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The B16 Standard Solar Models

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Abstract. We describe a new generation of standard solar models (SSMs), Barcelona 2016 or B16 for short, that includes recent updates on some important nuclear reaction rates, a more consistent treatment of the equation of state and a novel and flexible treatment of opacity uncertainties. Two large sets of SSMs, each based on a different canonical set of solar abundances with high and low metallicity, are calculated and compared with different ensembles of solar observables including solar neutrinos, surface helium abundance, depth of convective envelope and sound speed profile.

1. Introduction

In the last three decades, there was an enormous progress in our understanding of the sun. The predictions of the Standard Solar Model (SSM), which is the fundamental theoretical tool to investigate the solar interior, have been tested by solar neutrino experiments and by helioseismology. The deficit of the observed solar neutrino fluxes, reported initially by Homestake [1, 2] and then confirmed by GALLEX [3], SAGE [4], GNO [5], Kamiokande [6] and Super-Kamiokande [7], generated the so-called solar neutrino problem which stimulated a deep investigation of the solar structure. The problem was solved in 2002 when the SNO experiment [8] obtained a direct evidence for flavour oscillations of solar neutrinos and, moreover, confirmed the SSM prediction of the ^{8}B neutrino flux.

Nowadays, we have a good knowledge of the solar neutrino oscillation probability and a direct experimental determination of most of the solar neutrino components. Super-Kamiokande [9] and SNO [10] have provided a high accuracy determination of ^{8}B neutrinos. Borexino has recently obtained a direct measure of the *pp*, *pep*, ^{7}Be [11, 12] and ^{8}B [13] solar neutrino fluxes and it also has the potential to provide the first direct measurements of the CNO neutrinos [14] in the next future. In addition, helioseismic observations have allowed to determine precisely several important properties of the sun, such as the depth of the convective envelope which is known at the $\sim 0.2\%$ level, the surface helium abundance which is obtained at the $\sim 1.5\%$ level and the sound speed profile which is determined with an accuracy equal to $\sim 0.1\%$ in a large part of the sun (see e.g. [15, 16] and references therein). As a results of these observations, the solar structure is now very well constrained, so that the sun can be used as a solid benchmark for stellar evolution and as a laboratory for fundamental physics.

A new solar problem has, however, emerged during the last years. Recent determinations of the photospheric heavy element abundances [17, 18, 19] indicate that the sun metallicity is lower

	S(0)	Uncert.(%)	$\Delta S(0)/S(0)$	Ref.
S_{11}	$4.03 \cdot 10^{-25}$	1	0.5%	[27, 28, 29]
S_{17}	$2.13 \cdot 10^{-5}$	4.7	+2.4%	[30]
S_{114}	$1.59 \cdot 10^{-3}$	7.5	-4.2%	[31]

Table 1. *Astrophysical S-factors (in units of MeV b) and uncertainties updated in this work. Fractional changes with respect to [32] are also included.*

than previously assumed [20, 21]. Solar models that incorporate these lower abundances are no more able to reproduce the helioseismic results. As an example, the sound speed predicted by SSMs at the bottom of the convective envelope disagrees at the 1% level with the value inferred by helioseismic data (see e.g.[22]). Detailed studies have been done to resolve this controversy (see e.g.[23]), but a definitive solution of the solar composition problem still has to be obtained.

In this brief review, which is largely based on [24], we present a new generation of SSMs, Barcelona 2016 or B16 for short, that includes recent updates on some important nuclear reaction rates, a more consistent treatment of the equation of state and a novel and flexible treatment of opacity uncertainties. Two large sets of SSMs, each based on a different canonical set of solar abundances with high and low metallicity, and with input parameters chosen randomly from their respective distributions, are computed. The predictions (and the uncertainties) for different solar observables, including solar neutrino fluxes, surface helium abundance, depth of convective envelope and sound speed profile, are presented and compared with the observational determinations.

