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Effects on solar structure of opacity changes

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Abstract. We investigate the sensitivity of solar structure to localized changes in opacity by considering differences between models computed with locally modified opacity and unmodified references models. The results confirm that the sound-speed differences are small in most of the convection zone. Assuming that the linear approximation is valid, we further show that these differences can be reproduced by constructing envelope models with the same input physical parameters as the original model.

Key words: solar structure, solar oscillations, opacity

1. Introduction

Uncertainties in the opacity have substantial effects on the solar models and frequencies. Here we probe the changes to solar structure by making a localized change in opacity as a function of temperature T. The modified models were constructed by obtaining the opacity κ as $\log \kappa = \log \kappa_0 + f(T, T_0)$, where κ_0 is the unmodified opacity, obtained as a function of T, density ρ and composition and the function $f(T, T_0)$ has the form

$$f(T, T_0) = A \exp\left[-\left(\frac{\log T - \log T_0}{\Delta}\right)^2\right] \tag{1}$$

The constants A and Δ set the magnitude and width of the opacity modification, and log is logarithm to base 10. By varying T_0 we can investigate the effects of localized opacity changes in different parts of the model.

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2. Differences in solar structure

As an illustration we consider a modified static model, calibrated to the correct luminosity and radius by scaling the hydrogen profile and adjusting the mixing-length parameter α; the opacity modification was characterized by $A = 0.02$, $\Delta = 0.02$ and localized at $T_0 = 10^7\,\mathrm{K}$. The resulting differences, at fixed radius r, are shown in Fig. 1. It is apparent that $\delta \ln T$ exhibits a step, corresponding to the localized change in opacity and hence in the temperature gradient. This behaviour is reflected in $\delta \ln c$ and $\delta \ln \rho$ whereas $\delta \ln p$ has a smoother behaviour. We further notice that the change in the sound speed in the convection zone is quite small, except in the helium and hydrogen ionization zones. Further aspects of such opacity modifications were considered by Tripathy & Christensen-Dalsgaard (1995).

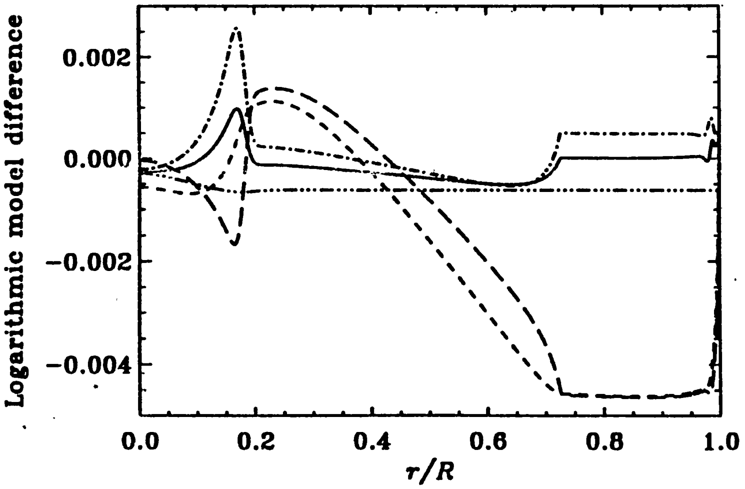

Figure 1. Differences at fixed fractional radius r/R between a static model modified at $T_0 = 10^7$ K and the reference model in the sense (modified) − (reference). Variables shown are $\delta \ln c$ (solid line); $\delta \ln p$ (short dashed line); $\delta \ln \rho$ (long dashed line); $\delta \ln T$ (dash-dot line) and δX (dash-triple-dot line); here ln is the natural logarithm.

3. Response of the envelope

For a given equation of state, the properties of the convection zone are essentially determined by the composition and the specific entropy. The latter is fixed by adjusting the mixing-length parameter α and by demanding that the model have the correct radius. Also, assuming that the heavy-element abundance can be determined spectroscopically, the composition can be characterized by the envelope hydrogen abundance X_s. Thus we expect to be able understand the response of the convection zone to modifications in the physics by considering envelope models characterized by the value of α and X_s.

The differences shown in Fig. 1 are small. Thus it is reasonable to apply a linear approximation to the response of the convection zone, according to which

$$\delta f \simeq \left(\frac{\partial f}{\partial X_s}\right)_\alpha \delta X_s + \left(\frac{\partial f}{\partial \alpha}\right)_{X_s} \delta\alpha \, , \tag{2}$$

for any quantity f; here the partial derivatives $(\partial f/\partial X_s)_\alpha$ and $(\partial f/\partial\alpha)_{X_s}$ are evaluated at fixed r, as functions of r. They can be estimated from envelope models as, e.g., $(\partial f/\partial X_s)_\alpha \simeq \delta f/\delta X_s$, for differences between two envelope models differing in X_s but having the same α.

