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The new solar abundances - Part II: the crisis and possible solutions

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Abstract

Recent 3D, NLTE analysis of the solar spectrum (Asplund et al. 2006, Part I; Asplund et al. 2005) have led to a significant reduction of the CNO and Ne abundances leading to a $(Z/X)_{\rm s}$ 30% smaller than the previously recommended value. The corresponding decrease in opacity increases dramatically the discrepancies between the sound-speed derived from helioseismology and our new standard solar models (SSM). We present in this paper some numerical experiments trying to reduce this discrepancy.

1. Introduction

Since the seventies, when the modal structure of solar oscillations was confirmed, a great number of observational experiments from ground networks (BiSON, GONG, LOWL IRIS,TON) and from space (GOLF, VIRGO, SOI/MDI) have provided the frequencies of the solar oscillations for low, intermediate and high degree modes. The great number of p-modes detected, and the high accuracy of their frequency determination (relative error smaller than 5.10^{-6}) have allowed to relate the frequencies to the properties of the solar internal structure. Within the adiabatic approximation, frequencies are completely determined by the density, $\rho(r)$, and the adiabatic sound-speed, $c(r)$; as a consequence, the inversion of these frequencies has made it possible to infer $c(r)$ in the Sun with an accuracy of a few parts in 10^4, and $\rho(r)$ with an accuracy of a few parts in 10^3. In addition, differential inversion of frequencies has allowed to derive precise values of the location of the bottom of the convective zone ($R_{\rm cz} = (0.713 \pm 0.001)R_{\odot}$, Christensen-Dalsgaard et al. 1991; Basu 1997), and to obtain the current mass fraction of He in the convective zone: $Y_{\rm s} = 0.24 - 0.25$ (depending on the equation of state, Basu & Antia 1995; see also Sackmann & Boothroyd 2003).

In 1996, putting together all the current updates to the physics: solar mixture of metals by Grevesse & Noels (1993, GN93), new opacity tables (Iglesias et al. 1992), a consistent equation of State from OPAL (Rogers et al. 1996), and helium diffusion and settling (Proffit & Michaud 1993), Christensen-Dalsgaard et al. (1996) generated what is referred to as Model S (or S96 model) of the Sun. The square of the sound speed, c^2, derived from this standard solar model agreed remarkably with the values obtained from helioseismology within 0.5%!

Since the publication of the standard Model S, successive updates to the physics, i.e. opacity (OPAL 1996), nuclear reaction rates (NACRE), and solar composition (Grevesse & Sauval 1998), have however led to larger differences between the observations and the predictions (Turck-Chièze et al. 1998). The recent update of the solar chemical composition (Asplund et al. 2006, Part I) has led to a decrease in the CNO and Ne abundances by more than 30%. When this new composition is used, the new SSM leads to a much larger disagreement with the helioseismological data. During the last year, a large number of papers have been published suggesting possible solutions to this problem.

2. New solar standard model

In the calibration procedure there are only three free parameters: the initial mass fractions of helium and metals (Y_0 and Z_0 respectively) and the mixing-length parameter (α). Y_0 determines the solar luminosity at the solar age ($\tau_\odot$), α allows to fit the solar radius and it also fixes the depth of the convective zone ($R_{\rm cz}$). The present $(Z/X)_{\rm s}$ (X is the hydrogen mass fraction) in the photosphere is given by the observations while $Z_{\rm s}$ and $Y_{\rm s}$ differ from the initial values through diffusion and settling processes and the depth of the convection zone. $Y_{\rm s}$ and $R_{\rm CZ}$ are not included as constraints in the calibration procedure, but an acceptable solar model should provide values in agreement with those ones derived by helioseismology.

Our new SSM has $Y_0 = 0.275$, $Z_0 = 0.0147$, and $Y_{\rm s} = 0.243$, BUT $R_{\rm cz}/R_\odot = 0.727$, significantly larger than the seismic inference. Furthermore, the disagreement between the sound-speed in this new SSM and the Sun is three times larger than the value for the SSM obtained by adopting the same physics but the GN93 mixture, and ten times larger than the corresponding departures for Model S (Fig. 1 left panel).

