SENSITIVITY OF THE SOUND SPEED TO THE PHYSICAL PROCESSES INCLUDED IN THE STANDARD SOLAR MODEL

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ABSTRACT

We compare several largely independent calculations of solar models performed by different groups. As a reference is used the sound-speed profile extracted from GOLF+LOWL or GOLF+MDI data by S. Basu and J. Christensen-Dalsgaard. First, we show some effects of the recent physical improvements included in the standard model: opacity calculations and nuclear reaction rates and the role of the solar age on the sound-speed profile. We then present, compare and discuss the results of the different models.

Key words: solar models; physical processes; sound speed; solar neutrinos.

1. INTRODUCTION

The accuracy of the present seismic data allows us to check the solar internal sound speed down to 0.07 $R_\odot$ with an accuracy of about 2 10^{-4}. This provides an excellent basis for checking the hypothesis of the classical stellar evolution codes and the solar neutrino flux predictions. Nevertheless, at the present level of accuracy, we must be seriously concerned about the potential biases at the three levels of analysis in the extraction of physical information from this seismic probe. These are: 1) the problem of the possible asymmetric profile of the lines; 2) the problem of the quality of the inversion in the energy-generating core; and 3) the sensitivity of the solar sound-speed profile to the physical ingredients introduced in the standard framework of stellar evolution. In this poster, we consider the last class of problems.

First, we discuss the new updated physics introduced in the solar models and the sensitivity of the sound-speed difference, between GOLF+MDI (or GOLF+LOWL) observations and models, to different ingredients such as the nuclear reaction rates or the solar age. Then we present and discuss the results coming from 6 solar models calculated by different groups of the GOLF consortium which include the most recent progress in atomic and nuclear physics. This study leads to some useful recommendations for a proper interpretation of the acoustic-mode measurements.

2. THE SEISMIC DATA SETS

In the solar sound-speed comparison, we use acoustic mode frequencies obtained by the classical maximum likelihood technique assuming symmetrical lorentzian profile. The low-degree modes, with $l = 0$ to 3, come from the GOLF consortium for 8 month measurements beginning on 11 April 1996 (Lazrek et al. 1997) or for the first 1 year, beginning at the same date (Roca Cortès et al., The solar acoustic spectrum as seen by GOLF. III Asymmetries, resonant frequencies and splitting, these proceedings). For higher-degree modes, we use 1 year of data from LOWL beginning in February 1995 (Tomczyk et al. 1995) or the first 144 days from MDI beginning in May 1996 (Rhodes et al. 1997).

Inversion of these data was performed by S. Basu and J. Christensen-Dalsgaard (for details on the inversion method, see Basu et al. 1996). Several intercomparisons between these different sets of data (including the 1 year MDI data set for $l > 3$) have not shown substantial differences in the sound-speed profile, even in the core, contrary to the use of BiSON+LOWL data sets (e.g. Basu et al. 1997). One can find some discussion on this point together with a first view of the solar core in the work performed by the GOLF interpretation team (Turck-Chièze et al. 1997).

3. SENSITIVITY OF THE SOUND SPEED PROFILE TO THE OPACITIES AND THE REACTION RATES

During the two last years, we have noted several improvements in the treatment of the physical processes included in standard models. Two of them modify the sound-speed profile in the radiative zone.

The updated opacity calculation of Iglesias and Rogers (1996) includes now 21 elements and the improved equation of state (Rogers, Swenson and Iglesias 1996), which plays a crucial role under the solar conditions. They have added to the previous list the contributions of P, Cl, K, Ti, Cr, and Mn, although these elements have number fraction smaller than $2\,10^{-6}$. The slight increase of the opacity coefficients due to their bound-bound contributions is largely compensated by a decrease due to the inclusion of the improved equation of state. The net result is a decrease of the opacity near the base of the convective zone (Figure 1), which contributes to the increase in the relative difference $\delta c^2/c^2$ in the squared sound speed by about 0.3%, and partly contributes to the largest peak in $\delta c^2/c^2$ (see Figure 2).

