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Surprising Sun: A New Step Towards a Complete Picture?

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Important revisions of the solar model ingredients have appeared recently. We first show that the updated CNO composition suppresses the anomalous position of the Sun in the known galactic enrichment. The following law, $\mathrm{He/H} = 0.075 + 44.6\ \mathrm{O/H}$ in number fraction, is now compatible with all the indicators. We then suggest some directions of investigation to solve the discrepancies between the standard model and solar seismic observations. We finally update our predicted neutrino fluxes using a seismic model and all the recent progress. We get $5.31 \pm 0.6 \times 10^6/\mathrm{cm}^2/\mathrm{s}$ for the total ^{8}B neutrinos, 66.5 ± 4.4 SNU and 2.76 ± 0.4 SNU for the gallium and chlorine detectors, all in remarkable agreement with the detected values including neutrino oscillations for the last two. So, the acoustic modes and detected neutrinos see the same Sun, but the standard model fails to reproduce them.

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The Sun is one of the best defined reference object in astrophysics. As it is the most studied and best known star in the Universe, the main characteristics of the Sun—luminosity, mass, radius, and composition—are used as standard units in astrophysics. Through the years, progress has been constant in better determining the different ingredients which enter in the description of a star: nuclear reaction rates, opacity coefficients, diffusion of elements, etc. Two types of probes (the solar acoustic modes and neutrino detections) have been particularly useful in checking the internal properties of the Sun. The first probe determines the sound speed, the adiabatic exponent, and the rotation profiles from which the amount of photospheric helium (due to the extraction of the adiabatic exponent), or the convective zone basis (due to the variation of the temperature gradient) are deduced.

Precise acoustic modes have recently been used to predict neutrino fluxes through seismic models [1,2]. Different flavors of neutrinos have been also detected with the direction of the Sun in Sudbury Neutrino Observatory (SNO) and the total neutrino flux associated with boron has been measured for the first time [3]. These two improvements and their agreement have demonstrated the great interest to use the Sun as a laboratory for progressing on fundamental properties of the Universe as neutrino masses.

Nevertheless, this satisfactory picture offers some contradictions. On one hand, it seems that the picture of the "standard" model is a reasonable description of what we observe. It was noticed that the "seismic models" were not far from standard model. On the other hand, the Sun appears to be a more complex star than we thought for which one needs to interpret the internal rotation profile, the origin and evolution of the solar magnetic cycle(s) and the presence of meridional circulation. It has so far been important to describe the thermodynamical status of the Sun; it is now a natural next step to reveal a dynamical picture of our star.

In this paper, we discuss different consequences of the impact of the recent updates of the CNO abundances (-20% or -30% depending on authors) and of the nuclear reaction rates for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ and $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ (decrease by a factor 2), following previous studies [4–6]. First, we caculate the galactic enrichment compatible with the updated CNO composition which suppresses the anomalous position of the Sun in the galactic evolution. Second, we present in new models of the Sun, their comparisons with seismic models and possible interpretations and verifications of the discrepancies. Finally, we recalculate neutrino predictions and show that we keep a coherent picture of the Sun.

Galactic evolution and the Sun.—Fifteen years ago, the Sun appeared to be strangely rich in oxygen in comparison with its environment and with the Magellanic clouds [7,8]. Its metallicity was $Z = 0.02$, where Z is the mass fraction of elements heavier than helium, and the galactic enrichment in oxygen excluded the Sun as representative of the near neighborhood (Fig. 1 [OC]). At that time, it had been suggested that the Sun was formed in a cloud enriched by a supernova explosion. However, the comparison between meteoritic composition and photospheric composition [9] revealed some contradictions.

One of the contradictions has been solved by a reduction of the solar iron photospheric composition by 30% [10], so that the metallicity of the Sun has been slightly reduced ($Z = 0.0173$). As a consequence, the central temperature has been reduced by 1.5% due to the crucial role of iron in the opacity coefficient, the ^{8}B neutrino flux has been reduced by 13% and an increase of the discrepancy between model and the Sun for the sound speed profile has been noticed [11]. This effect has been compensated for by other progresses, for example, the introduction of

