Solar models, neutrinos and composition

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In this presentation we review the current status of standard solar models (SSMs) and the solar abundance problem. We show that the most recent generation of SSMs (B16) yields neutrino fluxes that favors solar models with high metallicity interiors. This is in agreement with helioseismic probes of the solar interior, which also favor high-metallicity solar models. For the first time, both solar neutrino fluxes and helioseismology point towards the same preferred solution. However, because available neutrino data refers only to fluxes coming from the pp-chain, this preference is not towards a certain solar composition but rather towards a given internal temperature profile. At this point, the degeneracy between solar composition and radiative opacities cannot be broken. Future CNO solar neutrino experiments are the most promising way of elucidating the answer to this conundrum. In this presentation, we also show that for cases where the detailed solar composition is not a critical factor, SSMs are an excellent framework over which to test non-standard physics in solar (stellar) interiors and a laboratory for particle physics regardless of the solar abundance problem.

1 Introduction

About 15 years have passed since neutrino flavor oscillations were confirmed in solar neutrinos directly by the measurements of the ^{8}B solar neutrino flux, $\Phi(^8\mathrm{B})$, by SNO [1, 2]. The discovery came after more than 30 years of controversy, following the initial results of the Homestake experiment [3], that have seen neutrino experiments, solar models and incomplete understanding of the physics of neutrinos being discussed as possible culprits of the *solar neutrino problem*. Kamiokande first [4], and the gallium experiments afterwards (SAGE [5, 6] and GALLEX [7]), confirmed the problem of the missing neutrinos. At the same time they established a pattern of fluxes with strong indications that an astrophysical solution, i.e. lowering the fluxes predicted by solar models, could not be reconciled with the experiments. Moreover, during the mid 90s, helioseismology was established as a reliable diagnostics tool of the structure of the solar interior, and the agreement between standard solar models (SSMs) and helioseismic inferences was astoundingly good [8, 9]. As a result, the second half of that decade saw a rapidly decreasing number of advocates favoring a solar model solution to the solar neutrino problem. Then, Super-Kamiokande discovered oscillations of atmospheric neutrinos [10]. And soon, SNO not only discovered solar neutrino oscillations but showed that SSM predictions for the $\Phi(^8\mathrm{B})$ flux were spot on [11, 12]. These two experiments then firmly established the reality of neutrino flavor oscillations, showing at the same time the incompleteness of the standard model of particles and the soundness of SSMs as an accurate description of many properties of the Sun [11, 13]. A recent historical account of the development of solar neutrino experiments and models can be found in [14].

Coincidentally with the discovery of neutrino oscillations, development of three dimensional models of the convective solar atmosphere [15, 16] and refinement of spectroscopic techniques and data (oscillator strengths of line transitions, line formation in non-local thermodynamic equilibrium) brought about a strong reduction in the spectroscopically determined metal abundances in the solar photosphere compared to older determinations [17, 18]. This is particularly important for the volatile and abundant carbon, nitrogen and oxygen, which added together amount to more than 2/3 of the solar metal content. This reduction, that amounts to up to 40% depending on the element and the authors [19], has a strong impact in solar modeling and puts into question the quality of SSMs as description of the solar interior properties as determined from helioseismic measurements. The apparent limitations of SSMs are evident in the predicted sound speed and density profiles, depth of the convective envelope, surface helium abundance, small frequency separation ratios (e.g. [13, 20]) among other diagnostics. Is the solar abundance problem in fact a *standard solar model problem* that shows the limitations of this framework? If so, then it is extensive to stellar modeling in general. Does the problem lay in the assumptions (simplifications) entering standard solar model calculations or in the microphysics (equation of state, radiative opacities, nuclear reaction rates) employed? Is it, on the contrary, a problem with solar abundances? If so, then it is extensive to almost all inferences of cosmic abundances, for most of which solar abundances are the yardstick against which they are determined. Or is the problem in our understanding of atomic physics, or of 3D solar model atmospheres? All these questions are of paramount importance not only for stellar astrophysics and astronomy, but for any field for which cosmic abundances are a quantity of interest.

