Planetary influence on the young Sun’s evolution: the solar neutrino probe

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ABSTRACT

Recent observations of solar twin stars with planetary systems like the Sun, have uncovered that these present a peculiar surface chemical composition. This is believed to be related to the formation of earth-like planets. This suggests that twin stars have a radiative interior that is richer in heavy elements than their envelopes. Moreover, the current standard solar model does not fully agree with the helioseismology data and solar neutrino flux measurements. In this work, we find that this agreement can improve if the Sun has mass loss during the pre-main sequence, as was previously shown by other groups. Despite this better agreement, the internal composition of the Sun is still uncertain, especially for elements heavier than helium. With the goal of inferring the chemical abundance of the solar interior, we tested several chemical compositions. We found that heavy element abundances influence the sound speed and solar neutrinos equally. Nevertheless, the carbon-nitrogen-oxygen (CNO;\textsuperscript{13}N,\textsuperscript{15}O and\textsuperscript{17}F) neutrino fluxes are the most affected; this is due to the fact that contrarily to proton-proton (pp, pep,\textsuperscript{8}B and\textsuperscript{7}Be) neutrino fluxes, the CNO neutrino fluxes are less dependent on the total luminosity of the star. Furthermore, if the central solar metallicity increases by 30%, as hinted by the solar twin stars observations, this new solar model predicts that\textsuperscript{13}N,\textsuperscript{15}O and\textsuperscript{17}F neutrino fluxes increase by 25%-80% relative to the standard solar model. Finally, we highlight that the next generation of solar neutrino experiments will not only put constraints on the abundances of carbon, oxygen and nitrogen, but will also give some information about their radial distribution.

Key words: neutrinos – Sun: helioseismology – Sun: interior – planets and satellites: formation – planet-star interactions – stars: abundances

1 INTRODUCTION

In recent years, significant progress has been achieved in understanding the basic principles of the formation of planetary systems around low mass stars. Most of these findings were obtained due to high-resolution spectroscopic and photometric measurements focused on discovering earth-like planets (e.g. Udry & Santos 2007). More significantly, recent observations show evidence of a possible influence of the young planetary disc on the evolution of the host star. The most compelling evidence comes from high-resolution spectroscopic measurements of several solar twins, where it has been found that, contrary to what was previously thought, the Sun has an anomalous chemical composition when compared to identical stars without planetary systems. In fact, the Sun has a depletion of volatile and refractory elements, the effect being more pronounced for the latter, i.e., there is a 20% diminution of refractory elements relatively to the volatile ones (Meléndez et al. 2009; Ramirez et al. 2009). Only 15% of solar twins have a chemical composition identical to the Sun.

It is thought that the differentiation observed in the chemical composition occurs during the formation of planets in the young planetary disc. The spectroscopic observations suggest that the refractory elements are locked up in the inner planetary belt, where the earth-like planets are formed.

This is consistent with what is observed in our own Solar System and is backed up by two facts. The first is that if a depletion of 30% of refractory elements is assumed to occur in the external layers of the Sun, then the amount of mass removed in the convection zone is equivalent to the combined mass of the terrestrial planets, i.e., Mercury, Venus, Earth and Mars. The second is related to the latest chemical abundance determination of the Sun, a more accurate method of spectral analysis that led to a major re-
vision in the chemical abundances obtained from spectral absorption lines. The abundances are significantly reduced in the case of heavy chemical elements such as carbon, nitrogen, oxygen, neon, sodium and aluminium (Asplund et al. 2009). This led to a significant reduction in the value of the Sun’s metallicity. Such variations in chemical abundances worsen the previous, possibly fortuitous, agreement of the standard solar model (SSM) with the helioseismological data and solar neutrinos, namely by increasing the difference between the sound speed profiles and by changing the location of the convection zone boundary (i.e., Turck-Chieze & Couvidat 2011; Turck-Chieze & Lopes 2012; Haxton et al. 2012). Furthermore, Serenelli et al. (2011) have shown that the new chemical abundances lead to a reduction of 20% in the prediction of $^8$B neutrino fluxes.

