Solar abundance problem

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Abstract The chemical composition of the Sun is among the most important quantities in astrophysics. Solar abundances are needed for modelling stellar atmospheres, stellar structure and evolution, population synthesis, and galaxies as a whole. The solar abundance problem refers to the conflict of observed data from helioseismology and the predictions made by stellar interior models for the Sun, if these models use the newest solar chemical composition obtained with 3D and NLTE models of radiative transfer. Here we take a close look at the problem from observational and theoretical perspective. We also provide a list of possible solutions, which have yet to be tested.

1 Introduction

Until recently, we thought we understand the Sun very well: its surface temperature, surface pressure, age and mass, interior physical properties, abundances of different chemical elements. After all, most of these parameters can be determined by very precise direct methods: solar effective temperature is known to an astonishing accuracy of 0.01%, as measured from the radiated bolometric flux; neutrino fluxes provide the temperature in the solar core; solar age is obtained from isotopic ratios in meteorites; helioseismology - the analysis of propagation of acoustic waves in the solar interior - gives accurately the depth of the convective zone and surface helium abundance. It turned out, however, that what is still not known exactly is the solar
chemical composition. The main reasons for this gap in our knowledge of the Sun will be discussed in this lecture.

The first paper giving a reference set of the solar abundances for many chemical elements - standard solar composition (SSC), appeared about a century ago (Russell 1929). However, only a few decades later, when computer power increased enough to run complex numerical algorithms, this dataset acquired its main value. The abundances were rightly plugged into a variety of astrophysical models. The first major application of SSC was found in the standard solar models (SSM), which predict evolution of the Sun from its formation till present. SSC went into models of stellar evolution, stellar populations, and galaxies, becoming a ruler for measuring how dissimilar from the Sun are other cosmic objects. Highly accurate solar abundance distributions are nowadays needed for research into the physics of Galactic formation and evolution (e.g. Gehren et al. 2006; Feltzing and Chiba 2013), to search for solar twins, i.e. stars very similar to the Sun and thus potentially hosting earth-like planets (Meléndez et al. 2012). The Sun has also traditionally been used as a laboratory for particle physics, particularly for setting constraints on the properties of dark matter candidates such as axions, using the sensitivity of helio-seismic probes of the solar structure (Schlattl et al. 1999). Also in this case, highly accurate chemical composition of the Sun is needed: abundances in the solar interior determine the radiative opacities and affect the interaction between dark matter and baryons. For example, for certain dark matter candidate particles, interaction with baryons depends strongly on the properties of nuclei - charge, spin- and a detailed knowledge of the chemical composition and profiles in the solar interior is necessary. Another example is that of non-annihilating dark matter particles, which can strongly modify the energy transport in the solar interior.

Very recently, a revision of the SSC was proposed by (Asplund et al. 2009, hereafter AGSS09). The new dataset (Figure 1) immediately became a new standard in astronomy. But more than that, it led to a conflict with the theory of stellar evolution.

![Fig. 1 Present-day solar abundances, taken from AGSS09, as a function of atomic number.](image-url)
Solar abundance problem thus motivating a rapid increase of research efforts in the field. The predictions of standard solar models are now in conflict with the internal structure of the Sun, as measured by the helioseismology. This is known as the solar abundance problem (Serenelli et al, 2009). The problem has not been solved yet. Here we only review the methods, recent progress in the field, and provide our opinion on the problem.

2 Nomenclature

There are two commonly-used abundance scales: astronomical and cosmo-chemical. The astronomical scale sets the 'zero' point at \( \log(\varepsilon(H)) = 12 \), so then the abundance of each other element is given by:

\[
A(\text{El}) = \log \varepsilon = \log (n_{\text{El}}/n_{\text{H}}) + 12,
\]

where \( n_{\text{El}} \) is the number density of element atomic. The distribution of abundances on the astronomical scale, also known as \( \log \) scale, is shown in Figure 1. The cosmo-chemical scale normalises all abundances to the number of Si atoms, \( N_{\text{Si}} = 10^6 \). The latter can be coupled to the astronomical scale through a reference element, usually Si because it can be easily measured in the solar spectrum and in meteorites.

