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New Results on Standard Solar Models

Aldo M. Serenelli

Abstract We describe the current status of solar modelling and focus on the problems originated with the introduction of solar abundance determinations with low CNO abundance values. We use models computed with solar abundance compilations obtained during the last decade, including the newest published abundances by Asplund and collaborators. Results presented here make focus both on helioseismic properties and the models as well as in the neutrino fluxes predictions. We also discuss changes in radiative opacities to restore agreement between helioseismology, solar models, and solar abundances and show the effect of such modifications on solar neutrino fluxes.

Keywords Sun: helioseismology - Sun: interior - Sun: abundances - neutrinos

1 Introduction

Solar models are a corner stone of stellar astrophysics. The determination of the solar interior structure through helioseismology and, only a few years later, the discovery that neutrinos change flavor, gave spectacular confirmations of our ability to model the Sun and, by extension, of other stars. However, a series of works starting with a redetermination of the photospheric oxygen solar abundance (Allende Prieto et al. 2001) and finishing with a complete revision of solar abundances (Asplund et al. 2005), led to a strong reduction in the overall metallicity of the Sun driven by much lower CNO and Ne abundances than previously determined. Soon after, solar models that adopted the new composition were shown to have an interior structure at odds with helioseismology determinations. Since then, the so-called *solar abundance problem* has been in the spotlight of solar (and stellar) astrophysics. As nicely put by Delahaye & Pinsonneault (2006), it represents the incompatibility between the best solar atmosphere and interior models available.

The effects of the low metallicity in the solar interior has been widely discussed in the literature. Among many other references, the reader can refer to Basu & Antia (2004); Turck-Chiéze et al. (2004); Montalbán et al. (2004); Bahcall et al. (2005b); Delahaye & Pinsonneau (2006) and Bahcall et al. (2006). Some attempts to constrain the solar metallicity independently of photospheric measurements can be found in Antia & Basu (2006); Lin et al. (2007) and Chaplin et al. (2007). The connection between solar neutrinos and composition has also been discussed in different works, e.g. Turck-Chiéze et al. (2004); Bahcall & Pinsonneault (2004); Bahcall et al. (2005b, 2006); Peña-Garay & Serenelli (2008); Haxton & Serenelli (2008). Possible modifications in the physical inputs of solar models have also been discussed in connection to the *solar abundance problem*. The reader can refer to Montalbán et al. (2004); Guzik et al. (2005); Delahaye & Pinsonneault (2006); Castro et al. (2007) just to mention some relevant works.

In this article, we present a short review of the field and present new solar models that incorporate the most recent solar abundance determination by Asplund et al. (2009). In § 2 we describe the main characteristics of the models used to obtain the core results presented here, including the different options for solar compositions we used. Results are presented in § 3 where helioseismology properties of the models and solar neutrino fluxes are discussed in the context of current observational and experimental data. In § 4 we go to some length in discussing radiative opacities as a possible solution to the abundance problem, including the effects

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of opacities in solar neutrino fluxes. We summarize in § 5.

2 Solar Models

Over the years, standard solar models have played a fundamental role in the development of stellar astrophysics as well as in the

Most of the results presented here refer to solar models computed with the GARSTEC stellar evolution code (Weiss & Schlattl 2008) with modifications. Some of the differences are: the nuclear energy generation routine is *exportenergy.f*[1]; radiative opacities are those from the Opacity Project (Badnell et al. 2005) complemented at low temperatured by those from Ferguson et al. (2005). Unless stated otherwise, the equation of state (EOS) is the revised version of OPAL[2].

As it is usual practice in solar models, a 1 $M_\odot$ stellar model is evolved from the pre-main sequence (or zero age main sequence) up to the solar system age (which we take to be $\tau_\odot$=4.57 Gyr; see appendix in Bahcall et al. 1995). The solar model is forced to match the present day solar radius $R_\odot$ and luminosity $L_\odot$ and here we adopt the values 6.9598×10^{10} cm 3.8418×10^{33} erg s^{-1} respectively. The third condition for solar models is to match the present-day metal to hydrogen fraction $(Z/X)_{\rm ph}$ in the solar photosphere. The models presented here have been computed for three different basic sets of solar abundances as follows:

GS98: abundances from Grevesse & Sauval (1998) where meteoritic abundances for refractories are adopted and $(Z/X)_{\rm ph} = 0.0229$,
AGS05: meteoritic (for refractories) abundances from Asplund et al. (2005) give $(Z/X)_{\rm ph} = 0.0165$,
AGSS09: meteoritic (for refractories) abundances from the most recent determination of solar abundances by Asplund et al. (2009) for which $(Z/X)_{\rm ph} = 0.0178$. One additional model, AGSS09ph, has been computed with the photospheric abundances from Asplund et al. (2009) for which $(Z/X)_{\rm ph} = 0.0181$.