The reconciliation of the SSM (Turck-Chieze & Lopes 1993) with the helioseismic and solar neutrino data was in part re-established by several research groups, by considering alternative modifications of the evolution of the Sun (e.g. Basu & Antia 2008). Among the various attempts to solve the problem, some test the validity of the solar abundance determination (e.g. Antia & Basu 2005; Delahaye et al. 2010) and others revisit the constitutive physics of the solar model (e.g., Bahcall et al. 2005), or tentatively include the impact of rotation on the evolution of the Sun (Turck-Chieze et al. 2010). The scenarios that lead to better results assume that an additional physical process occurred during the evolution of the star. The agreement was found to be best in the case of solar models that take into account mass accretion and/or mass-loss during its evolution (e.g. Guzik & Mussack 2010; Serenelli et al. 2011). Some authors (Castro et al. 2007; Guzik & Mussack 2010) go a step further and consider that depletion of heavy elements occurs in the convection zone of the star, explaining in this way the deficit in heavy elements observed in the new abundance determinations (Asplund et al. 2009), as compared with the previous ones (Grevesse & Sauval 1998). Furthermore, the evolution of the star during the gravitational contraction phase, before arriving on the main sequence, is not well known, in particular, the internal structure of the protostar is still quite uncertain. It has been suggested that, during this phase, the protostar has a radiative core rather than being fully convective, as is usually assumed (e.g., Nordlund 2009). If this is the case, there is a possibility that the radiative core of the protostar has a higher content of metals than previously assumed. These latter evolution scenarios suggest that the composition of the interior of the Sun is quite different from the composition of the convection zone. Nevertheless, by what amount the composition of the different elements decreases between the centre and the surface is not easy to justify in the presence of a quite varied set of theoretical proposals. Therefore, it is paramount that we find a way to constrain the composition inside the Sun, and if possible at different locations. The solar neutrino fluxes have the potential to discriminate between these different types of solar models, because they are produced in the core of the Sun at different locations, between the centre and 0.3 of the solar radius. Moreover, neutrino fluxes can provide a direct measure of the metallicity in the Sun’s core. In this work, we address the question of whether a radial enhancement of metallicity in the core could resolve the solar abundance problem, and if so, then by what amount. In particular, we will discuss the impact of the chemical composition on the solar neutrino fluxes. We believe this could help settle the origin of such a high-metallicity radiative region and/or core, and in this way we determine the mechanism which is responsible.

| Model | $M_\odot$ (M$_\odot$) | $10^{-10}M$ (M$_\odot$) | (A, $\zeta$) | $R_{HCZ}$ (R$_\odot$) | Line colour | Line type |
|-------|----------------|-----------------|----------|----------------|-------------|----------|
| SSM   | 0.7260         |                 |          |                 |             |          |
| $\alpha_1$ | 1.15 | 0.5       | 0.7187 | Blue           |             |          |
| $\beta_1$ : | -    |            | 0.7152 | Green          |             |          |
| $\gamma_1$ : | -    |            | 0.7136 | Magenta        |             |          |
| $\delta_1$ : | 1.125 | -3.0      | 0.7224 | Cyan           |             |          |
| $\alpha_2$ : | 1.15 | -0.5      | 0.7152 | Blue           |             |          |
| $\alpha_3$ : | -    |            | 0.7100 | Green          |             |          |
| $\alpha_4$ : | -    |            | 0.5200 | Magenta        |             |          |
| $\alpha_5$ : | -    |            | 0.5200 | Cyan           |             |          |
| $\gamma_2$ : | 1.15 | 0.4       | 0.7136 | Blue           |             |          |
| $\gamma_3$ : | -    |            | 0.7100 | Green          |             |          |
| $\gamma_4$ : | -    |            | 0.5200 | Magenta        |             |          |
| $\gamma_5$ : | -    |            | 0.5200 | Cyan           |             |          |
| $\delta_2$ : | 1.125 | -3.0      | 0.7224 | Repeated       |             |          |
| $\delta_3$ : | 1.15 | -0.4      | 0.7136 | Repeated       |             |          |
| $\delta_4$ : | -    |            | 0.7100 | Repeated       |             |          |
| $\delta_5$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\beta$ : | -    |            | 0.7100 | Repeated       |             |          |
| $\gamma_6$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\delta_6$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\delta_7$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\delta_8$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\delta_9$ : | -    |            | 0.5200 | Repeated       |             |          |
| $\delta_{10}$ : | -    |            | 0.5200 | Repeated       |             |          |