Furthermore, to compare with the models of stellar structure and evolution, it is necessary to introduce the notations of mass fractions:

\[
X + Y + Z = 1,
\]

where \( X, Y, Z \) are the mass fractions of H, He, and all other heavier elements; \( Z \) being the so-called metallicity\(^1\).

3 Methods

Different methods have been developed to determine solar abundances. They include empirical, semi-empirical, and theoretical methods. The former two subclasses refer to analysis of the observed solar spectrum, from the IR and optical (photospheric spectrum) to X-Ray (corona), sunspots, measurements of the solar wind, flares, and energetic particles. Another rich source of information is provided by the most primitive CI chondritic meteorites that have avoided chemical fractionation and are thus believed to preserve the solar system pristine relative abundances of refractory metals (Lodders et al, 2009). Theoretical methods include inversions

\(^1\) Note, however, another very common definition of metallicity in stellar astrophysics, which is the relative abundance of iron in a star relative to the Sun, \([\text{Fe}/\text{H}] = \log(n_{\text{Fe}}/n_{\text{H}})_{\text{star}} - \log(n_{\text{Fe}}/n_{\text{H}})_{\text{Sun}}\). Both definitions are used interchangeably, and there are transformation relations between \( Z \) and \([\text{Fe}/\text{H}]\).
of helioseismic data (e.g. [Basu and Antia, 2004]) and nucleosynthesis models for heavy noble gases (e.g. [Asplund et al, 2009]).

The notation of photospheric abundances strictly applies only to the abundances determined from the spectral lines, which are formed in the solar 'photosphere', i.e. where the dominant part of the solar radiation flux is emitted. However, the region is poorly defined. Usually, lines formed at optical depths $-5 < \log \tau_{500} < 0$ are tagged as photospheric, even though the $T$ minimum occurs at $\log \tau \sim -3$ and above this point chromosphere has a non-negligible influence on the line formation. The entire UV quasi-continuum at $\lambda < 250$ nm has a chromospheric origin. But also IR lines, as well as some strong lines in the UV and optical (e.g., Ca triplet at 850 nm and $H\alpha$), may show signatures of chromospheric emission in the cores.

Unfortunately, each method is prone to its own limitations and thus provides only a subset of data points on the element abundance diagram. So, volatile elements: H, He, C, N, O and noble gases are absent or heavily depleted in meteorites; the solar photospheric spectrum does not contain lines of elements with very high ionisation potential, such as He and other noble gases; some elements have spectral lines in the wavelength regions unaccessible from the ground, such as the B line in the far-UV. Furthermore, to convert the abundances derived by different methods to the same scale, a reference element is needed. For homogenising meteoritic and photospheric scales, Si is often used as the anchor point between the two scales. Abundances from solar wind, corona, flares, or sunspots are converted to the photospheric scale using $Ne/Mg$ or $Ne/O$ ratios. This involves modelling the complex dynamical behaviour of elements with different ionisation potentials in the outermost layers of the Sun, and the robustness of such methods is questionable.

In short, the following methods are used for the analysis of different element groups:

- inert He has a very high ionisation potential (24.6 eV), and the important lines are located in the far UV. Its abundance can be inferred from the solar wind and corona, but the value is poorly-constrained and highly variable. Theoretical models of stellar evolution and the data from helioseismology ([Basu and Antia, 2004]) provide a more accurate estimate, consistent with each other to 10% (see below);
- light elements Li, B, and B are determined from the solar spectrum. The important lines, are, however, model dependent: because of very low abundances and very simple electronic configurations, the atoms give rise to one or few spectral lines only (Li I) or they are located in a very problematic part of a spectrum (Be II, B I). Li is depleted in the Sun by a factor of $\sim 150$ compared to meteorites, but Be and B are consistent.
- volatile elements C, N, O can be determined from the solar coronal and photospheric spectrum, where they are present in the form of atomic and molecular
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(e.g. CO, C₂, CH, OH, NH, CN) lines. Despite the wealth of spectral lines, the abundances of C, N, and O have always been a matter of debate.

• the abundances of refractory elements can be determined from meteorites and from the solar photospheric spectrum. The two techniques give generally consistent values, apart from selected elements like Co, W, Au, Pb, Pd (Asplund et al., 2009). Meteoritic abundances can be directly measured in a laboratory through chemical analysis. However, some degree of aqueous alteration might be present and samples have to be selected carefully (Lodders et al., 2009). In contrast, photospheric abundances are model-dependent, because they require a model of radiation transport in the solar atmosphere. Moreover, there are non-negligible differences in the results caused by different spectroscopic techniques, which are partly subjective (more below). Redeterminations of meteoritic abundances of refractory elements have been very robust over the years, therefore they can be taken as a reference.

