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The Standard Solar Model and beyond

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Abstract. The Standard Solar Model (SSM) is an important reference in Astrophysics as the Sun stays today the most observed star. This model is used to predict the internal observables like neutrino fluxes and oscillation frequencies and consequently to validate its assumptions for its generalization to other stars. The model outputs result from the resolution of the classical stellar equations and the knowledge of fundamental physics like nuclear reaction rates, screening, photon interaction, plasma physics. The plasma conditions remained unmeasurable in laboratory for long due to the high temperature and high density conditions of the solar interior. Today, neutrino detections and helioseismology aboard SoHO have largely revealed the solar interior, in particular the nuclear solar core so one can estimate the reliability of SSM and also its coherence with the different indicators and between them. This has been possible thanks to a Seismic Solar Model (SeSM) which takes into account in addition the observed sound speed profile. Seismology quantifies also some internal dynamical processes that need to be properly introduced in the description of stars. This review describes the different steps of building of the SSM, its predictions and the comparisons with observations. It discusses the accuracy of such model compared to the accuracy of the SeSM. The noticed differences and observational constraints put some limits on other possible processes like dark matter, magnetic field or waves and determine the directions of progress for the near future that will come from precise emitted neutrino fluxes. High density laser facilities promise also unprecedented checks of energy transfer by photons and nuclear reaction rates.

1. The historical context

Standard Solar Model (SSM) produces the thermodynamical profiles of the present Sun together with all the useful observables. It results from the resolution of stellar evolution equations from the contraction of the Sun (or from the arrival on the main sequence) up to the present age. This model is a reference in Astrophysics, because it is useful for establishing the chemical evolution of the galaxy through helium and oxygen evolution and for validating the physics which relies stellar evolution to cosmology through the age of globular clusters...

SSM has been strongly developed in the eighties, stimulated by the coming observations and detections which were for the first time compared to its detailed predictions. Today it stays a basis on which dynamical processes are slowly introduced.

The first seismic observations appeared in 1962 but have been understood only around 1970, then ground networks have been deployed, the space helioseismology began with the launch of SoHO in December the 2nd 1995. This satellite is still observing the Sun. On board, the resonant spectrometer GOLF [1] is dedicated to the core of the Sun and the MDI instrument looks locally to it, exploring mainly the above layers. The observations of GOLF and of the successor of MDI, HMI on SDO, will continue up to at least 2016. Using both instruments, and in particular the high quality of the GOLF instrument, a precise sound speed profile has been used to extract precise neutrinos fluxes in 2001 [2]. In parallel, the first neutrino limit by Homestake was given in 1968, then followed by Kamiokande, Gallex, SAGE, Super Kamiokande, SNO and BOREXINO. It is well known that the SNO detection has been determinant in the understanding between predictions, detections and neutrinos oscillations, already suspected with Gallex and SAGE results [3]. The originality of SNO is due to its ability to get charge current and neutral current estimates, so to determine the flux of the three different flavours of neutrinos coming initially from the Sun, after transformation of some electronic neutrinos in vacuum and matter in muon and tau neutrinos. The same year 2001, the neutrino puzzle has been definitively solved by the confrontation of seismic predictions of boron flux [2] to SNO neutrino counts [4]. Their remarkable agreement (also with SSM predictions at that time) has been crucial in the attribution of the Nobel Prize to R. Davis and M. Koshiba in 2002, the two precursors of neutrino detections in USA and Japan. For details, quantitative values of these two fields, see the two reviews [5, 6]. The generalization of helioseismology to other stars (asteroseismology) has more recently shown its great potential with the space COROT (2008) and KEPLER (2010) satellites.

Today, 10 years after the Nobel Prize, it is interesting to see what we can say about the SSM, how it compares to the seismic model and to the detailed observations and what we can deduce from the present significant discrepancies. The discussion is justified by the recent progress obtained on the solar photospheric composition and on some reaction rate which has led to poorer neutrino predictions of the SSM.