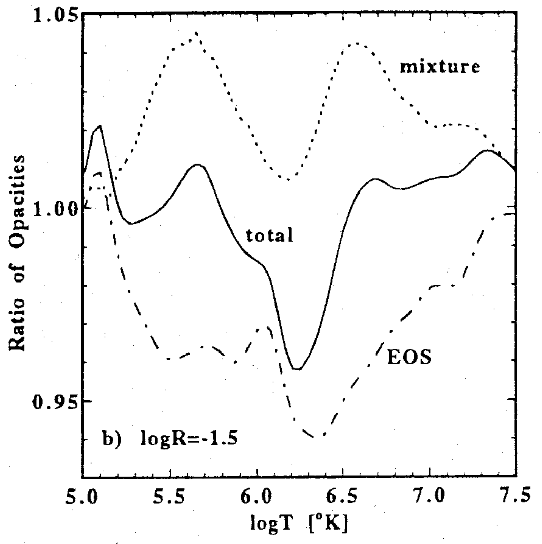

Figure 1. Ratio of Rosseland mean opacities for a solar mixture after the 1996 updated: effect of the mixture (dashed line), effect of the equation of state (dot-dashed line) [From Iglesias and Rogers, Fig. 5].

A very recent update of the nuclear reaction rates (Adelberger et al. 1998) includes recent results on screening (Dzitko et al. 1995; Gruzinov and Bahcall 1998) and on (^{3}He,^{3}He) and (^{7}Be,p) experiments, together with a re-examination of the latter reaction rate (resulting in a 15% decrease, although still with large error bars). The net result is a slight increase of the sound speed in the solar core in comparison with the use of Caughlan and Fowler (1988) which was up to now often used (Figure 2).

Globally, the present difference in the square of the sound speed between observations and models including these improvements is modified and even increased, compared with previous results.

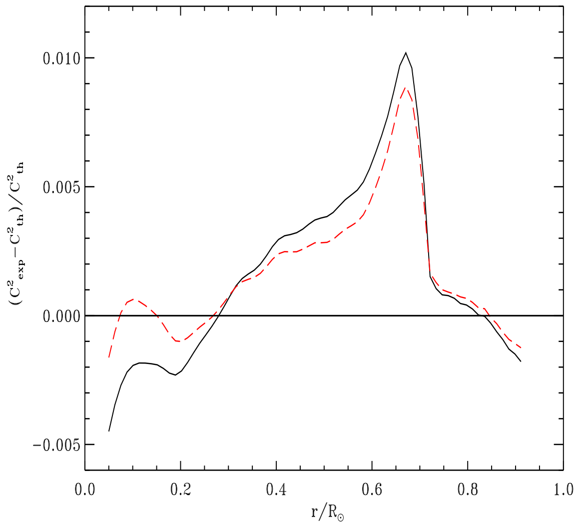

Figure 2. Change in the difference in the squared sound speed between the Sun measured by GOLF+LOWL experiments (Lazrek et al. 1997; Tomczyk et al. 1995) and models computed with different nuclear reaction rates: Caughlan and Fowler + weak screening (1989) (dashed line) and Adelberger et al. including intermediate screening (1998) (full line). The models, including updated opacities, were obtained by the Saclay group for an age of 4.52 Gyr.

4. WHAT CAN BE LEARNED FROM THE INTERCOMPARISON BETWEEN DIFFERENT GROUPS ?

As these effects on the sound speed are significant, we have decided to carry out an intercomparison between groups belonging to the GOLF team to avoid any specific misunderstanding in the interpretation of the sound-speed difference. Using the same set of data and the same inversion, we have initially noticed differences between us which as high as $5\,10^{-3}$; this corresponds to differences relative to solar structure of a similar size.

This was partly due to different versions of the previous fundamental ingredients. But we have noticed some other divergences of considerable interest.

The first one is the way to interpolate in the opacity tables. The opacity increases strongly from the central core to the base of the convection zone (at least by a factor 20) and must be represented with sufficient accuracy. The original grid of the Livermore group, between 0.3 and $0.7\,R_\odot$, is not sufficiently dense for an analysis at the required level of precision; thus a better resolution of the corresponding part of the tables is required if, for example, we would like to obtain information about heavy-element composition through helioseismic measurements (Turck-Chièze 1998). Consequently the interpolation procedure plays a crucial role. We have compared two interpolation subroutines: the one given by the Livermore group and the one produced by Houdek and Rogl (1996), with their option 4 to use 5 tables for the interpolation. We have found a difference of about 1% in the opacity, leading to a difference of about 0.1% in the sound speed over the solar interior, between these two interpolation schemes. It seems that using a different option in the Houdek and Rogl interpolation may lead to larger effects, including change by 0.003 in the difference in the squared sound speed, so the first option mentioned above is probably to be recommended.