• Kr and Xe are determined from nucleosynthesis models of slow-neutron capture process. The neutron-capture cross-section are accurately known from experimental measurements (Lodders et al., 2009).

4 Solar abundance problem

The solar abundance problem refers to the conflict of observed data from helioseismology and the predictions made by stellar interior models for the Sun. The 'problem' emerged only recently, when a new set of solar abundances computed with the 3D and NLTE spectroscopic methods became available. When used as a basis for calibrating the solar models, the new abundances lead to the solar interior properties, which cannot describe the present-day Sun.

To understand the roots of this problem, we first need to delve into some aspects of spectroscopic analysis that is the subject of the next section.

4.1 Solar abundances and metallicity

Traditionally, solar abundance has been derived from the analysis of the solar spectrum based on one-dimensional (1D) hydrostatic model atmospheres. Moreover, local thermodynamic equilibrium (LTE) has been generally adopted. Both approximations were necessary in the past because of computational limitations. An example of an SSC based on these assumptions is that of (Grevesse and Sauval, 1998 hereafter, GS98), which is in fact one of the most famous datasets in astronomy.

We follow the definition of refractory vs. volatile elements used in planetary sciences (not in industry), as e.g. in Taylor (2001). In this definition, a material which has relatively high condensation temperature is refractory.

See the lecture on 3D NLTE line formation.
Recently, stellar spectroscopy has evidenced two major developments. First it has become possible to perform three-dimensional (3D) radiation hydrodynamics (RHD) simulations \( \text{[Nordlund et al., 2009]} \) see for an extensive review on the topic). Another major improvement is the development of accurate non-LTE radiation transport models. The 3D RHD and NLTE models are very successful in describing a great variety of observational data, such as center-to-limb variation of the solar radiation field, shapes and asymmetries of spectral lines, brightness intensity contrast, and they predict consistent abundances for various diagnostic lines of a given chemical element. Up to date, the most complete and consistent SSC set is that by \( \text{[Asplund et al., 2009]} \).

For the reasons given in Sec. 3, meteoritic abundances of refractory elements and photospheric abundances for the volatile elements have been traditionally used in solar interior models. In what follows, we adopt this combination as our reference solar abundances, both for AGSS09 and GS98. Figure 2 shows the difference between GS98 and AGSS09 results for the elements most relevant to the solar abundance problem (C, N, O, Ne, Ar, Na, Al, Ca, Cr, Mn, Ni, Mg, Si, Fe, S). The error bars correspond to those from AGSS09.

AGSS09 abundances are systematically lower than the older GS98 values that can be explained by several reasons (see a detailed discussion in AGSS09 and in \( \text{[Grevesse et al., 2011]} \)). First, 3D RHD models produce temperature fluctuations in the solar atmosphere, which are absent by construction in 1D models that results in lower molecular abundances. Secondly, it was recognised that the important for-

![Figure 2](image-url)

**Fig. 2** Difference between AGSS09 and GS98 solar abundances. Elements shown here are the most relevant for solar model calculations. We use photospheric abundances for the volatile elements and meteoritic abundances for all other elements in both sets of abundances.
hidden [O I] line at 630 nm is blended by a Ni I line, a fact that was overlooked in previous studies and led to an overestimation of the O abundance. Finally, the NLTE abundance obtained from the O I 777 nm triplet is lower compared to LTE. According to AGSS09, CNO atomic and molecular indicators are now in a good agreement. Another important element, Ne, is lower in AGSS09 because its abundance is determined from the measured Ne/O ratio in the solar corona and the photospheric O abundance. Finally, for the refractory elements, the difference is caused by the lower abundance of the photospheric determination of Si, the anchor element between the photospheric and meteoritic scales. The AGSS09 Si abundance is 0.05 dex lower compared to GS98, and this brings down all refractory abundances by the same amount.

