The Sun and solar neutrinos

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Abstract. We present the predictions of updated standard solar models and we briefly discuss the solar composition problem, i.e. the conflict between helioseismology and standard solar models implementing the state-of-the-art photospheric abundances, emphasizing the importance of measuring neutrinos produced in the CNO cycle for its comprehension.

1. Introduction
In the last few years a new solar problem has emerged. Recent determinations of the solar photospheric abundances [1, 2, 3] indicate that the solar metallicity is lower by 30 to 40% than previous measurements [4, 5]. The internal structure of standard solar models (SSMs) calibrated against the newly determined solar surface metallicity, however, does not reproduce the helioseismic constraints. Detailed studies have been done to resolve this controversy (see e.g. [6] and references therein) but a definitive solution of this ”solar composition problem” still has to be obtained.

In this short review, we briefly discuss the present situation. In the next section, we present a new generation of SSM calculations [7]. Then, we compare updated SSMs predictions with helioseismic constraints and with neutrino fluxes inferred from solar neutrino data. Finally, we comment on the degeneracy between solar composition and radiative opacity in determining the thermal stratification of the Sun and we emphasize the importance of measuring neutrinos produced in the CNO cycle (that do not suffer from this degeneracy) for the comprehension of the solar composition problem.

2. The B16 standard solar models
SSMs are a snapshot in the evolution of a 1M☉ star, calibrated to match present-day surface properties of the Sun. The calibration is done by adjusting the mixing length parameter (αMLT) and the initial helium and metal mass fractions (Yini and Zini respectively) in order to satisfy the constraints imposed by the present-day solar luminosity L☉, radius R☉, and surface metal to hydrogen abundance ratio (Z/X)☉. In [7], a new generation of SSM, Barcelona 2016 or B16 for short, has been presented. The new B16 models share with previous calculations [8] much of the input physics, but include important updates in Equation of State (EoS), nuclear reaction rates and a different treatment of uncertainties due to radiative opacities. A brief account of few relevant ingredients in B16 SSMs is given in the following (see [7] for details).
Composition: Solar photospheric (surface) abundances of almost all metals can be determined from spectroscopy. For refractories, meteorites offer an alternative method and, in fact, elemental abundances determined from meteorites have been historically more robust than spectroscopic ones. For this reason, the sets of solar abundances that are used in SSM calculations are composed by meteoritic values for refractory elements and photospheric values for volatile elements. The two scales are tied together by forcing a rigid translation of the meteoritic scale such that the meteoritic abundance of Si matches the photospheric value. The two central sets of solar abundances used in B16 SSMs are the same employed in [8]:

- GS98 - Photospheric (volatiles) + meteoritic (refractories) abundances from [4] that correspond to metal-to-hydrogen ratio used for the calibration \((Z/X)_{\odot} = 0.0229\);
- AGSS09met - Photospheric (volatiles) + meteoritic (refractories) abundances from [1] that give \((Z/X)_{\odot} = 0.0178\).

Note that the recent results from [9, 10, 11] that have updated the abundances of [1] for all but CNO elements (which are the most abundant among the volatiles elements) do not lead to a revision of the AGSS09met composition.

Equation of State: B16 SSMs employ, for the first time, EoS tables calculated consistently for each of the compositions used in the solar calibrations (GS98 and AGSS09met) by using FreeEOS [12]. This is a qualitative step forward, although differences in the predicted solar properties by use of consistent EoS tables are small and have minimal impact in the production of solar neutrinos or helioseismic diagnostics presented in this work. This can be, nevertheless, much more important in the context of abundance determinations from EoS features such as the depression of the adiabatic index \(\Gamma_1\) (see e.g. [13]).