The second lesson from this comparison is the large sensitivity of the sound-speed difference to the solar age. The models compared within the team are based on three different definitions of start of evolution and hence the solar age: models including a pre-main-sequence phase (of typical duration of around 70 Myr); models computed from the beginning of the hydrogen burning; and models computed from the end of the phase with a small convective core (60 Myr later).

5. SENSITIVITY OF THE SOUND SPEED PROFILE TO THE SOLAR AGE

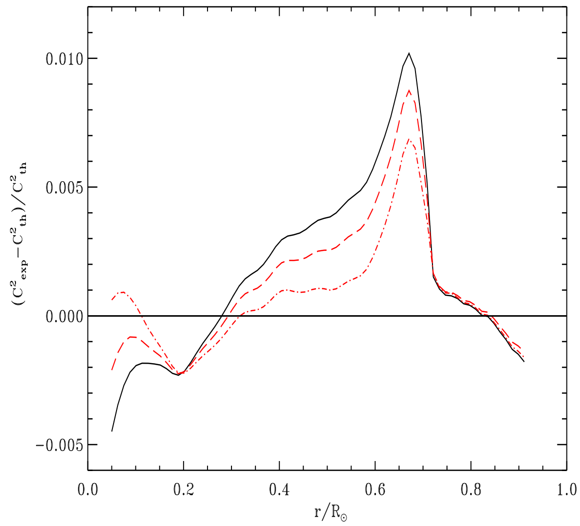

Figure 3. Difference in squared sound speed between the Sun, inferred from the GOLF+LOWL experiments (Lazrek et al. 1997, Tomczyk et al. 1995), and three models of different ages: full line 4.52 Gyr, dashed line 4.6 Gyr, dot-dashed line 4.7 Gyr. (Models from Saclay group).

Figure 3 illustrates the age dependence, by showing the difference in squared sound speed, relative to the inversion, for three different solar ages: 4.52, 4.6, 4.7 Gyr with a starting point at the arrival on the main sequence. There is a large variation in the solar core, leading to a negative or a positive value of the difference. It might be noticed that the three curves pass through the same point at 0.2 $R_\odot$: at this point, evidently, the sound speed is relatively insensitive to the age.

There are two studies of the solar age. Guenther et al. (1992) recommended an age of 4.52 ± 0.04 Gyr, if the computation begins when hydrogen burning starts. Another study by Wassenburg (cf. Bahcall and Pinsonneault, 1995) leads to a value of 4.57 ± 0.005 Gyr, including the pre-main-sequence evolution. These two values are compatible; we estimate that at present the most probable estimate is 4.55 ± 0.04 Gyr; The main problem is the uncertainty in the duration of the pre-main-sequence phase which must be considered, in relating the planet formation to solar evolution.

It is clear also that with present accuracy requirements it would be preferable to begin the evolution during the gravitational collapse in the pre-main-sequence phase.

6. THE DIFFERENT MODELS

In this study, we compare 5 codes: the CESAM code developed in France for calculations of high accuracy (Morel 1997) in two versions, the Nice version (Morel, Provost and Berthomieu 1997) with updated physics and the Saclay version with a somewhat different formulation of the updated physics (Brun, Turck-Chièze and Morel 1998), the Aarhus code, developed by Christensen-Dalsgaard (1982) and regularly updated and improved (Christensen-Dalsgaard et al. 1996), the Max Planck code especially implemented to improve the subatmospheric stratification (Schlattl et al. 1997) used by the Catania group, the Liège code with improved physics but using a different equation of state (Gabriel, 1997) and the Montreal code dedicated to a detailed study of the microscopic diffusion (Turcotte et al. 1998). All these codes are classical stellar evolution codes written with a high numerical accuracy. Table 1 specifies some characteristics of the different computations.