In the new determination of solar abundances by Asplund et al. (2009), the difference between meteoritic and photospheric abundances is 0.00 ± 0.04 dex. While this agreement is of unprecedented quality, some elements relevant to detailed solar modelling show larger deviations. This is particularly the case for Mg, Ca, and Fe for which differences are 0.07, 0.05 and 0.05 dex

Table 1 Adopted solar chemical compositions.

	log ϵ			
Elem	GS98	AGS05[a]	AGSS09[a]	AGSS09ph[b]
C	8.52	8.39	8.43	8.43
N	7.92	7.78	7.83	7.83
O	8.83	8.66	8.69	8.69
Ne	8.08	7.84	7.93	7.93
Na	6.32	6.27	6.27	6.24
Mg	7.58	7.53	7.53	7.60
Al	6.49	6.43	6.43	6.45
Si	7.56	7.51	7.51	7.51
S	7.20	7.16	7.15	7.12
Ar	6.40	6.18	6.40	6.40
Ca	6.35	6.29	6.29	6.34
Cr	5.69	5.63	5.64	5.64
Mn	5.53	5.47	5.48	5.43
Fe	7.50	7.45	7.45	7.50
Ni	6.25	6.19	6.20	6.22

[a]The adopted abundances are the recommended solar photospheric abundances for the volatile elements (C, N, O, Ne and Ar) and the CI chondritic meteoritic values for the remaining elements.
[b]The adopted abundances are the recommended solar photospheric abundances throughout.

Note: Abudances given as $\log \epsilon_i \equiv \log N_i/N_H + 12$.

with the photospheric values being larger in all cases. To understand the effects of these differences in the structure of the solar interior we have computed two solar models with AGSS09 composition, one with meteoritic and the other with photospheric abundances. In Table 1 the relative number fractions of all relevant metals are given for all sets of solar abundances used in the models discussed in this work.

3 Results

In what follows, we discuss the most relevant results related to the interior structure of the Sun for the four solar models described in the previous section. Qualitatively, there is a clear difference in the results from the GS98 model compared to the others that use a much lower value for $(Z/X)_{\rm ph}$, i.e. AGS05 and AGSS09 models. This dichotomy has been widely discussed in the literature in connection to models using solar abundances from Grevesse & Noels (1993) or Grevesse & Sauval (1998) on one hand and the Asplund et al. (2005) solar composition on the other (Bahcall et al. 2004, 2005b; Basu & Antia 2004; Turck-Chiéze et al. 2004; Montalbán et al. 2004). Presentation of results is divided in two sections, the first one comprising general

[1]Publicly available at http://www.sns.ias.edu/∼jnb
[2]http://adg.llnl.gov/Research/OPAL/EOS_2005/

Table 2 Main characteristics of solar models.

	GS98	AGS05	AGSS09	AGSS09ph
$Z_{\rm S}$	0.0170	0.0126	0.0134	0.0136
$Y_{\rm S}$	0.2423	0.2292	0.2314	0.2349
$R_{\rm CZ}/R_\odot$	0.713	0.728	0.724	0.722
$\langle\delta c/c\rangle$	0.0010	0.0049	0.0038	0.0031
$\langle\delta\rho/\rho\rangle$	0.011	0.048	0.040	0.033
$Y_{\rm c}$	0.6330	0.6195	0.6220	0.6263
$Z_{\rm c}$	0.0201	0.0149	0.0160	0.0161
$Y_{\rm ini}$	0.2721	0.2593	0.2617	0.2653
$Z_{\rm ini}$	0.0187	0.0139	0.0149	0.0151
$\alpha_{\rm MLT}$	2.15	2.10	2.09	2.12

results on solar structure and inferences from helioseismology, while the second one is devoted to discussion of solar neutrinos and, briefly, a possible connection with the *solar abundance problem*.