Nuclear rates: The rates of \(p(p,e^+\nu_e)d\), \(^7\text{Be}(p,\gamma)^8\text{B}\) and \(^{14}\text{N}(p,\gamma)^{15}\text{O}\) reactions have been updated. The astrophysical factor at zero energy \(S_{ij}(0)\) adopted in B16 SSMs calculations are given in Tab.1. In the third column, we show the fractional changes with respect to the previously adopted values given in [19]. For the \(p(p,e^+\nu_e)d\) reaction, the quoted value for \(S_{11}(0)\) underestimates the actual increase of the rate because the variation of \(S_{11}(E)\) at solar energies is dominated by changes in the first and higher order derivatives of the Taylor expansion of the astrophysical factor around \(E = 0\) (see [7] for details). For the important reaction \(^3\text{He}(^4\text{He},\gamma)^7\text{Be}\) (not included in Tab.1), two recent analyses [20, 21] have provided determinations of the astrophysical factor that differs by about 6% (to be compared with a claimed accuracy equal to 4% and 2% for [20] and [21], respectively). Considering that the results from [20] and [21] bracket the previously adopted value from [19], the latter was considered as preferred choice in B16 SSMs\(^1\).

\(^1\) Note that the results presented in [22] were obtained by using the \(S_{34}(0)\) value recommended by deBoer et al. (2014) [20] before the results from [21] became available. This explains the small differences between the neutrino fluxes quoted in [22] with respect to the values given in present work.

| \(S(0)\) | Uncert. (%) \(\Delta S(0)/S(0)\) | Ref. |
|---|---|---|
| \(S_{11}\) | \(4.03 \cdot 10^{-25}\) | 1 \(0.5\%\) | [14, 15, 16] |
| \(S_{17}\) | \(2.13 \cdot 10^{-5}\) | 4.7 \(+2.4\%\) | [17] |
| \(S_{114}\) | \(1.59 \cdot 10^{-3}\) | 7.5 \(-4.2\%\) | [18] |

Table 1. Astrophysical S-factors (in units of MeV b) and uncertainties updated in this work. Fractional changes with respect to [19] are also included.
for the opacity change
(wheremetals contribute by realistic because the accuracy of opacity calculations is expected to be better at the solar core among each other and integrate to zero for a global rescaling of the opacity. Moreover this is not the solar radiative region. It was shown, however, in [25] that this prescription underestimates the overall reduction in the \( \Phi(\)...

| Neutrino fluxes for the two B16 SSMs and as determined by [28]. The fluxes are given in units of \(10^{10}\) (pp), \(10^{8}\) (^{10}Be), \(10^{8}\) (pep,^{13}N,^{15}O), \(10^{9}\) (^{8}B,^{17}F) and \(10^{3}\) (hep) cm\(^{-2}\)s\(^{-1}\). The last two lines give the surface helium \(Y_S\) and the convective radius \(R_{CZ}\). The observational values are given by [29] and [30], respectively.

|          | GS98       | AGSS09met  | Obs          |
|----------|------------|------------|--------------|
| \(\Phi(pp)\) | 5.98(1 ± 0.006) | 6.03(1 ± 0.005) | 5.971\(^{+0.037}_{-0.033}\) |
| \(\Phi(\text{pep})\) | 1.44(1 ± 0.01) | 1.46(1 ± 0.009) | 1.448 ± 0.013 |
| \(\Phi(\text{hep})\) | 7.98(1 ± 0.30) | 8.25(1 ± 0.30) | 19\(^{+12}_{-9}\) |
| \(\Phi(^{7}\text{Be})\) | 4.93(1 ± 0.06) | 4.50(1 ± 0.06) | 4.80\(^{+0.24}_{-0.22}\) |
| \(\Phi(^{8}\text{B})\) | 5.46(1 ± 0.12) | 4.50(1 ± 0.12) | 5.16\(^{+0.13}_{-0.09}\) |
| \(\Phi(^{13}\text{N})\) | 2.78(1 ± 0.15) | 2.04(1 ± 0.14) | \(< 1.37\) |
| \(\Phi(^{15}\text{O})\) | 2.05(1 ± 0.17) | 1.44(1 ± 0.16) | \(< 2.8\) |
| \(\Phi(^{17}\text{F})\) | 5.29(1 ± 0.20) | 3.26(1 ± 0.18) | \(< 85\) |
| \(Y_S\) | 0.2426 ± 0.0059 | 0.2317 ± 0.0059 | 0.2485 ± 0.0035 |
| \(R_{CZ}\) | 0.7116 ± 0.0048 | 0.7223 ± 0.0053 | 0.713 ± 0.001 |