2. The building of the Standard Solar Model

SSM satisfies the well known structural equations of stellar evolution applied to any star. These equations describe the hydrostatic equilibrium, the conservation of mass and energy and the transport of energy by photons in the radiative zone and by convective motions in the more external layers. The reference [5] summarizes the detailed models and predictions along the last two decades. The resolution of the two first equations (hydrostatic equilibrium and conservation of mass) needs to use a proper equation of state of the plasma that determines P $(\mathrm{T},\ \rho, \mathrm{X_i})$, respectively pressure, temperature, density and fraction of mass of each elements. The plasma is mainly formed by hydrogen and helium completely ionized in the central conditions plus about 20 elements for which one needs to know the degree of ionization. The recent progress on the equation of state has been the introduction of the relativistic electronic correction. The other equations justify more caution. SSM assumes that the nuclear energy flux $4\pi r^2\rho\epsilon$ produced per second equilibrates the energy flux *L(r)* emerging from a sphere of radius r. Of course, the energy loss by neutrinos must be subtracted to this energy flux. This neutrino energy is small during the hydrogen-burning phase. Taking into account quasi-static gravitational readjustment and composition variation, the heat transfer term TdS where S is the total entropy per gram of the gas must be incorporated, and the energy bookkeeping yields:

$$\frac{\mathrm{dL(r)}}{\mathrm{dr}} = 4\pi \mathrm{r}^2 \rho(\mathrm{r}) \left(\epsilon_{\mathrm{nucl}}(\mathrm{r}) - \frac{\mathrm{T(r)}\, \partial \mathrm{S(r)}}{\partial \mathrm{t}} \right) \tag{1}$$

The contraction at the beginning of the pre-main sequence, when the star is formed, allows the increase in the central temperature up to the required level to ignite nuclear reactions. Following this equation, during the main sequence, the star is really equilibrates and the Sun is practically at the middle of this stage. At the end of the hydrogen-burning phase, when the nuclear energy vanishes, a second contraction of the core with dilatation of the envelope leads to a new increase in the central temperature up to the beginning of helium fusion.

A second important equation of stellar evolution describes the transfer of energy from the center to the surface. The star chooses the most favorable type of transport between convection or radiation. In the inner solar radiative region, the diffusion approximation is appropriate, and the relation between temperature gradient and luminosity is:

$$\frac{\mathrm{dT(r)}}{\mathrm{dr}} = \frac{-3}{4\mathrm{ac}} \frac{\kappa(\mathrm{r})\rho(\mathrm{r})}{\mathrm{T}^3(\mathrm{r})} \frac{\mathrm{L(r)}}{4\pi\mathrm{r}^2} \tag{2}$$

The Rosseland mean value κ(r) depends on T, ρ and X_i. When it increases strongly, like in the external part of the Sun, the radiative gradient increases and matter becomes convectively unstable. The solar time evolution is governed through the fifth equation which describes the change in composition due to nuclear reaction rates, microscopic diffusion and turbulence [7]:

$$\frac{\partial \mathrm{X_i(r)}}{\partial \mathrm{t}} = -\frac{\partial[(4\pi\rho\mathrm{r}^2)^2(\mathrm{D_i}+\mathrm{D_T})(\partial\mathrm{X_i}/\partial\mathrm{M(r)})]}{\partial\mathrm{M(r)}} + \frac{\partial(4\pi\rho\mathrm{r}^2\mathrm{v_i}\mathrm{X_i})}{\partial\mathrm{M(r)}} + \Sigma_\mathrm{j}\Sigma_\mathrm{k}\mathrm{R_{ijk}}\mathrm{X_j}\mathrm{X_k} \tag{3}$$

the last term is the nuclear term and the first one includes both turbulent term (D_T) and microscopic diffusion terms which depends on the concentration gradient, the second term introduces the diffusive velocity. The turbulent term dominates near the transition region between convection and radiation [8]. The five equations are non linear and coupled so they must be solved simultaneously up to the present solar age which is established at 4.6 Gyrs (including premainsequence). At the beginning of the evolution only the mass and the heavy elements relative to hydrogen are given, the initial helium content Y and the coefficient α of convection is adjusted a posteriori to get the proper radius and luminosity at the present time. As appeared in the previous expressions, complex physical processes must be determined to solve these equations that have justified several updated of the SSM along the last decades.

3. The SSM quality and predicted observable accuracy

The SSM delivers radial profiles of all the thermodynamical quantities and of all the different species for the present Sun from which one derives the observables that are detectable (neutrino fluxes) and measurable (mode frequencies or abundances).

