THE SOLAR ENERGETIC BALANCE REVISITED BY YOUNG SOLAR ANALOGS, HELIOSEISMOLOGY, AND NEUTRINOS

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ABSTRACT

The energetic balance of the standard solar model (SSM) results from equilibrium between nuclear energy production, energy transfer, and photospheric emission. In this Letter, we give an order of magnitude of several percent for the loss of energy in kinetic energy, magnetic energy, and X-ray or UV radiation during the entire solar lifetime from the observations of the present Sun. We also estimate the loss of mass from the observations of young solar analogs, which could reach up to 30%. We deduce new models of the present Sun, their associated neutrino fluxes, and internal sound-speed profile. This approach sheds quantitative lights on the disagreement between the sound speed obtained by helioseismology and the sound speed derived from the SSM including the updated photospheric CNO abundances, based on recent observations. We conclude that about 20% of the present discrepancy could come from the incorrect description of the early phases of the Sun, its activity, its initial mass, and mass-loss history. This study has obvious consequences on the solar system formation and the early evolution of the closest planets.

Key words: neutrinos – stars: mass-loss – Sun: helioseismology – Sun: rotation – Sun: surface magnetism – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Impressive observational constraints unfolded during the past two decades to help check the physics of the solar interior. These efforts led to a remarkable agreement between two complementary probes: neutrinos and seismology (Turck-Chièze et al. 2004, 2010; Turck-Chièze & Couvidat 2010). However, a reduction in the CNO solar photospheric composition has now been confirmed by two independent groups (Asplund et al. 2009; Caffau et al. 2008, 2010) who directly extracted it from photospheric and atmospheric lines, although a slight difference exists between them. This long-expected revision (see Section 2.1 of Turck-Chièze et al. 1993) produced an inconsistency between standard solar model (SSM) predictions and the two aforementioned probes: neutrino fluxes and radial sound-speed profile (Turck-Chièze et al. 2004; Bahcall et al. 2005). Several hypotheses were proposed to address the discrepancy (Guzik et al. 2005; Basu & Antia 2008; Turck-Chièze et al. 2008; Guzik & Mussack 2010). Some of them have now been rejected, such as a large error in the new photospheric abundance estimate. Others are currently not easy to verify: (1) an incorrect microscopic diffusion—helium diffusion is, at least, measurable but the extraction of radiation-zone CNO signatures in the equation of state casts some doubt on low subsurface values (Lin et al. 2007) even if this information is more difficult to obtain; (2) role of a fossil magnetic field on the bound–bound contributions and of the atmospheric magnetic field on the photospheric composition; (3) underestimated opacity calculations—less than 10%–15% per element if elements other than CNO are incorrect (see Turck-Chièze et al. 2011). The latter is stimulating extensive opacity comparisons and specific laboratory investigations (Bailey et al. 2007; Turck-Chièze et al. 2009). Unfortunately, such experiments are not yet available for the entire solar radiative zone (RZ).

In this Letter, we examine another source of limitation of the SSM: the absence of solar activity effects during its evolution. Our paper on the transport of momentum by rotation showed the limits of SSM in predicting the observed rotation profile (Turck-Chièze et al. 2010) and the need for including magnetic field in the stellar equations (Duez et al. 2010), but we showed that their structural effects are small. Strong activity phenomena are now observed on young solar analogs, and consequently a transformation of nuclear energy into kinetic and magnetic energies during the solar life must be studied. These phenomena produce a large variability in the X-ray and UV spectra, inevitably accompanied by mass loss during the early phase of the solar evolution. The SSM does not take into account this dynamical aspect. Here, we focus on the order of magnitude of such effects and on their past and present impacts. This Letter is organized into three main sections. In Section 2, we recall the SSM energetic balance and its limits. In Section 3, we describe three updated solar models showing different types of loss of irradiance and mass loss connected to the past solar activity. The results are discussed in Section 4.

