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Solar structure as revealed by 1 year LOWL data

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Abstract. We have used solar frequencies obtained from 1 year of observations with the LOWL instrument to investigate the radial stratification of the Sun. Models which include the diffusion of helium and heavy elements below the solar convection zone are found to have a structure much closer to that of the Sun than models without diffusion. Also, models constructed with the Livermore (OPAL) equation of state seem to match the real Sun better than models constructed with the MHD equation of state. Finally, we find that an increase in the value of Z/X reduces the difference between models and Sun.

Key words: Sun: interior — Sun: oscillations — Diffusion

1. Introduction

Observations with the LOWL instrument have provided the first uniform and homogeneous set of solar frequencies with a wide range of degrees, allowing detailed inversion for the structure of the Sun from the core to very near the surface. The observations span a period of 1 year, and the resulting frequency estimates have relative errors as small as a few parts in 10^6. We have inverted these data to test some aspects of the physics of the solar interior. Specifically, we test the effect of two proposed equations of state, namely MHD (Hummer & Mihalas 1988; Mihalas, Däppen & Hummer 1988; Mihalas et al. 1990) and OPAL (Rogers et al. 1995). We also consider the effect of element diffusion beneath the base of the convection zone, and the effect of changing the assumed abundance ratio of heavy elements to hydrogen (Z/X). We do so by considering the inferred sound-speed difference between the Sun and each of four models constructed with different physical assumptions.

Solar oscillations can be described by the equations governing linear adiabatic oscillations (cf. Unno et al. 1989). After linearising the oscillation equations around a reference solar model, the differences between the Sun and the reference model satisfy

$$\frac{\delta\omega_i}{\omega_i} = \int K_i^{(c,\rho)}(r)\frac{\delta c^2(r)}{c^2(r)}\mathrm{d}r + \int K_i^{(\rho,c)}(r)\frac{\delta\rho(r)}{\rho(r)}\mathrm{d}r + \frac{F_{\mathrm{surf}}(\omega_i)}{S_i} \tag{1}$$

Here $\delta\omega_i$ is the difference in the frequency ω_i of the i^{th} mode between the solar data and a reference model; c and ρ are, respectively, sound speed and density as functions of radius r; the kernels $K_i^{(c,\rho)}$ and $K_i^{(\rho,c)}$ are known functions of the reference model and relate changes in frequencies to changes in c and ρ; and the F_{surf} term results from the near-surface errors in the physics, S_i being the inertia of the mode.

We use the method of Subtractive Optimally Localised Averages (SOLA; cf. Pijpers & Thompson 1994; Christensen-Dalsgaard & Thompson 1995), to carry out the inversions. The details of the procedure were described by Basu et al. (1995a).

2. Solar Models Used

We use four solar models as reference models to perform the inversions. Some of their properties, including the depth of the convective envelope (d_{CZ}s) and the central temperature (T_{c}) and density (ρ_{c}), are given in Table 1. All models were constructed with OPAL opacities (Iglesias et al. 1992). Models MHD1 and MHD2 use the MHD equation of state (EOS), whereas models OPAL1 and OPAL2 use the OPAL EOS. Where included, diffusion of helium and heavier elements is treated as prescribed by Michaud & Proffitt (1993). The quoted Z/X abundance ratios are present surface values.

Table 1. Properties of the solar models used.

Model	EOS	Diffusion	$(Z/X)_{\mathrm{s}}$	d_{CZ} ($\mathrm{R}_\odot$)	T_{c} (10^6K)	ρ_{c} (g cm^{-3})
MHD1	MHD	None	0.0245	0.2746	15.44	150.2
MHD2	MHD	He, Z	0.0245	0.2876	15.67	154.5
OPAL1	OPAL	He, Z	0.0245	0.2885	15.67	154.2
OPAL2	OPAL	He, Z	0.0259	0.2903	15.74	154.9

3. Results

The results of the inversions are shown in Figs. 1 and 2. Fig. 1 shows the inferred sound-speed difference relative to the MHD models, in the sense Sun minus model. The difference between the results in $0.4 \lesssim r/R_\odot \lesssim 0.7$ arises partly from the difference in depths of convection zone of the models and partly from their different hydrogen abundances (see Basu et al. 1995b for a fuller discussion). Model MHD1 can be firmly ruled out on the basis of this inversion. Coupled with the fact that diffusive models also have envelope helium abundances in better agreement with direct seismological determinations of the helium abundance in the ionization zones (cf. Christensen-Dalsgaard et al. 1993), it appears that element diffusion is an important physical effect in the Sun.