Table 1. Main parameters of Z-element modified solar models. In the table are shown the following quantities: $M_\odot$ and $M$ - the initial mass and mass-loss rate of the model; $R_{HCZ}$ - radius of the base of the convective region; (A, $\zeta$) - parameters of the function $W(r) = A \exp[-(r/R_\odot)^\zeta]$, which gives the anomalous composition of C, O and N. The sound speed profiles of these solar models are shown in Fig. 1 ($\alpha_1$, $\beta_1$, $\gamma_1$ and $\delta_1$ with $i = 2$ - 5) and Fig. 2 ($\gamma_2$ and $\delta_2$ with $i = 2 - 7$). The rightmost column indicates the line type used in the Figs 1 and 2. Note: helioseismology data suggests that the base of the convection zone is located at 0.713 $R_\odot$ and the helium abundance in the convection zone is $\delta_{10} = 0.2485 \pm 0.0035$ (Basu & Antia 2004). The location of the base of the convection zone for the SSM, $\alpha$, $\beta$, $\gamma$ and $\delta$ are 0.7260 $R_\odot$ (+1.8%), 0.7152 $R_\odot$ (+0.3%) 0.7187 $R_\odot$ (+0.8%), 0.7136 $R_\odot$ (+0.08%) and 0.7224 $R_\odot$ (+1.32%), respectively. Similarly, the helium abundance in the envelope for the SSM, $\alpha$, $\beta$, $\gamma$ and $\delta$ are 0.2224(-10.5%), 0.2176 (-12.4%) 0.2192 (-11.7%), 0.2169(-12.7%) and 0.2210(-11.0%), respectively.

2 THE ORIGIN OF CENTRAL METALLICITY

The origin of excess of metals in the Sun’s interior and the mechanism responsible for their accumulation is an unresolved question: two types of scenarios could be responsible - metals were accreted from the initial host molecular cloud in the early stages of the formation of the protostar or an accretion process that occurred later on in the life of the star, when the radiative solar region was already formed; or even possibly some compromise between the two scenarios. In the latter case, the higher or lower concentration of heavy elements in the Sun’s interior is very much related to the joint evolution of the host star and the planetary disc. The observational result suggests that the process of formation of the planetary disc (5% of the total mass) by conservation of angular momentum is accompanied or followed by the formation of planets, which capture 90 earth masses in metals from the initial disc (Guillot 2005). It
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Table 2. Main parameters of the solar models. In the table are shown the following quantities: \( \Delta \alpha_{\text{hel}} \) and \( \Delta \alpha_{\text{core}} \) - maximum of the absolute sound speed relative difference below the base of convection zone and in the central core (\( r \leq 0.3 \, R_\odot \)); \( Z_{\text{core}} \) - Z-element abundance in the core; \( \Delta \Phi(\beta \text{Be}) \) and \( \Delta \Phi(\gamma \text{B}) \). \( \beta \text{Be} \) and \( \gamma \text{B} \) total solar neutrino fluxes variation relative to SSM. The SSM corresponds to an updated solar model computed for the new estimates of solar abundances made by Asplund et al. (2009).