7. INTERCOMPARISON

We have performed an intercomparison of the different models for a solar age of 4.6 Gyr, with the updated reaction rates, equation of state and recent Livermore opacities. The results are summarized in Table 2 and Figures 4 and 5. One may note that the agreement is very good between different groups, using different codes when exactly the same physical treatment is included in the calculation, see the Aarhus, Catania, Nice and Saclay results. Some difference in neutrino predictions is attributed to different nuclear screening effect. This study has shown also that, at the accuracy reached by the present acoustic-mode observations, noticeable differences in the departure of the sound speed from the helioseismically inferred behaviour may appear as a result of small differences in the computation, for example the age adopted, the screening enhancement adopted, or the procedure of fitting. This is illustrated by the Nice and Saclay results which are based on the same code but with different ways to introduce the physical processes (screening, opacity interpolation, atmospheric layer physics...).

We have not observed significant difference between the two ways to introduce the microscopic diffusion: the prescription of Thoul et al. (1994) or the prescription of Proffitt and Michaud (1991). Nevertheless, Turcotte et al. (1998) showed that including a complete treatment of diffusion leads to larger abundance variations throughout the solar interior, most notably at the base of the convective zone. The gradual depletion of helium and heavy elements from that region leads to a reduction in opacity and mean molecular weight. This causes a relative cooling of the region just below the convective zone. Since the sound speed is roughly proportional to the ratio between temperature and mean molecular weight, the effect partially cancels itself. However, the net effect is a reduction

Table 1. Table 1: Treatment used in the different models for the screening enhancement factor introduced in the nuclear reaction rates [Mitler (Dzitko et al. 1995) or weak screening (WS)], equation of state (mass fraction of heavy elements used), the type of interpolation used, and the prescription of microscopic diffusion [Proffitt and Michaud (1991) or Thoul (1994)]

Code	screening RR	eq state (Z)	Opacity interp	Diffusion
Aarhus	Mitler	Livermore(0.02)	Houdek 4	Proffitt Michaud
Catania	WS	0.021	Livermore	Thoul
Liège	WS	specific eq state	Livermore	Thoul
Montreal	WS	CEFF	Livermore	complete
Nice	WS	Livermore(0.019)	Houdek 4	Proffitt Michaud
Saclay	Mitler	Livermore(0.0195)	Livermore	Proffitt Michaud

Table 2. Table 2: Thermodynamical Quantities and Neutrino Predictions of a solar model which starts from ZAMS; age 4.60 Gyr. Solar Model: $\Delta R/R_\odot$ *and* $\Delta L/L_\odot$*: accuracy on* $R_\odot$ *and* $L_\odot$*,* α*: mixing length parameter,* Y_0*,* Z_0*,* $(Z/X)_0$*: initial helium and heavy-element abundances and initial ratio of heavy elements to hydrogen,* Y_s*,* Z_S*,* $(Z/X)_S$*: idem for present photospheric compositions,* τ_b *is the optical depth of the bottom of the atmosphere,* R_{bcz}*,* T_{bcz} *are the radius and temperature at the base of the convective zone,* Y_c*,* Z_c*,* T_c*,* ρ_c*: central helium, heavy-element contents, central temperature and density;* P_0*: gravity mode period spacing;* ^{37}Cl, ^{71}Ga, ^{8}B*: neutrino predictions for, respectively, the chlorine, gallium and water detectors.*