In order to test this hypothesis, three different envelope models were used; their properties are listed in Table 1. Models EN1 and EN2 have the same values of surface hydrogen abundance X_s while EN1 and EN3 have the same values of α. Correspondingly the depth of the convection zone in all the models is different; in particular, higher α gives rise to a deeper convection zone. From these three models the partial derivatives in eq. (2) can be estimated.

Table 1. Properties of envelope models

Model	X_s	α	D_{cz}
EN1	0.69786	1.81586	0.27410
EN2	0.69786	1.84273	0.27700
EN3	0.70288	1.81586	0.27376

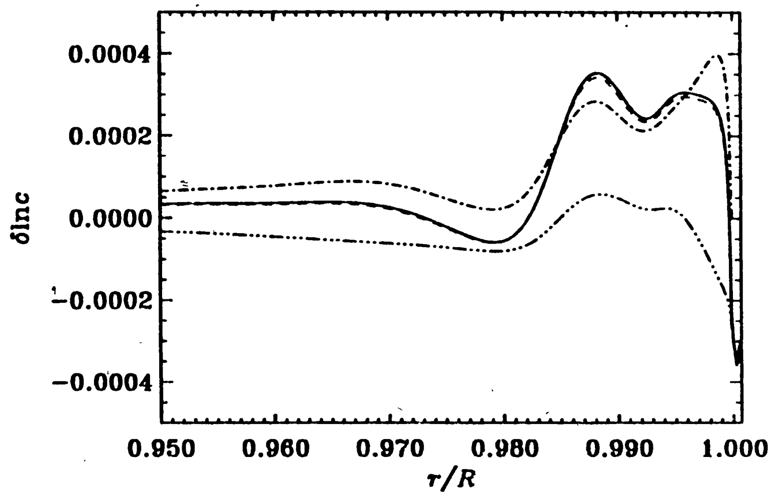

Figure 2. The sound-speed difference as constructed from the envelope models according to eq. (2). The solid line shows the original difference as in Fig. 1, the dash-dot and dash-triple-dot lines show the contributions from α and X_s respectively, while the dashed line shows the sum of these contributions.

Figure 2 presents the result of using the partial derivatives so obtained to reconstruct the sound-speed difference shown in Fig. 1 between the modified and reference model, on the basis of eq. (2) and the differences in α and X_s between the two models. It is remarkable that the differences can be reproduced so accurately. We also notice that the contribution from α is dominant and positive, while the contribution from X_s is negative except in the first helium ionization zone.

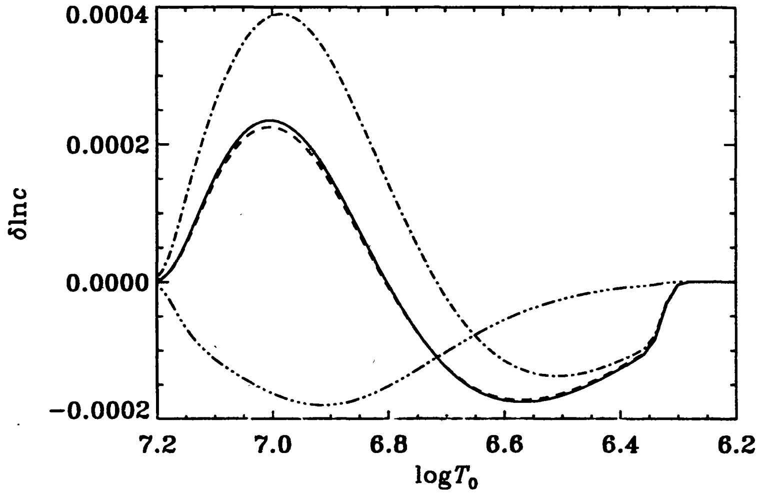

Figure 3. Fitted (dashed) and actual (solid) sound-speed difference as constructed from the envelope models as a function of log (T_0) at $r/R = 0.999$. The line styles have the same meaning as in Fig. 2.

Figure 3 shows the variation with the location T_0 of the opacity modification in the contributions to the sound-speed difference, and their sum, at a fixed point in the convection zone. When $\log T_0 \lesssim 6.3$ the opacity modification is confined to the convection zone and hence has no effect on the structure of the model. The contribution from the change in X_s is negative at all values of T_0. In contrast, the contribution from $\delta\alpha$ displays a more complex behaviour, although it generally dominates. Again we find that the linearized approximation in eq. (2) reproduces the sound-speed difference between the complete models quite accurately at all T_0, confirming the usefulness of this relation for understanding the response of the convection zone.

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