Some neutrino fluxes are strongly dependent on the solar central temperature: the whole ^8B flux, associated to the reaction p+^{7}Be, varies as T^{18} and even T^{24} just at the center, ^{7}Be flux, associated to the electronic capture like T^8, so of course, they are strongly depend on the detailed description of the solar core. In contrast, pp neutrino flux appears directly connected to the solar luminosity so very few dependent on such description if equation (1) is correct. But it is very difficult to detect low energy neutrinos (like pp neutrinos) and all the neutrino fluxes independently, so chlorine detector like gallium ones were detecting a range of neutrino energies which favors ^{8}B in the first case and pp in the second case with some contribution of ^{7}Be neutrino flux in both cases, consequently the accuracy of the neutrino flux predictions of the SSM has always been crucial in the comparison with detection.

Three main sources of uncertainties have been quickly identified, see for example table 8 of [9]: the uncertainties coming from reaction rates, from abundances and from the opacity coefficients. So a lot of work has been performed to improve their accuracy. If it is not too difficult to determine an error bar deduced from an experimental cross section, it is more difficult to give an error bar for processes which are only known theoretically like screening effects, Rosseland mean values or microscopic effects.

So the error bars assigned to SSM predictions have always been minimal error bars (introduction of what we know, estimation of what we do not know). Consequently, it is not surprising to note larger variations on the predictions than previously estimated. Nevertheless the predictions have been always improved by time as more physics has been understood and implemented. By chance two groups have dedicated efforts to improve the SSM predictions, they have contributed to these improvements in coordination with physicists of different disciplines. The Bahcall team has predicted values for chlorine experiment from 9 to 7.5 SNU (1SNU=

10^{37}captures/cm^2/s). The Saclay group has given values from about 5.8 to 7 SNU and the two teams have obtained a reasonable agreement around 2000, see figure 1 of [10] with an accuracy of about 12% (of course the uncertainty on pp flux is smaller). These values were far from the mean experimental value of about 2.3 SNU even the fluctuations of the chlorine detection for each run were very large but compatible with the low statistical significance of each run. These fluctuations were largely greater than the 10% accuracy over 20 years which is only justified within the above SSM assumptions, see sections 6 and 7.

The change of the SSM predictions with time was maximal for the boron emitted neutrino flux, due to its extreme sensitivity to the description of the core. The impact of updated physics of SSM on its predictions has been summarized in table 6 of [5]. The predictions have changed by more than 20% and returned practically to the first predictions today as the reduction of the CNO photospheric abundances has compensated the previous effect of the microscopic diffusion. So, the accuracy of 15% attributed to the prediction of that flux could be underestimated.

4. The SSM predictions compared to seismic observations and neutrino detections

Our most recent SSM [11], built using the CESAM code, includes Adelberger reaction rates [13], Mitler screening effects, OPAL opacities, microscopic diffusion and photospheric abundances of Asplund (2009), see all the details on the input physics in [5]. Table 1 recalls the main characteristics of that model. As previously mentioned in both publications, the surface helium is a little low compared to the value determined by helioseismology (around 0.25) and consequently the initial helium also if one follows the general enrichment of the galaxy. Moreover the base of the convective zone at 0.727 is in disagreement with the seismic value of 0.713 $R_\odot$ [14].

Table 1. Main characteristics of our most recent published SSM compared to seismic observations of photospheric helium: 0.25 and BCZ: 0.713 $R_\odot$.

Model	T_c °K	ρ_c g/cm^3	Y_i mass fraction	Y_s mass fraction	Z/X_i	Z/X_s
SSM Saclay	15.54	150.6	0.2645	0.235	0.0181	0.0136

Several publications have also shown that the recent change of the photospheric composition of carbon, nitrogen and oxygen has largely deteriorated the agreement of SSM prediction with the seismic sound speed obtained in 2001, and with the neutrino predictions too, see [16, 17, 18, 19], it is the reason why some authors have been reluctant to use it. Nevertheless the reduced photospheric CNO composition by 20-30 % is justified by the choice of the observed lines, the use of 3D simulation to determine their shape. This result is confirmed by [15], even some small differences exist between the two works. Moreover, as mentioned in [16], it solves a fundamental problem which was the solar oxygen anomaly compared to the oxygen of stars of the neighboring environment as recalled in Figure 1. It is clear also since the beginning of the seismic investigation of the solar interior that the SSM assumptions are not sufficient to reproduce the real Sun. Figure 2 shows the dynamical processes that must be introduced to describe the real Sun, see [20]. They are not considered in the SSM approach even most of them are already seen in the solar interior. I shall come back on this point in Section 6.

Figure 3 shows also the strong sensitivity of the sound speed to the used photospheric solar composition and its time evolution. Consequent central condition changes are observed [5].