In this presentation we briefly review the status of the solar abundance problem and present some results of an up-to-date generation of SSMs for both high (based on 1D model atmospheres, e.g. [17]) and low (based on 3D model atmospheres, [18]) solar metallicity. Theoretical predictions, based on updated SSMs, show for the first time since the solar abundance problem appeared, that helioseimic properties of the Sun and solar neutrino fluxes reflect the same stratification in the solar interior, consistent with that of high-metallicity SSMs. We argue, however, that this is not necessarily an indication of a high-metallicity but rather of a well determined temperature profile. Also, we discuss the limitations of the framework defined by SSMs and show that, by allowing variations of the microscopic inputs within the experimentally allowed space, SSMs continue to offer a good description of the solar interior. Therefore, and despite of the solar abundance problem, SSM predictions are still a benchmark against which to test more complex physical descriptions of the solar interior or even to test properties of hypothetical candidates to dark matter or non-standard properties of particles.

2 B16: a new generation of SSMs

In 2011, a round of SSMs was published [21] that included the nuclear cross sections recommended by the then recently published Solar Fusion II review article [22]. Since then, rates for some of the relevant nuclear reactions for solar models have been revised following both theoretical work or a reanalysis of existing experimental data. The changes in the rates are not dramatic, but $\Phi(^8\mathrm{B})$ and $\Phi(^7\mathrm{Be})$ solar fluxes are now measured to excellent precision [23, 12, 24] so even modest changes in the models translate into differences that are potentially

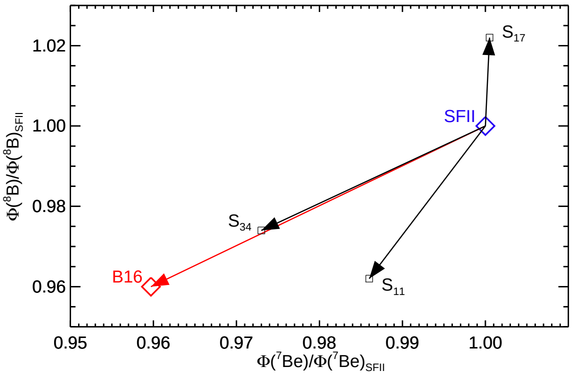

Figure 1: Fractional change of the SSM $\Phi(^7\mathrm{Be})$ and $\Phi(^8\mathrm{B})$ fluxes with respect to the previous generation of SSMs based on Solar Fusion II reaction rates.

measurable by current and future neutrino experiments.

The most important changes have occurred for $p+p$ [25], $^3\mathrm{He}+^4\mathrm{He}$ [26] and $p+^7Be$ [27]. While the latter only impacts the prediction of $\Phi(^8\mathrm{B})$, the former two affect $\Phi(^7\mathrm{Be})$ as well. It is worth mentioning changes in the astrophysical factor $\mathrm{S}_{11}(E)$ stem not only from changes in $S(0)$ but also in $S'(0)$ and higher order derivatives. The relative variations introduced by each of these rates in the fluxes are shown in Fig. 1 in black arrows while the red arrow shows their cumulative effect, i.e. the overall change from the older generation of SSMs (SFII) to the new one (Barcelona 2016, B16 in short form). These changes are common to all SSMs regardless the detailed composition used to build them, so they are the same for GS98 and AGSS09 solar compositions. As shown in the figure, B16 predictions for $\Phi(^8\mathrm{B})$ and $\Phi(^7\mathrm{Be})$ are about 4% lower than for the SFII SSMs. Changes in other fluxes of the pp-chains are smaller, and well within the uncertainty from neutrino experiments.

	GS98	AGSS09	Helios.
α_{MLT}	2.18 ± 0.05	2.11	-
Y_{ini}	0.2717 ± 0.0056	0.2613	-
Z_{ini}	0.0187 ± 0.0013	0.0159	-
Y_{S}	0.2426 ± 0.0059	0.2316	0.2485 ± 0.0035
Z_{S}	0.0170 ± 0.0012	0.0134	-
Y_{C}	0.6320 ± 0.0053	0.6209	-
Z_{C}	0.0200 ± 0.0014	0.0159	-
$R_{\mathrm{CZ}}/\mathrm{R}_{\odot}$	0.7117 ± 0.0048	0.7224	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021	-

Table 1: Main SSM characteristics from the different sets of MC simulations. Also included are helioseismically inferred values.