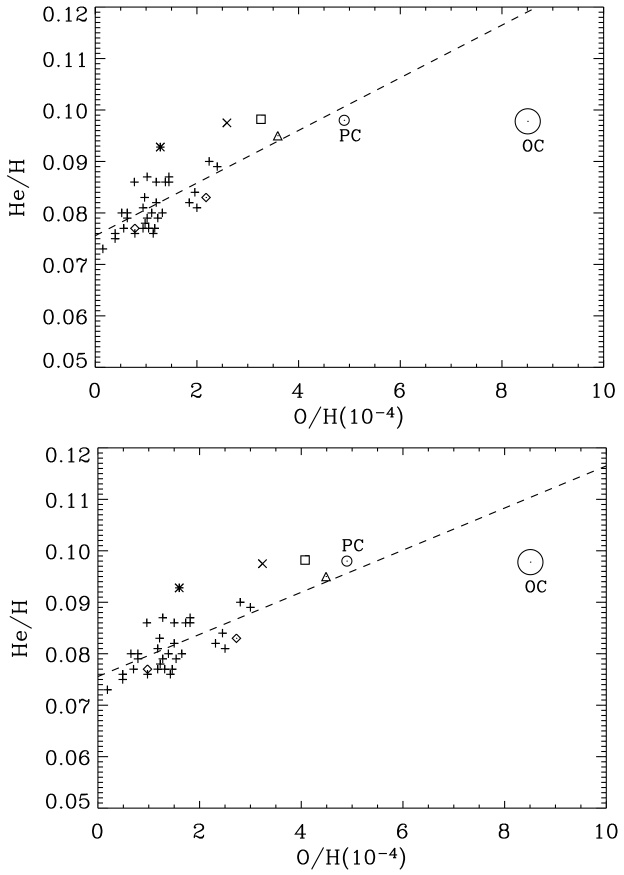

FIG. 1. Evolution of the ratio Y/H (helium/hydrogen in fraction number) versus O/H for extragalactic HII (+), SMC (*), LMC (× and diamonds), M42 (square), and M17 (triangle) [32–34]; the present composition (PC) for the Sun is compared to the old composition (OC) [8]. The top panel is extracted directly from observations, the bottom one includes a correction for oxygen in grains recommended by [7].

the microscopic diffusion [12]. See [4] for the evolution of neutrino predictions. Today, CNO composition has been revisited and reduced by almost the same amount with a stronger impact on the metallicity (Z as low as 0.013). In the oxygen case, the overestimate of the abundance has two origins: a false contribution due to a previously unidentified nickel line and the current use of hydrodynamical calculations of the atmosphere which lead to a better coherence between different lines analysis [13,14].

The solar initial helium abundance, obtained through a solar model, is not very sensitive to the details of the models. So we can look to the impact of the recent oxygen measurement on the place of the Sun in the general oxygen evolution along time (Fig. 1). Contrary to the past situation, we note that the Sun appears now naturally enriched in oxygen in comparison with extragalactic HII regions, Magellanic clouds, other clusters and neighbors [present composition (PC)]. We can now deduce a galactic enrichment in oxygen, including the Sun, after the introduction of a correction for taking into account the oxygen locked in grains [7]. The best value we get is $\mathrm{He/H} = 44.6\ \mathrm{O/H} + 0.075$.

Recently, [15] also noticed that the radioactive ^{26}Al, ^{10}Be and even ^{7}Be abundances in meteorites are compatible with production by irradiation in the disk of the young Sun. They conclude that the presence of a supernova in the neighborhood is not favored.

So these new estimates of the Sun composition solve serious problems and must be taken as the result of ten years of improvements in this field.

Standard and seismic models.—The consequences of the CNO abundance variations are well known: CNO play a role in the energy generation and consequently on the chlorine and gallium neutrino experimental predictions. They also play an important role in the opacity coefficients at all depths in the Sun but more specifically in the zone of the transition between radiation to convection, where the change in the degree of ionization of oxygen increases the opacity coefficient (see [8]). To test this impact, solar models were computed with the 1D stellar evolution code CESAM using the most updated basic physical ingredients already described in [2]. All the models are calibrated at the solar radius $R_\odot = 6.9599 \times 10^{10}$ cm, solar mass $M_\odot = 1.9891 \times 10^{33}$ g, and solar luminosity $L_\odot = 3.8460 \times 10^{33}$ erg, values at the age of 4.6 Gyr including premainsequence. We also calibrate the photospheric metallicity, expressed by the ratio Z/X, where X is the mass fraction of hydrogen; each model is calibrated at a specific Z/X value.

