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Challenges in Stellar Models from Helioseismology to Asteroseismology

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Abstract. Experience in helioseismology provides guidance for modeling challenges in asteroseismology. It guides choices of targets and conditions of observation. The main objectives are the interplay between rotation and convection and the knowledge of the internal magnetic field. Progress on the structure of the outer layers is crucial to avoid mode identification problems.

1. Introduction

Stellar modeling has been recently improved by a better understanding of many physical phenomena; e.g. the interaction of photons with complex plasmas or the way stars lose mass and rotate. Additional progress has been achieved by a better determination of stellar composition, distance, and geometry. Seismic investigation of stellar interiors will give us a real insight and consequently will contribute to answering outstanding questions concerning on convection, magnetic field and rotation. Currently, the absence of a proper description of such phenomena limits our understanding of early and late stages of evolution, and the objective is to directly introduce them in stellar structure equations.

In this review, we anticipate from the solar case the potential progress for solar-like stars, including young or massive stars. Of course, the Sun is a unique object as we can detect a large number of modes. For solar-like stars, the detection will be limited to low-degree acoustic modes. But the richness of our experience in helioseismology allows us to deduce from the understanding of the mode characteristics the way to achieve a real insight from the surface to the core if we have the opportunity to achieve the required accuracy.

2. The Solar Experience

The investigation of the stellar interior with seismic probes (Ballot et al. 2003, 2004) depends on the ability to identify the observed modes, to get a sufficient number of them (from 20 to 50 at least) and to have a sufficient length of observations (typically several months). In these conditions, the extension of convective zones and helium content are accessible. Moreover, we notice that the correct extraction of the rotation profile (Couvidat et al. 2003a) in the radiative zone benefits from limited instrumental perturbations at low frequencies to approach the range of mixed modes. A major lesson from helioseimic data is that we can considerably improve the quality of the information if we integrate the signal for several years at low frequencies (Turck-Chièze et al. 2001; Couvidat et al. 2003b), in reducing the stellar activity effect together with the role of the stochastic excitation, encouraging seismic observations during exoplanet observations which will cover several successive years. Due to the high quality of the solar seismic information, which allows an extraction of the sound speed at the level of 10^{-4} down to $0.06R_{\odot}$, a deep understanding of the physical ingredients such as nuclear reaction rates, opacities and surface composition has been possible, which is directly useful for asteroseismology.

3. Future Major Challenges

The knowledge of the metallicity through only the iron composition is not sufficient and the composition of carbon, nitrogen and mainly oxygen is necessary to interpret the sound speed profile. These elements play a crucial role at the base of the convective zone and just below, so the detailed knowledge of the composition helps to disentangle competition between radiation and convection.

In the possible cases, we will determine the edge of external convective zones of solar-like stars, and deduce strong constraints on convective phenomena using several stellar calibrators. The aim is to go beyond the mixing length approximation and the notion of over or undershooting. This is one of the important issues for asteroseismology. For this objective, hydrodynamical 3D simulations will be of great utility (Brun & Toomre, 2002), if we can observe the internal behavior of stars with different surface rotation. It will be extremely exciting to really understand the role of the rotation in convective layers, by looking at a large number of clusters of different ages. Progress will come from the study of young clusters with higher rotation rates for which we are waiting confrontation with present modeling (Piau & Turck-Chièze 2002; Piau, Ballot & Turck-Chièze 2005).

In simulating the perturbed characteristics of the modes (stochastic excitation and variability along stellar cycle), we are confident that we can extract the depth of outer convective zone at a level of several percent, and the determination of photospheric helium content; this will be critical for a good estimate of the stellar ages of solar like stars of different metallicities, thanks also to the precise determination of stellar diameters for nearby observed stars. We hope also to make progress on the magnetohydrodynamic role of the interlayer between radiation and convection. Any improvements in computer performance will be immediately used to simulate such still inaccessible regions of stars. Today's tachocline parameters must be replaced by a real understanding of the processes in action. Another very important goal consists of improving determinations of the frequencies of the modes, which is important for the identification of the observed peaks and consequently it will help in going towards higher masses and other areas of the HR diagram. This progress supposes a correct introduction of the turbulence, which is mainly concentrated in the solar case in the outer 1000 km, and of the external magnetic field.