Note that another set of CNO solar abundances has been recently provided by the CO5BOLD collaboration (Caffau et al. 2011). These abundances are also based on a 3D RHD model of the solar atmosphere, but using a different approach abundance determinations. CO5BOLD abundances of CNO elements lie in between GS98 and AGSS09 and the quoted uncertainties are larger than those given in AGSS09. The differences between AGSS09 and CO5BOLD have been attributed to the differences in the spectrum normalisation and the choice of diagnostics lines (Grevesse et al. 2011, 2012), which are both partly subjective aspects of a spectroscopic analysis.

In summary, the differences between GS98 and AGSS09 abundances amount to 20% to 40% for CNO, Ne and 12% for refractories. Since spectroscopy provides only the relative abundances of metals to hydrogen, it is very convenient to combine all these numbers into the metal-to-hydrogen mass ratio \((Z/X)_{\odot}\). For the three sets of SSC discussed above, the values are:

\[
(Z/X)_{\text{GS98}} = 0.0229; \quad (Z/X)_{\text{CO5BOLD}} = 0.0209; \quad (Z/X)_{\text{AGSS09}} = 0.0178.
\]

\(Z/X\) is one of the three fundamental constraints that have to be satisfied by SSMs. The value of \(Z/X\) provided by CO5BOLD is obtained by complementing their photospheric measurements with abundances from Lodders et al. (2009) for refractories and noble gases.

SSMs are one-dimensional evolutionary models of a 1 M\(_{\odot}\) star, starting from a homogeneous model in the pre-main sequence up to the present-day age of the solar system \(\tau_{\odot} = 4.57\) Gyr. At this age, the model has to satisfy three observational constraints: the present-day luminosity and radius \((L_{\odot} = 3.8418 \times 10^{33}\) ergs s\(^{-1}\) and \(R_{\odot} = 6.9598 \times 10^{10}\) cm\) and the \((Z/X)_{\odot}\). Three free parameters are calibrated to fulfil these conditions: the mixing length parameter \(\alpha_{\text{MLT}}\) that controls the efficiency of convection in the Mixing Length Theory, \(Y_{\text{ini}}\) and \(Z_{\text{ini}}\). The relative abundances of individual metals are

\(^4\) Note that the given \((Z/X)\) were computed using photospheric abundances for the volatile elements and meteoritic abundances for all other elements. Therefore, it is slightly different from the present-day photospheric value, as e.g. given by Asplund et al. (2009) Table 4, \((Z/X) = 0.0181\).
assumed to be the same for a given \((Z/X)_\odot\). The initial hydrogen abundance is determined from the normalisation \(X + Y + Z = 1\).

### 4.2 Helioseismology and the Standard Solar Models

From the discussion above, it is clear that solar abundances are critical for the calibration of SSM. Here, we focus our discussion on the GS98 and AGSS09 abundances, and label the solar models accordingly, i.e. GS98 SSM and AGSS09 SSM.

The internal structure of the Sun can be accurately determined by helioseismology. The observed oscillation spectrum can be derived from the measured light curves or from the Doppler shifts of photospheric absorption lines. The quantities we are interested in are the trapped ‘eigenmodes’, i.e. standing waves. The resonant cavity of these modes has its outer boundary in the solar atmosphere but the location of the inner boundary depends on the characteristics of each individual mode: its frequency and angular degree. As a result, different modes map the Sun to different depths and that allows to determine the physical properties of the interior structure as a function of depth, all the way down to the core (see Christensen-Dalsgaard 2002 for a comprehensive review on helioseismology). Several very important physical characteristics of the Sun can be derived: the radial profile of the sound speed and the density in the interior, the location of the base of the convective envelope \(R_{\text{CZ}}\), and the helium abundance of the envelope \(Y_S\).

The main results for the SSMs and the results from helioseismology are presented in Table 1. SSMs results are taken from Serenelli et al (2011) but, with small differences, they are common to SSM calculations from other authors (Montalban et al, 2004; Delahaye and Pinsonneault, 2006; Guzik and Mussack, 2010). \((\delta c/c)\) and \((\delta \rho/\rho)\) are the average root-mean-square deviations of the relative difference between the model (SSM) and the solar (helioseismic) quantities. Note that the errors for the helioseismic \(R_{\text{CZ}}\) and \(Y_S\) are extremely small. Figure 3 also shows the relative differences of the sound speed profile and of the mean density profile for both models.