Parameters	Saclay	Aarhus	Catania	Liège	Nice	Montreal
Opacities	OPAL95/K	OPAL95	OPAL95	OPAL95+Neuforge	OPAL95/A	OPAL95
$\Delta R/R_\odot$	-2.045 10^{-5}	-4.79 10^{-8}	-8.66$10^{-5}$	1.51 10^{-6}	1.77 10^{-5}	3.33$10^{-5}$
$\Delta L/L_\odot$	6.82 10^{-5}	-1.80 10^{-7}	-1.45$10^{-4}$	7.96 10^{-6}	8.49 10^{-5}	1.05 10^{-5}
α	1.885	1.981	1.744	2.424	1.772	2.099
Y_0	0.272	0.272	0.273	0.277	0.272	0.285
Z_0	1.968 10^{-2}	1.963 10^{-2}	1.971 10^{-2}	2.05 10^{-2}	1.96 10^{-2}	1.957 10^{-2}
$(Z/X)_0$	0.0278	0.0277	0.0278	0.0290	0.0277	0.028
Y_s	0.242	0.245	0.243	0.254	0.243	0.258
Z_s	1.812 10^{-2}	1.804 10^{-2}	1.810 10^{-2}	1.907 10^{-2}	1.803 10^{-2}	1.792 10^{-2}
$(Z/X)_s$	0.0245	0.0245	0.0245	0.0262	0.0245	0.0247
$R_{bcz}/R_\odot$	0.7139	0.7138	0.7130	0.7136	0.7126	0.719
$T_{bcz} \times 10^{-6}$ (K)	2.183	2.187	2.182	2.201	2.196	2.160
Y_c	0.639	0.641	0.644	0.641	0.643	0.636
Z_c	2.089$10^{-2}$	2.031 10^{-2}	2.106 10^{-2}	2.089 10^{-2}	2.094 10^{-2}	2.052 10^{-2}
$T_c \times 10^{-6}$ (K)	15.689	15.691	15.73	15.74	15.70	15.77
ρ_c (g/cm^3)	153.12	154.17	153.55	154.33	153.3	149.49
P_0 (mn)		35.32	35.41	35.125	35.17	
^{37}Cl (SNU)	7.33	7.165	7.84	not calculated	7.32	
^{71}Ga (SNU)	128.	127.6	130.	not calculated	128.5	
^{8}B (10^6/cm^2/s)	4.93	4.77	5.26	not calculated	5.21	

of the sound speed below the convective zone as shown in Figure 5c. The somewhat discrepant results on the initial and present photospheric helium abundance require further investigation.

We note that the model of Liège, which includes slight different inputs such as the equation of state and some effect of mixing due to the rotation during the lifetime of the Sun, may lead to different results for the initial helium content or the present Z/X in the photospheric abundance. This model proposes a way to treat the large bump located just below the convective zone. Indeed, it is well established that part of this difference could come from some inhibition of the microscopic diffusion in this region due to material motion (see also Brun, Turck-Chièze and Zahn, these proceedings; Elliott, Gough & Sekii, these proceedings).

8. RECOMMENDATIONS

This study has investigated the difference in sound speed between the Sun, inferred from the GOLF+MDI data, and models including the best updated physics and microscopic settling of helium and heavy elements. In addition, some models were considered where settling was partially inhibited by mixing processes.

We note that recent progress in nuclear physics and opacity has somewhat increased the discrepancy with the Sun, showing the great sensitivity of the sound-speed profile to these physical properties of the solar interior. These improvements, connected to new nuclear measurements or theoretical efforts on the equation of state, must be pursued and confirmed.

A clear recommendation following this study concerns:

- In the opacity tables used for the present computation, some intermediate values in the range $0.3 - 0.7\,R_\odot$ would be useful to describe properly this region of the Sun which could be sensitive to the heavy-element composition (see Turck-Chièze, Brun, Chièze & Garcia, these proceedings; Turcotte and Christensen-Dalsgaard, these proceedings).
- The solar age, used for the computation, substantially influences the comparison in the nuclear core and must be chosen between 4.52-4.57 Gyr, for a computation beginning at the arrival on the main sequence.

Following this analysis, it is clear that the interpretation of the present discrepancy between acoustic observations and theoretical predictions encourages at least the introduction of turbulent diffusion at the base of the convective zone.

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REFERENCES

Adelberger, E. et al. 1998, Rev. Mod. Phys. Oct.

Bahcall, J.N. & Pinsonneault, M.H. and Wasserburg, G. J. 1995, Rev. Mod. Phys., 67, 781.

Basu, S., Christensen-Dalsgaard, J., Pérez Hernández, F. & Thompson, M. J., 1996, MNRAS, 280, 651.

Basu, S. et al., 1997, MNRAS, 291, 243.

Brun, A.S., Turck-Chièze, S. and Morel, P., 1998, to appear in ApJ vol 506,2.

Caughlan, G. R., & Fowler, W. A. 1988, Atomic Data and Nuclear Data Tables, 40, 284.

Christensen-Dalsgaard, J. 1982, MNRAS, 199, 735.