This difference in c^2 , as it was already the situation in the eighties, must be due to a deficiency in the opacity of the models (see Fig 1., right panel). In fact, the new initial Z has decreased by 45%, from 0.0199 to 0.0126. Furthermore, in the new solar mixture, the CNO and Ne mass fractions have decreased by 36%. From a quantitative analysis made by Turcotte et al. (1998) for the GN93 mixture, the main contributors to the radiative opacity at the bottom the solar convective region are O (35%), Fe (20%), H (15%), Ne (13%) and less than 10% for N and C. So, in addition to the reduction of metal mass fraction, the decrease of O and Ne abundance has a dramatic impact on the opacity provided by the new metal mixture. In fact, the opacity at the bottom of the convective zone decreases by 25%. The radiative temperature gradient $\nabla_{\rm rad}$ being proportional to κ, decreasing κ implies a shallower convective region.

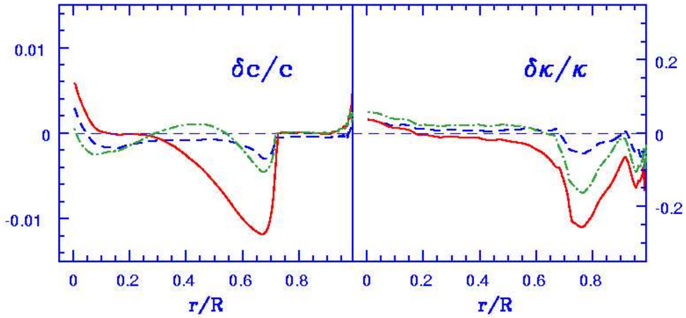

Figure 1: Relative differences between Model S and: *i.* current GN93 SSM (dashed lines), *ii.* new SSM with Asplund et al. 2004 mixture (solid lines), and *iii.* new mixture with increased opacity by 7% and diffusion coefficients by 50% (dashed-doted lines)

3. Solutions

Several groups have tried during the last year to solve the problem by searching the missing opacity among the uncertainties of the currently used physics, i.e. uncertainty in the opacity, in the diffusion coefficients, as well as in the chemical composition, or a combination of these uncertainties.

3.1 Opacity

Bahcall et al. (2004) estimated that an increase of 21% of the OPAL opacities is needed to recover the good agreement at the bottom of the convective zone. However, an error of 20% in the radiative opacity does not seem possible. In fact, Rogers & Iglesias (1998) estimated an uncertainty in the OPAL96 tables of the order of 4%. In addition, recent re-computations by Badnell et al. (2005) for the OP project, and the LEDCOP opacities (Neuforge-Verheecke et al. 2001), agree with the OPAL96 values within 3%, even if very different methods were used.

Montalbán et al. (2004) increased the opacity as suggested by Seaton & Badnell (2004) in their preliminary comparison with OPAL96 i.e. a maximum of 7% at $\log T = 6.3$, corresponding to the bottom of convective zone, without getting a significant improvement in the comparison with the observations. Young & Arnett (2005) suggest that the increase of the effective opacity predicted by Press & Rybicki (1981) in the case of internal waves propagation could solve the problem, but no quantitative estimations have been published up to now.

3.2 Diffusion coefficients

The thermal diffusion rate is known only within 30% (Michaud 2004, private communication), and, according to Turcotte et al. (1998), 40% of the diffusion velocity below the convective zone comes from the thermal diffusion : this leads to an uncertainty of 12% in the total diffusion velocity. Furthermore, we use the computation by Thoul et al. (1994) assuming fully ionized stellar matter, and, following Turcotte et al. (1998), this approach underestimates the diffusion velocities by 20% for Fe, and by 9% for O. The combination of both uncertainties could lead to an uncertainty on the diffusion velocity of 35% for the two main contributors to the opacity below the convective zone.