2. The B16 standard solar models

SSMs are a snapshot in the evolution of a $1M_{\odot}$ star, calibrated to match present-day surface properties of the Sun. The calibration is done by adjusting the mixing length parameter ($\alpha_{\rm MLT}$) and the initial helium and metal mass fractions ($Y_{\rm ini}$ and $Z_{\rm ini}$ respectively) in order to satisfy the constraints imposed by the present-day solar luminosity $L_{\odot}$, radius $R_{\odot}$, and surface metal to hydrogen abundance ratio $(Z/X)_{\odot}$. The new B16 models share with previous calculations [25] much of the input physics, but include important updates. A brief account of few relevant ingredients is given in the following.

Equation of State: B16 SSMs employ, for the first time, EoS tables calculated consistently for each of the compositions used in the solar calibrations by using FreeEOS [26].

Nuclear rates: The rates of $\rm p(p, e^{+}\nu_e)d$, $\rm ^7Be(p,\gamma)^8B$ and $\rm ^{14}N(p,\gamma)^{15}O$ reactions have been updated, see Tab.1[1]. For the important reaction $\rm ^3He(^4He,\gamma)^7Be$ (not included in Tab.1), two recent analyses [33, 34] 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 [33] and [34], respectively). Considering that the results from [33] and [34] bracket the previously adopted value from [32], the latter was considered as preferred choice in B16 SSMs.

Radiative opacities: In [25] the opacity error was modelled as a 2.5% constant factor at 1σ level, comparable to the maximum difference between OP [35] and OPAL [36] opacities in the solar radiative region. It was shown, however, in [37] that this prescription underestimates the contribution of opacity uncertainty to the sound speed and convective radius error budgets

[1] For the $\rm p(p, e^{+}\nu_e)d$ 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 [24] for details).

	GS98	AGSS09met	Obs
$\Phi(\mathrm{pp})$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{+0.037}_{-0.033}$
$\Phi(\mathrm{pep})$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	1.448 ± 0.013
$\Phi(\mathrm{hep})$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	19^{+12}_{-9}
$\Phi(^7\mathrm{Be})$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{+0.24}_{-0.22}$
$\Phi(^8\mathrm{B})$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{+0.13}_{-0.09}$
$\Phi(^{13}\mathrm{N})$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}\mathrm{O})$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}\mathrm{F})$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 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 [43]. The 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) $\mathrm{cm^{-2}s^{-1}}$. *The last two lines give the surface helium* Y_S *and the convective radius* R_CZ. *The observational values are given by [44] and [45], respectively.*

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 than in the region around the base of the convective envelope. Taking this into account, the following parameterization for the opacity change $\delta\kappa(T)$ was considered:

$$\delta\kappa(T) = a + b\frac{\log\left(T_\mathrm{C}/T\right)}{\Delta} \tag{1}$$

where T is the temperature of the solar plasma, $\Delta = \log\left(T_\mathrm{C}/T_\mathrm{CZ}\right) = 0.9$, $T_\mathrm{C} = 15.6 \times 10^6$ K and $T_\mathrm{CZ} = 2.3 \times 10^6$ 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 $\sigma_\mathrm{in} = \sigma_a = 2\%$, while it is given by $\sigma_\mathrm{out} = (\sigma_a^2 + \sigma_b^2)^{1/2} = 7\%$ at the base of the convective zone, as can be motivated by the recent experimental results of [38] and the theoretical work by [39].

Surface composition: The solar surface composition is a fundamental constraint in the construction of SSMs. In this paper, we consider two different canonical sets of solar abundances which are the same employed in [25]:

- GS98 - Photospheric (volatiles) + meteoritic (refractories) abundances from [20] that correspond to metal-to-hydrogen ratio used for the calibration $(Z/X)_\odot = 0.0229$;
- AGSS09met - Photospheric (volatiles) + meteoritic (refractories) abundances from [17] that give $(Z/X)_\odot = 0.0178$.