3.1 Helioseismology

In Table 2 we summarize the most relevant characteristics of the solar models used in this work. The first row gives the surface metal mass fraction $Z_{\rm S}$. The next four rows give quantities that can be directly tested against helioseismology determinations of solar properties: surface helium mass fraction $Y_{\rm S}$, depth of the convective envelope $R_{\rm CZ}/R_\odot$, and average rms relative differences of the sound speed and density profiles $\langle\delta c/c\rangle$ and $\langle\delta\rho/\rho\rangle$ respectively. $Y_{\rm c}$ and $Z_{\rm c}$ are the present day central mass fractions of helium and metals and the last three rows give the initial composition and mixing length parameter, i.e. the free parameters used to construct an SSM.

Results for the GS98 and AGS05 models are very similar to those already discussed in the literature (see references above). The updated EOS and some changes in the nuclear cross sections of a few reactions have very little impact on the global properties of the models. We describe them here only briefly. From helioseismology, we know $Y_{\rm S} = 0.2485\pm0.0035$ (Basu & Antia 2004) and $R_{\rm CZ}/{\rm R}_\odot = 0.713 \pm 0.001$ (Basu & Antia 1997). The GS98 model predicts the right location of the boundary of the convective envelope and a value of the surface helium mass fraction in agreement with helioseismology to about 1.8$-\sigma$. On the other hand, the AGS05 model performance is much worse, giving a 15$-\sigma$ discrepancy for $R_{\rm CZ}/{\rm R}_\odot$ and 5.5-σ for $Y_{\rm S}$. Here we note that only uncertainties from helioseismology are considered. Bahcall et al. (2006) have estimated by a series of MonteCarlo simulations the modelling uncertainties for $R_{\rm CZ}/{\rm R}_\odot$ to be approximately 0.0037 and for $Y_{\rm S}$, coincidentally, 0.0037 as well.

The new solar abundances as determined by Asplund et al. (2009) are slightly higher than those previously determined by the same group (Asplund et al. 2005) (see Table 1). Changes between 0.03 and 0.05 dex in CNO abundances are small and, together with the 0.09 dex change in Ne, are not able to restore the agreement between solar models and helioseismology. Although the disagreement is less severe now, 5$-\sigma$ and 11$-\sigma$ for $Y_{\rm S}$ and $R_{\rm CZ}/{\rm R}_\odot$ respectively, it is very large compared to results of solar models with older (Grevesse & Sauval 1998; Grevesse & Noels 1993) solar abundances. This is also evident when considering the sound speed and density profiles that are shown in Figure 1. The AGS05 and AGSS09 models give $\langle\delta c/c\rangle$ that are 5 and 4 times worse than the GS98 model respectively. The peak of the discrepancy in the sound speed profiles is 0.3% for the GS98 model, 1.2% for AGS05 and 1% for AGSS09. Analogous results are found for the density profiles. In this case, however, the larger discrepancies seen in the convective envelopes are associated with the fact that density inversions include the constraint that the solar mass is known and, consequently, small differences in density in the innermost region, at high densities, have to be compensated by larger fractional changes in the outer much less dense. Both in Table 2 and in Figure 1, it can be seen that the model AGSS09ph, that uses only photospheric abundances performs better than AGSS09. The reason can be found mostly in the increased values of Mg and Fe, by 0.07 and 0.05 dex respectively, in the photospheric abundances, and not in the overall change in solar metallicity. For example, Mg contributes to the radiative opacity right the convective envelope and careful examination of top panel in Figure 1 shows that the sound speed profile of AGSS09ph shows the largest improvement with respect to AGSS09 in the region around 0.6 ${\rm R}_\odot$. The effect of the increased Fe abundance can be indirectly appreciated by the initial and surface helium content of the AGSS09ph model compared to AGSS09. This change results from the relevance of Fe in the opacity in the central regions and thus in the central most temperature gradient, which ultimately affects the initial composition of the model by the condition of fixed solar luminosity imposed on standard solar models.

Despite the better performance of the AGSS09ph model, we consider meteoritic abundances as given in Table 1 our preferred choice. The arguments are that historically, whenever there has been significant differences between photospheric and meteoritic abundances for refractory elements, the problem laid in the photospheric determinations. Also, the excellent overall agreement between the two scales found by Asplund et al. (2009), and the lack of accurate atomic data for certain elements, e.g. for Mg, and the impossi[redacted]ility of having a homogeneous method of determination of photospheric abundances for all elements (see