| Model | \( \Delta \alpha_{\text{hel}} \) | \( \Delta \alpha_{\text{core}} \) | \( Z_{\text{core}} \) | \( \Delta \Phi(\beta \text{Be}) \) | \( \Delta \Phi(\gamma \text{B}) \) |
|-------|-----------------|-----------------|---------------|-----------------|-----------------|
| SSM   | 1.19            | 0.69            | 0.0161        | –               | –               |
| \( \alpha_1 \) | 0.19            | 0.47            | 0.0155        | 15.32           | 27.44           |
| \( \beta_1 \) | 0.51            | 0.27            | 0.0157        | 10.54           | 18.84           |
| \( \gamma_1 \) | 0.13            | 0.65            | 0.0154        | 18.57           | 33.73           |
| \( \delta_1 \) | 0.86            | 0.31            | 0.0159        | 4.96            | 8.68            |
| \( \epsilon_2 \) | 0.31            | 0.69            | 0.0202        | 15.9            | 27.18           |
| \( \epsilon_3 \) | 0.19            | 0.68            | 0.0202        | 15.88           | 27.17           |
| \( \epsilon_4 \) | 0.19            | 0.62            | 0.0202        | 15.70           | 27.20           |
| \( \epsilon_5 \) | 0.19            | 0.64            | 0.0233        | 15.70           | 27.12           |
| \( \gamma_2 \) | 0.19            | 0.94            | 0.0216        | 19.36           | 33.32           |
| \( \gamma_3 \) | 0.23            | 1.02            | 0.0231        | 19.56           | 33.21           |
| \( \gamma_4 \) | 0.09            | 0.86            | 0.0200        | 19.13           | 33.44           |
| \( \gamma_5 \) | 0.08            | 0.87            | 0.0200        | 19.15           | 33.41           |
| \( \gamma_6 \) | 0.13            | 0.80            | 0.0200        | 18.95           | 33.47           |
| \( \gamma_7 \) | 0.09            | 0.93            | 0.0216        | 19.33           | 33.32           |
| \( \delta_2 \) | 1.03            | 0.25            | 0.0223        | 5.68            | 8.45            |
| \( \delta_3 \) | 1.07            | 0.31            | 0.0239        | 5.85            | 8.37            |
| \( \delta_4 \) | 0.87            | 0.15            | 0.0207        | 5.47            | 8.51            |
| \( \delta_5 \) | 0.86            | 0.12            | 0.0207        | 5.49            | 8.51            |
| \( \delta_6 \) | 0.86            | 0.27            | 0.0207        | 5.29            | 8.54            |
| \( \delta_7 \) | 0.86            | 0.11            | 0.0223        | 5.65            | 8.45            |

also suggests that during the planetary disc formation, ice, dust and other metal-rich material accumulate into planets (McClure et al. 2012; Johnson et al. 2012). In the stellar disc, at a latter phase of the planetary disc formation, the material is segregated into two components, gas and metals. The first is deposited on to the Sun, and the second is used in the formation of planets (McClure et al. 2012). The Sun develops a radiative core and a convective envelope, for which its metallicity is reduced with the accumulation of the gas from the stellar disc. In the former scenario, numerical simulations that follow the formation of the protostar from the host molecular cloud (e.g. Padoan & Nordlund 2002; Bate 2009) suggest that the protostar already possesses a radiative interior, when it arrives at the top of the Hayashi track (Wuchterl & Tscharnuter 2003). In certain cases, the protostar has a radiative core extending up to 2/3 of the solar radius. This protostar is quite different from the fully convective star considered in the standard evolution scenario, just before the star starts its gravitational collapse towards the main sequence. If the protostar already has a radiative core before gravitational collapse, then this could produce a distribution of heavy elements in the Sun’s core which is quite different from that used for the SSM.

Figure 1. Relative differences between the sound speed inverted using the helioseismic data (Turck-Chieze et al. 1997; Basu et al. 2009), and the sound speed deduced from the SSM (continuous red curve with error bars). The error bars are multiplied by a factor of 10. The other curves correspond to solar models: \( \alpha_1, \beta_1, \gamma, \delta_1 \) and \( \epsilon_3 \) with \( i = 2 - 5 \). The correspondence between the solar models and line type is shown in Table 1. This figure shows a set of solar models with mass-loss, with (and without) an anomalous chemical composition that improves the agreement between the solar model and the helioseismic data (cf. Fig. 3). Note: the curves corresponding to models \( \alpha_1 \) with \( i = 3 - 5 \) are identical (curves green-dotted, cyan-dotted and magenta-dotted) to model \( \alpha_1 \) (curve blue-continuous) excepted in the central region (\( r \leq 0.35 \, R_\odot \)).