Let recall the reactions that produce the different neutrino fluxes: p+p called pp ν, capture electronic on p called pep ν, capture electronic on Be^7 called ^7Be ν, p +Be^7 called ^8B ν, and neutrinos coming from the CNO cycle called CNO ν which are the sum of ^{13}C ν, ^{15}O ν, ^{17}F ν.

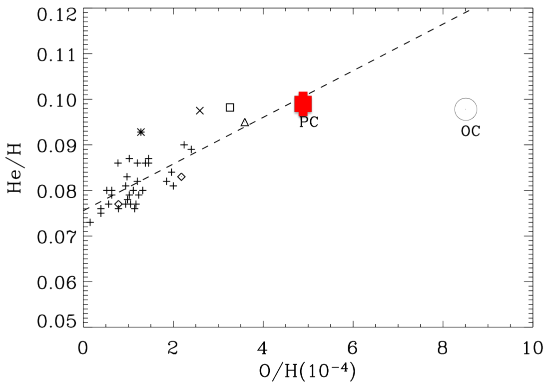

Figure 1. Galactic evolution of helium versus oxygen showing the anomaly of the old value (OC). O/H = 4.90 ± 0.06 10^{-4} now (PC red arrow). Extended from [16].

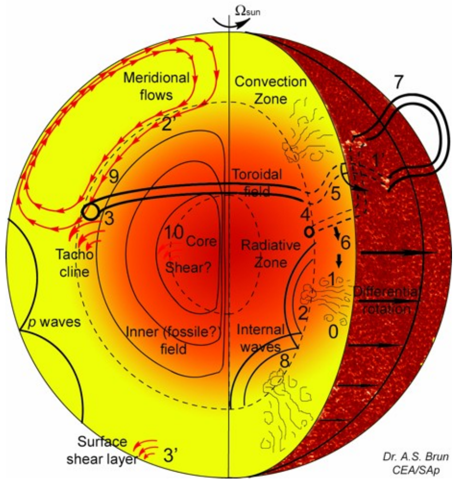

Figure 2. Integrated dynamical view of the solar interior. From [20].

All these individual fluxes differ by the region of emission, the energy and the efficiency of the channels that generate them. ^{8}B ν is the lower flux (weak chain ppIII) but the most energetic, pp ν the higher flux but the less energetic. The pioneer chlorine experiment measures ^{7}Be, ^{8}B and CNO ν fluxes, the gallium detectors have a smaller threshold and are dominated by the pp flux but all the others are present, SNO and SK measure only part of ^{8}B neutrinos. Borexino extracts separately ^{7}Be ν, ^{8}B ν and CNO ν. See [5] for all the details.

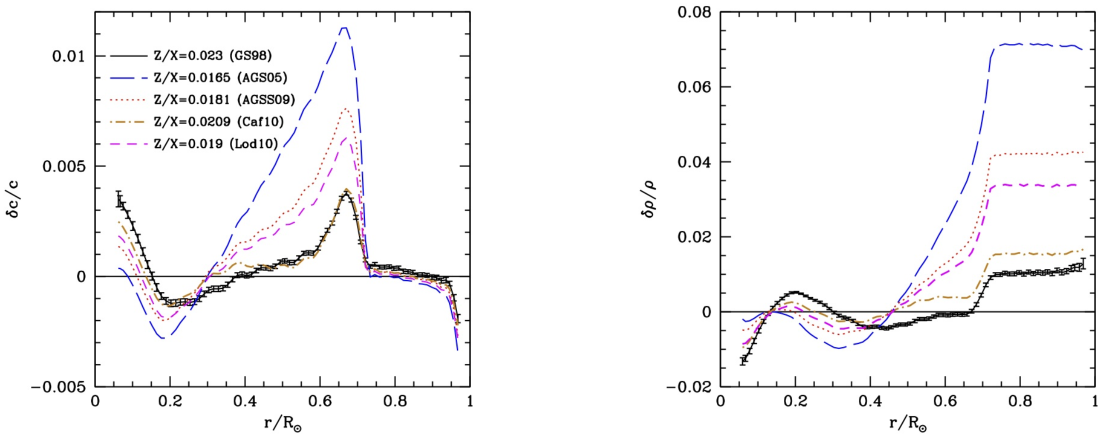

Figure 3. Sound speed and sensitivity profile differences between seismic inversion done by S. Basu and different SSM of the same group using different compositions corresponding to estimates obtained along the last decades. From [21].