Note that the recent results from [40, 41, 42] that have updated the abundances of [17] for all but CNO elements (which are the most abundant among the volatiles elements) do not lead to a revision of the AGSS09met composition.

3. 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, Fig.1 and 2 and are discussed below.

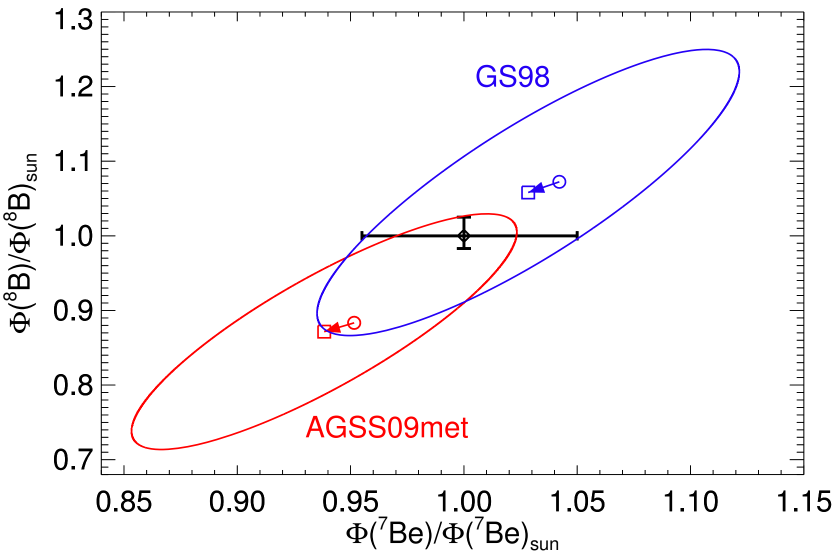

Figure 1. $\Phi(^8\mathrm{B})$ *and* $\Phi(^7\mathrm{Be})$ *fluxes normalized to solar values [43]. Black circle and error bars: solar values. Squares and circles: results for B16 (current) and (older) generation of SSMs respectively. Ellipses denote theoretical* 1σ *C.L. for 2 dof.*

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 [25]. The overall reduction in the $\Phi(^8\mathrm{B})$ and $\Phi(^8\mathrm{Be})$ fluxes comes from the increase in S_{11}. In the case of $\Phi(^8\mathrm{B})$, this is partially compensated by the 2.4% increase in S_{17}. The most important changes in the neutrino fluxes occur for $\Phi(^{13}\mathrm{N})$ and $\Phi(^{15}\mathrm{O})$, in the CN-cycle. The expectation values in the B16 SSMs are about 6% and 8% lower than for the previous SSMs [25]. This results from the combined changes in the p+p and ^{14}N+p reaction rates.

The predicted fluxes should be compared with the observational values in the last column of Tab.2 which have been obtained in [43] from a fit to the results of solar neutrino experiments by allowing for three-flavour neutrino oscillations. Note that observational errors for $\Phi(^8\mathrm{B})$ and $\Phi(^8\mathrm{Be})$ fluxes are smaller than uncertainties in theoretical predictions, as can be also appreciated in Fig.1 where we summarize the present situation for these two components of the solar neutrino spectrum. 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. 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 [25], we find a small decrease in the predicted Y_{S} by 0.0003 and in the predicted R_{CZ} by $0.0007R_\odot$ 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.2 shows the fractional difference between the sound speed inferred from