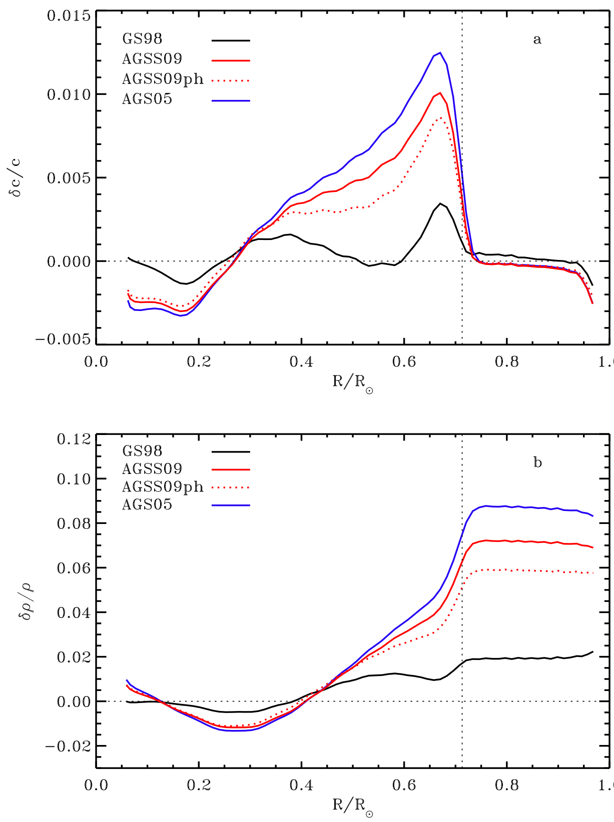

Fig. 1 Panel *a*: relative sound speed difference in the sense (Sun - Model)/Model between the solar sound speed profile as obtained from helioseismology inversions and model sound speed profiles. Panel *b*: same but for density profiles. Vertical dotted line in both panels denotes the location of the bottom of the convective envelope as inferred from helioseismology

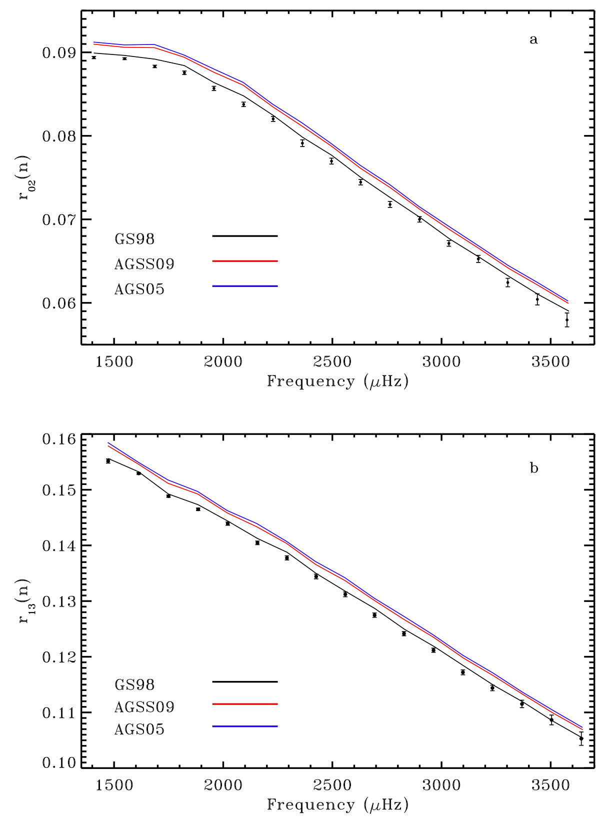

Fig. 2 Separation ratios. Comparison between values determined from BiSON data and the solar models presented in this work. Panel *a*: r_{02} ratios; panel *b*: r_{13} ratios

discussions in Asplund et al. 2009 for details) favor in our view meteoritic abundances as a more secure and robust option. Hence, our choice.

