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Solar models with helioseismologically correct sound speed profile

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Abstract. The problem of computation of the model of the present Sun with given sound speed profile in the solar radiative zone is considered. It is shown that the chemical composition is still a free parameter but the entropy of the adiabatic part of the convection zone is determined by this procedure. Parameters of the models are compared with the helioseismic calibration of solar envelope and the disagreement is revealed. A study of the seismic properties of the models' cores indicates that the best model is the one closest to the standard solar model.

Key words: solar interior, helioseismology

1. Introduction

We are investigating the possibility of computing of the helioseismologically consistent model of the Sun. The final goal would be the model those frequencies are indentical to the observed ones. However, this way is plagued with many difficulties, mainly due to two facts: 1) frequencies depend on lots of factors, like outermost layers properties; 2) frequencies are integrands over wide parts of the Sun. To avoid these difficulties we used special derivatives instead of an oscillation spectrum: the parameters of the solar envelope: Y (surface helium abundance) and S (specific entropy of the adiabatic part of the convection zone) (Baturin, Vorontsov 1995), convection zone depth (Christensen-Dalsgaard et al. 1991) and sound speed profile (Vorontsov, Shibahashi 1991). Then we try to obtain the model of the Sun which is consistent with them.

To be able to get a model which is different from the standard one, we are broadening the class of solar models by introducing an assumption that modern opacity tables (namely, Livermore opacities (Iglesias, Rogers 1991)) can be modified in a reasonable manner. The opacity is probably the most poorly known component of solar model physics, so this assumption wouldn't look unnatural.

The possibility to obtain a solar model with the seismic envelope parameters (S, Y) and convection zone depth was studied by (Baturin, Ajukov 1995a,b). It is shown that such model can be computed, but required opacity changes are very large and have non-uniform shape (see Baturin, Ajukov (1995b)). Furthermore, this 'best' model has a sound speed profile inconsistent with seismic one (Vorontsov, Shibahashi 1991); see Fig. 1.

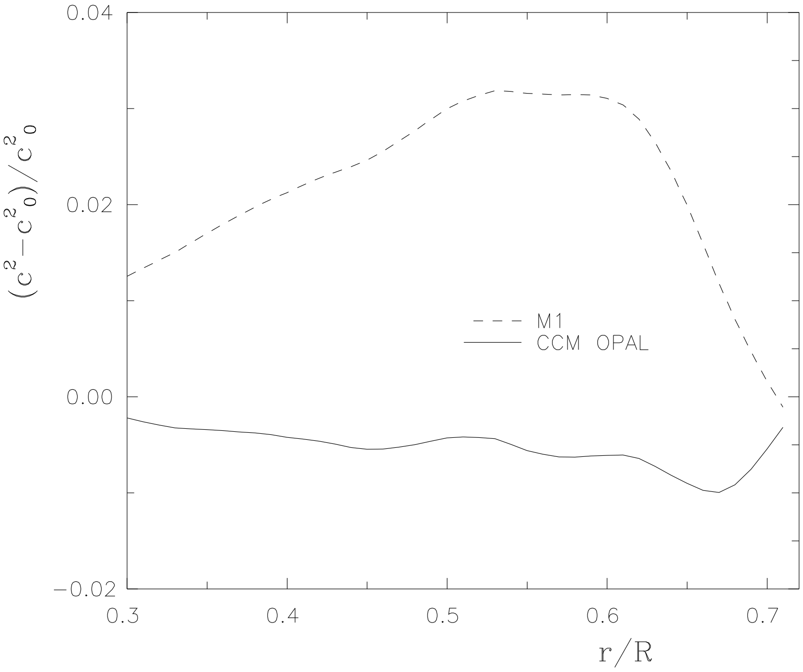

Figure 1. Sound speed profiles in two solar models – standard model using Livermore opacities (Iglesias, Rogers 1991) and the model M1 from (Baturin, Ajukov 1995b) which has opacity adjusted to obtain right values of solar envelope parameters. Zero (c_0) is the sound speed from (Vorontsov, Shibahashi 1991), derived from oscillation frequencies.

As you can see from Fig. 1, the standard solar model has sound speed profile pretty close to helioseismic one.

2. Solar models with given sound speed profile

Having failed to obtain solar model using seismic envelope parameters (Baturin, Vorontsov, 1995), one can try to use the sound speed profile instead. The sound speed profile isn't available everywhere in the Sun: it cannot be obtained with good accuracy in the solar core mainly due to restricted range of acoustic spectrum. On the other hand, all solar models have nearly the same sound speed profile in the most part of the convective zone due to adiabatic stratification. Hence we only considered fitting the sound speed in the radiative zone of the Sun, i.e. from $r/R = 0.3$ to the lower boundary of the convection zone (approximately $r/R = 0.7$).