3 THE SENSITIVITY OF SOLAR NEUTRINO FLUXES TO METALLICITY

The production of solar neutrinos occurs in the central region of the Sun, within a shell with a radius of 0.35 \( R_\odot \). The precise location of the different neutrino sources depends on the specific location where the reactions occur. The neutrinos produced in the proton-proton (PP) nuclear reactions, usually known as \( \beta \text{Be} \), \( \gamma \text{B} \), pp and pep neutrinos are produced throughout the nuclear region, \( \beta \text{Be} \) and \( \gamma \text{B} \) neutrinos are produced near the centre (5% of the solar radius), and pp and pep, although produced in all the nuclear region, have a maximum flux that occurs at 10% of the solar radius. The neutrinos produced in the nuclear reactions of the carbon-nitrogen-oxygen (CNO) cycle, usually referred to as \( \alpha \text{O} \), \( \alpha \text{N} \) and \( \alpha \text{F} \), are produced within the inner shell of 10% of the solar radius, with their maxima located at 5% of the solar radius (Turck-Chieze & Couvidat 2011; Lopes & Turck-Chieze 2013). Almost all the nuclear reactions that produce solar neutrinos are highly sensitive to the central temperature, such \( T_9 \) where \( \eta \) takes the values, 10, 24, 24, 27 and 27 for \( \beta \text{Be}, \beta \text{Be}, \alpha \text{O} \) and \( \alpha \text{F} \), respectively (Bahcall & Ulmer 1996; Lopes & Silk 2012). The exceptions are the pp and pep neutrino fluxes which have a much smaller dependence on the central temperature (\( \eta \) takes the values \( -1.1 \) and \( -2.4 \)) due to their dependence on the total luminosity of the star.

The neutrino fluxes are the ideal tools to probe the metallicity in the Sun’s core due to their sensitivity to the core plasma physics. Two reasons favour such an argument: as previously indicated, the high dependence of the nuclear reactions on the local temperature of the plasma and the dependence of the CNO cycle on the chemical composition (including the neutrino nuclear reactions). As we will show in the next section, the solar neutrino fluxes can com-
The correspondence between solar models and line type is shown in Table 1. This figure highlights the impact that the change in the Z-element abundance has in the sound speed (cf. Fig. 3). Note: the curves that correspond to solar models $\delta_i$ with $i = 2 - 7$ are identical to model $\eta$ (cyan continuous), and the curves that correspond to solar models $\gamma_i$ with $i = 4 - 7$ are identical to model $\gamma_i$ (magenta continuous), the difference between curves is only visible in the Sun’s core.

Figure 2. Relative differences between the sound speed deduced from the SSM and the sound speed obtained from helioseismic data (see Fig. 1 for details). The other curves correspond to solar models: $\eta_i$ and $\delta_i$ with $i = 2 - 7$. The correspondence between solar models and line type is shown in Table 1. This figure highlights the impact that the change in the Z-element abundance has in the sound speed (cf. Fig. 3). Note: the curves that correspond to solar models $\delta_i$ with $i = 4 - 7$ are identical to model $\eta_i$ (cyan continuous), and the curves that correspond to solar models $\gamma_i$ with $i = 4 - 7$ are identical to model $\gamma_i$ (magenta continuous), the difference between curves is only visible in the Sun’s core.

4 THE STANDARD SOLAR EVOLUTION

If not stated otherwise, the standard evolution model is computed starting from a young self-gravitating, full convective protostar, formed during the first stages of gravitational collapse of the host molecular cloud. The current stellar codes simulate the evolution of the Sun, following the gravitational collapse of the star on the Hayashi track and the ignition of nuclear reactions in the main sequence. The calculation is stopped when the Sun arrives at its present age. In these computations, we follow the usual convention that the young protostar composition (expressed as a proportion of matter) is divided into hydrogen $X_i$, helium $Y_i$ and metals $Z_i$, such that $X_i + Y_i + Z_i = 1$. The relative abundances of $Z_i$, i.e., metals, are measured from meteoric data or/and photospheric absorption lines. The former metals are known as refractory elements and the latter as volatile elements. The most important contribution to $Z_i$ comes from the volatile elements, carbon, nitrogen and oxygen.