|      | \((Z/X)_\odot\) | \(Z_\odot\) | \(Y_S\) | \(R_{\text{CZ}}/R_\odot\) | \((\delta c/c)\) | \((\delta \rho/\rho)\) | \(Z_{\text{ini}}\) | \(Y_{\text{ini}}\) |
|------|-----------------|-------------|--------|--------------------------|----------------|------------------|-------------|-------------|
| GS98 | 0.0229          | 0.0170      | 0.243  | 0.712                    | 0.0009         | 0.011            | 0.0187      | 0.272       |
| AGSS09 | 0.0178        | 0.0134      | 0.232  | 0.723                    | 0.0037         | 0.040            | 0.0149      | 0.262       |
| Solar | 0.0229/0.0178\(^a\) | 0.0168/0.0131\(^b\) | 0.2485\(^b\) | 0.713\(^b\) | 0(def)       | 0(def)       | —           | —           |

\(^a\)Refers to GS98 and AGSS09 SSCs, respectively; \(^b\)Basu & Antia (2004).

First of all, the GS98 SSM shows a very good agreement with the helioseismic inferences for \(Y_S\) and \(R_{\text{CZ}}\) (Table 1). The results obtained with the AGSS09 com-
position are in stark contrast with the latter. Furthermore, the choice of \( (Z/X)_\odot \) has a direct impact on the calibration of solar models, as seen from the differences in the initial mass fractions of helium and of metals, \( Y_{ini} \) and \( Z_{ini} \). The changes in \( Z_{ini} \) almost directly reflect the differences in \( (Z/X)_\odot \). Metals are the dominant contributors to the radiative opacity \( \kappa \) in the solar interior, which in turn determines the temperature gradient in the radiative region (white area, Figure 3). A lower metallicity leads to a smaller temperature gradient in this region and, by virtue of the Schwarzschild convection criterion, a shallower depth of the convective envelope \( R_{CZ} \) (Table 1). In the convective envelope (shaded area, Figure 3), where the temperature gradient does not depend on \( \kappa \), but only on the equation of state, both the GS98 and AGSS09 models agree well with the seismic data, \( \delta c/c \sim 0 \). However, in the radiative zone, where \( \kappa \) affects the solar structure, differences in the sound speed profiles show up.

The density values at different solar radii are strongly correlated because the density profile is constrained by the total mass of the Sun. The large differences seen in the convective envelope are anticorrelated with changes in the deeper interior where density is larger (region between 0.15 and 0.4 \( R_\odot \)). A smaller difference between the Sun and the model in a deep region leads to a large, compensating, difference in outer layers. Finally, the surface He abundance \( Y_S \) is also affected by the metallicity of the models. The reason is that SSMs are constrained by \( L_\odot \). The AGSS09 SSM, with its shallower temperature gradient, has a lower core temperature, leading to a slower rate of nuclear energy generation. But, because nuclear reactions are the only relevant energy source in the Sun, the decrease in temperature has to be compensated by another means so that the fusion of hydrogen still produces energy at the same rate. This is achieved in the AGSS09 SSM by the increase of hydrogen abundance or, equivalently, by the decrease of helium abundance. The lower \( Y_S \) in the AGSS09 SSM also conflicts with helioseismology.

![Fig. 3 Profiles of the relative difference in sound speed (left panel) and density (right panel) between the Sun and two SSMs. Models are labeled according to the SSC that was adopted in the calibration of the SSM. The grey area denotes the solar convective envelope. The error bars reflect the uncertainties from the helioseismic data.](image-url)
In summary, all manifestations of the solar abundance problem can be traced back to the lower radiative opacity in the interior that is a consequence of lower metal abundances in the AGSS09 dataset. Oxygen, neon, and iron are very important in this respect, as they contribute to $\kappa$ in the region around $R_{\text{CZ}}$, where their fractional contribution to $\kappa$ is about 25%, 15%, and 10% respectively (Basu and Antia 2008, Fig. 12, Villante et al. 2013, Fig. 10). Other abundant refractories like magnesium and silicon are less relevant (opacity contribution of < 4%).