At low temperature ($T < 5600$ K), we use opacity tables provided by coauthor, Ferguson, which were specifically calculated for this work and based on [16]. These tables were computed for $Y = 0.27$ (photospheric mass fraction of helium). For higher temperatures, we have computed three different sets opacity tables from the OPAL website [17]. The first opacity set is based on the abundances of Asplund (A) [14] for C, N, O, Ne, and Ar elements, completed by the abundances of [10]. The second set is based on the abundances of Holweger (H) [13] for C, N, O, Ne, Mg, Si, and Fe elements, completed by the abundances of [10]. A last set is based on the photospheric abundances of Lodders (L) Table I [18], with the isotopic abundances from Table VI, instead of the isotopic abundances of [9]. Therefore we produce three kinds of solar models. For each kind we derive two models, one with mixing in the tachocline (transition region between radiation and convection, prefix "tac" in the model name) and one without (prefix "St" in the model name). The models are, respectively, calibrated at $Z/X = 0.0172$, 0.0176, 0.0210 for Asplund, Lodders, and Holweger composition and their main characteristics presented in Table I, in comparison with seismic model results. The seismic models we have built are not yet considered as physical models but they are representative models of the present seismic observations. They allow a determination of the main ingredients for neutrino predictions which

TABLE I. Characteristics of the new models using Lodders (L), Asplund (A), and Holweger (H) compositions for standard (St) and model with turbulence in the tachocline (tac) compared with seismic model 2 of [2].[a]

	St A	tac L	tac H	tac A	Seismic
X_i	0.7195	0.7245	0.7203	0.7240	0.7064
Y_i	0.2664	0.2617	0.2633	0.2625	0.2722
X_c	0.3526	0.3591	0.3522	0.3577	0.3371
Y_c	0.6323	0.6261	0.6301	0.6278	0.6428
T_c	15.58	15.495	15.55	15.52	15.71
Y_s	0.2353	0.2400	0.2419	0.2407	0.251
α	1.782	1.762	1.856	1.754	2.04
BZC	0.7285	0.7307	0.7241	0.7312	0.7113
$(Z/X)_s$	0.0172	0.0176	0.0210	0.0172	0.0245
Ga	120.9	118.3	121.6	119.0	126.8
Cl	6.314	5.813	6.165	5.956	6.9
Boron	4.175	3.801	3.982	3.909	4.88

[a] The indices i and s are for initial and surface, the central temperature T_C is in 1×10^6 degrees, boron flux in $10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

are the temperature and density profiles in the radiative region. We present in Fig. 2 the sound speed and the density of the standard models with turbulent mixing in the tachocline and the seismic model 2 of [2] compared to those determined by the measurement of the acoustic modes. This figure illustrates the discrepancies between these new standard models and the seismic results.

As already mentioned [4–6], it is evident that the introduction of the new CNO composition substantially deteriorates the previous agreement in the sound speed profile and does not improve the density profile in the radiative zone and particularly at the edge between the two types of energy transfer. Moreover, the ^{8}B neutrino flux is substantially reduced and is no more compatible with the SNO results. This does not mean that the new composition is incorrect, but that these models are not in agreement with the seismic and neutrino observations.

It could be partly due to the determination of the opacity coefficients in partially ionized elements. It is interesting to note that Seaton and Badnell [19] show differences in their calculation in comparison with those of Livermore [17], which may explain part of the differences. Opacity coefficients are important ingredients of the solar model. So we recommend checking them with the new generation of high intensity lasers like the "Ligne d'Intégration Laser" or future Laser MégaJoule or National Ignition Facility [20] as it has been done for lower temperatures and densities [21]. There is a clear need for experimental investigation in the million of degree range and density of fraction of g/cm^3. The introduction of the microscopic diffusion has substantially improved the sound speed profile but the present discrepancy may encourage to improve the present treatment of this process. Another possibility is that the discrepancies are partly due to the absence of rotation effects in the radiative zone. Meridional circulation and magnetic field must be introduced to justify a narrow sudden transition in the rotation profile [22–24]. Moreover a detailed energy balance must be looked for to check if the nuclear energy balances precisely the surface luminosity. Is this new update of the composition the first evidence showing that the standard model is no longer representative of the present Sun?