Using heavy water, SNO realizes charge current interaction and elastic scattering on electron. The first one is only sensitive to electronic neutrino, but elastic scattering (unique interaction in SK) allows to detect both electronic, tau and muon neutrinos. The elastic scattering detects ν_e + 0.16 (ν_μ + ν_τ). In comparing the two counting rates, one deduces the sum ν_e+ν_μ+ν_τ coming from the Sun, of course the last two are a manifestation of the oscillation of neutrinos as the Sun emits only ν_e.

Table 2. Neutrino predictions of our most recent SSM [11] compared to all neutrino experiments. The SNO results come from [24].
1SNU = 10^{-37}interactions/s/cm^2. See our recent reviews for the other references.

	Predictions	Predictions including neutrino oscillation
Chlorine detector		2.56 ± 0.23 SNU
SSM 2011	6.315 SNU	2.24 SNU
Gallium detectors	**GALLEX+GNO+SAGE**	66.1 ± 3. SNU
SSM 2011	120.9 SNU	64.1 SNU
Water detectors	**SNO**	**SNO + SK** in 10^6cm^{-2}s^{-1}
	5.09 ± 0.44 (stat)± 0.45 (syst)	5.27 ± 0.27 (stat)± 0.38 (syst)
SSM 2011	4.21 ± 1.2	4.21 ± 1.2

Table 2 confronts the predictions of the SSM [11] with the detected neutrino fluxes. The direct comparison is only possible for the SNO detector. For the others, the comparison needs to multiply the emitted flux by the probability for a ν_e to stay a ν_e at its arrival on the detector. This probability depends on the values of $\sin^2\theta_{12}$ and Δm^2_{12} that are now well established, see Figure 6 left and [22, 23]. The final results are done in the right column instead the left column corresponds to the emitted flux. One sees that the SSM predictions are systematically below the detections as also noticed in [19]. As the error bars given for these predictions can be wrong, it is only given for boron ν flux where we have a direct comparison, this error bar is quite large. One cannot say that there is a strong disagreement but one sees in Table 2 that the agreement is marginal. If one compares the sound speed and the density profiles (Figures 3 and 4) we note a strong disagreement because in these cases the vertical error bars are very small, We discuss now a better way to estimate the accuracy of the predictions for the different fluxes.

5. Seismic results and Seismic Model predictions of the neutrino fluxes

As already shown on Figure 3, the SoHO satellite has revealed the sound speed and density profiles down to the core, see [5, 6] where detailed final information is given. These two quantities have been compared to SSM predictions all along these two decades and the agreement has varied with time and details of the SSM as neutrino fluxes were varying too. So to stabilize the neutrino emitted fluxes coming from solar models, we have decided to build a model called Seismic Solar Model (SeSM) using the same equations than SSM but using slight modified inputs (reaction rate and opacity coefficients) to micmic as properly as possible the very precise observed sound speed (better than 10^{-4} accuracy), see Figure 4. The modification of the reactions rates has been rather small and the modification of the opacities (never verified experimentally, like screening effect) has been relatively small at the beginning and is now amplified by the effect of recent estimates on the composition [2, 26]. Different checks have been done which lead to thermodynamical quantities which differ from the SSM ones. Of course the physics of the SeSM is not different from SSM but this model is more representative of the solar core and consequently can predict the neutrino emission fluxes with a better accuracy which avoids uncertainties on the most important reaction rates (including screening), on the opacities and detailed composition....

Table 3 shows the SeSM neutrino predictions compared to the detected values discussed previously. One easily notices that the predictions are in better agreement with the detections