Helioseismic probes are not sensitive to the changes in the nuclear rates from SFII to the newly adopted values to a measurable level. Only S_{11} could introduce some changes but these are too small to be of relevance. Fig. 2 shows results for the sound speed profile of SSMs corresponding to GS98 and AGSS09, the most widely used compositions. These are results of two sets of Monte Carlo simulations (Vinyoles et al. in prep.) consisting of 10000 SSMs each. In each panel, the red curve shows the results for the central SSM, green dotted lines show the 1-σ contours and the intensity of the color shade represents a histogram of the frequency of a given $\delta c/c$ occurring at a given depth r/R_{sun}. From the figures, it is clear that models based on AGSS09 do not describe helioseismic inferences properly, as it has been demonstrated often

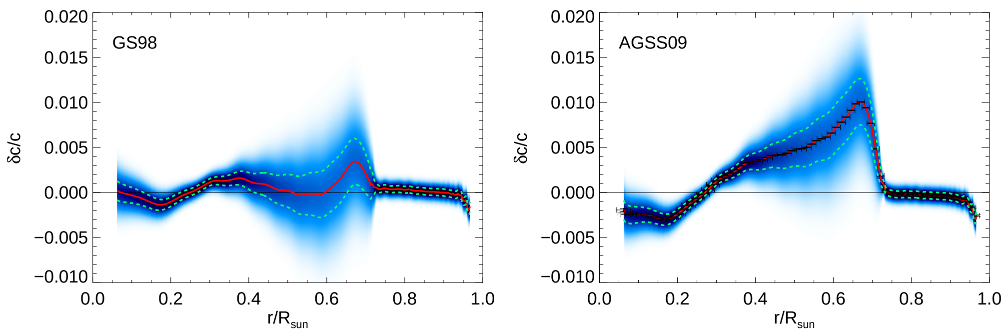

Figure 2: Histograms of sound speed profiles of SSMs where intensity indicates the frequency of $\delta c/c$ values at given $r/R_{\rm sun}$ in the MC simulations. Red lines correspond to central values and green dotted lines represent 1-σ contours of model uncertainties. Black crosses are the sound speed uncertainties propagated from uncertainties in p-mode frequencies.

in the past. Table 1 offers a summary of SSM properties and uncertainties derived from the MC simulations. For reasons of space, errors of the AGSS09 set have not been included in the table, but are quite similar to those of the GS98 MC set.

	GS98	AGSS09	Exper.
$\Phi(pp)$	$5.99(1 \pm 0.006)$	6.04	$5.971^{+0.037}_{-0.033}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	1.47	1.448 ± 0.013
$\Phi(hep)$	$8.00(1 \pm 0.30)$	8.27	$\leq 19^{+12}_{-9}$
$\Phi(^{7}Be)$	$4.80(1 \pm 0.06)$	4.38	$4.80^{+0.24}_{-0.22}$
$\Phi(^{8}B)$	$5.32(1 \pm 0.12)$	4.37	$5.16^{+0.013}_{-0.09}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	2.05	≤ 12.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	1.44	≤ 2.8
$\Phi(^{17}F)$	$5.30(1 \pm 0.20)$	3.26	≤ 85

Table 2: Neutrino fluxes for the different B16 SSMs with the correspondent model errors and experimental results from a combined analysis of all neutrino experiments [24].

Results confirm earlier findings, with the B16 set of SSMs yielding very similar helioseismic results than the previous SFII generation of SSMs. Helioseismic probes of the solar interior clearly favor solar models based upon the GS98 composition, i.e. a high-metallicity solar composition, over the more modern and physically sound AGSS09 values. It is important to emphasize that the available set of helioseismic probes is not directly sensitive to the solar composition but to the actual temperature-density-pressure composition which, in turn, depends on the radiative opacity in the solar interior. The impact of metals in the solar structure is mostly through their importance as opacity sources. Therefore, helioseismic probes should be considered dependent on the opacity profile rather than on the abundance of metals. *The solar abundance problem still remains open.*