2. THE ENERGETIC BALANCE OF THE STANDARD SOLAR MODEL

At the end of the 1980s, the \( pp \) neutrino flux was easily estimated (Spiro & Vignaud 1990) and the results of GALEX and SAGE (Anselmann et al. 1992; Gavrin et al. 1992) could be interpreted as a first evidence that neutrinos might oscillate during their travel from the solar center to the Earth. Indeed, a reasonable estimate of the \( pp \) neutrino flux reaching Earth is

\[
\Phi_{\nu_{pp}} = 2 \frac{L_\odot}{L_{\text{nucl}}} \frac{1}{4\pi d^2},
\]

where \( L_{\text{nucl}} \) is the energy produced by the \( pp \) chain, \( L_\odot \) is the solar luminosity fixed at \( 3.846 \times 10^{33} \text{ erg s}^{-1} \) (Guenther et al. 1992; Turck-Chièze & Couvidat 2010), and \( d \) is the Sun–Earth distance. This equation is derived directly from the fact that

\[
4 \rho \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 26.2 \text{ MeV},
\]
where 26.2 MeV is an approximate average value of the energy produced by the three chains ppI, ppII, and ppIII. From these equations, the pp neutrino flux reaching Earth is $6.49 \times 10^{10} \text{cm}^{-2} \text{s}^{-1}$. This estimate is correct at the 10% accuracy level, knowing that part of the solar neutrinos are also produced by the electronic capture of the $^7$Be and a small fraction ($2 \times 10^{-4}$) comes from the disintegration of $^8$B. The detailed estimate of the different neutrino fluxes was improved in the framework of the SSM, which allows us to solve the four equations of stellar structure with extremely refined physics. The Sun is evolved up to its present age (Guenther et al. 1992) at 4.60 $\pm$ 0.04 Gyr, including 48 Myr for the pre-main sequence. The solar luminosity increases by 30% during this evolution. The transport of energy by photons, through interactions with the different species, is treated as properly as possible (Iglesias & Rogers 1996). The hydrostatic equilibrium is assumed during the evolution and no other source of energy is introduced. In the 1990s, the predicted value of $6 \times 10^{10} \text{cm}^{-2} \text{s}^{-1}$ at a 2% accuracy level was obtained by different groups (see Table 13 of Turck-Chièze et al. 1993). This predicted value remained nearly unchanged in recent years; therefore, its only change results from the impact of the CNO cycle on the luminosity produced, which was slightly reduced by the recent CNO abundance update.

Then, the Sudbury Neutrino Observatory (SNO) definitely confirmed the existence of solar neutrino oscillations (Ahmed et al. 2004), measured a precise boron neutrino flux, and consequently provided an accurate determination of the solar central temperature $T_c$. The inclusion of neutrino oscillations and the CNO abundance revision led the SSM pp, $^7$Be, and $^8$B neutrino predictions to be only in marginal agreement with the neutrino detections (Couvadat et al. 2003; Turck-Chièze et al. 2001, 2004, 2010). On the contrary, the evolved solar seismic model (SSeM), built to reproduce the observed sound speed, shows a remarkable agreement between its predictions and all the detection results (GALLEX–SAGE, CHLORINE, SNO, SUPER KAMIOKANDE, and BOREXINO), but it produces central solar conditions different from the SSM (see Turck-Chièze et al. 2010 and Table 1).

More and more, seismic observations emphasize a dynamical view of the solar interior. The Hale cycle of 22 years (Hale & Nicholson 1938) seems to result from motions of the entire convective zone (CZ; Brun et al. 2004; Dikpati & Gilman 2008). In MHD simulations of this zone, the radial luminosity at a fractional radius $r$, can be expressed as the sum of different components:

$$\frac{L(r)}{4\pi r^2} = F_e + F_k + F_r + F_u + F_v + F_m,$$  \hspace{1cm} (3)

where $F_e$, $F_k$, $F_r$, $F_u$, $F_v$, and $F_m$ are, respectively, the enthalpy, kinetic, radiative, unresolved eddy, viscosity, and Pointing fluxes (see Brun et al. 2004 for their definition). These terms are ignored in the equations governing the SSM. If most of them are believed to be small in the CZ, none have been estimated in the RZ, in particular for the young Sun that could rotate 10–100 times faster than it does today, accompanied with related strong activity.

Unfortunately, three-dimensional simulations cannot yet produce an evolutionary model of the global Sun. Nevertheless, it is now well established that the present constant luminosity, a name justified by the fact that the solar luminosity variation is of $10^{-8}$ during the last 100 years in the SSM (constrained at $10^{-4}$ in our models), is not confirmed by observations (Fröhlich 2006). Indeed, the observed variability is directly correlated with the solar Hale dynamo, which produces a mean $10^{-3}$ luminosity variation, with an additional $(3-4) \times 10^{-3}$ variation during the maximum period of about 4–5 years due to the presence of preferred longitudinal spots appearing at the solar rotation periodicity. This variability can be accompanied by longer term variations (Turck-Chièze & Lambert 2007; Turck-Chièze & Lefebvre 2011).