5 Possible solutions

The implications of the solar abundance problem in the astrophysical context are, in fact, very large. The problem is that stellar evolution models, when applied to the Sun, produce results which are incompatible with observations (helioseismology), if these models adopt the solar chemical composition obtained by the state-of-the-art spectroscopic models. However, both stellar evolution and stellar atmosphere theory are general. All models based on these theories are calibrated on the Sun and they are routinely used to interpret any other star or stellar population. Therefore, our understanding of stars and galaxies in general is nowhere better than our current knowledge of the Sun.

What are the possible ways to reconcile the spectroscopic measurements with the solar interior models? Here we review the key possibilities that can be or have already been considered.

- Model atmospheres. It is difficult to assess and quantify uncertainties in stellar atmosphere models. Possible sources of uncertainties are: numerics (e.g., numerical methods, resolution of simulations), accuracy of the input physics (e.g., the equation of state), approximate treatment of physical processes (e.g., simplified radiative transfer). The models can be tested by comparison with observations and by comparing models from different groups. For example, Beeck et al. (2012) showed that the average stratifications of different 3D hydrodynamical model atmospheres agree well with each other. The 3D hydro models are also much more successful than classical 1D static models in reproducing a wealth of observational information, including the line shapes, center-to-limb variation, brightness contrast (Asplund et al., 2009). However, there are implicit assumptions, which remain to be tested.

- The spectroscopic analysis. This is also a highly non-trivial problem: the uncertainties in the atomic data, line broadening, the continuum placement, selection of lines, directly impact the calculated abundances.

NLTE radiative transfer and 3D hydrodynamical model atmospheres are clearly setting a new basis for spectroscopy, however, it is still very difficult to combine them in one framework. 3D NLTE calculations can be performed on realistic timescales only for the simplest atoms, such as Li and O. More complex atoms can be only treated in a very approximated form (see the lecture on 3D NLTE mod-
Future developments related to 3D and NLTE may eventually lead to revisions of abundances. However, it is unclear whether the abundances will increase back to the level needed for the solar abundance problem to disappear.

From the perspective of solar models, a number of possibilities to solve the solar abundance crisis have also been considered.

- The accuracy of radiative opacities for stellar interior models could be questioned. Recently, Villante et al. (2013) have shown that current helioseismic and solar neutrino data constrain well the opacity profile of the Sun, independently of the reference solar models and abundances. But in models, the opacity profile results from a combination of atomic opacity calculations and a given solar abundance. The effects of a decreasing metallicity can be mimicked by an increase in opacity. In fact, it has been shown that an increase in the radiative opacities in the range of 15 to 20% at the base of the convective zone, smoothly decreasing to 3 to 4% in the solar core, would suffice to reconcile AGSS09 composition with the helioseismic results (Bahcall et al. 2004, Christensen-Dalsgaard et al. 2009, Villante 2010). This solution is very attractive, because radiative opacities are the result of very sophisticated (and, unfortunately, incomplete) theoretical calculations of interaction of atoms and radiation in extremely dense physical environments. There is basically no experimental data to support these calculations. In contrast to the atmosphere models, presently the best that can be done to gain confidence in such calculations is to compare the results from different groups. Three opacity sets have been compared by Blancard et al. (2012), who found much more modest differences amounting to just 3% at the base of the convective zone, much smaller than needed. A possible way out of problem imposed by the degeneracy between opacity and composition might be offered by solar neutrino measurements. In particular, the neutrino fluxes originating in the CN-cycle, depend linearly with the C and N abundance in the solar core. But C and N do not affect the solar opacity, so if the CN neutrino fluxes are measured (e.g. by the Borexino Experiment or SNO+) the solar core C and N abundance can be determined independently of the solar opacity (Serenelli et al. 2013).

- Enhanced gravitational settling in the Sun. In the conditions of the solar interior, chemical elements suffer a slow segregation process due to the combined effect of the gravitational and electric field. This process, generally known as gravitational settling affects differently elements (actually, isotopes) based on their nuclear charge to mass ratio \( Z_{\text{nuc}}/A_{\text{nuc}} \). However, in the Sun, settling rates are quite similar for all metals and helium (Turcotte et al. 1998). SSM calculations show that the gravitational settling has led to the \( \sim 10−12\% \) decrease of the solar surface metallicity and helium abundance with respect to the primordial values (compare the initial and surface values in Table 1). Increasing the efficiency of settling, one could construct a solar model with the initial composition comparable to GS98 and a low metallicity in the convective envelope, compatible with AGSS09. However, such a model would predict a too low \( Y_S \), worsening the agreement with helioseismology, as discussed, for example, in Guzik and Musack (2010). They do not offer a satisfactory solution. In order to improve the agreement with helioseismology, an ad-hoc modification of settling rates should
be applied such that metals sink faster, but helium slower. Such an ad-hoc solution is not sufficiently justified and should be avoided.