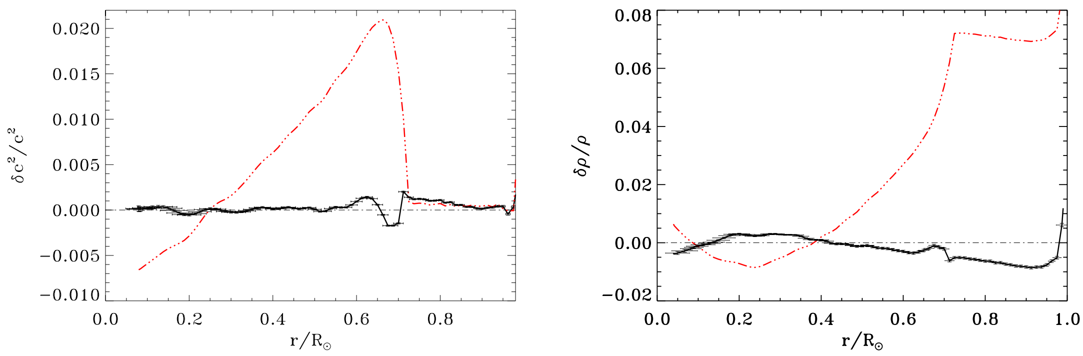

Figure 4. Squared sound speed and density profile differences between seismic inversion from GOLF and MDI [2], SSM (in dashed red line) and SeSM (in black, with error bars). From [5].

Table 3. Neutrino predictions of the SeSM [2, 26] compared to all the neutrino experiments. The Borexino results from [25]. Same references than in Table 2.

	Neutrino Predictions	Predictions including neutrino oscillation
Chlorine detector		2.56 ± 0.23 SNU
Seismic model	7.67 ± 1.1 SNU	2.76 ± 0.4 SNU
Gallium detectors	**GALLEX+GNO+SAGE**	66.1 ± 3. SNU
Seismic model	123.4 ± 8.2 SNU	67.1 ± 4.4 SNU
Borexino ^{7}**Be**		3.36 ± 0.36 $10^9 cm^{-2}s^{-1}$
Seismic model	4.72 $10^9 cm^{-2}s^{-1}$	3.05 ± 0.35 $10^9 cm^{-2}s^{-1}$
Water detectors	**SNO**	**SNO + SK** in $10^6 cm^{-2}s^{-1}$
	5.09 ± 0.44 (stat)± 0.45 (syst)	5.27 ± 0.27 (stat)± 0.38 (syst)
Seismic model	5.31 ± 0.6	5.31 ± 0.6

and even in excellent agreement with all of them. This is a great success of the two totally independent approaches of the solar interior to agree with each other through the SeSM. This result does not support the existence of a forth neutrino, the sterile neutrino, except if its existence does not perturbed the detected range of energy. Such model has also shown that it reasonably describes the core because its gravity mode frequency predictions agree with the first observations and rejects the low mass range of WIMP candidates to dark matter as the seismic model predicts a higher temperature of the central region than the SSM, see 7.3, the opposite behavior than the action of WIMPs in the core [27]. We note also that the error bars of the predictions are reduced and easier to determine as the sources of uncertainty are reduced to the weak interaction of neutrinos with matter and some specific cross section like $^7Be+p->^8B+\nu_e$ which is not at all constrained by the solar luminosity, no error bar needs to be attributed to deep composition, opacity or plasma effects, which are constrained by the observed sound speed.

As this step has been successful but not sufficient to describe the whole internal dynamics of the Sun, dynamics which could be amplified in more evolved and more massive stars, we can question the future. Can we learn more on the neutrino properties and on the solar interior with the precise solar neutrino fluxes or the gravity mode detections ?

6. Beyond the SSM

The answer is of course yes for two reasons. First one has learned so much from solar neutrinos that one cannot exclude that better statistics will bring other constraints on their properties. The second and important reason is that the Sun is not static and that there are good reasons to learn more in the next two decades.

- We know that at the surface, the Sun appears as a magnetic star, but the dynamo effects inside the Sun are not yet observed except near the surface, so one cannot conclude if there is only one cycle of 22 years with a reversal of the polarity of the poles every 11 year or if there are other longer cycles inside the convective zone (about 100, 200, 400 yrs...).

- We know the rotation profile from the surface to the core but we have not established all the properties of the transition region between radiation and convection, in particular its magnetic topology and its efficiency to generate gravity waves in the radiative zone.

- We have only detected the first gravity modes which suggest a higher rotation profile in the core but it is not established yet if it stays a fossil field in that region.

- We have built a seismic model of the Sun which is able to predict better the neutrino fluxes than SSM but we do not know why the thermodynamical quantities are what we get? is it due to an incorrect microscopic description of the energy transfer, is it due to an incorrect energy balance? is it due to a poor description of the dynamical processes in the radiative zone. Is it due to other fundamental physics like sterile neutrinos acting like dark matter ?

The best is to explore the present and coming data and see how they will help us to interpret the present situation.

7. Precise Nuclear Astrophysics and Future Observational Constraints

The dynamical phenomena in the radiative zone are difficult to catch. Let see how to interpret the present discrepancies and how to progress on the signatures of such phenomena.