Desirable sound speed profile can be achieved by choosing opacity value according to the sound speed gradient:

$$d\ln c^2/\ln P = 1 - 1/\Gamma_1 - Q\left[\nabla_{ad} - \frac{3L}{16ac\pi GM_r}\frac{P}{T^4}\kappa\right] \tag{1}$$

(assuming $\Gamma_1 = const$).We assume that no diffusion takes place, so helium abundance in the convective zone is the same as in the radiative zone. However we still have one free parameter to adjust while fixing sound speed profile: a surface helium abundance Y. We've computed a set of models with different Ys, (Baturin, Ajukov 1995b); opacity corrections in these models are plotted on Fig. 2.

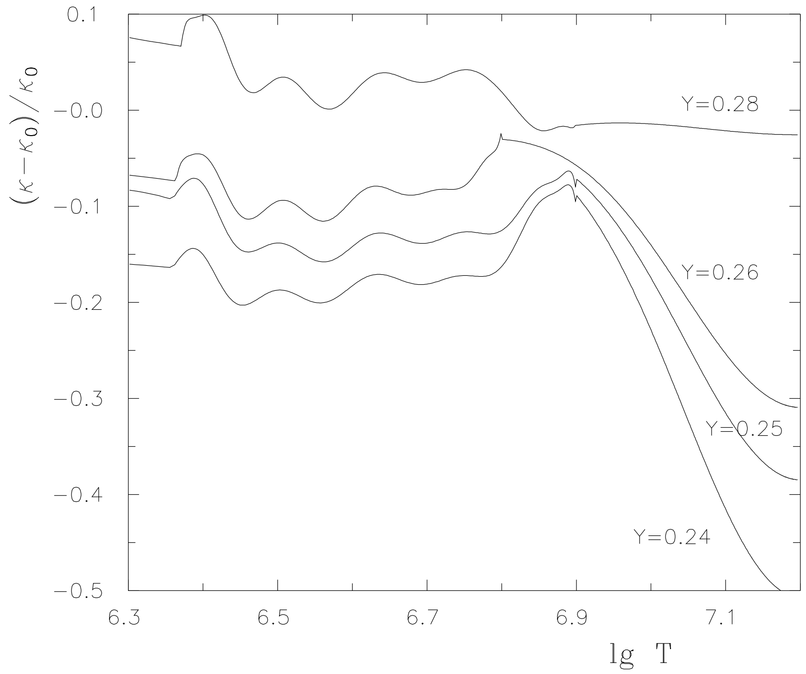

Figure 2. Opacity corrections in the models with different surface helium abundancies Y. All models have helioseismic sound speed profile in the radiative zone.

Correction is minimal for the model with $Y \approx 0.28$. Most of the latest helioseismic helium abundance estimations agree at $Y = 0.25$ ($Y = 0.2505 \pm 0.004$ (Baturin, Vorontsov 1995), $Y = 0.252 \pm 0.003$ (Antia, Basu 1994), $Y \approx 0.25$ (Christensen-Dalsgaard, Pérez Hernández 1991), $Y = 0.268 \pm 0.01$ (Däppen et. al. 1991), $Y = 0.234 \pm 0.003$ (Dziembowski et al. 1995)). Model with $Y = 0.25$ requires very large opacity correction in the core. The situation indicates that structure of the core is close to one from the standard model, but there must be gradient of helium abundance in the radiation zone, to achieve the low Y in the convection zone. This may point to diffusion-like effects.

We also have computed a small spacing of low-l frequencies which is determined mainly by the solar core structure. Comparison with observational data values (Elsworth et al. 1994) indicates that the best model again has high helium abundance in the core ($Y = 0.28$), just like the standard solar model. (see Table 1).

Table 1. Oscillation properties of model's cores.

		$l = 0, 2$			$l = 1, 3$	
	δ	δ_0	$d\delta/dn$	δ	δ_0	$d\delta/dn$
$Y = 0.24$	8.570	8.657	−0.2950	15.335	15.341	−0.4215
$Y = 0.25$	8.463	8.533	−0.2943	15.199	15.212	−0.4295
$Y = 0.26$	8.157	8.233	−0.2928	14.799	14.830	−0.4313
$Y = 0.28$	9.157	9.210	−0.3034	16.077	16.063	−0.4281
Standard model	9.201	9.266	−0.3061	16.150	16.137	−0.4302
Elsworth et al.	8.960	9.040	−0.3044	15.770	15.747	−0.4435

3. Conclusions

1) It is shown that models with the helioseismic sound speed profile exhibit a relation between the specific entropy of the convection zone and opacity in radiative zone. This relation is parametrized by the surface helium abundance.

2) Convective zone parameters in the model with the seismic sound speed profile are inconsistent with values obtained in phase-shift helioseismic study (Baturin, Vorontsov 1995). However, the standard solar model has sound speed profile rather close to the helioseismic one.

3) A set of models with seismic sound speed profile is computed. Seismic properties of the model's cores again indicate that the best solar model has opacities close to recent Livermore ones.

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