Another interesting possibility that global helioseismology offers is to probe the solar core by means of low-degree ($\ell \leq 3$) modes that penetrate to the deepest solar regions. In particular, Roxburgh & Vorontsov (2003) have shown that low-ℓ mode frequencies can be used to form the so-called separation ratios $r_{02}(n) = (\nu_{n,0} - \nu_{n-1,2})/(\nu_{n,1} - \nu_{n-1,1})$ and $r_{13}(n) = (\nu_{n,1} - \nu_{n-1,3})/(\nu_{n,0} - \nu_{n-1,0})$, which are insensitive to the external characteristics of the models. Separation ratios constructed with very long time series of BiSON data have been used (Basu et al. 2007; Chaplin et al. 2007) to show that discrepant results between solar structure inferred from helioseismology and solar models with the AGS05 composition are not restricted to the outer regions of the Sun (where simplified treatments of convection by using Mixing Length Theory or similar approaches could in principle be thought of as the culprits of problems in solar modelling) and extend all the way to the core. In Figure 2 we compare the separation ratios from our models with those ratios derived by Basu et al. (2007) from 4752 days of BiSON data. Results are shown for the GS98, AGS05, and AGSS09 models and ratios have been connected with lines to help the eye. We omit results from AGSS09ph model as they practically overlap with those of the AGSS09 model. As already discussed in Basu et al. (2007) and later in Chaplin et al. (2007), models with higher metallicity, e.g. from Grevesse & Sauval (1998), give good agreement with helioseismology while those using the Asplund et al. (2005) composition grossly disagree. In this regard, the new AGSS09 model with the updated solar abundances from Asplund et al. (2009) does not show any improvements with respect to the AGS05 composition.

Related to the separation ratios, it is interesting to note a recent work (Christensen-Dalsgaard 2009) where the high sensitivity of the separation ratios and the small separation frequencies (numerators in the definition of separation ratios) to the properties of the solar core, particularly to the molecular weight profile, has been used to date the Sun. Interestingly enough, comparison of the time evolution of the separation ratios and small separation frequencies in the S model (Christensen-Dalsgaard et al. 1996) that uses the Grevesse & Noels (1993) composition shows the best agreement with the observed quantities at an age in excellent agreement with the solar system age as determined from meteoritic samples (see appendix in Bahcall et al. 1995). On the other hand, a solar model with the AGS05 shows the best agreement with data (which is, nevertheless, much worse than that obtained with the S model) at an age between 4.8 and 4.9 Gyr.

3.2 Solar Neutrinos

For many years, solar neutrinos received a great deal of attention due to the *solar neutrino problem*. With the definite establishment of the oscillatory nature of neutrinos, the center of attention for studying solar neutrinos has shifted towards the original goal defined in the early 1960s: to use neutrinos as a direct probe of how stars shine and of the properties of the solar core. Currently, two solar neutrino fluxes have been measured directly: the SNO collaboration has determined directly and with very good precision the ^{8}B flux, an excellent thermometer of the solar core. More recently, this flux has also been determined by the Borexino collaboration. More importantly, however, Borexino has been able to determine the ^{7}Be directly and has already achieved a 10% accuracy (with 3% as the current goal of the collaboration).

In Table 3 the neutrino fluxes predicted by the models used in this work are given. Results for models with the Grevesse & Sauval (1998) and Asplund et al. (2005) compositions have already been discussed in the literature, e.g. Bahcall et al. (2005b). We resort here to a qualitative discussion of the differences. The central temperature in the GS98 model is about 1.2% higher than in the AGS05 model and this accounts for the difference ($\sim 20\%$) in the highly sensitive ($\propto (T/T_0)^{16-20}$) ^{8}B flux and also for the reduction in the ^{7}Be flux ($\sim 10\%$) in the AGS05 model. Since solar models assume a fixed solar luminosity, the reduction in nuclear energy released by the ppII chain is compensated by a slight increase in the rate of ppI chain and the pp and pep fluxes are slightly increased.

Larger fractional changes are found for the three fluxes associated with the CNO bi-cycle. We focus on the ^{13}N and ^{15}O fluxes for which possibilities of direct detection exist in the (relatively) near future with ongoing efforts by Borexino but mainly with SuperK and SNO+ experiments. These two fluxes have high sensitive to temperature but are mostly suppressed because their rate is directly proportional to the summed abundance of C and N that is reduced by ($\sim 30\%$) in the Asplund et al. (2005) composition.

Table 3 Predicted neutrino fluxes.

Flux[a]	GS98	AGS05	AGSS09	AGSS09ph
pp	5.97	6.04	6.03	6.01
pep	1.41	1.44	1.44	1.43
hep	7.91	8.24	8.18	8.10
^{7}Be	5.08	4.54	4.64	4.79
^{8}B	5.88	4.66	4.85	5.22
^{13}N	2.82	1.85	2.07	2.15
^{15}O	2.09	1.29	1.47	1.55
^{17}F	5.65	3.14	3.48	3.70

[a]Neutrino fluxes are given in units of 10^{10}(pp), 10^9(^{7}Be), 10^8(pep, ^{13}N, ^{15}O), 10^6(^{8}B, ^{17}F) and 10^3(hep) cm^{-2} s^{-1}.