Detailed results for solar neutrino fluxes are given in Table 2. SSM results correspond to the MC sets and, again for reasons of space, fractional errors for the AGSS09 have been omitted (being very similar to those from GS98). Experimental results correspond to the results of the combined analysis of all available neutrino data [24] together with the luminosity constraint. Interestingly, the reduction in the predictions of $\Phi(^{8}\mathrm{B})$ and $\Phi(^{7}\mathrm{Be})$ in the B16 solar models brings the B16-GS98 results to a closer agreement with experimental results than its B16-AGSS09 counterpart for which now theoretical predictions are lower than experimental values. This is at odds with the previous SFII generation of models for which GS98 and

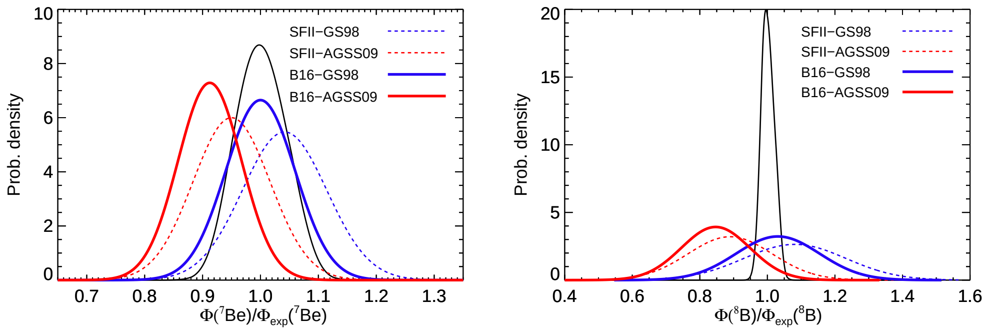

Figure 3: Comparison of solar neutrino fluxes determined from all available neutrino data (black lines [24]) and the previous (SFII - dotted lines) and current (B16 - thick solid lines) generations of SSMs.

AGSS09 compositions led to solar models that had $\Phi(^8\mathrm{B})$ and $\Phi(^7\mathrm{Be})$ fluxes in practially equal agreement with experimental data [21].

The new situation is more clearly illustrated in Fig 3 where model and experimental results are compared. Fluxes are normalized to experimental values [24]. Results from the older SFII SSMs are shown in dotted lines and, for GS98 and AGSS09 compositions, are almost symmetrically located to each side of the experimental result of the corresponding flux, $\Phi(^8\mathrm{B})$ or $\Phi(^7\mathrm{Be})$. With the B16 models, in solid lines, experimental results clearly show a preference for the GS98 SSM. A detailed quantification of the level of agreement of each of the B16 SSMs is ongoing work (Song et al. 2016 in prep.).

As stated above, helioseismic probes have a strong preference for GS98 based SSMs, although as also mentioned this cannot be interpreted as direct measurement of the solar composition but rather an indirect determination of the opacity profile in the solar interior [28, 29]. For the SFII models, it was not possible to claim that neutrino experiments had a preference of models of a given composition. Now, however, this situation has changed and for the B16 set of models solar neutrino fluxes also show the same results: GS98-based SSMs are to be preferred. *For the first time solar neutrinos and helioseismology favor the same solar interior properties, consistent with those inferred from high metallicity solar models.*

It is important to realize that neutrino fluxes originating in any of the pp-chain reactions are sensitive also to the temperature stratification in the solar core. This is to say, they are not directly sensitive to the composition but rather to the opacity profile. The situation is therefore very much the same as for the helioseismic probes: the sensitivity lies in the opacity profile, not the composition. For any of these probes, there is a degeneracy between opacity and metal abundances that needs independent constraints to be broken. At this moment, it is not possible to state whether AGSS09 metal abundances are too low or all atomic opacity calculations are intrinsically flawed and underestimate the actual radiative opacity in solar (and stellar) interiors.

