations are sensitive to the differences in the structure of the central layers between the main-sequence and the post-main-sequence model (see Fig. 2). Our seismic analysis of \( \beta \) Virginis also show that an improvement of the accuracy on the oscillation frequencies is required to thoroughly studied the effects of rotation on stellar interior.

3. Modelling of binary stars
As we have just seen in the preceding section, the classical measurements available for an isolated star combined with the oscillation frequencies provide strong constraints to the global parameters of the star but are often not sufficient to unambiguously determine a unique model and to really test the input physics included in the stellar evolution codes. In the case of binary stars, the situation is quite different. The additional constraints imposed by the binary nature of the system, namely the same age and initial chemical composition, are indeed extremely valuable to accurately determine the global properties of the stars. Moreover, in the case of a binary system, the masses of both components are accurately known by combining visual and spectroscopic orbits. The prime example of the theoretical analysis of a binary system is of course the calibration of the \( \alpha \) Centauri system. In this case, the numerous non-asteroseismic observational constraints combined with the asteroseismic measurements available for both components lead to an accurate determination of all the global parameters of the system [19; 20].

Another example of the modelling of binary stars, is the calibration of the 70 Ophiuchi system.
Figure 1. Evolutionary tracks in the HR diagram for the two models of \(\beta\) Virginis. The dot and the square indicate the location of the solution with a mass of 1.28 and 1.21 M\(_\odot\), respectively.

Figure 2. Small separation \(\delta\nu_{02}\) as a function of frequency for the two models of \(\beta\) Virginis. The continuous and dotted lines correspond to the solution with a mass of 1.28 and 1.21 M\(_\odot\), respectively.

for which solar-like oscillations have been recently detected for the A component [21]. The analysis of this system enables us to illustrate the importance of a precise measurement of the mean value of the small separation in order to obtain an accurate independent determination of the initial helium mass fraction \(Y_i\), the mixing-length parameter \(\alpha\) and the age (see Fig. 3). There is indeed a degeneracy between the value of the initial helium abundance and the mixing-length parameter, since a decrease (increase) of the initial helium abundance \(Y_i\) can be compensated by an increase (decrease) of the mixing-length parameter \(\alpha\) to match the observed position of 70 Oph A in the HR diagram as found previously for the calibration of the star Procyon A [22]. As shown in Fig. 3, the mean small separation is found to significantly decreases with the age. The increase of the age of the system is directly correlated to the decrease of the initial helium abundance which is in turn directly related to the increase of the value of mixing-length
Figure 3. Mean small separation $\delta \nu_{02}$ of the component A for different models of the 70 Ophiuchi system.

parameter needed to reproduce the observed location of 70 Oph A in the HR diagram and the observed mean large separation. We thus conclude that a precise observation of the mean small separation of 70 Oph A will lift the degeneracy between the value of the mixing-length parameter and the initial helium abundance by adding a strong observational constraint on the age of the system and will therefore enable an independent and precise determination of the mixing-length parameter and the initial helium abundance of the 70 Ophiuchi system.

4. Modelling of rotation

Finally, we briefly discuss the modelling of rotation for solar-type stars and in particular the problem of the solar rotation profile. Helioseismic observations show that the solar angular velocity is approximately constant in the radiative down to about 0.2 $R_\odot$, while models with shellular rotation only produce an insufficient internal coupling to ensure solid body rotation. This suggests that another effect intervenes. There are currently two main possible explanations: the transport of angular momentum by internal gravity waves or magnetic fields. As shown by Talon & Charbonnel [23], internal gravity waves are able to efficiently extract angular momentum from the central parts of a solar-type star. We also recently studied the effects of magnetic fields, and in particular of the Tayler-Spruit dynamo [24], on the solar rotation profile. We find that models computed with both shellular rotation and the Tayler Spruit dynamo can account for the flat rotation profile of the Sun as deduced from helioseismic measurements [25]. This is illustrated in Fig. 4 which compares the theoretical rotation profile of models computed with an initial velocity of 50 km s$^{-1}$. The key question concerning this type of dynamo is to know whether it is really active in the radiative zone of a solar-type star [see for instance 26].
Figure 4. Rotation profile for a model with rotation only (dashed line) and with both rotation and magnetic field (dotted line) at the age of the Sun. The initial velocity is $50 \, \text{km} \, \text{s}^{-1}$. The points with their respective error bars correspond to the angular velocities in the solar radiative zone deduced from GOLF+MDI and LOWL data [27].

5. Conclusion

We conclude that binary stars offer a valuable opportunity to determine accurate global parameters and to constrain the input physics of evolution codes by combining seismological data to the numerous additional constraints resulting from the binary nature of the system. For a single star, only a limited number of non–asteroseismic observational constraints are available. As a result, it is more difficult to thoroughly test our knowledge of stellar physics through the seismic analysis of an isolated star than of a binary star. Asteroseismic measurements of single stars are however extremely valuable in order to explore the properties of stars with various global parameters, i.e. various locations in the HR diagram, as well as to study the effect of a specific physical process on the stellar structure such as rotation. In the case of single stars, we note that interferometric measurements of angular diameters constitute valuable additional constraints.

The main limitation of current seismic studies of solar-type stars comes from the limited accuracy on individual observed oscillation frequencies. In order to really probe the internal structure of the stars and to improve thereby our modeling of the various physical processes at work in stellar interiors, long and continuous asteroseismic observations are needed. The space missions COROT and KEPLER will be able to realize such an improvement and are therefore very promising to make significant progress in our knowledge of stellar physics.

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