Helioseismic constraints on the structure of the present Sun

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1. Introduction

Given the chemical composition (hydrogen abundance mainly), the mass and internal physics, the structure of the star is determined uniquely. The commonly used method for the choice of the hydrogen abundance profile in the model of the present Sun is evolutionary calculations. But the existing uncertainties in physics and evolution give us an idea to consider a more extended set of possible solar models. We consider models with solar values of radius, luminosity and mass, but with an arbitrary profiles of hydrogen abundance in the core. Of course, to get up to solar values, profile $X(m/M)$ must satisfy some (nonstrict) restrictions, which are determined by fitting.

In this poster we propose a hypothesis that within fixed assumptions about internal physics (opacity, thermodynamics, nuclear reactions) a strict relation between the surface helium abundance and the entropy of the adiabatic part of the convective zone exists for all solar models. This hypothesis is verified with models under simplified physics (Christensen-Dalsgaard 1988) and with six evolutionary models computed by Christensen-Dalsgaard (1992). Such relation mainly depends on the functions of the opacities in radiative zone between the lower boundary of convection and the region of nuclear reactions. The possibilities of the agreement between such relation and helioseismic determination of surface helium abundance and entropy is discussed.

2. Solar models with fixed envelope

Let's consider solar models assuming that chemical composition (hydrogen and helium abundance Y_0) in convective envelope is fixed. To obtain solar values of radius R and luminosity L of the model we vary the hydrogen profile $X(m/M)$ in the core and the convective envelope entropy s. We use the specific entropy s in the adiabatic part of the convective zone as a parameter of the solar envelope instead of convection parameter α because of the value of α depends on structure of the outermost layers (in particularly, opacities). The specific entropy s is also related with convection zone depth but opacities affect this connection too. To compute the specific entropy we use the expression for free energy from Mihalas et al. (1988), but electron degeneracy was omitted:

$$s = -\left(\frac{\partial F}{\partial T}\right)_{V,N} = \left(k\sum_s n_s\left(\frac{5}{2} + \ln\frac{g_s}{n_s\Lambda_s^3}\right) + \frac{4}{3}aT^3\right)\Big/\rho$$

where sum is taken over all particles, $g_s = 2$ for electrons and g_s is a partition function for atoms and ions. Λ_s denotes thermal wavelength: $\Lambda_s = h/\sqrt{2\pi kTm_s}$.

As a result, fitted value of s was revealed to be the same for these models, and all our attempts to construct solar model with another entropy in convective envelope, but constant Y_0 in envelope were a failure. In other words, there are many models with different $X(m/M)$ profiles in the interior, but the same Y_0 in envelope, and all of them have the same s.

3. Relation between helium and entropy in envelope

We also have computed solar models with various helium abundance Y_0 in the envelope. Fitting to solar R and L is possible again, but these models have other entropy in the convective zone (and accordingly other convective zone depth d_b). However, for given Y_0 only one s is allowed, i.e. there is a relation between surface helium abundance Y_0 and convective zone entropy s in models with various $X(m/M)$ profiles in the interior (as it plotted on Figure 1 by crosses). To investigate the sensitivity of this $Y_0 - s$ relation to the internal physics we have computed models with the opacity locally altered a) in the energy-generating core and b) in the radiative zone. While opacity is changed in the core (where luminosity is not constant), the relation $Y_0 - s$ is preserved. However, changing of opacity in the radiative zone (between energy-generating core and convective zone bottom) shifts $Y_0 - s$ curve as a whole. Thus opacity in the radiative zone is one of the factors determining the position of the curve on $Y_0 - s$ plane.

Our calculations were performed with simplified model physics (according Christensen-Dalsgaard (1988)) and the helium abundance and entropy of our evolutionary model do not correspond commonly obtained in recent evolutionary calculations (Kim et al. 1991, Sackmann et al. 1990, Courtaud et al. 1990, Christensen-Dalsgaard 1991). To reveal the relation $Y_0 - s$ for other models we have calculated specific entropy for 8 models computed by J.Christensen-Dalsgaard (1992). We find a similar relation for three models with different age (22, 6, 21) and for three models with corrected opacity in the core (7, 27, 28). Model 4 differs from model 6 due to another opacities and model 14 from model 4 because of including Coulomb interactions. But all these models have too high entropy comparing with helioseismic determination by Vorontsov et al. (1991) (marked by $\odot$ on figure). Preliminary investigation indicates that to reach low entropy and required helium contents it is necessary to increase opacities in radiative zone (by factor 1.5 or 2) in comparison with used by us opacities (formulae from Christensen-Dalsgaard 1988) and accordingly to change opacities and/or profile of hydrogen abundance in the core.