Figure 2 shows the relative sound-speed difference between the Sun and the diffusive models MHD2, OPAL1 and OPAL2. Comparing the results of models MHD2 and OPAL1 we see indeed that the latter is closer to the Sun. The OPAL models match the solar sound speed more closely both beneath the convection zone and also in the region $r \gtrsim 0.85R_\odot$. This supports the result of Basu & Antia (1995) who found that the OPAL EOS produces more accurate solar models in the layers immediately below the helium ionisation zones. We find that that this improvement is not restricted to this region alone — in the deeper layers too the OPAL have smaller sound-speed differences than the MHD models, the improvement being most pronounced at the base of the convection zone. In terms of its effect on the sound speed of a calibrated solar model, it does seem therefore that the OPAL equation of state is more appropriate for modelling the solar interior.

Comparing models OPAL1 and OPAL2, a small increase in the value of the heavy element abundance (through its effect on opacity) reduces the sound-speed difference between the Sun and model. The increase required is modest and well within the uncertainties of the observed heavy element abundance of the Sun.

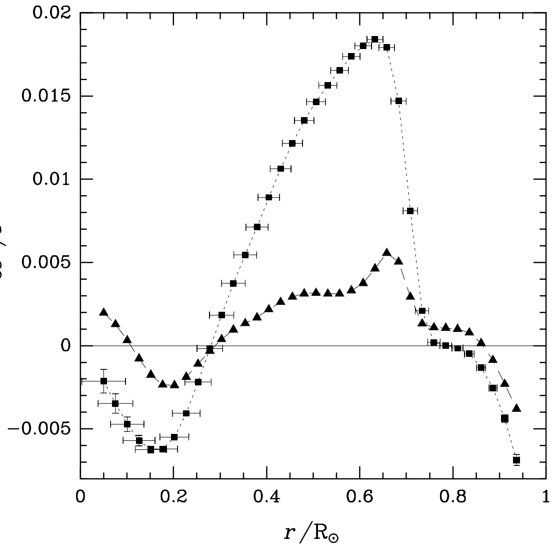

Figure 1. The sound-speed difference between the Sun and the two MHD models. The squares are the difference with model MHD1, the triangle with model MHD2. The error bars for model MHD1 are similar to those of MHD2 and hence not shown for the sake of clarity.

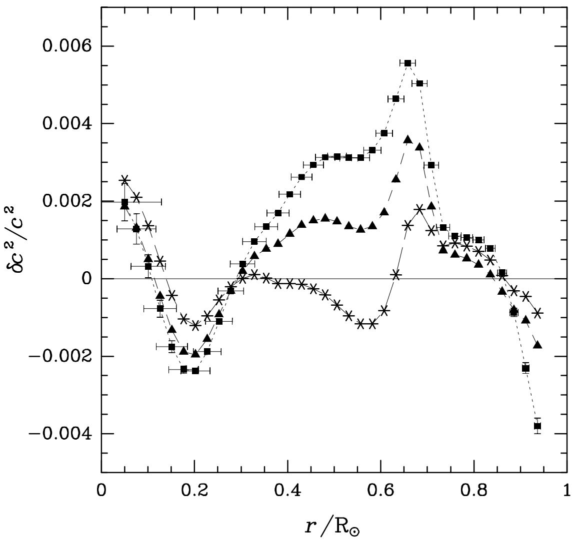

Figure 2. The sound-speed difference between the Sun and solar models MHD2, OPAL1 and OPAl2. The squares are the difference with model MHD2, the triangle with model OPAL1 and the asterisks those for model OPAL2. The error bars for models OPAL1 and OPAL2 are similar to those of MHD2 and hence not shown for the sake of clarity.

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