3. A REVISED ENERGETIC BALANCE OF THE SOLAR INTERIOR

The solar RZ encompasses $\approx 98\%$ of the total solar mass and its microscopic ingredients (nuclear reaction rates, opacity coefficients associated to the composition) imprint the sound-speed profile. The equilibrium between gravitational energy, nuclear energy production, and the energy escaping by photon interaction is achieved in the radiative interior over long timescales. The sound-speed profile down to 0.06 $R_\odot$ has been extracted from the Global Oscillations at Low Frequency (GOLF; Gabriel et al. 1995) and the Michelson Doppler Imager (MDI; Scherrer et al. 1995) instruments on board the Solar and Heliospheric Observatory (SOHO; Turck-Chièze et al. 2001; Couvidat et al. 2003) and has recently been confirmed by BiSON and MDI (Buso et al. 2009). In this region, a very slow meridional circulation could be in action (Turck-Chièze et al. 2010) and a stable fossil magnetic field could still be present due to the very low diffusion coefficients considered. Both can affect the energetic balance, even though the introduction of these processes in the stellar equations shows that their present structural effects are small (Duez et al. 2010; Turck-Chièze et al. 2010). However, a quantitative estimate of these dynamical processes on the energetic balance requires one to describe the early evolutionary stage, the evolution of the solar-core rotation, and the magnitude and topology of the fossil field. The present study attempts to give an order of magnitude of these different effects.

First, we estimate the maximum energy loss due to current RZ dynamics. To this end, we use the central temperature difference between SSM and SSeM given in Table 1. This central temperature is now determined with an accuracy of $5 \times 10^{-3}$, thanks to the accuracy of neutrino fluxes. The pp luminosity varies like $T_c^4$, where $T_c$ is the central solar temperature. Therefore, an increase in $T_c$ of 1.5% could be interpreted as an increase in the central luminosity of 6% due to some energy loss by dynamical processes during the past million years, corresponding to the travel time of photons from the solar center to the surface. This value is an upper limit because if the nuclear energy was partly transformed into another type of energy and evacuated, the Sun burnt more hydrogen and its density was also slightly increased. Therefore, we built two new solar models, for which we changed the calibrated luminosity at the present age by, respectively, 2.5% and 5%.

The second estimate comes from the observation of young stars. In its infancy, the Sun was certainly more active and emitted more strongly in X-ray and ultraviolet (XUV). In the review of Gudel (2007), the study of young solar analogs shows how the evolved X-ray luminosity varies with time with respect to the total bolometric luminosity. This wavelength range represents between $5 \times 10^{-7}$ and $10^{-4}$ of the total solar luminosity $L_\odot$ and varies today 10–20 times more. Moreover, Ribas (2010) notes a variation of about 1000–2000 times the present emission in XUV for these young solar analogs. Therefore, we applied the law described by these authors from
their work on young stars:

\[
\frac{dL(t)}{L} = \alpha \tau (\text{Gyr})^{-1.23}, \tag{4}
\]

where \( \alpha \) is equal to 1.31 \times 10^{-2} and \( \tau \) is the age in Gyr. This results in a luminosity loss of \( \approx 3 \times 10^{-2} \) at 0.5 Gyr, which is similar to the previous estimate when it is integrated over time because this loss decreases quickly with time. Thus, the idea that the central solar region may be more evolved than what is today assumed in the classical stellar equations is not unreasonable.

Another consequence of solar activity is the associated loss of mass. This loss is directly connected to the X-ray luminosity. In order to see the consequences of this effect, we used the law suggested by Wood et al. (2005) and we adopted the following decrease in mass for the first Gyr:

\[
M_W = 1.0 \times 10^{-11} \tau (\text{Gyr})^{-2.23} \tag{5}
\]
as recommended by Ribas (2010).

All the solar models of the present study include the recent inputs on reaction rates (Turck-Chièze et al. 2004), the recent composition of Asplund et al. (2009), and the equation of state and opacity tables built with this composition. We also introduced the formalism suggested by Canuto et al. (1996) that improves the description of convection (see references in Piau et al. 2011). All the results are summarized in Table 1 and Figures 1–3.