7.1. Pure energy transfer problem

The origin of the noticed discrepancies can come from an inaccurate determination of the opacity coefficients used in the SSM calculation in equation (2). Effectively most of the discrepancy or change of the SSM predictions comes from the impact of the deep composition on the sound speed through their Z contribution and in particular its oxygen and iron contribution (but not only). Face to this possibility, we are pushing new opacity calculations OPAS [29] and new measurements of the transfer of radiation through specific elements and mixtures [28]. Internal comparisons have already been made with OPAL tables, some specific differences have been noticed for specific elements, but the mean Rosseland differences on the solar mixture reach only some % mainly at the base of the convective zone. The new calculations OPAS seem in rather good agreement with the first measurement in conditions not too far from the BCZ [30]. New tables will be provided and one cannot exclude some plasma effect which could slightly modify the properties of ionization of the different species at higher temperature and density. To verify these assumptions, experiments are under study on large laser facilities like LMJ+PETAL [31, 32] for specific elements and mixtures equivalent to the solar composition. These experiments are very difficult to perform as one needs to produce density of the order or greater than solid density at Local Thermodynamics Equilibrium or near.

7.2. Interaction between macroscopic and microscopic diffusion in the RZ

The quality of the SSM has been largely improved by the introduction of the microscopic diffusion that depends on both gravitational settling and radiative acceleration built on opacity spectra. These processes, first two terms of equation (3) have not been revised after the observation of the very complex transition region called tachocline (see Figure 2) which delimits the radiative-convective transition. Seismic data show that this region has an extension of about 5% $R_\odot$ and is not totally spherical [33]. The strong difference of meridional velocity between radiative zone (RZ) and convective zone (CZ) extracted from the modeling of the transport of momentum [34] creates such shear horizontal instability zone. It is a very complex region where the observed differential rotation of the CZ disappears in favor of a solid rotation. As an extension of the convective motions, this layer produces gravity waves in the RZ [36] and contributes probably to regenerate the toroidal field from the poloidal field. One cannot exclude that these dynamical effects can impact more differentially the heavy elements than one gets today. New calculations will estimate such idea but in addition there is some hope to verify their predictions on the central CNO composition if one gets a precise determination of the CNO flux from Borexino or from future neutrino detectors.

7.3. Energetic balance of the Sun and its time evolution

It is interesting to compare the central thermodynamical conditions of the SeSM to those of the SSM given in table 1. For the SeSM, we get:

$$\mathrm{T_C} = 15.74\ 10^6\,^\circ\mathrm{K} \quad \rho_\mathrm{C} = 153\,\mathrm{g/cm^3} \quad \mathrm{Y_{init}} = 0.277 \quad \mathrm{Y_{surf}} = 0.250$$

This model agrees with the different helioseismic constraints: photospheric helium, BCZ, sound speed and has a reasonable helium enrichment. If one compares the difference with SSM in term of energetic production, one notices that the difference is about 5% [11]. As the modeling of the Sun assumes that the energy transfer is instantaneous, and that the emergent flux at the surface just compensates the flux emitted through nuclear energy (equation 1), one can question the precise reliability of such equality at the level of accuracy obtained today. Effectively the motions inside the Sun create internal kinetic energy, meridional circulation energy which are partly transformed in magnetic energy. Figure 5 shows the emergence of the energy flux at the surface now measured for about three decades, the total flux increases by about 0.1% near solar maximum [37], although the radius very slightly shrinks simultaneously [35]. We know that this excess of released energy is not totally regular, but we do not know which part of energy stays inside the Sun, part of it could be stored inside the tachocline. Seismology tells us that the energy tank is $< 5\%$. One way to verify if there is a real difference between central production

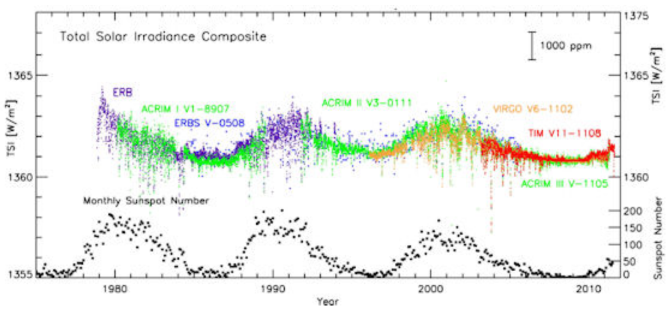

Figure 5. Time variability of the solar irradiance obtained by different satellite measurements. The relative normalization between the data sets has been obtained by Kopp and collaborators.