Table 2. Neutrino fluxes for the two B16 SSMs and as determined by [28]. The fluxes are given in units of \(10^{10}\) (pp), \(10^{9}\) (^{10}Be), \(10^{8}\) (pep,^{13}N,^{15}O), \(10^{9}\) (^{8}B,^{17}F) and \(10^{3}\) (hep) cm\(^{-2}\)s\(^{-1}\). The last two lines give the surface helium \(Y_S\) and the convective radius \(R_{CZ}\). The observational values are given by [29] and [30], respectively.

Radiative opacities: In [8] the opacity error was modelled as a 2.5% constant factor at 1\sigma level, comparable to the maximum difference between OP [23] and OPAL [24] opacities in the solar radiative region. It was shown, however, in [25] that this prescription underestimates the contribution of opacity uncertainty to the sound speed and convective radius error budgets because the effects produced by opacity variations in different zones of the Sun compensate among each other and integrate to zero for a global rescaling of the opacity. Moreover this is not realistic because the accuracy of opacity calculations is expected to be better at the solar core (where metals contribute by \(~\)30%) than in the region around the base of the convective envelope (where metals contribution is \(~\)70%). Taking this into account, the following parameterization for the opacity change \(\delta\kappa(T)\) was considered:

\[
\delta\kappa(T) = a + \frac{b \log(T_C/T)}{\Delta}
\]

where \(T\) is the temperature of the solar plasma, \(\Delta = \log(T_C/T_{CZ}) = 0.9\), \(T_C = 15.6 \times 10^6\) K and \(T_{CZ} = 2.3 \times 10^6\) K are the temperatures at the solar center and at the bottom of the convective zone respectively. The parameters \(a\) and \(b\) are treated as independent random variables with mean equal to zero and dispersions \(\sigma_a = 2\%\) and \(\sigma_b = 6.7\%\), respectively. This corresponds to assuming that the opacity error at the solar center is \(\sigma_{in} = \sigma_a = 2\%\), while it is given by \(\sigma_{out} = (\sigma_a^2 + \sigma_b^2)^{1/2} = 7\%\) at the base of the convective zone, as can be motivated by the recent experimental results of [26] and the theoretical work by [27].

3. The B16 SSMs results
The main results obtained with the new generation of B16 SSMs for the two choices of solar composition, GS98 and AGSS09met, are shown in Tab.2 and Fig.1 and are discussed below.

Neutrino fluxes: The updates of nuclear reaction rates have a direct effect on neutrino production. In particular, the boron and beryllium neutrino fluxes are reduced for both GS98 and AGSS09met compositions by about 2% with respect to previous SSM calculations [8]. The overall reduction in the \(\Phi(^{8}\text{B})\) and \(\Phi(^{9}\text{Be})\) fluxes comes from the increase in \(S_{11}\). In the case of \(\Phi(^{8}\text{B})\), this is partially compensated by the 2.4% increase in \(S_{17}\). The most important changes in the neutrino fluxes occur for \(\Phi(^{13}\text{N})\) and \(\Phi(^{15}\text{O})\), in the CN-cycle. The expectation values in the B16 SSMs are about 6% and 8% lower than for the previous SSMs [8]. This results from the combined changes in the p+p and \(^{14}\text{N}+p\) reaction rates.
Figure 1. Fractional sound speed difference $\delta c = \frac{(c_\odot - c_{\text{mod}})}{c_{\text{mod}}}$. The red line corresponds to AGSS09met-B16 and the blue one to GS98-B16 SSMs. The grey and red shadow regions correspond to "statistical" errors in the inversion procedure given by [32] and to 1σ theoretical uncertainties in SSM predictions, respectively. The black dotted curves are obtained by neglecting the opacity contribution to theoretical uncertainties.