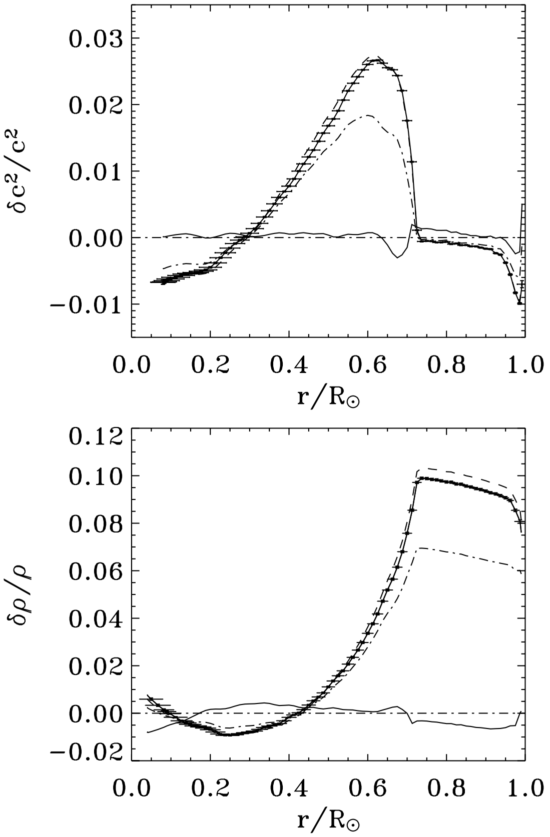

FIG. 2. Squared sound speed and density profile discrepancies between new updated standard models (full line with error bars coming from seismic observations: tac A model, dot line: tac L model, dot dashed line: tac H model) and the seismic model (full line) with the present seismic observations [25].

Revised neutrino predictions.—In our recent studies [1,2] we have deduced neutrino fluxes from the seismic results of SoHO [25] through seismic models. It is reasonable to think that these measurements are now sufficiently good in the region of emission of the neutrinos to give real insight into the plasma properties and the mean central core temperature.

At the same time, it is of great interest to improve the knowledge of the nuclear reaction rates as we improve the modeling of stars since such rates are essential ingredients necessary to predict the neutrino fluxes. Conversely, it is also of great interest to extract the physical conditions of the core from the detected neutrino fluxes. So, recent revisions of the reaction rate ^{7}Be$(p, \gamma)^8$B or of ^{14}N$(p, \gamma)^{15}$O, which is the slowest reaction of the CNO cycle, are extremely important.

^{7}Be$(p, \gamma)^8$B has been remeasured several times these last few years, but without real agreement between measurements. This confirms the difficulty to determine this cross section, so a mean value between the recent measurements has been estimated by [26] of $S(20\text{ keV}) = 20.7 \pm 0.8$ eV barn instead of the value of 19.4 eV barn [27] used in our previous predictions. Using this revised value and seismic models, the new prediction for the ^{8}B neutrino is $5.31 \times 10^6 \pm 0.6\text{ cm}^{-2}\text{ s}^{-1}$. This value stays in complete agreement with the SNO result of $5.21 \pm 0.27 \pm 0.38\text{ cm}^{-2}\text{ s}^{-1}$ [3]. The uncertainties of this prediction have been slightly reduced with the recent progresses. The main contributor to the error is at present the knowledge of the (^{3}He, ^{4}He) reaction rate which will be improved rather soon.

The new estimate of ^{14}N$(p, \gamma)^{15}$O astrophysical factor $S(0)$ of 1.7 ± 0.2 keV b [28] instead of the recommended value of $3.5^{+0.4}_{-1.6}$ keV b [29] is an important result for the lifetime of the hydrogen burning (increase by 0.7–1 Gyr of the globular cluster age). The CNO contribution to the luminosity decreases from 1.5% to 0.7%, it is compensated by the pp luminosity, so the impact on the neutrino fluxes coming from the pp chain is small. But this new estimate also influences the neutrino predictions in the case of chlorine and gallium experiments. In fact, the ^{13}N, ^{15}O, and ^{17}F neutrino fluxes are doubly reduced by the effect of composition and reaction rate. They are reduced at 40% of their previous values.

Consequently, we get 123.4 ± 8.2 SNU for the gallium prediction and 7.6 ± 1.10 SNU for the chlorine experiment. By applying the reduction on the neutrino fluxes due to large mixing angle oscillation solution $\Delta m^2 = 7.3 \times 10^{-5}$ and $tg^2\theta_{12} = 0.41$ given by [30], we get, respectively, 66.65 ± 4.4 SNU and 2.76 ± 0.4 SNU (in solar neutrino unit) for the detected fluxes which must be compared to 68.1 ± 3.75 SNU for combined gallium value [31] and 2.56 ± 0.23 SNU for the chlorine experiment.

So, in introducing current observations, there is still a very good agreement between seismic predictions of neutrino fluxes and detected neutrinos; they see the same Sun. But the standard model predictions do not agree with them. One needs to pursue the detailed observations of the radiative zone to guide the main progresses we need to get to properly reproduce the present Sun.

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