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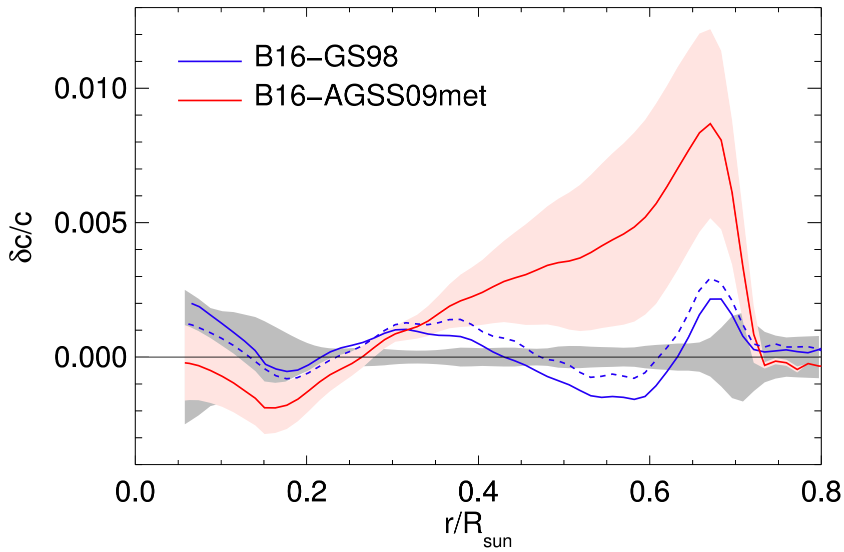

Figure 2. *Fractional sound speed difference* $\delta c/c = (c_\odot - c_{\rm SSM})/c_{\rm SSM}$. *The grey shaded region corresponds to errors in the helioseismic inversion procedure. The red shaded region around the AGSS09met central value (solid red line) describes uncertainties in SSM calculations. An equivalent relative error band holds around the central value of the GS98 central value (solid blue line) which we do not plot for the sake of clarity. Dashed line shows, for comparison, results for old SSM calculations [25].*

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 [46] 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. Summary and Conclusions

In this review which is largely based on the results of [24], we have presented B16-GS98 and B16-AGSS09met, a new generation of SSMs calculated for different canonical set of abundances with high and low metallicity. We summarize our most important findings here:

- Central values for $\Phi(^7\mathrm{Be})$ and $\Phi(^8\mathrm{B})$ in B16 SSMs are reduced by about 2% with respect to the previous generation of models that were based completely on nuclear reaction rates from [32]. The CN-cycle fluxes, $\Phi(^{13}\mathrm{N})$ and $\Phi(^{15}\mathrm{O})$, are reduced by 6% and 8% respectively. Solar neutrino fluxes [43] are reproduced almost equally well by both B16-GS98 and B16-AGSS09met, with only a very minor preference for B16-GS98.
- Helioseismic properties of B16 models are almost unchanged with respect to older models. However, our estimation of errors is larger due to our more pessimistic assumption of a 7% uncertainty in the radiative opacity at the base of the convective envelope. Comparison of models against $Y_{\rm S}$ and $R_{\rm CZ}$ and the helioseimic inferred solar sound speed profile yields a much better agreement for B16-GS98 than for B16-AGSS09met.