In the following, we choose our reference model to correspond to the SSM with updated physics, including an updated equation of state (EOS), opacities, nuclear reactions rates, and an accurate treatment of microscopic diffusion of heavy elements (Turck-Chieze & Couvidat 2011). The calculation of the solar models is done using the stellar evolution code CESAM (Morel 1997). CESAM is regularly updated with the most recent EOS and opacity coefficients (Iglesias & Rogers 1996; Iglesias & Rose 1996). The models in this work use the Hopf atmosphere and different updates on the solar composition with an adapted low-temperature opacity table. A detailed discussion on the impact of these input physics on the solar evolution can be found in Couvidat et al. (2003) and Turck-Chieze et al. (2004). The CESAM nuclear physics network uses the fusion cross-sections recommended values for the Sun (Adelberger et al. 2011, 1998), with the most recently updated nuclear reactions (Turck-Chieze & Couvidat 2011). The computation also included the appropriate screening, and uses the Mittel prescription (Dzitko et al. 1995). Furthermore, the stellar evolution code also includes the microscopic diffusion of helium and other chemical elements, as described in Brun et al. (1998). This reference model is in full agreement with the standard picture of solar evolution (e.g., Turck-Chieze & Lopes 1993; Serenelli et al. 2009; Guzik & Mussack 2010; Turck-Chieze et al. 2010; Serenelli et al. 2011; Lopes & Turck-Chieze 2013). The solar composition used corresponds to that determined by Asplund et al. (2009). All solar models are computed by adjusting $Y_i$ and the mixing length parameter $\alpha_{MLT}$ in such a way that at the present age (4.6 Gyear) the models reproduce the solar mass, radius, luminosity, and $Z/X$ surface abundance (Turck-Chieze & Couvidat 2011).

In this computation, we use a modified version of the stellar evolution code CESAM which allows us to specify a mass-loss rate and prescribe a radial distribution of heavy metals in the Sun’s radiative core. The mass loss occurs in the upper layers of the star during a certain period before the star attains its present age. The method used to implement the mass loss in the pre-sequence phase of the star follows a procedure identical to others (Sackmann & Boothroyd 2003; Morel et al. 1998; Guzik & Cox 1995; Swenson & Faulkner 1992). In particular, we consider that the initial mass of the star is 1.125 $M_\odot$ or 1.15 $M_\odot$ and the mass-loss rate $\dot{M}$ takes values close to $10^{-16} M_\odot$ yr$^{-1}$. These are identical to the values found in the literature. The proposed values are consistent with the upper limit allowed by the observed $^7$Li lithium depletion (Boothroyd et al. 1991). Furthermore, the different values of $\dot{M}$ were chosen to improve the agreement between the
5 DISCUSSION

Different solar models that have distinct mass-loss rates will produce a solar structure model with a sound speed profile closely close to that favoured by helioseismology (cf. Fig. 1 and Table 1). The base of the convection zone also is close to the results obtained from helioseismological inferences (Turck-Chièze et al. 1997; Basu & Antia 2004). In our best case scenario, the sound speed difference in the radiative region just below the convection zone is smaller than 0.1% (cf. Figs 1 and 2). This agreement is possible even without any specific considerations about the chemical composition.

Actually, as previously mentioned, there are several physical processes that improve the sound speed agreement between the SSM and helioseismology, regardless of the specific chemical composition considered. Even if we consider only models with mass loss, several solutions are possible just by fine-tuning the specific parameters such as the initial mass of the protostar, the mass-loss rate and the specific period in the evolution when the mass loss occurs. These results are identical to those found in the literature (Guzik & Mussack 2010; Serenelli et al. 2011).

If the chemical composition of heavy elements inside the star increases by a significant amount, such as 30%, as suggested by solar twin observations, the sound speed difference is reduced (cf. Fig. 1). The improvement is mainly located in the radiative region of the Sun (cf. Figs 1 and 2 and Table 2). This situation occurs for all the solar mass-loss models, and actually the result holds for quite distinct Z-element radial profiles (cf. Fig. 3). The base of the convective zone is not affected, if the change occurs only in Z-element profile (its value is fixed, cf. Table 1). This improvement can be explained by the dependence that the square of the sound speed profile has on the mean molecular weight $\mu$, i.e., $\delta c^2/c^2 \sim \delta T/T - \delta \mu/\mu$, since $\mu$ strongly depends on $Z$. The increase of $Z$ below the base of the convective zone, although less important than the mass loss, still improves the agreement between the sound speed of the model and the helioseismological sound speed in the Sun’s core. The sound speed difference $\delta c$ is reduced to less than 0.1%, although with a slight degradation of the agreement in the upper layers. On the other hand, the $^7\text{Be}$ and $^8\text{B}$ neutrino flux predictions becomes in slight disagreement with neutrino flux measurements. As mentioned previously, neutrino fluxes have the potential to distinguish between solar models with higher or lower metallicity (i.e., $Z$), in particular the CNO neutrino fluxes, by taking advantage of the high sensitivity of neutrino nuclear reaction rates to chemical composition.