The predicted fluxes should be compared with the observational values in the last column of Tab.2 which have been obtained in [28] from a fit to the results of solar neutrino experiments by allowing for three-flavour neutrino oscillations. Note that observational errors for $\Phi(^{8}\text{B})$ and $\Phi(^{8}\text{Be})$ fluxes are smaller than uncertainties in theoretical predictions. On the contrary, CN fluxes have not yet been determined experimentally and the global analysis of solar neutrino data provides only the upper limits included in Tab.2. The Borexino collaboration, based on a different analysis of Borexino data alone, has reported an upper limit for the added fluxes $\Phi(^{13}\text{N}) + \Phi(^{15}\text{O}) < 7.7 \times 10^8 \text{cm}^{-2} \text{s}^{-1}$ [31]. From the comparison of predicted and observed fluxes, we see that both solar compositions lead to SSMs that are consistent with experimental results within 1σ.

Helioseismology: In the last two lines of Tab.2, we report two helioseismic quantities widely used in assessing the quality of SSMs, i.e. the surface helium abundance $Y_S$ and the depth of the convective envelope $R_{CZ}$, together with the corresponding seismically determined values. The model errors associated to these quantities are larger than previously computed because of the different treatment of uncertainties in radiative opacities. Compared to previous SSMs [8], we find a small decrease in the predicted $Y_S$ by 0.0003 and in the predicted $R_{CZ}$ by 0.0007 $R_\odot$ for both compositions. These small changes together with the larger theoretical uncertainties lead B16-GS98 to a 0.9σ ($Y_S$) and 0.3σ ($R_{CZ}$) difference with respect to data while for B16-AGSS09met differences are at the 2.5σ ($Y_S$) and 1.8σ ($R_{CZ}$) level.

Finally, Fig.1 shows the fractional difference between the sound speed inferred from helioseismic frequencies and that predicted by B16 SSMs as a function of solar radius for the two choices of solar composition. The solar sound speed has been obtained by new inversions based on the so-called BiSON-13 dataset [33] and using consistently both B16 SSMs as reference models. Results are only slightly different with respect to previous calculations, mainly as a result of the updated $S_{11}(0)$ value. We see that B16-GS98 model yields a much better agreement, everywhere in the solar structure, with the helioseismically derived sound speed profile than B16-AGSS09met. In particular, the B16-AGSS09 model disagrees by $\sim 1\%$ with sound speed inferred from helioseismology at the bottom of the convective envelope. This has to be compared with a theoretical uncertainty of $\sim 0.3\%$ and an error in the inversion procedure smaller than 0.1%.
4. The opacity profile of the Sun and the importance of CNO neutrinos

The conflict between helioseismology and SSMs implementing the state-of-the-art photospheric abundances (i.e. AGSS09met composition [1]) which was described in the previous section constitutes the so-called "solar composition problem". In order to assess its relevance and to consider possible solutions, it is important to understand the role of metals in the Sun.

The primary effect of a change of solar surface composition is to induce a modification of the solar opacity profile and, thus, of the thermal stratification of the Sun. Indeed, according to the SSM chemical evolution paradigm, the distribution of metals in the present Sun is nearly homogeneous\(^2\). A modification of the photospheric admixture \(\{z_i\}\), here expressed in terms of the quantities \(z_i \equiv Z_i/S\), where \(Z_i\) is the surface abundance of the \(i\)-element and \(S\) is that of hydrogen, implies then a different distribution of metals all over the Sun. Heavy elements contribute significantly to the radiative opacity which is then changed in each solar shell \(r\) by a factor \(1 + \delta \kappa Z(r)\), where:

\[
\delta \kappa Z(r) \simeq \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j} \delta z_j,
\]

is the composition opacity change, \(\partial \ln \kappa/\partial \ln Z_j\) are the logarithmic derivatives presented in Fig. 10 of [34] and \(\delta z_j\) is the fractional variation of \(z_j\).