With the new Asplund et al. (2009) abundances, neutrino fluxes are very similar to those from the AGS05 model. In particular, for our preferred meteoritic scale, the only important differences between these two sets of abundances are the moderate increase in CNO values that directly affect CNO neutrino fluxes and the 0.09 dex increase in Ne and the large (0.22 dex) increase in Ar. The last two elements have some influence on the central temperature of the models and are responsible for the differences in ^{8}B and ^{7}Be fluxes between AGS05 and AGSS09 models. Finally, as in the previous section, we also present results for the AGSS09ph model. It is interesting because it illustrates how not only the overall metallicity of the model is important, but how relative abundances of elements matter as well. In particular, the larger Fe abundance in the photospheric abundances account for most of the difference between the fluxes predicted for this model with respect to the AGSS09 model. The interested reader in how individual elements affect neutrino fluxes can refer to Bahcall & Serenelli (2005) and Peña-Garay & Serenelli (2008).

The most relevant results for solar neutrinos are summarized in Figure 3. The top panel shows the ^{8}B and ^{7}Be fluxes from the models and the experimental results from SNO (^{8}B) and Borexino (^{7}Be). In the case of SNO results, because we still lack a joint analysis of the three different phases, we use the value $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6$ cm^{-2} s^{-1} for the flux, a weighed average of the three phases (Ahmad et al. 2002; Aharmim et al. 2005, 2008) . In the case of Borexino, the measured flux after only 192 days of data taking is $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9$ cm^{-2} s^{-1} Arpesella et al. (2008). Model uncertainties for the fluxes are taken from Peña-Garay & Serenelli (2008).

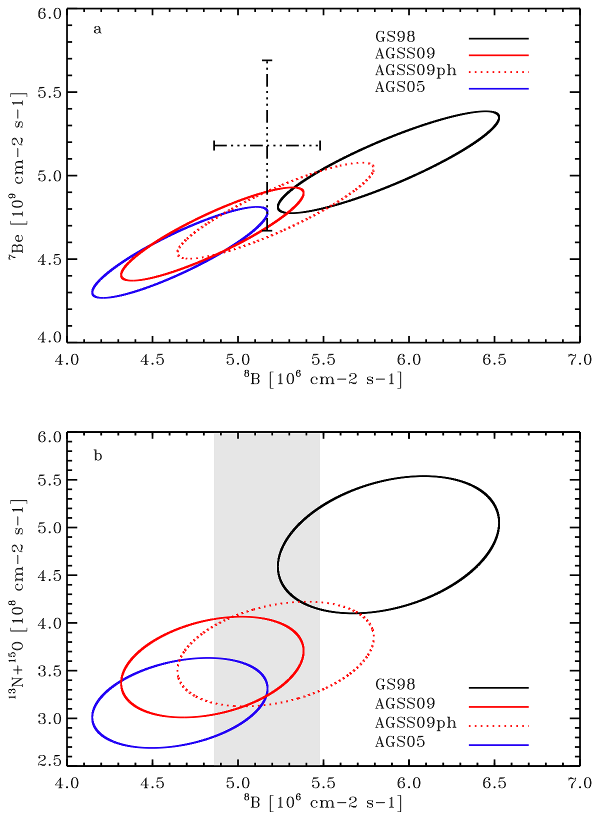

Fig. 3 Solar neutrino fluxes. Panel *a* shows the fluxes determined directly from experiments: ^{7}Be and ^{8}B. Current measurements from Borexino (^{7}Be) and the average from the three phases of SNO (8B) are shown with corresponding error bars at $1-\sigma$ level. Panel *b* shows the added contributions of the ^{13}N and 15O fluxes against the ^{8}B flux. The shaded area represents the SNO measurement for the ^{8}B including $1-\sigma$ uncertainties

As discussed in that work, current neutrino measurements slightly favor results of models with GS98 abundances over those with AGS05 (or AGSS09). We note, however, that the GS98 and the AGSS09ph model are at the same level of agreement with helioseismology: GS98 predicts exactly the measured value for ^{7}Be and differs from the SNO value for ^{8}B by $1-\sigma$ (combined model and experimental uncertainties). For the AGSS09ph model, the situation is exactly opposite.

