New Solar metallicity measurements

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In the past years, a systematic downward revision of the metallicity of the Sun has led to the "Solar composition problem", namely the disagreement between predictions of Standard Solar Models and inferences from helioseismology. Recent solar wind measurements of the abundance of metals in the Sun, however, favour once more a *high-Z* Sun. Because of possible residual fractionation, the derived value of the metallicity $Z_\odot = 0.0196$ actually represents a lower limit on the true metallicity of Sun. In this talk I discuss how these new measurements could bring us one step closer to solving the Solar composition problem.

1 The Standard Solar Model and helioseismology

Our Sun is a laboratory wherein we can test our understanding of the most disparate fields in physics and astronomy. Mathematically speaking, the Sun is described by the Standard Solar Model (SSM hereafter). In the SSM, our star is treated as a spherically symmetric quasi-static ball of gas within different states of ionisation, described by five basic quantities: matter density $\rho(r)$, pressure $P(r)$, temperature $T(r)$, luminosity $l(r)$, and mass $m(r)$. These quantities obey the four *stellar structure equations*:

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho \,, \tag{1}$$

$$\frac{\partial P}{\partial r} = -\frac{GM_r}{r^2}\rho \,, \tag{2}$$

$$\frac{\partial l}{\partial r} = 4\pi r^2 \epsilon(\rho, T, X_i) \,, \tag{3}$$

$$\frac{\partial T}{\partial r} = -\frac{GmT\rho}{r^2 P}\nabla \,, \tag{4}$$

where ϵ is the energy generation coefficient and the functional form of ∇ depends on the type of energy transport (radiative or convective). In the order above, the four equations describe respectively mass continuity, hydrostatic equilibrium, energy generation, and energy transport. To close the system, we furthermore need the equation of state (EoS), which relates the pressure to the mass density: $P = P(\rho, T, X_i)$, where X_i denotes the abundance of the ith chemical element present in the Sun. The photospheric composition of the Sun is currently, in mass, $\sim 75\%$ Hydrogen and $\sim 24\%$ Helium, with the remaining $\lesssim 2\%$ consisting of heavier elements, known as *metals*.

The above four equations are used as input, and a key input in particular is the detailed composition of the Sun. Furthermore, boundary conditions are required to constrain the problem: namely, the luminosity $l_\odot$, radius $R_\odot$, age $t_\odot$ and composition of the Sun, which are all well known.[a] A one solar mass stellar model at age $t = 0$ is then evolved numerically up to the current age of the Sun, $t = t_\odot$. Two free parameters can then be adjusted in order to meet the required boundary conditions: the initial Helium abundance $Y_{\rm ini}$ and the mixing length parameter (which is used to model convection).

The outputs of the SSM can be compared with inferences from helioseismology (the study of the propagation of acoustic p-waves), which represent a key test of our understanding of the Sun. There are four main observables one can consider: the sound speed $u(r)$, the surface Helium abundance Y_s, the convective zone boundary (CZB) R_b (where the transition between radiative and convective energy transport occurs), and the Solar neutrino fluxes (Φ_{pp}, Φ_{Be}, Φ_B, $\Phi_{\rm CNO}$).

2 The Solar composition problem

The metallicity of the Sun, $Z_\odot$, i.e. the fraction of Solar mass residing in elements heavier than Helium, is not only a key input to the SSM, but also a fundamental diagnostic of the evolutionary history of our star. Therefore, it is of paramount importance to determine this quantity accurately. Up to 1998, the state-of-the-art was given by the measurements of Anders & Grevesse (AG89)[1] and Grevesse & Sauval (GS98)[2], which yielded metallicities of $Z_\odot = 0.0202$ and $Z_\odot = 0.0170$ respectively. Moreover, heavy element mixtures provided by AG89 and GS98 also yielded good agreement with inferences from helioseismology.

However, following 1998, a systematic downward revision of the Solar metallicity has degraded the agreement between SSM and helioseismology. In particular, the sets of abundances known as AGS05[3] and AGSS09[4] report a metallicity of $Z_\odot = 0.0122$ and $Z_\odot = 0.0133$ respectively. These revisions have completely spoilt the previous agreement between SSM and helioseismology, leading to what is now known as the "Solar composition problem" (see e.g. [5] for a review). The sound speed $u(r)$ is inferred to be $\sim 1\%$ lower than predicted at the bottom of the convective envelope (a discrepancy of about 10σ), whereas Y_s and R_b are approximately 7% lower and 1.5% higher than those deduced from helioseismology, which amount to discrepancies of approximately 6σ and 15σ respectively. Various solution to the problem have been proposed, including exotic energy transport due to captured dark matter (see e.g. [6]), but none appears compelling.

3 In situ solar wind measurements of metallicity

All of the heavy element abundances determinations listed above relied on the techniques of photospheric spectroscopy. Despite its broad use within the Solar physics community, the interpretation of such measurements is actually quite nontrivial. Sophisticated inversion techniques taking into account departures from local thermodynamic equilibrium, 3D structures, and radiative transport, and an accurate knowledge of atomic transition probabilities is required. Photospheric spectroscopy could be plagued by several systematics (e.g. line blending), but it is not clear up to what extent.

There is, nonetheless, a more direct way of measuring the metallicity of the Sun, through *in situ* collection of solar samples. Two current-time sampling techniques exist, which rely on the collection of energetic particles or solar wind samples. We will focus on the latter, i.e. *in situ* solar wind measurements. These types of measurements do not suffer from the difficulties discussed above for spectroscopy. Nonetheless, difficulties and possible systematics exist here too. For instance, fractionation processes can enhance or deplete the amount of certain ions depending on their ionization and transport histories. Collisional coupling and first ionization potential fractionation are among the most important processes at work in this direction.