of energy and external output and how it evolves with time, consists to simulate the dynamical processes in 1D and 3D. This is a difficult work because in 1D one can follow the readjustment of the star but the interplay between processes are better described in 3D which cannot presently mimic sufficient longer series. The other way consists to measure directly the central energetic flux through the simultaneously precise neutrino fluxes coming from ^8B neutrinos (sensitive to central temperature and possible fluctuations) and from pp or pep neutrinos that are directly sensitive to the production of energy. One notes on Figures 6 and 7 that we have already some estimate of the pep flux. Its error bar is today too large to assume really a deviation [38] but this information will be improved during the next decade and we shall be in a position to conclude.

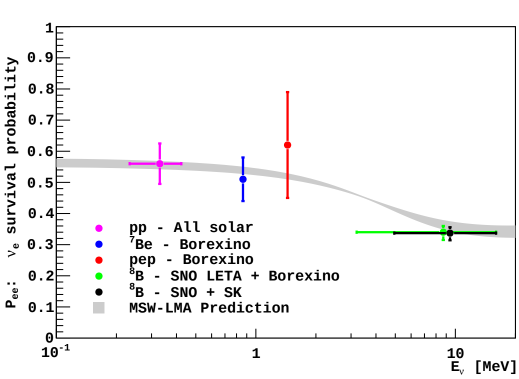

Figure 6. Probability for a ν_e to stay a ν_e. From [38].

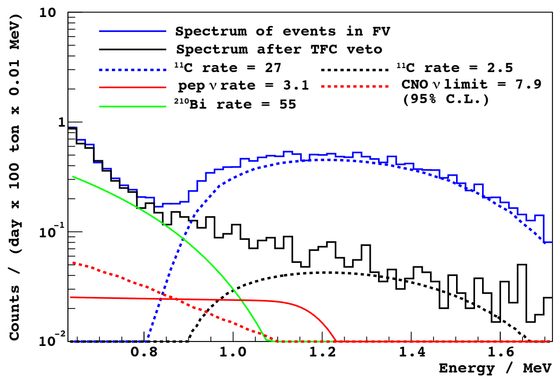

Figure 7. Extraction of the different fluxes of neutrinos from Borexino. From [38].

7.4. Precise nuclear core reaction rates and Fluctuations in the radiative zone

It is important to accompany the coming neutrino projects, SNO+ and HyperKamiokande which will deliver very precise neutrino fluxes. They could see the dynamics of the central core. One can hope to check if they present time variabilities which are compatible with gravity waves in the RZ and if their characteristics agree with improved internal dynamical models of the Sun.

In parallel precise predictions of the fluxes are required. Numerous studies have been dedicated to the knowledge of all the nuclear reactions that act in the Sun [13], but two fundamental problems limit their accuracy: the domain of energy corresponding to very low cross sections and the absence of measurements of the plasma screening effects. Such difficulties can be solved in the near future with the large laser facilities like LMJ+PETAL or the NIF facilities. They provide real opportunities to measure directly the reaction rates that appear in stars which by essence include the electron acceleration of the reaction rates, the maxwellian distribution of the velocity and the role of ion neighbors. This direction is promising and already explored on more modest installation [39]. Such experiments require a lot of expertise and new detectors which are in construction [32].

8. Conclusion

This review shows that the SSM is an excellent basis for stellar evolution, the development of asteroseismology and galactic evolution studies. Nevertheless the impressive progress of the helioseismic probe has confirmed the presence of dynamical processes which are not included in the SSM framework and can partly contribute to the limitation of its predictions of the present neutrino fluxes. The building of a SeSM has stabilized these predictions and has helped to quantify the role of the dynamical effects on different indicators. The very brilliant neutrino program with HyperKamiokande and SNO+ open very important directions of progress. We have shown that precise nuclear astrophysical studies and plasma effects verification need to be performed in parallel. Large laser facilities are well adapted to accompany such progress. Modeling the Sun at timescales which concern the human behavior (hundreds and thousands of years) is a new challenge for the coming decades. Such golden future will contribute also to enrich the modeling of solar-like stars and the relationship between stars and planets.

This review has been enriched by space ESA-NASA SoHO observations, neutrino detections and by numerous collaborations in different fields.

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