THE POTENTIAL OF HELIOSEISMIC DATA: REVEALING NEW DETAILS OF THE INTERNAL STRUCTURE

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ABSTRACT. Helioseismic inversions of the new precise and large set of p-mode frequencies, such as obtained from the MDI instrument flying on board the SOHO satellite (Rhodes et al. 1998), have the potential to improve highly the investigation of the features of the structure of the solar interior. In particular the use of frequencies of high-degree modes ($l < 1000$) allows us to resolve the near-surface region where effects of the equation of state are felt more strongly, and where dynamical effects of convection, and processes that excite and damp the solar oscillations, are predominantly concentrated.

1. Introduction

Helioseismology, the study of the global solar oscillations, has proved to be an extremely powerful tool for the investigation of the internal structure and dynamics of the Sun. The observed oscillations are due to standing acoustic waves (*i.e.* p-modes) - generated for some not well known reason in the convection zone and maintained by pressure force - trapped in resonant cavities between the Sun's surface and an inner turning point. Since the oscillations are largely adiabatic (except very near the surface), their frequencies depend predominantly on the local adiabatic speed of sound and in addition on the distribution of the density and the adiabatic gradient in the Sun. So, inversions of accurate observed acoustic frequencies, available from a variety of helioseismology experiments on Earth and in space, can be used to probe details of the solar structure (Basu et al. 1996). Inversion results, so far, have confirmed that the solar structure is remarkably close to the predictions of the standard solar model, but have also suggested further refinements. The near-surface region of the Sun, in particular, is of very great interest for helioseismic inversion (Rabello-Soares et al. 2000). The most direct way to probe the solar upper layers is through observation of high-degree acoustic modes ($l \geq 100$), trapped near the solar surface. Unfortunately, effects of atmospheric seeing and the difficulty to isolate each single mode have so far limited the use of high-degree data for helioseismic inversions.

The current analyses have been carried out by inversion of preliminary helioseismic data (Rhodes et al. 1998), which include high-degree modes ($l < 1000$), obtained in 1996 by the MDI instrument on board the SOHO satellite. The set is made up of a very large number of data (7480 modes), which makes the computations slow and very demanding in terms of computer memory.

For comparison, we have also inverted another set obtained by the same instrument, which includes only modes with harmonic degree $l \leq 100$ (Schou 1998).

2. Helioseismic inversion

An inversion for solar structure is usually based on the linearization of the equations of stellar oscillations around a known reference model, under the assumption of hydrostatic equilibrium. This allows us to define some useful integral equations that can be used in an inverse procedure to determine the corrections which have to be imposed to the reference model in order to obtain the observed oscillation frequencies ω_i.
The relative differences in sound speed c and density ρ between the structure of the Sun and the reference model are related to the relative differences in frequencies (Dziembowski et al. 1990), for a given set of modes $i = 1, \ldots, M$, by the following integral equation:

$$\frac{\delta\omega_i}{\omega_i} = \int_0^{R_\odot} K^i_{c^2}(r)\frac{\delta c^2}{c^2}(r)dr + \int_0^{R_\odot} K^i_\rho(r)\frac{\delta\rho}{\rho}(r)dr + \frac{F_{\rm surf}}{Q_i} + \epsilon_i \ , \qquad (1)$$

where r is the radial distance from the centre, $R_\odot$ is the solar photospheric radius and ϵ_i the observational errors in the data. The kernels $K^i_{c^2,\rho}$ and K^i_{ρ,c^2} are calculated, for each mode i, on the equilibrium model quantities and oscillation eigenfunctions.
Non-adiabatic effects and other errors in modeling the surface layers, that can give rise to frequency shifts, have been taken into account by including an arbitrary function of frequency $F_{\rm surf}$ in the variational formulation. The term Q_i is the inertia of the modes, normalized by the inertia of a radial mode of the same frequency.
An integral equation analogous to Eq. (1) can be derived to determine the behaviour of $(\delta\Gamma_1/\Gamma_1)_{\rm int}$, the relative intrinsic difference in the first adiabatic exponent Γ_1 between the equation of state of the Sun and the one of the reference model (Basu & Christensen-Dalsgaard 1997) .

The integral equation (1) has been solved by using the Subtractive Optimally Localized Averages (SOLA) method (Pijpers & Thompson 1992), while the adiabatic exponent differences has been inferred by the Multiplicative Optimally Localized Averages (MOLA) method (Backus & Gilbert 1968).

The Model S of Christensen-Dalsgaard et al. (1996) has been used as reference model. It assumes that the Sun has an age of $4.6\,Gyr$ and uses the OPAL equation of state (Rogers, Swenson & Iglesias 1996). In addition, a modified model S has been considered which differs from the previous one only in that it uses the MHD equation of state (Mihalas, Dappen & Hummer 1988).