The current neutrino experiments Sudbury Neutrino Observatory (SNO) and Borexino measure a value of neutrino flux of $^8\text{B}$ that corresponds to $\Phi_{\nu,\text{SNO}}(^8\text{B}) = 5.05 \pm 0.19 \times 10^{9} \text{cm}^2 \text{s}^{-1}$ (Aharmim et al. 2010) and $\Phi_{\nu,\text{Borexino}}(^8\text{B}) = 5.88 \pm 0.65 \times 10^{9} \text{cm}^2 \text{s}^{-1}$ (Bellini et al. 2010). Furthermore, the Borexino experiment also measures the $^7\text{Be}$ solar neutrino rate with an accuracy better than 5% which corresponds to $\Phi_{\nu,\text{Borexino}}(^7\text{Be}) = 4.87 \pm 0.24 \times 10^{9} \text{cm}^2 \text{s}^{-1}$, under the assumption of the Mikheyev-Smirnov-Wolfenstein (MSW) large mixing angle scenario of solar neutrino oscillations (Bellini et al. 2011). Recently, the Borexino experiment made the first measurement of the pep neutrinos (Bellini et al. 2012). For $\Phi_{\nu,\text{Borexino}}(\text{pep}) = 1.6 \pm 0.3 \times 10^{9} \text{cm}^2 \text{s}^{-1}$. In Fig. 4, $\Phi_{\nu}(\text{pep})$, $\Phi_{\nu}(^8\text{B})$ and $\Phi_{\nu}(^7\text{Be})$ neutrino fluxes, among others, are presented as a variation relative to the values of the neutrino fluxes as per the SSM. In the same figure, we present the variation of modified solar models relative to the solar reference model. In solar models for which only mass loss is considered (no variation in
Z), the improvement in agreement between the sound speed profile and the sound speed inferred from helioseismology is followed by an increase of the difference between the 7Be and 8B neutrino flux measurements and the solar model. The reverse also is true. This corresponds to the sets of solar models γ and δ, respectively (cf. Table 1 and Figs 2 and 5). The measurement in pep neutrinos is still very imprecise, therefore no reliable constraint can be made on the physics of the solar model.

The neutrino fluxes produced in nuclear reactions of the proton-proton chain are less sensitive to Z than neutrinos fluxes produced in the CNO cycle (cf. Fig. 4). The first depends mainly on the central abundance of hydrogen and helium, and only indirectly on Z. This is the reason why 7Be and 8B neutrino fluxes increase with a decrease of mass-loss rate, i.e., dependence on the total luminosity of the star is almost unaffected by the variation of chemical composition (cf. Fig. 4). Distinct Z-element profiles (with radial dependence) produce quite identical sound speed profiles and 7Be and 8B neutrino fluxes (cf. Fig. 3). Nevertheless, there is a small improvement of the sound speed difference in the Sun’s core (cf. Fig. 2). In particular, notice that the models γ and δ have distinct Z-element profiles (cf. Fig. 3) as well as the same sound speed profile (cf. Fig. 2 and Table 2) and 7Be and 8B neutrino fluxes, but different 17F, 15O and 13N neutrino fluxes (cf. Fig. 5).

Although there is some uncertainty in the basic physics of the SSM, namely which physical mechanisms lead to the present structure of the Sun, like mass loss (Guzik & Mussack 2010) or mass ac-
concretion (Serenelli et al. 2011), these types of processes act mainly by fixing the central temperature of the Sun, and by doing so affecting the sound speed profile and $^7$B and $^7$Be neutrino fluxes. The change in the chemical composition of heavy elements as shown in this work has a less pronounced impact on these quantities, but its impact is very distinct in CNO neutrino fluxes. Indeed, Z-element profiles have a quite distinct and large impact on the neutrino fluxes produced in the CNO cycle (cf. Figs 4 and 5). Two distinct signatures can be identified, the magnitude by which Z varies in the centre and the dependence of Z on the radius.