In the bottom panel of Figure 3, we show the added ^{13}N and ^{15}O fluxes against the ^{8}B flux. Models of different composition (AGSS09 or GS98) can be more easily distinguished using CNO fluxes as illustrated in this figure. It should be kept in mind, however, that current model uncertainties seem to prevent any possibility of a $2-\sigma$ or better result. Discussion on main sources of uncertainties and how the situation can be improved can be found in Peña-Garay & Serenelli (2008).

4 Who is the culprit?

Since revisions of solar CNO photospheric abundances were strongly revised downwards (Asplund et al. 2005), attempts have been made to obtain independent determinations of, or at least to impose constraints on, the solar composition (Basu & Antia 2004; Delahaye & Pinsonneault 2006; Chaplin et al. 2007). There has also been a number of works devoted to analize what changes in the input physics of the models would allow to construct solar models with low metallicity that are consistent with helioseismology measurements. We mention, but do not discuss, some of the proposed changes are: changes in composition, e.g. large enhancement of neon abundances (Antia & Basu 2005; Bahcall et al. 2005; Delahaye & Pinsonneault 2006), enhanced microscopic diffusion (Basu & Antia 2004; Montalbán et al. 2004; Guzik et al. 2005), accretion of metal-poor material (Guzik et al. 2005; Castro et al. 2007). The viability of these changes and others has been reviewed at some length by Guzik (2008) and we refer the interested reader to that reference for details. The short summary is that none of the proposed changes can, by itself, offer a solution to the conundrum originated by the low CNO and Ne abundances presented by Asplund and collaborators. One is left with the unpleasant option of combining different effects to improve the helioseismology properties of the low-Z models, and/or to fine tune the necessary changes in the models.

Here, we consider in certain amount of detail the effect of new abundances in the opacities. This has certainly considered before in the light of Asplund et al. (2005) abundances by a number of authors (Montalbán et al. 2004; Antia & Basu 2005; Bahcall et al. 2004, 2005). More recently, Christensen-Dalsgaard et al. (2009) has considered this issue by comparing the opacity difference between Model S and a solar model with solar composition from Asplund et al. (2005). The authors find differences in opacities of the order of 30% at the bottom of the convective envelope that smoothly decrease towards the center, where 5% differences are found. Here, we have followed a very similar line of argument but considered our GS98 model as the reference model and, in addition to the AGS05 model, considered those constructed with the two flavors of the new solar abundances, our AGSS09 and AGSS09ph models.

The main results are shown in Figure 4 where we present the relative differences in opacities between the low-Z models and the GS98 model. For the new AGSS09 model, differences are of the order of 15%, i.e. a factor of 2 smaller that those found by Christensen-Dalsgaard et al. (2009), close to the base of the convective zone. Somewhat smaller

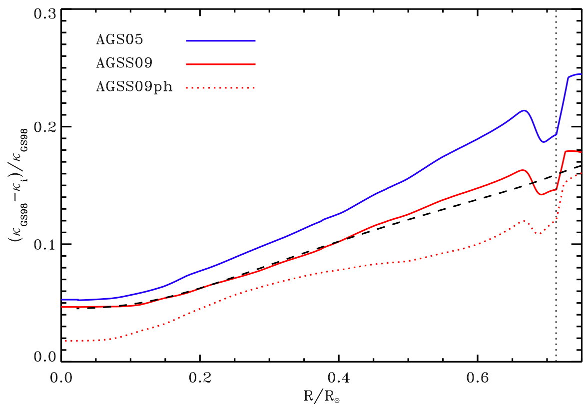

Fig. 4 Relative opacity deficit of low metallicity solar models relative to the GS98 model as a function of radius. Dashed line shows the correction applied to the AGSS09 opacities in the AGSS09+OPAC model (see text). Vertical dotted line denotes the location of the bottom of the convective envelope

values result in the same region for the AGSS09ph model due to the larger Mg photospheric abundance. Close to the center, the opacity in the AGSS09 model is about 5% lower than in GS98 (similar result as in Christensen-Dalsgaard et al. 2009) while the AGSS09ph has a deficit of only 2% due to its enhanced Fe abundance. We do not open judgement here as whether these differences are comparable or not to uncertainties in current opacity calculations. In this regard, we do recall the reader that in the radiative solar interior, differences between OPAL and Opacity Project opacities do not rise above 2.5%, quite below to what is needed to restore the agreement between solar models with low-Z and helioseismology.