3. Inversion results

Fig. 1 shows the relative squared sound-speed and density differences between the Sun and the solar standard model S as function of the fractional radius. High-degree modes are able to determine variations very near the solar surface, through the He II ionization zone and also part of the He I ionisation zone, while by using only low and intermediate-degree modes, we cannot determine solutions further than $r \simeq 0.96 R_\odot$.
The results of the speed of the sound, obtained with the use of the two sets of frequencies, are similar in the core. This indicates that high-degree modes have not influence when all observed modes of oscillation are considered and they do not affect the helioseismic

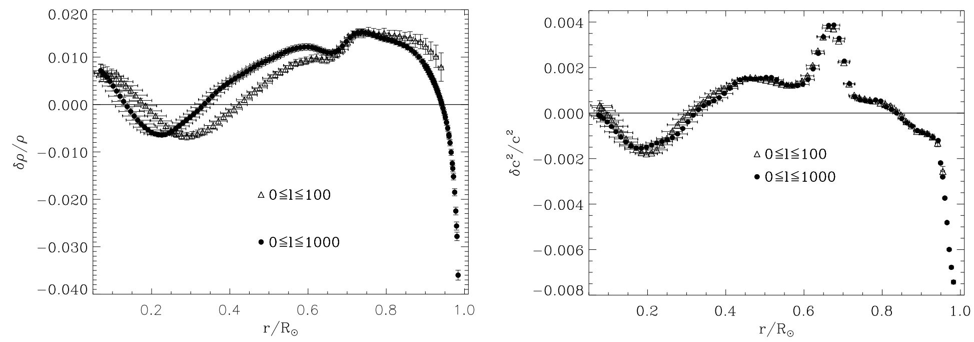

Fig. 1. The relative density (left panel) and squared sound-speed (right panel) differences between the Sun and the solar standard model S (Christensen-Dalsgaard et al. 1996) by using two different sets of data by Rhodes et al. (1998) with high-degree modes (filled circle) and by Schou (1998) with no high-degree modes (open triangle). The vertical error bars correspond to the standard deviations based on the errors in the mode sets, whereas the horizontal bars give a measure of the localization of the solution.

inferences of the deeper interior. On the contrary, we can notice that the profile of the density, in the radiative zone, is slightly influenced by higher-degree modes.

Fig. 2 shows the resulting intrinsic differences in Γ_1 between the Sun and the currently available equations of state, as obtained by inversion of the two data sets. As already shown by Basu & Christensen-Dalsgaard 1997, by using only low and intermediate-degree modes it is difficult to judge the significance of the differences between the two equations of state. Nevertheless, we are able to confirm previous findings (Elliott & Kosovichev 1998) that Γ_1 deviate from 5/3 in the central core, probably due to relativistic effects. The precise high-degree modes allow us to affirm that, as noticed by Basu et al. (1999), the OPAL equation of state is able to describe better the plasma conditions in the interior of the Sun below $0.97\,R_\odot$, while the differences between the two equations of state are very small in the upper layers above $0.97 R_\odot$. Here the results indicate a large discrepancy between the models and the observed Sun, even considering higher-order asymptotic terms in $F_{\rm surf}$ of equation (1).

We conclude that the structure of the near-surface region is still quite uncertain, since there remains substantial ambiguity in considering the convective flux, the non-adiabatic effects in the frequencies, the processes that excite and damp the solar oscillations and the appropiate equation of state to describe the thermodynamic properties of the solar structure. The treatment of the effects of near-surface errors in the model is also a serious concern and the expression of the surface term we use may not be completely valid. Obviously, in order to obtain reliable results from inversion in the outermost layers of the Sun, it is also necessary to acquire more experience in the observation of higher-degree modes to produce very accurate measurements.

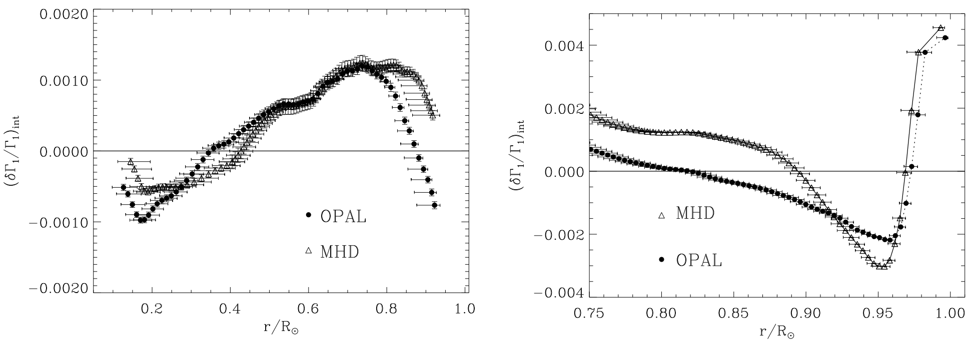

Fig. 2. The intrinsic difference in the adiabatic exponent Γ_1 between the Sun and the OPAL model (model S of Christensen-Dalsgaard et al. 1996) (filled circle) and the Sun and the MHD model (open triangles) obtained by inversion of two different sets of data by Schou (1998) with no high-degree modes (left panel) and by Rhodes et al. (1998) with high-degree modes (right panel).

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