Recently, the first ever experimental measurements of iron opacity under conditions quite close to those found at the base of the convective envelope of the Sun have become available [30]. These results seem to indicate that, in fact, opacity calculations [31, 32] underestimate the true iron opacity by large fractions that result in a final Rosseland mean opacity (the one actually relevant in solar interior calculations) that is underestimated by about 7% at the base of the convective envelope. While clearly not enough to bring AGSS09 models into agreement with helioseismic data because an increase of the order of 15 to 20% is needed, these results are the first indication that in fact atomic opacity calculations might need a thorough revision. Some work in this direction has been carried our recently [33], showing that the treatment of line broadening alone may introduce an uncertainty level of several percents in opacity calculations.

3 Best-fit SSM

In the *standard* framework of SSM calculations the number of free parameters is kept to a minimum and phenomenological calibrations are avoided as much as possible (see e.g. [34] for more details). This strategy ensures that SSMs the *recipe* with which they are computed, being well defined, yields robust predictions. But, at the same time, it is clear that physical phenomena are modeled poorly in SSMs (e.g. near surface convection) or not modeled at all (e.g. rotation). It is also well known SSMs cannot account for some observations, e.g. the solar surface lithium abundance (more then 2 orders of magnitude lower than found in meteorites) among others.

A question that can be asked is: what are the limits of the SSM framework? Or, posed differently, what is the best possible description of solar interior properties the SSM framework can offer? The answer is important for several reasons. Among others: SSMs are used to set limits to exotic particles or non-standard properties of standard particles, SSM framework is the same entering most of stellar structure and evolution models, SSMs are the reference against which non-standard stellar physics is tested.

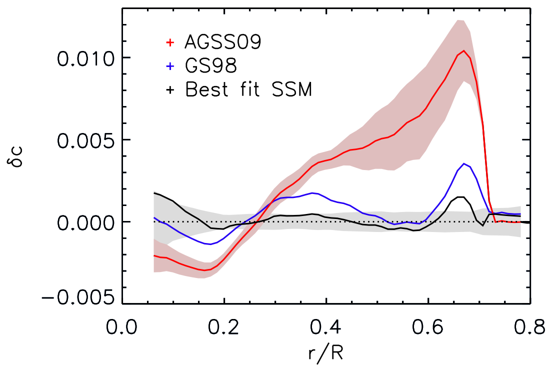

Figure 4: Sound speed profiles as in Fig. 2. The *best-fit SSM* (see text for details) is shown in black. The red and grey shaded area show the 1-σ model and sound speed inversion uncertainties respectively.

A way of answering this question is to allow input parameters (nuclear reaction rates, composition, opacity profile, etc.) in the SSMs as quantities that can be varied to provide the best possible fit to combined helioseismic and solar neutrino data. This exercise was carried out initially by [29], where a global χ^2 function was built using 32 helioseismic constraints (30 points of the sound speed profile, depth of convective envelope, surface helium abundance) and the $\Phi(^8\mathrm{B})$ and $\Phi(^7\mathrm{Be})$ neutrino fluxes. The response of each of these quantities to changes in the input parameters was built using power-law expansions and the input parameters were allowed to vary around their measured values by introducing the concept of pulls with a penalty function in the global χ^2. χ^2 is then minimized with respect to these pulls to offer a set of varied input parameters that allow the reconstruction of a *best-fit SSM*.

Later, the idea was extended to produce bounds for properties of exotic particles (axions and dark photons) [35]. In this approach, the solar composition is allowed to vary freely (no penalty). In the case of SSMs, the resulting sound speed profile of the *best-fit SSM* is shown in Fig. 4, where it is compared to those from GS98 and AGSS09 SSMs. As it can be seen in the figure, the performance of the GS98 model can be improved if input parameters in the SSM are varied (usually within 1-σ) from the currently accepted values. Of course, the best-fit SSM reflects a solar composition close to that of GS98. The idea that SSMs can be used in studies of particle physics, regardless of the unsolved solar abundance problem, then relies on the fact that the interaction of these particles with standard matter (e.g. magnetic dipole of neutrinos), or the energy loss rates (in the case of weakly interacting particles), does not depend (or does so very weakly) on the detailed composition of the solar interior. This is very often the case, and under these conditions, the best-fit SSM offers a very stringent limit to the maximum impact non-standard physics can have in modifying solar interior properties. This has been exploited, for the first time, to improve existing constraints in axion-photon coupling and dark-photons kinetic coupling

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