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References

[1] Davis R Jr., Harmer D S and Hoffman K C 1968 *Phys. Rev. Lett.* **20** 1205
[2] Cleveland B R et al. 1968 *ApJ* **496** 505
[3] Hampel W at al. 1999 *Phys. Lett. B* **447** 127
[4] Abdurashitov J N et al. 1999 *Phys. Rev. Lett.* **83** 4686
[5] Altmann M et al. 2005 *Phys.Lett. B* **616** 174
[6] Hirata K S et al. 1989 *Phys. Rev. Lett.* **63** 16
[7] Cravens J P et al. 2008 *Phys. Rev. D* **78** 032002
[8] Ahmad Q R et al. 2002 *Phys. Rev. Lett.* **89** 011301
[9] Abe K et al. 2016 *Phys. Rev. D* **94** 052010
[10] Bellerive A et al. 2016 *Nucl. Phys. B* **908** 30
[11] Bellini G et al. 2014 *Nature*, **512** 383.
[12] Agostini M et al. 2017 *Preprint* arXiv:1707.09279 [hep-ex].
[13] Agostini M et al. 2017 *Preprint* arXiv:1709.00756 [hep-ex].
[14] Villante F L, Ianni A, Lombardi F, Pagliaroli G and Vissani F 2011 *Phys. Lett. B* **701** 336
[15] Degl'Innocenti S, Dziembowski W A, Fiorentini G, Ricci B 1997 *Astrop. Phys.* **7** 77
[16] Gough D O et al. 1996, *Science* **272** 1296
[17] Asplund M, Grevesse N, Sauval A J and Scott P 2009 *Ann. Rev. Astron. Astrophys.* **47** 481
[18] Caffau E, Ludwig H G, Steffen M, Freytag B, Bonifacio P 2011 *Solar Physics* **268** 255
[19] Asplund M, Grevesse N, Sauval A J 2005 *Astronomical Society of the Pacific Conference Series* **336** ed T G Barnes and F N Bash p 25
[20] Grevesse N, Sauval A J 1998 *Space Sci.Rev.* **85** 161
[21] Grevesse N, Noels A 1993 *Origin and Evolution of the Elements* ed N Prantzos, E Vangioni-Flam E and M Casse p 15
[22] Bergemann M and Serenelli A 2014 *Determination of Atmospheric Parameters of B-, A-, F- and G-Type Stars. Series: GeoPlanet: Earth and Planetary Sciences* (Springer, Cham) ed E Niemczura, B Smalley and W Pych p 245
[23] Basu S and Antia H M 2008 *Phys. Rept.* **457** 217
[24] Vinyoles N et al. 2017 *ApJ* **835** 202
[25] Serenelli A M, Haxton W C and Pena-Garay C 2011 *ApJ* **743** 24
[26] Cassisi S, Salaris M and Irwin A W 2003 *ApJ* **588** 862
[27] Marcucci L E, Schiavilla R and Viviani M 2013 *Phys. Rev. Lett.* **110** 192503
[28] Tognelli E, Degl'Innocenti S, Marcucci L E and Prada Moroni P G 2015 *Phys. Lett. B* **742** 189
[29] Acharya B, Carlsson B D, Ekstrm A, Forssn C and Platter L 2016 *Phys. Lett. B* **760** 584
[30] Zhang X, Nollett K M and Phillips D R 2015 *Phys. Lett. B* **751** 535
[31] Marta M, Formicola A, Bemmerer D et al. 2011 *Phys. Rev C* **83** 045804
[32] Adelberger E G et al. 2011 *Reviews of Modern Physics* **83** 195
[33] deBoer R J et al. 2014 *Phys. Rev. C* **90** 035804
[34] Iliadis C, Anderson K, Coc A, Timmes F and Starrfield S 2016 *ApJ* **831** 107
[35] Badnell N R et al. 2005 *MNRAS* **360** 458
[36] Iglesias C A and Rogers F J 1996 *ApJ* **464** 943
[37] Villante F L 2010 *ApJ* **724** 98
[38] Bailey J E et al. 2015 *Nature* **517** 56
[39] Krief M, Feigel A and Gazit D 2016 *Preprint, arXiv:1603.01153* [astro-ph.SR]
[40] Scott P et al. 2015 *Astron. and Astophys.* **573** A25
[41] Scott P, Asplund M, Grevesse N, Bergemann M and Sauval A J 2015 *Astron. and Astophys.* **573** A26
[42] Grevesse N, Scott P, Asplund M and Sauval A J 2015 *Astron. and Astophys.* **573** A27
[43] Bergström J et al. 2016 *Journal of High Energy Physics* **3** 132
[44] Basu S and Antia H M 2004 *ApJL* **606** L85
[45] Basu S and Antia H M 1997 *MNRAS* **287** 189
[46] Basu S, Chaplin W J, Elsworth Y, New R and Serenelli A M 2009 *ApJ* **699** 1403