In closing this discussion, we present results of a solar model, AGSS09+OPAC, with the same composition as used in the AGSS09 where opacities have been increased by the fractional amount shown in the black dashed line shown in Figure 4. Christensen-Dalsgaard et al. (2009) showed that models where the opacity is increased to compensate changes induced by the modified composition reproduce all helioseismic properties of the reference model. In this respect, our results are in the same line; the model with increased opacity performs equally well than the GS98 model in terms of helioseismic quantities. In Figure 5 we show for GS98, AGSS09, and AGSS09+OPAC models the results for solar neutrino fluxes. In the top panel it is shown that the ^{7}Be and ^{8}B fluxes, affected by the solar composition mostly through its effect on opacities, of the AGSS09+OPAC model are very similar to those from the reference GS98 model. There is a degeneracy in these fluxes between the solar composition and the opacities. Based on this,

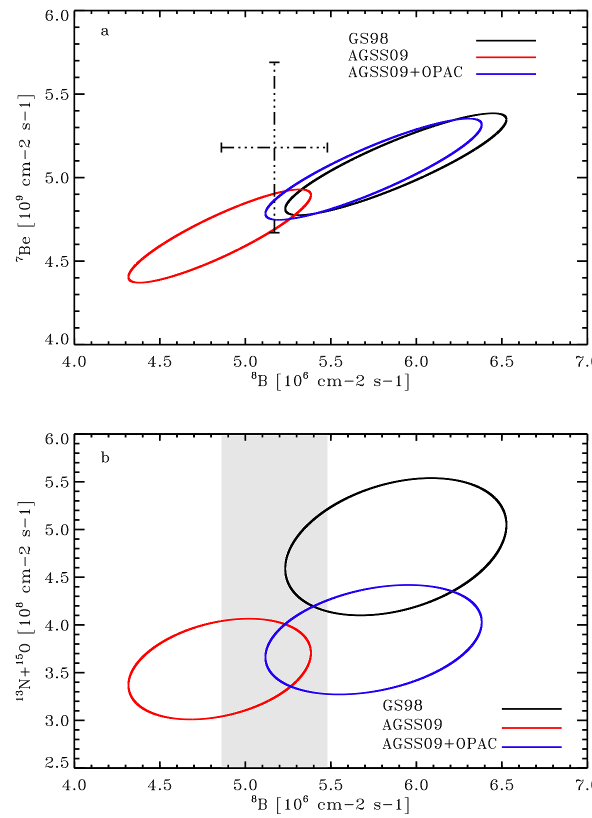

Fig. 5 Same as Fig. 3 for the standard AGSS09 and GS98 models and a model with AGSS09 composition but the opacity increased as described in the text

one should be careful when comparing neutrino fluxes from models (with wrong helioseismic properties, as it is the case for AGSS09) with experimental determinations: fixing helioseismic properties, e.g. by changing opacities, will likely affect neutrino predictions. On the other hand, in the lower panel, the added ^{13}N and ^{15}O fluxes could in principle be used to determine the solar core metallicity (more exactly, the total C+N abun[redacted]ance). In view of this, we point out the importance of current and future efforts to measure neutrino fluxes coming from CNO reactions.

5 Summary

We have attempted, in this incomplete review, to describe the current status of the *solar abundance problem* that originated with new determinations of solar photospheric abundances from Asplund and collaborators. Results discussed here are based on models computed with both the original (Asplund et al. 2005) and the newest (Asplund et al. 2009) solar compositions. Our reference for a *good* solar model is based on the Grevesse & Sauval (1998) composition. The most important result is that with the new (Asplund et al. 2009) abundances, the qualitative picture that emerged a few years ago, i.e. that low-Z solar models are in gross disagreement with helioseismology, remains the same. Quantitatively, the disagreement is less severe because the new abundances have slightly higher CNO abundances and a somewhat larger Ne abundance. The changes, however, do not help much neither in restoring the agreement with helioseismology nor in facilitating the way for alternative solutions in the form of modified input physics for solar models. We have described with some detail the effect of the new composition in opacities and the required change to recover good helioseismic properties. Changes of order 15% are needed, which are still much higher than currently estimated uncertainties in radiative opacities for the solar interior. In addition to helioseismic properties of the models, we have discussed the effects of the composition on the predicted neutrino fluxes and compared, when possible, with results from solar neutrino experiments. Additionally, we have tried to encourage efforts to experimentally determine neutrino fluxes from CNO bicycle, since these are the most sensitive fluxes to changes in abundances of CNO elements, thus offering the best chances for neutrinos to put direct constraints on the solar core composition.

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