If Z increases by a fixed amount between solar models (compare models $\gamma_1$ and $\gamma_2$ in Fig. 3), then all the CNO neutrino fluxes will increase, although maintaining their relative proportionality difference (cf. Fig. 5). This is valid only if the Z-element profiles in these solar models are constant from the centre to the base of the convective zone. This Z-element profile is almost equivalent to the one obtained with the old composition (e.g. Grevesse & Sauval 1998). However, if the Z-element radial profile decreases towards the surface, the neutrino sources are progressively affected, the first ones to be affected being located closest to the centre of the star. It follows that the impact is more significant for neutrinos associated with the $^{12}$F, $^{15}$O and $^{13}$N chemical elements. The increase of Z in the core by 30% produces large changes in the neutrino fluxes of $^{11}$N, $^{13}$O and $^{17}$F. In some cases, this increases the neutrino fluxes by more than 50%.

6 CONCLUSION

We found that different physical processes can adjust to the observed Sun’s present luminosity leading to readjusting the internal structure of the Sun, and in particular by fixing its central temperature, in such a way that these solar models come in better agreement with the solar neutrino fluxes and helioseismic data. However, for most of the cases, the simultaneous agreement between the $^7$Be and $^8$B neutrino fluxes and the sound speed profile between the solar model and the real data is only possible by making a very fine tuning of the open parameters related with the physical processes considered. The typical examples are the processes related with the mass loss or mass accretion by the star during its pre-main sequence phase. We also found that if the metallicity content present in the Sun’s interior, including the Sun’s core, is quite different from the metallicity predicted by the SSM (and also by most of the non-standard models), then the impact of these distinct Z-element profiles on the previously mentioned observed quantities is relatively small, but interestingly enough, the impact on the CNO neutrino fluxes is very pronounced. In particular, we found that a solar model with a significant increase in abundances such as carbon, oxygen and nitrogen of the order of 30%, as suggested by solar twins observations (or even a higher increase of these abundances), still presents an internal structure for the present Sun quite close to the SSM. The impact of these high metallicity profiles in the $^7$Be and $^8$B neutrino fluxes and helioseismology data is moderate, but its impact on the CNO neutrino fluxes is quite large. The future measurements of CNO neutrino fluxes could resolve this problem.

The new generation of neutrino experiments, such as the SNO, Borexino and Low Energy Neutrino Astrophysics (LENA), will allow a precise determination of such solar neutrino fluxes, leading to the establishment of important constraints on the composition of heavy elements in the Sun’s core (Wurm et al. 2012). In particular, as pointed out by Haxton & Serenelli (2008), the future upgrade of Borexino and SNO will be able to put some constraints on the abundance of carbon and nitrogen present in the Sun’s core. Furthermore, as stressed by these authors, preliminary simulations done by Chen (2007) of the SNO+ detector (Maneira 2011) suggest that after three years of operation the CNO neutrino rate should be known with an accuracy of 10% (cf. Figs 4 and 5). Moreover, on the current version of the LENA project the promoters expect to improve the signal of CNO and pep neutrino fluxes relatively to the background “noise” generated by the $^{11}$C beta decays. The $^{11}$C beta decays are known to be the main problem in these types of experiments. The $^{11}$C background rate will be 1:8. Furthermore, Monte Carlo simulations done for the LENA detector (Wurm et al. 2011) suggest that it will be possible to find minute temporal variations (with the period window: $10^5 - 10^6$ s) for the amplitude of $^7$Be neutrino flux.

If CNO neutrino flux measurements are obtained with the expected precision, we will be able to precisely determine the abundances of carbon, nitrogen and oxygen in the solar radiative region, including the deepest layers of the core. In agreement with the results obtained in this work, if the abundances of carbon, nitrogen and oxygen in the solar core are 30% above the current values, then the $^{13}$N, $^{15}$O and $^{17}$F neutrino fluxes should be 25%-80% above the predicted values of the current SSM.

On that account, as shown in this work, with the large improvements expected in the accuracy of future neutrino flux measurements and given the high sensitivity of neutrino fluxes to the metallicity of the Sun’s interior, it should be possible to put very strong constraints on the chemical composition of the Sun.

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