PARAMETERS OF THE SOLAR CONVECTION ZONE IN EVOLUTIONARY AND SEISMIC MODELS

VLADIMIR A. BATURIN
Queen Mary & Westfield College, Mile End Road, London E1 4NS, UK

AND

SERGEY V. AYUKOV
Sternberg Astronomical Institute, Moscow 119899, Russia

Abstract. Three alternative approaches in evaluating of the entropy of the adiabatic part of the solar convection zone are compared.

Key words: solar physics, equation of state

1. Entropy as a parameter of solar structure

The specific entropy (s) and the helium abundance (Y), chief parameters of the solar convection zone, are still poorly determined. They are principal characteristics of the equation of state (EOS hereafter), whereas others apparent to be significant EOS's features can be rarely characterized in a simple way (*e.g.* nonideality deviations).

We focus on the specific entropy, which is "implicitly" presented in a wide range of solar studies. Thus the evolutionary calibration of a convection parameter appears to be anything else but calibration of the entropy. Entropy defines $(T-\rho)$ profile of the adiabatic convection zone, but together with surface conditions it accurately determines the mechanical structure $(\rho(r), m(r))$ too. A direct way to calibrate the entropy is adequate modelling of the superadiabatic convection and finding the jump of the entropy between the atmosphere and adiabatic layers. On the other hand, one should equalize the entropy jump before compare of different convection theories.

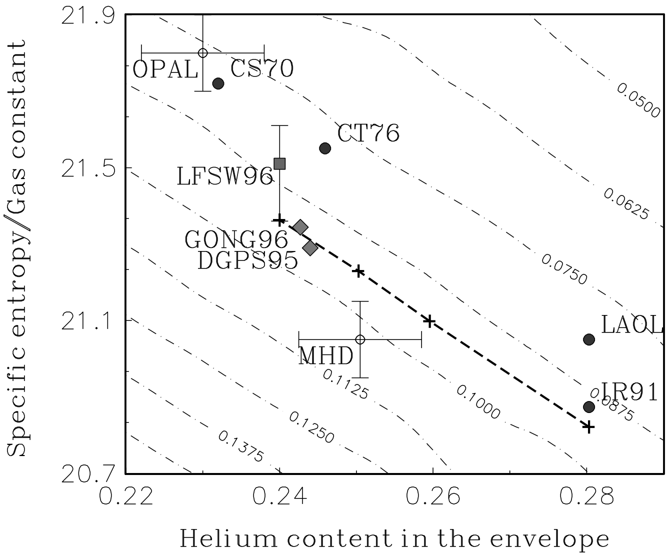

Figure 1. Filled circles correspond to the standard solar model from Baturin and Ayukov, 1995 (labels are opacity tables used). Filled diamonds are for models of others authors. Dashed line connects the crosses is $Y(s)$-dependence of models with helioseismic sound of speed. Two empty circles with error bars represent results of phase-shift calibrations of the helium ionization zone (with type of EOS as labels). Filled square with a vertical error bar is the result of the convective calibration by Ludwig *et al.*, 1996. Dot-dashed lines show density at the radius $r = 0.8$ in models.

An arbitrary constant in the thermodynamic definition of entropy is naturally eliminated in the statistical descriptions of contemporary EOS's. The numerical approximation of absolute entropy in MHD EOS needed for comparative studies is given by Baturin and Ayukov, 1996 (Hereafter MHD EOS is collectively for Mihalas, Hummer, Däppen).

2. Determination of the entropy in a solar model

Classic procedure of "evolutionary calibration" is in matching of a convective parameter and the initial helium abundance to get the correct radius and luminosity of a model of the present Sun. As a result one can get the helium content (and such estimation is widely accepted in astrophysics) and, at the same time, specify the entropy of the adiabatic convection zone as a conjugated to helium parameter. On Fig. 1, where coordinates are Y_{env} and s_{env}, the parameters of several standard models (Baturin and Ayukov, 1995) with different opacity are plotted as filled circles.

But we intend to extend the method of "model calibration" of the entropy to nonevolutionary models of the Sun. Indeed entropy calibration is essentially connected with mechanical relations. The condition of hydrostatic equilibrium is enough to get a mechanical structure (*i.e.* $P(r), \rho(r)$) from the profile of $u = P/\rho = c^2/\Gamma_1$ (Dziembowski *et al.*, 1990). Moreover, the necessary information can be restricted further. Due to mass concentration in solar-type model, the profile $u(r)$ only below considered point is sufficient to get $(P, \rho)_{r_0}$ in the lower part of the convective zone. Furthermore, Baturin and Ayukov, 1996 showed that $u(r)$ in the very core of the model ($r < 0.3$) does not affect convection zone entropy. So to define mechanical parameters we need $u(r)$ only in the radiative zone ($0.3 < r < r_{CZ}$), which is available from helioseismic inversion of $c^2(r)$, assuming Γ_1 is close to 5/3. But knowledge of (P, ρ) is equivalent to some $Y(s)$-dependance, because Y is not mechanical variable (and it does not appear in this consideration), but it affects an absolute value of entropy. As a result, any model with some given (seismically inverted one, for example) sound speed in the radiative zone will lay on the $Y(s)$-dependence. This dependence represents also the line of the equial density at a fixed temperature/radius, see Fig. 1.