Table 1 summarizes the models computed. The evolved SSeM, built to reproduce the observed sound speed, agrees with all the observables: neutrino fluxes and photospheric helium abundance. The new SSM shows a clear disagreement for the photospheric helium content. The discrepancy on helium is reduced by 20% with the introduction of mixing in the tachocline following Brun et al. (1999). The SSM models with a central luminosity increased by, respectively, 2.5% and 5% through a change in calibration show a net increase in the central temperature and consequently an improvement of the boron neutrino predictions, even though the second case overestimates the neutrino flux. The mass-loss impact is less visible on the temperature than on the composition.

Figure 1 shows the sound speed in the core obtained from the GOLF (Turck-Chièze et al. 2001) and confirmed by BiSON (Basu et al. 2009). While the vertical error bars are extremely small, the horizontal ones remain large in the region below 0.3 \( R_\odot \) that contains more than half of the solar mass. This uncertainty could be reduced by measuring mixed-mode frequencies of different degrees or high-frequency gravity modes (Mathur et al. 2007). By construction, the seismic model (full black line) is in perfect agreement with the inverted sound speed from helioseismic data. We added three solar models: the SSM with luminosity increased by 2.5% (dashed red line), and to a model with luminosity increased by 5% (dot-dashed red line). The vertical 3\( \sigma \) error bars are very small and have been multiplied by 10 on this figure, while the horizontal error bars are rather large because few acoustic modes penetrate down to the core.

(A color version of this figure is available in the online journal.)

Table 1

| Model  | Boron Neutrino Flux | \( T_c \) | \( Y_0 \) | \( \rho_c \) |
|--------|---------------------|----------|----------|----------|
| SSeM   | 5.31 \pm 0.6        | 15.74    | 0.277    | 153.02   |
| \( X_c = 0.339 \) | \( Y_c = 0.645 \) | \( \alpha_{\text{MLT}} = 2.04 \) | \( Y_c = 0.251 \) |
| SSM    | 4.50                | 15.54    | 0.2645   | 150.6    |
| \( X_c = 0.357 \) | \( Y_c = 0.627 \) | \( \alpha_{\text{CGM}} = 0.786 \) | \( Y_c = 0.235 \) |
| SSM L+0.025 | 5.32 | 15.67 | 0.2670 | 153.8 |
| \( X_c = 0.347 \) | \( Y_c = 0.637 \) | \( \alpha_{\text{CGM}} = 0.810 \) | \( Y_c = 0.237 \) |
| SSM L+0.050 | 6.33 | 15.79 | 0.269 | 157.0 |
| \( X_c = 0.338 \) | \( Y_c = 0.647 \) | \( \alpha_{\text{CGM}} = 0.836 \) | \( Y_c = 0.239 \) |
| SSM Tac | 4.2 | 15.49 | 0.2671 | 150.3 |
| \( X_c = 0.362 \) | \( Y_c = 0.623 \) | \( \alpha_{\text{CGM}} = 0.712 \) | \( Y_c = 0.240 \) |
| SSM M_{\text{ext}}=1.33 | 4.74 | 15.58 | 0.2603 | 154.1 |
| \( X_c = 0.347 \) | \( Y_c = 0.637 \) | \( \alpha_{\text{CGM}} = 0.829 \) | \( Y_c = 0.234 \) |

Notes. Boron neutrino flux prediction (expressed in \( 10^6 \text{ cm}^{-2} \text{s}^{-1} \)) compared to the measured SNO value of 5.21 \pm 0.45, central temperature \( T_c \), initial helium content \( Y_0 \), central density \( \rho_c \), central composition in hydrogen \( X_c \) and helium \( Y_c \), surface helium \( Y_s \), and \( \alpha \) parameter, for the seismic solar model, and the standard and non-standard solar models. All the SSMs are computed with the Asplund et al. (2009) composition.
Figure 2 shows the squared sound-speed and density differences between helioseismic inversions, obtained from the GOLF+MDI/SOHO acoustic modes, and various solar models: the standard solar model with Asplund et al. (2009) composition (green double dashed line), the seismic solar model (black line) with the seismic error bars, and two models where a luminosity increase was introduced in the core (by 2.5% in red dashed line and by 5% in large dashed line).

(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 2. The updated standard solar model is the green double dashed line, the SSM model with mixing in the tachocline is the red dashed line, the seismic solar model is the black line with the seismic error bars, and a model with mass loss in the early evolutionary phases following observations from young solar analogs is the blue long dashed line.

(A color version of this figure is available in the online journal.)