- Solar models with the accretion of metal-poor material. Young stars interact and accrete material from their proto-planetary disk (see Williams & Cieza 2011 for a comprehensive review). In the inner solar system, planets are clearly metal-rich compared to the Sun. This is true for Jupiter as well. The process of planet formation is likely to alter the average composition of the proto-planetary disk. If a part of the disk, partially depleted in metals, is accreted onto the young Sun, the solar interior will have a higher metal content than the envelope. Such models have been considered by Castro et al (2007), Guzik and Mussack (2010) and in more detail by Serenelli et al (2011). Unfortunately, only partial solutions to the problem have been found. One can fine-tune the mass and chemical composition of the accreted material so that $R_{CZ}$ is close to the seismic value but, at the expense of $Y_S$. Under some conditions, $Y_S$ agreement can be improved, but at the expense of degrading $R_{CZ}$.

- Enhanced solar neon abundance. As discussed before, the determination of the solar neon abundance is indirect. The coronal Ne/O ratio can be measured and, by assuming the same ratio is present in the solar photosphere, the photospheric neon abundance can be determined. Keep in mind this is a strong assumption. How different elements are transported from stellar photospheres to corona is far from being well understood, and this also depends strongly on other issues such as the stellar activity (Robrade et al, 2008). As a consequence, the Ne/O coronal ratio is not constant in time (neither for the Sun nor for other stars).

Ne is an interesting element for SSMs because it contributes to the radiative opacity at the base of the convective envelope. Bahcall et al (2005) and Antia and Basu (2005) constructed solar models with arbitrarily enhanced neon abundance and found that an increase of a factor of about 2 would be necessary to solve the solar abundance problem. Drake and Testa (2005) found, based on X-ray spectroscopy of nearby active stars, that neon abundances were a factor of 2.5 larger with respect to oxygen in those stars with respect to the measured solar value and concluded that the solar value was underestimated. However, it is now thought that the large Ne/O values observed in the coronae of very active stars are linked to the high activity levels and do not reflect the photospheric Ne/O ratio (Robrade et al, 2008). Thus it does not seem likely that the solar Ne/O could be large enough to solve the solar abundance problem.

- Non standard solar models (non-SSM). Undoubtedly the SSM, with all its intricacies, is a simplified picture of the actual Sun and its evolution. Physical processes such as rotation or internal magnetic fields are not accounted for in the SSM, and effects such as the transport of angular momentum in the solar interior might have measurable consequences in the solar structure. Modelling these processes is an inherently multi-dimensional problem and such models (to study not just the present-day structure, but the evolution of the course of 4.57 Gyr) have not yet been constructed. The models are also not feasible with present-day computational capabilities. Simplified prescriptions have been implemented into 1D solar models. These parametrized models present a number of problems:
The solar abundance problem is that stellar evolution models, when applied to the Sun, produce results which are incompatible with observations (helioseismology), if these models adopt the solar chemical composition obtained by the state-of-the-art spectroscopic models. This should be taken as a manifestation of our incomplete understanding of the theories of stellar atmospheres and/or of stellar structure and evolution.

As discussed in these notes, at present there is no clear solution to the problem. A plausible solution is that radiative opacity calculations for stellar interiors are off by 3 to 20% or so. While only 3% is the maximum discrepancy that has been found among different opacity calculations, changes of up to 20% might not be unreasonable. For example, the OPAL opacities [Rogers and Iglesias, 1992], that first saw the light back in 1992, implied changes of up to a factor of 3 with respect to previously available calculations.

Continuous progress in different subfields might lead to a revision of the solar abundances and to changes in the solar interior models. Various options remain to be studied in greater detail and with more powerful computers, including radiative transfer models in the solar atmosphere, opacity calculations and laboratory experiments, inclusion of more realistic physics in the stellar interior modelling. It is up to you, new generation of scientists, to find the ultimate solution to the problem.
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