3. Calibration of entropy on the helium ionization zone

Apart from the model calibration of entropy, a study of the helium ionization zone can be used as an alternative approach. The peculiarity of a sound speed profile gives a trace in the oscillation spectrum and can be calibrated with the phase-shift of a frequency-dependent function (Vorontsov *et al.*, 1992, Baturin, Vorontsov, 1995, Perez Hernandez and Christensen-Dalsgaard, 1994, Basu and Antia, 1995), or within helioseismic inversion, based on variational principle (Dziembowski *et al.*, 1995, Kosovichev, 1995). We refer mainly on our results of the phase-shift calibration due to two reasons. First, the variational calibrations are not unconditional in $Y - s$ space, because only models with "good" sound speed are considered, and they always belong to specific $Y(s)$-dependence. Second, the value of the calibrated entropy is rarely available from other authors. Our present results were obtained with a technique very close to described by Baturin, Vorontsov, 1995, except two improvements: we analyze the differential signal and scale the atmospheric opacity individually in every model.

Because the helium zone calibration is dealing with the thermodynamic peculiarity, it is very sensitive to EOS. We used two modern EOS's – MHD and OPAL (OPAL EOS described by Rogers *et al.*, 1996) and compared with other's results (see Table 1 and Fig. 1). We should point out that neither MHD nor OPAL EOS's do not supply us with an exact description of the helium ionization zone (although OPAL EOS has advantages in the description of deep layers of the convection zone) – the residuals for calibrated models still exceed a level of noise. So the differences between Y-calibrations with both EOS's (mentioned also by Kosovichev, 1995) and

TABLE 1. Helioseismic calibration of the helium zone

Author(s)	MHD EOS	OPAL EOS
Our results, 1996	$Y = 0.25 \pm 0.008$	$Y = 0.23 \pm 0.008$
	$S/R_g = 21.05 \pm 0.08$	$S/R_g = 21.8 \pm 0.1$
Kosovichev, 1995	$Y = 0.232 \pm 0.006$	$Y = 0.253 \pm 0.006$
Basu and Antia, 1995	$Y = 0.246$	$Y = 0.249$
Dziembowski *et al.*, 1995	$Y = 0.244 \pm 0.003$	$Y = 0.2505$
Perez Hernandez,		
Christensen-Dalsgaard, 1994	$Y = 0.242 \pm 0.003$	

the disagreement with the model calibration do not look surprising.

4. Entropy from hydrodynamic simulation

Ludwig *et al.*, 1996 presented the result of the most direct calibration of the entropy – from 2D numerical hydrodynamic calculation of convection. Results for model with $Y = 0.24$ are also plotted on Fig. 1. Note that their point is rather close to the $Y(s)$-dependence for the models with helioseismic sound speed.

5. Conclusions

The model calibration of the entropy appears to be most certain. The direct helium ionization calibration is perhaps too sensitive to any EOS's errors, so the discrepancy between approaches can indicate EOS's errors.

References

Basu, S., Antia, H.M., (1995), *M.N.R.A.S.* **276**, 1402.

Baturin, V.A., Ayukov, S.V., (1995), *Astronomy reports* **39**, 489.

Baturin, V.A., Ayukov, S.V., (1996), *Astronomy reports* **40**, 233.

Baturin, V.A., Vorontsov, S.V. (1995), *GONG'94: Helio- and Astero- seismology from the Earth and space*, ASP Conference series, **76**, p.188.

Dziembowski, W.A., Goode, P.R., Pamyatnykh, A.A., Sienkiewich, R. (1995), *ApJ* **445**, 509.

Dziembowski, W.A., Pamyatnykh, A.A., Sienkiewich, R. (1990), *M.N.R.A.S.* **244**, 542.

Kosovichev, A.G., (1995), *GONG'94: Helio- and Astro-Seismology from the Earth and space*, ASP Conference Series, **76**, p.89.

Ludwig, H.-G., Freytag, B., Steffen, M., Wagenhuber, J. (1996), *Solar Convection and Oscillations and their Relationship*, this proceedings.

Perez Hernandez, F., Christensen-Dalsgaard, J. (1994), *M.N.R.A.S.* **267**, 111.

Richard, O., Vauclair, S., Charbonnel, C., Dziembowski, W.A. (1996), *A& A*, in press.

Rogers, F.J., Swenson, F.J., Iglesias, C.A. (1996), *ApJ* **456**, 902.

Vorontsov, S.V., Baturin, V.A., Pamyatnykh, A.A. (1992), *M.N.R.A.S.* **257**, 32.