Figure 2 shows the squared sound-speed and density differences between helioseismic values and various solar models for the entire solar interior. The differences for the SSM (dotted line) using the new photospheric composition and the full spectrum of turbulence model of Canuto remain important. In order to separate the effect of luminosity loss from the effect of mass loss, we show the models where the luminosity is increased by +2.5% in small dashed line and by +5% in large dashed line. The effect is not large and has a sign opposite to the one in the core (see Figure 1). Using Equation (4) for the luminosity loss at the surface during the early stage leads to a smaller effect because the star readjusts very quickly at each loss. The comparison of the two approaches shows that during the solar life an energy loss of a few percent is possible. However, these simulations are too crude, as the energy produced is not explicitly transformed into another energy type. Therefore, Equation (4) alone cannot reproduce the actual RZ.

In addition to SSM (in large dashed blue) and SSeM (in black), Figure 3 shows the influence of mixing in the tachocline (Brun et al. 1999; Piau & Turck-Chièze 2002). The horizontal turbulence in the tachocline slightly shifts the peak discrepancy downward and suppresses the peak in density at the transition between radiation and convection. It reduces the discrepancy in the photospheric helium by 20% (Table 1), but slightly decreases the central temperature. These points have already been mentioned in our previous works. Figure 3 also shows the influence of mass loss given by Equation (5) on the present squared sound speed and density differences. This mass loss is applied starting at 50 Myr, corresponding to the beginning of the main sequence, and mimics the result of magnetic wind. The initial solar mass is $1.33 \, M_\odot$ (where $M_\odot$ is the present solar mass). An even higher initial mass could be considered if the mass loss was applied at the separation of the solar disk near 3 Myr. In the present study, the luminosity at the beginning of the main sequence is $1.5 \, L_\odot$ instead of $0.7 \, L_\odot$, and the young Sun reaches $1 \, M_\odot$ at 0.77 Gyr. Its luminosity is smaller by 10% than the present luminosity at 1.5 Gyr, instead of 20% as found with the SSM. In that case, the discrepancy on the squared sound speed and density profiles is reduced and the predicted boron neutrino flux is slightly increased (Table 1).

4. SUMMARY, DISCUSSION, AND CONSEQUENCES

This Letter confirms the difficulty for the SSM to appropriately reproduce all the present solar observations: neutrino fluxes, sound speed and density profiles, photospheric helium...
content, and location of the base of the CZ. This Letter proposes two directions of investigation related to the activity of the young Sun and to the comparison of central temperature between SSM and SSeM. It suggests the order of magnitude of the corresponding effects and the quantitative implications on the aforementioned observables: (1) the Sun could have transformed about 2.5%–4% of the energy produced during the early evolutionary phases into another form of energy due to strong activity and the related interior dynamics, with a redistribution (or evacuation) of nuclear energy through kinetic and magnetic energies in the RZ and (2) its initial mass could have been greater by 20%–30% than the present solar mass if the relation observed on young solar analogs is used. Then, some residual effects on the present observables cannot be ruled out if we compare the difference of squared sound speed, the central temperature between SSM and SSeM, and the boron neutrino fluxes.

These ideas are not new (Turck-Chièze et al. 1988; Sackmann & Boothroyd 2003; Guzik & Massack 2010) but, for the first time, they are deduced from observations of young solar analogs and from the comparison of two solar probes, and are not only parameterized. Of course the mass loss studied here is rather large in comparison with previous works (limited by the previous agreement on the sound speed and lithium depletion) but is not ruled out by observation of young solar analogs. The knowledge of the present rotation rate in the solar core could help put more constraints on the phenomena studied here. This study will be pursued by a dedicated work on the history of the internal magnetism after introduction of the rotation history (Turck-Chièze et al. 2010). An active young Sun probably possesses a convective core and an early internal dynamo in addition to some mass loss: this would greatly modify the initial conditions of planet formation and could partly solve the “solar paradox” mentioned a long time ago by Sagan & Muller (1972) and never really totally solved: how could such a low initial solar luminosity be compatible with Mars early history (Forget & Pierrehumbert 1997; Haberle 1998)? This young Sun and solar analogs would also affect the poorly understood history of $^7$Li during their early evolution (Piau & Turck-Chièze 2002).

Moreover, other ideas must be explored, such as the magnetic field effect on solar spectral lines, which may impact the composition determination in the solar atmosphere (Fabbian et al. 2010), or the effect of a potential fossil field on opacities in the RZ, or the role of gravity waves.

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