4. The surface magnetic field

For many years, the high precision achieved in the measurement and the calculation of solar acoustic frequencies has shed light on the detailed disagreement between them, which varies much more with frequency than with the mode degree ℓ. For low values of ℓ, this discrepancy can be considered to be independent of ℓ, and reaches several tens of μHz at high frequencies. Since Woodard & Noyes (1985), it has been well known that frequency variations with the solar cycle present qualitatively the same properties: independent of ℓ for $\ell = 0$ - 10, reaching a maximum of several tenths of μHz at high frequencies.

These specific behaviors are attributed to very near-surface effects. Indeed, for low values of ℓ, the wave vector becomes nearly radial. But until now, despite numerous studies, it has been difficult to build up a scenario that can give rise to the frequency changes capable of reproducing the observations. The most concrete result was obtained very recently by Li et al. (2003), where the frequency variations with the cycle were relatively well reproduced, with a combination of turbulent pressure and magnetic field.

Nghiem (2002) developed a semi-analytical calculation using a boundary condition directly implying the stellar structure studied without any other hypothesis on this structure. Such an approach, despite its reduced precision compared to the numerical methods, could be pertinent in the study of near surface layers. It consists in examining pure acoustic waves traveling in a locally homogeneous gas sphere. At the surface, these waves are reflected when the environment is no longer homogeneous, that is when its characteristic length, identified here with the pressure scale height H_p, is of the same magnitude as the wavelength. So the external cavity limit r_2 is the radial position obeying the following equation: $\frac{1}{k_r}\frac{\omega^2}{c_0^2} = \frac{2\pi}{11.3H_p}$. k_r the radial wave number which is equal to ω/c_0 at the surface for low ℓ. When comparing the observations and the resulting eigenfrequencies obtained with a solar model of Brun, Turck-Chièze & Zahn (1999), an ℓ-independent discrepancy can be seen, characteristic of surface effects, but different from the classical figure, due to the relaxing of the isothermal atmosphere approximation.

A conventional inversion method is used to search for a sound speed change. But that cannot be a solution; on the contrary, a change in H_p with c_0 constant, or almost constant, will lead to a net change of r_2 and thus a frequency change independent of ℓ. The magnetic field is a good candidate satisfying this latter condition. Because the magnetic pressure induces a change in H_p as well as the sound speed, but the latter is compensated by the Alfven speed. The effect on the gas pressure and the sound speed of an horizontal field B_h is:

$$p_1 - p_0 = -\frac{B_h^2}{8\pi} \text{ ; and } \mathrm{c}_1^2 - \mathrm{c}_0^2 = (\mathrm{p}_0 - \mathrm{p}_1)(\frac{2-\Gamma_1}{\rho_0}) \tag{1}$$

and a change from B_h to $B_h + \delta B_h$ leads to:

$$p_2 - p_1 = -\frac{B_h \delta B_h}{4\pi} - \frac{\delta B_h^2}{8\pi} \text{ ; and } \mathrm{c}_2^2 - \mathrm{c}_1^2 = (\mathrm{p}_1 - \mathrm{p}_2)(\frac{2-\Gamma_1}{\rho_0}) \tag{2}$$

where the indices 0, 1, 2 refer to the cases without magnetic field, with magnetic field, and with a magnetic field change. In this study, the adiabatic coefficient Γ_1

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and the density ρ_0 remain unchanged, provided that the hydrostatic equilibrium is maintained with the same total pressure. The above equations clearly show that the determination of the variation δB_h depends on the determination of B_h.

To determine the surface magnetic field, we calculate first the eigenfrequencies with the above mentioned method, applied to the solar structure of our solar model. By comparing with the LOWL observed frequencies of Jiménez-Reyes (2001) near the minimum and maximum of magnetic activity, i.e. in 1996-1997 and 1999-2000, we can infer B_h and δB_h. The results are the following. We are able to extract an order of magnitude of the magnetic field and of its variation through the solar cycle, down to about 0.995 increasing from 0 to 10 kG for the permanent magnetic field, and down to 0.997 increasing from 0 to 100 G for the variation of this magnetic field. Below, the magnetic pressure is so small in comparison with the gas pressure, that we can deduce nothing from the absolute values of the frequencies. Near the surface, the introduction of a turbulent pressure term does not modify these conclusions as the impact of this term is very localized.

Despite some questionable approximations used here, the B_h profile shows magnetic field values at roughly the same range as the ones estimated from measurements, and the δB_h profile is not very different from the one infered in Li et al. (2003).

This method may be extended to other stars in the future and provides input for stellar models to improve the identification of the detected modes.

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