Montalbán et al. (2004) showed that they needed to increase the diffusion coefficient by a factor 2 in order to reach a good agreement for $R_{\rm cz}$ and for the c^2 profile. On the other hand, if they increase the opacity by 7% at the boundary of the convective zone, they only need to increase the diffusion coefficient by 50%. Similar results were obtained by Basu & Antia (2004), who required an increase of 65% of the diffusion coefficient, however combined with an increase of the O abundance by 38% with respect to the Asplund et al. (2006, PartI) value; this implies an increase of the opacity of $\sim$10%. Guzik et al. (2005) have also proposed to change separately the diffusion coefficients for C, N, O, Ne, Mg and He in order to recover a mixture at the bottom of the convective zone close to the one given by GN93 that provided good agreement with helioseismology.

The problem of all these attempts is that, while they are able to recover the observed depth of the convective zone ($R_{\rm cz}/R_\odot$ between 0.7138 and 0.7175) and a c^2 profile close to the one reached with GN93, $Y_{\rm s}$ has decreased below the value determined by inversion of solar oscillations. The new values are $Y_{\rm s}$=0.226 or 0.239 (Montalbán et al. 2004), $Y_{\rm s}$=0.232 (Basu & Antia 2004), and $Y_{\rm s}$=0.227 (Guzik et al. 2005), to be compared to the observed value $Y_{\rm s}$=0.24-0.25.

3.3 Changing the chemical composition

Even with the new 3-D methods, there is an uncertainty of the order of 10-12% in the estimated $(Z/X)_{\rm s}$. However, as it was shown by Montalbán et al. (2004), increasing the value of the $(Z/X)_{\rm s}$ constraint up to the upper limit, is not sufficient. In any case, they needed to increase the diffusion velocity by 50% to reduce the discrepancies with helioseismology. Even the large increase of the oxygen abundance, by 38%, suggested by Basu & Antia (2004) is not sufficient and, as mentioned in the previous section, they also needed to increase the diffusion velocity.

Neon plays a significant role in the opacity below the convective zone. Recently, Bahcall et al. (2005) have shown that, if Ne is increased by more than a factor 3 (Ne/O=0.52 instead of 0.15), the old agreement between SSM and the observations is restored. This suggestion has been encouraged by recent measurements of Ne in very active stars by Drake & Testa (2005), that could lead to Ne/O=0.41 in the Sun. However, the reliability of Ne/O measurements in very active stars as representative of photospheric abundances is very questionable (Asplund et al. 2006, Part I).

3.4 Overshooting

If we adopt an overshoot parameter of the order of $0.15\mathrm{H_p}$ (pressure scale height), this would allow to increase the depth of the convective envelope without leading to the development of a convective core during the main sequence of the Sun. Such a core could possibly lead to large discrepancies in the sound-speed between the SSM and the helioseismological data (below $0.2\mathrm{R}_\odot$). If we then increase the opacity by ~7%, within the uncertainty limits of the abundances, we are able to reconcile the predicted bottom of the convective zone, and the He abundance in this region, with the seismic values. But the discrepancies in the sound-speed in the radiative region are still quite large.

4. Conclusion

We have seen that none of the solutions proposed is fully satisfactory. Even if combinations of increases in opacity and diffusion rates are able to restore most of the sound-speed profile agreement, the required changes are larger than the uncertainties accepted for the opacity and the diffusion coefficients. In addition, these models still have slightly too low convective zone helium abundances. Further investigations should be done to assert the seismic Y_s. As reported by Sackmann & Boothroyd (2003), its value strongly depends on the equation of state and on the method of analysis.

Other "non-standard" physical processes should probably be considered in order to restore the agreement with helioseismology, such as, for instance, the processes required to explain the rotational velocity profile of the Sun, and the abundances of the light elements.

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