For most of the solar observable properties, the effects which are produced by a change of composition and/or a suitable modification of solar opacity are completely equivalent. This implies that one could reconcile AGSS09met composition with helioseismic results by assuming that opacity at each point \(r\) of the Sun is wrong by a suitable factor \(1 + \delta \kappa(r)\). It was shown in [34] that opacity should be increased by \(\sim\) few\% at the center of the Sun and by \(\sim 25\%\) at the bottom of the convective envelope in order to restore agreement of AGSS09met SSMs with helioseismic and solar neutrino data. Uncertainties in opacity calculations are at few \(\sim\%\) level and do not allow for such a possibility. However, it should be taken into account that radiative opacities are the result of very sophisticated (and, unfortunately, incomplete) theoretical calculations and that the quoted uncertainties are usually obtained by comparing results by different groups.

A breakthrough in the solar composition problem could be obtained in the future by observing the neutrino fluxes produced in the CN-cycle. These fluxes, besides being sensitive to the central solar temperature, are roughly proportional to the carbon and nitrogen abundance in the solar core, since these elements are used as "catalysts" for hydrogen fusion in the CN-cycle. Even a low accuracy measurement, providing a direct determination of the metallicity of the solar core, could remove the degeneracy between opacity and composition effects and, thus, would be extremely important. Let us imagine e.g. to measure the CNO flux at the 20\% level. If the detected fluxes were consistent with the carbon and nitrogen abundances in the GS98 composition (i.e. about 40\% larger than the AGSS09met SSMs predictions), this would be sufficient to conclude that the AGSS09met surface abundances are wrong and/or the chemical evolution paradigm of SSM is not correct. There would be no possibility to explain the observed results by assuming that opacity (or, more in general, energy transport in the Sun) is not correctly described. On the contrary, if the detected fluxes were consistent with those predicted by SSMs using AGSS09met admixture, then this would imply a tension with other observational constraints which could be only explained by assuming that opacity calculations are wrong by a factor much larger than the presently estimated uncertainties. Both these results would have enormous implications for stellar evolution.

Unfortunately, the detection of CNO neutrinos is a very difficult task. Not only the flux is relatively low, but also their energy is not large. The neutrinos produced by \(\beta-\)decay of \(^{13}\text{N},\ ^{15}\text{O}\) and \(^{17}\text{F}\) in the CNO cycle have continuous energy spectra with endpoints at about 1.5MeV. Differently from the monochromatic \(^7\text{Be}\) and pep solar neutrinos, they do not produce

\(^2\) A \(\sim 10\%\) increase of metal abundances at the center of the Sun is produced by microscopic diffusion.
specific spectral features that permit to extract them unambiguously from the background event spectrum in high purity liquid scintillators. In particular, the electrons produced in the detector by the $\beta-$decay of $^{210}$Bi have a spectrum that is similar to that produced by CNO neutrinos. As a consequence, spectral fits are able to determine only combined Bismuth+CNO contribution, as it was done e.g. by Borexino. In order to remove this degeneracy, it was proposed in [35] to determine the $^{210}$Bi background by looking at the time evolution of $\alpha-$decay rate of $^{210}$Po. It was shown that a Borexino-like detector could start discerning CNO neutrino signal from $^{210}$Bi background in $\Delta t \sim 1$ yr, provided that $\alpha$ particle detection efficiency is stable and external sources of $^{210}$Po are negligible. Finally, it was observed in [36] that the so-called ecCNO neutrinos, produced in the Sun by electron capture reactions on $^{13}$N, $^{15}$O and $^{17}$F, provides the same information on the metallic content of the solar core as the "conventional" CNO neutrinos. The ecCNO neutrino fluxes are extremely low and their experimental determination is very difficult. It was shown [36], however, that this challenging task could be at reach for future gigantic ultra-pure liquid scintillator detectors, such as LENA.

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