Is it possible to turn this possible weakness into a strength? Fortunately the answer is yes! It has been extensively shown and recently definitely confirmed that fractionation processes

[a] With the likely exception of the composition of the Sun being uncertain, which is the topic of this talk.

are significantly reduced, if not completely absent, in solar wind emerging from Polar Coronal Holes (that is, polar regions near solar minimum) [7]. It is possible, and indeed likely, that an important systematic is still at play, namely that we cannot completely exclude a small amount of residual fractionation in these regions. However, it has been shown that any unaccounted residual fractionation would go in the direction of reducing the measured metallicity, and thus the derived metallicity $Z_\odot$ is actually a *lower limit* on the photospheric metallicity. In view of the recent downward revisions which have led to the "Solar composition problem", such a measurement can provide a very important cross-check to the values of metallicity obtained through spectroscopy.

4 New measurements: vSZ16

Very recently, Rüdi von Steiger and Thomas Zurbuchen have analysed data from the "Solar Wind Ion Composition Spectrometer" provided by the *Ulysses* mission [8] to reassess the abundance of heavy elements in the Sun [9]. Below we report such values (which we refer to as vSZ16), comparing them to the previous state-of-the-art given by AGSS09. The abundances are reported using the customary logarithmic abundance scale where the abundance of Hydrogen is set to be $\epsilon_H = 12.00$. The fractional variation in abundance for a given element i between vSZ16 and AGSS09 is thus given by $\delta Z_i = 10^{(\epsilon_{\rm vSZ16},i-\epsilon_{\rm AGSS09},i)} - 1$. The total metallicity of the Sun is given by $Z_\odot = 0.0196 \pm 0.0014$.

Table 1: Elemental abundances in the vSZ16 and AGSS09 catalogues, and fractional variation between the two.

Element	$\epsilon_{\rm AGSS09}$	$\epsilon_{\rm vSZ16}$	δZ_i
C	8.43 ± 0.05	8.65 ± 0.08	0.66 ± 0.15
N	7.83 ± 0.05	7.97 ± 0.08	0.38 ± 0.08
O	8.69 ± 0.07	8.82 ± 0.11	0.35 ± 0.10
Ne	7.93 ± 0.10	7.79 ± 0.08	-0.28 ± 0.08
Mg	7.60 ± 0.04	7.85 ± 0.08	0.78 ± 0.16
Si	7.51 ± 0.03	7.82 ± 0.08	1.04 ± 0.21
S	7.12 ± 0.03	7.56 ± 0.08	1.75 ± 0.35
Fe	7.50 ± 0.04	7.73 ± 0.08	0.70 ± 0.15

5 Implications for the Solar composition problem

The changes in elemental abundances listed here directly affect the helioseismological observables previously described, which in turn has implications for the Solar composition problem. This occurs because varying the abundance of metals directly affects the radiative opacity of the Sun. This quantity describes the coupling between radiation and matter in the hot dense interior of the Sun. In [10], we worked out the response of three helioseismological observables to the change in metallicity: $u(r)$, Y_s and R_b. We did so by making use of the Linear Solar Model (LSM), an alternative to running fully-fledged nonlinear solar codes [11].

We find that broadly the variations of the helioseismological observables go in the right direction to address the Solar composition problem. In particular, the disagreement for Y_s is brought down to $\sim 1.3\sigma$, for R_b down to $\sim 0.6\sigma$, and for $u(r)$ down to $\sim 1.4\sigma$ (the sound speed profile is visually very much improved, see Figure 7 of [10]). As a note of caution, the large changes in the abundances of refractory elements (Mg, Si, S, Fe) leads to a large change in Y_s. In fact, its central value would appear to be in some tension with the required value (i.e. discrepant but in the opposite direction compared to AGSS09). However, the error bars at play are quite large (uncertainties from solar wind measurements are typically a factor of 2 or more larger than those from photospheric spectroscopy) and for this the agreement with helioseismology is improved.

Ultimately, neutrino fluxes would be necessary to discriminate between different abundances sets, or between proposed modifications to other input parameters for a fixed abundance set (e.g. radiative opacity). An important diagnostic in this sense are the yet to be detected CNO neutrinos. The neutrino fluxes are highly sensitive to the metal composition of the Sun, in particular to that of the refractory elements. In [10], we estimated a $\sim 50\%$ increase in the CNO neutrino fluxes with respect to baseline predictions, although a later study suggests that these numbers might have been underestimated [12], to the extent that current neutrino fluxes measurements or upper limits could pose a challenge to the vSZ16 abundances. Detailed studies are currently underway to resolve this controversy.

6 Conclusion

A step towards solving the Solar composition problem might be the realization that spectroscopy might be underestimating the true metallicity of the Sun. Indeed, this is what recent solar wind measurements suggest. The recent determinations by von Steiger & Zurbuchen provide a lower limit (due to possible residual fractionation) on the metallicity of the Sun of $Z_{\odot} = 0.0196$, thus preferring a *high-Z* Sun. In this talk I have discussed how these new measurements improve the agreement of three helioseismological observables with respect to previous predictions with *low-Z* abundances: sound speed, surface Helium abundance, and convective zone boundary. Ultimately, more precise measurements of solar neutrino fluxes should be able to pin down which is the correct set of abundances.

Before we can claim that the Solar composition problem has been truly solved, more accurate analyses of solar wind composition would be required to reduce the error bars at play, in order to check whether the improved agreement we determined still holds. But perhaps we are already moving towards a solution?

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