Christensen-Dalsgaard, J. et al., 1996, Science, 272, 1286.

Dzitko, H., Turck-Chièze, S., Delbourgo-Salvador, P., & Lagrange, G. 1995, ApJ., 447, 428.

Houdek, G. and Rogl. J., 1996, Bull. Astro. Soc. India, 24.317.

Gabriel, M., 1997, A.A., 327, 771.

Guenther, D. B., Demarque, P., Kim, Y.-C., & Pinsonneault, M. H. 1992, ApJ, 387, 372.

Gruzinov, A. V. & Bahcall J. N. 1998, ApJ, vol 504.

Iglesias, C. & Rogers, F. J. 1996, ApJ, 464, 943.

Lazrek, M. et al., 1997, Sol. Phys., 175, 227.

Morel, P. 1997, A&A Sup., 124, 597.

Morel, P., Provost, J., and Berthomieu, G., 1997, A&A, 327, 349.

Proffitt, C. R., & Michaud, G., 1991, ApJ, 380, 238.

Rhodes et al. 1997, Sol. Phys., 175,287.

Rogers, F. J., Swenson, J. & Iglesias, C. 1996, ApJ, 456, 902.

Schlattl, H., Weiss, A., Ludwig, H.-G. 1997, Astron. Astrophys., 322,646.

Thoul, A. A., Bahcall, J. N., Loeb, A., 1994, ApJ., 421, 828.

Tomczyk, S., Streander, K., Card, G., Elmore, D., Hull, H., & Cacciani, A. 1995, Sol. Phys., 159, 1.

Turck-Chièze, S. 1998, ISSI workshop on solar composition and its evolution. From core to corona. Bern, January 1998, Space Science Review, Kluwer Academic publishers.

Turcotte, S., Richer, J., Michaud, G., Iglesias, C. A., & Rogers, F. J. 1998, to be published in ApJ

Turck-Chièze, S. et al., 1997, Sol. Phys., 175, 247.