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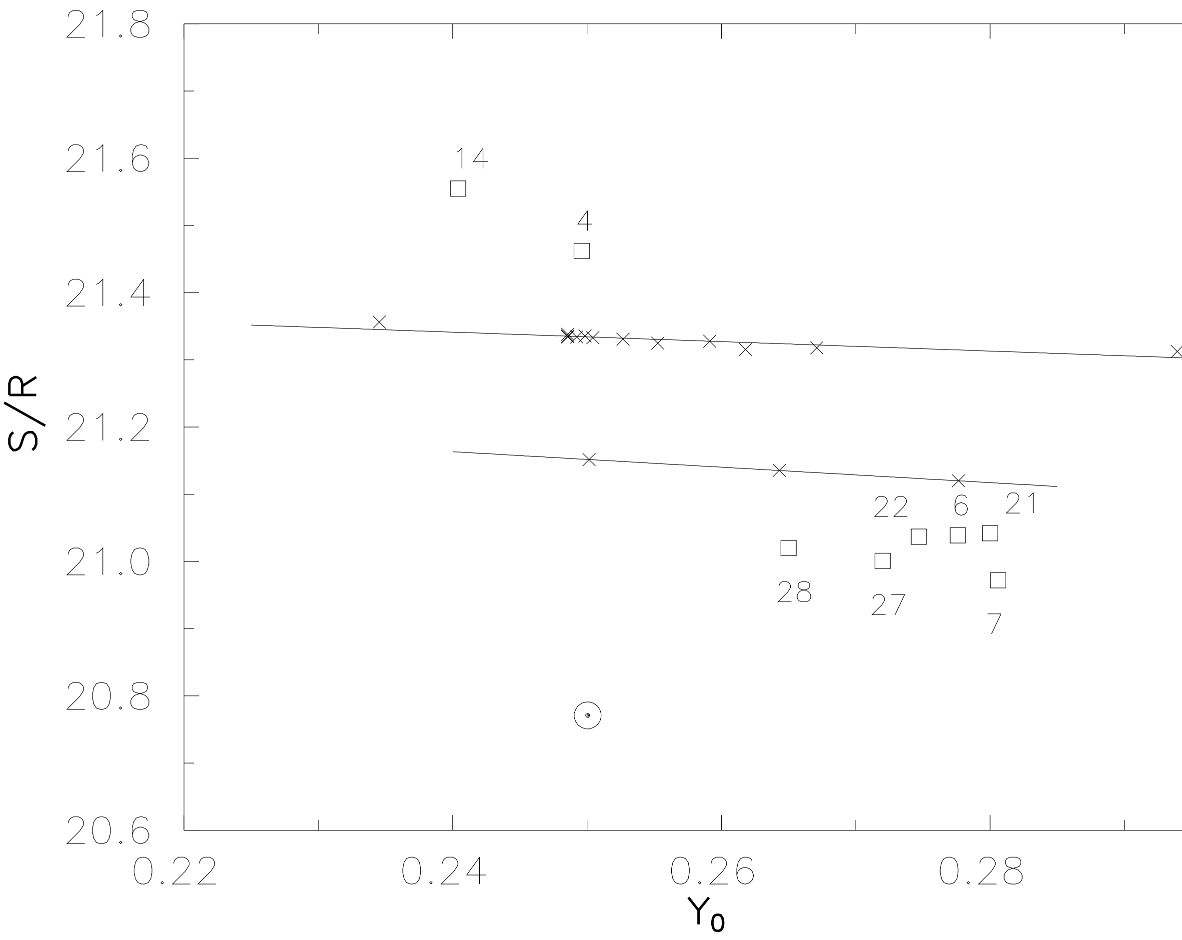

Figure 1. The specific entropy s/R (R - gas constant) and the surface helium abundance in the solar models. The crosses connected by lines represent relation $Y_0 - s$ in our models. Labelled squares denote models from Christensen-Dalsgaard 1992. $\odot$ - helioseismic determination of envelope parameters (Vorontsov et al. 1991).

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