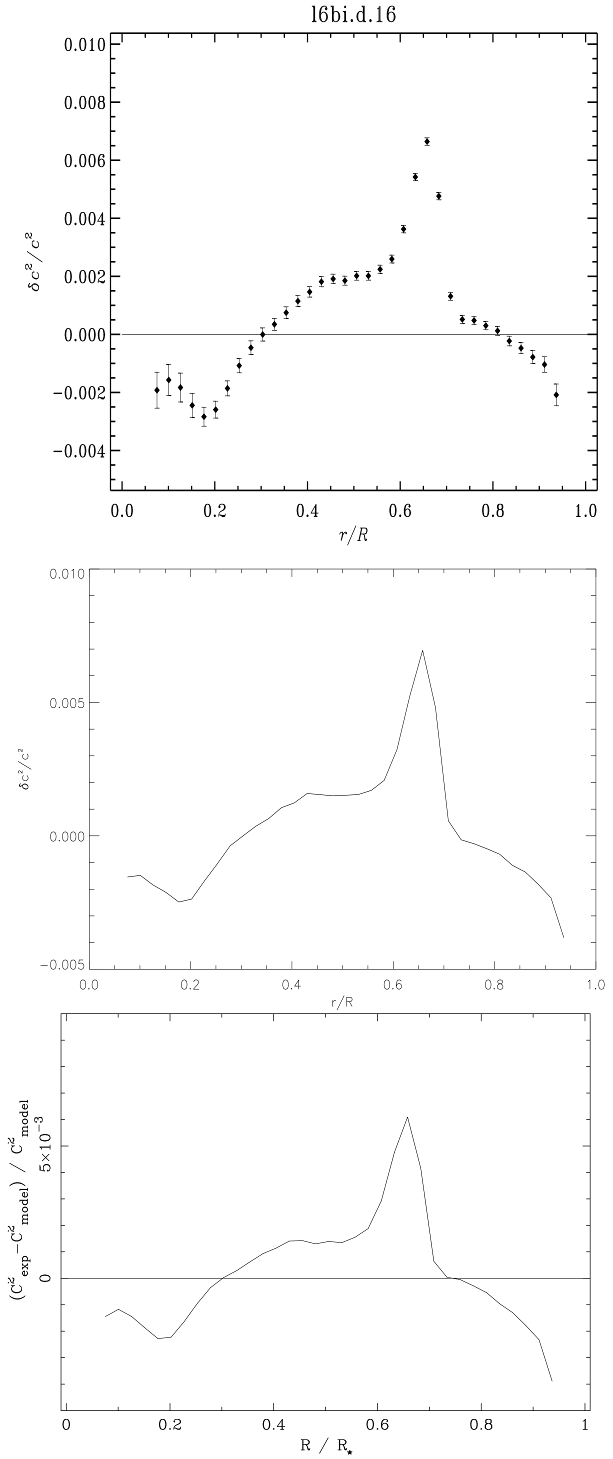

Figure 4. Sound speed square difference between the Sun measured by GOLF+MDI and models from Aarhus, from Catania and from Nice.

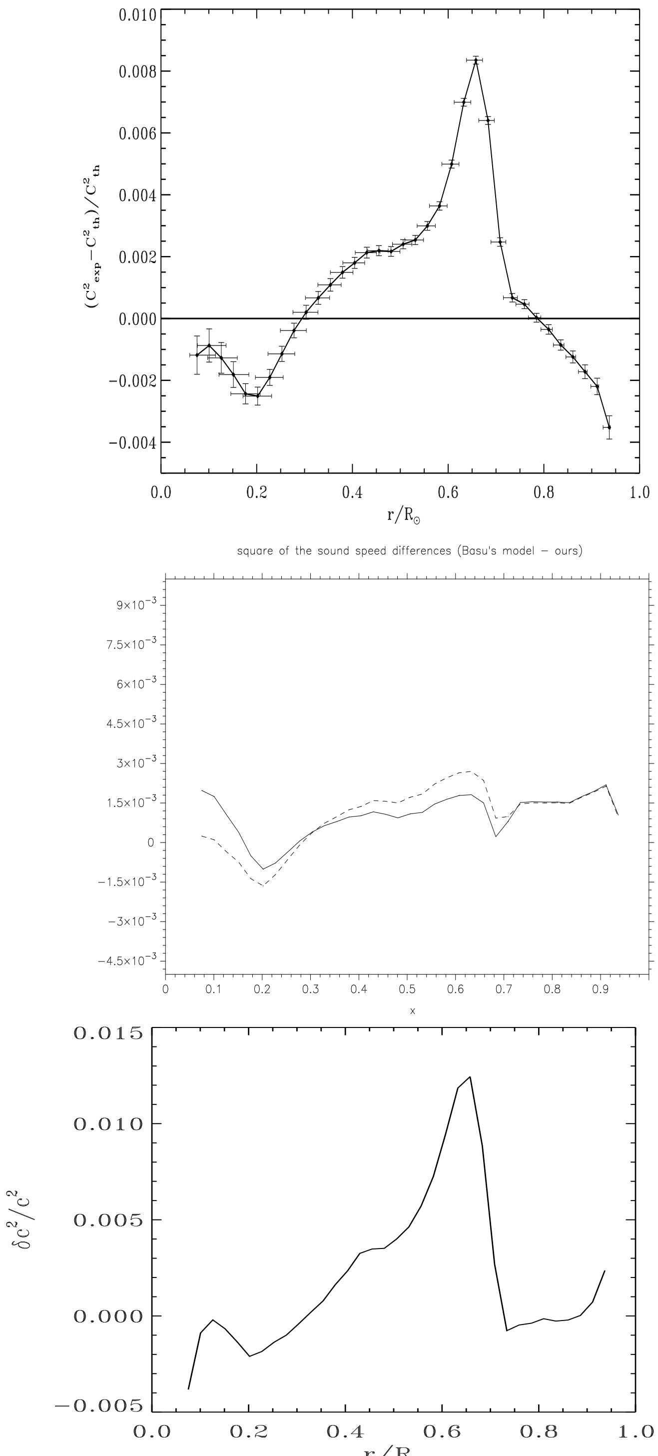

Figure 5. Sound speed square difference between the Sun measured by GOLF+MDI and models from Saclay, Liège (the full line corresponds to old reaction rates according to Gabriel 1994, the dashed line to the new ones), and from Montreal.