Are recent solar heavy element abundances consistent with helioseismology?

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Abstract. During the last decade the abundances of heavy elements in the Sun have been revised downwards leading to serious discrepancy between solar models constructed using these abundances and the available seismic data. Much of these downward revision of abundances of Oxygen and other light elements was attributed to use of improved 3D solar atmospheric models. Recently, independent 3D models have been used to calculate solar abundances of these elements and calculated values are higher than the earlier estimates also obtained using 3D atmospheric models. In this work we investigate if these revised abundances are consistent with seismic data. We also investigate whether an increase in Neon abundance can help in resolving the discrepancy.

1. Introduction

During the last decade solar abundances of oxygen and other heavy elements have been revised significantly. For example, Grevesse & Sauval (1998, henceforth GS98) determined oxygen abundance to be $8.83 \pm 0.06$ dex, which was revised to $8.66 \pm 0.05$ by Asplund et al. (2005, henceforth AGS05) leading to serious discrepancy between solar models constructed using these revised abundances and the seismically inferred solar structure. Much of the differences in structure can be attributed to a mismatch between the position of the convention-zone base in these models compared to that in the Sun. Additionally, models constructed with the AGS05 abundances have a lower helium abundance in the convection zone compared with the seismic estimates of the convection-zone helium abundance of the Sun. The main cause of the revision in solar abundances was attributed to the use of improved 3D models of solar atmosphere in place of 1D models used until then. The main effect of the abundances on solar structure is through reduced opacities in the radiative interior. Considerable effort has been put into resolving this discrepancy both by modifying the solar models by changing some of the input physics like diffusion rates (see e.g., Basu & Antia 2008) as well as by independent determination of abundances. Modifications in solar models have not helped in resolving the discrepancy. Recently, Caffau et al. (2010, henceforth Caf10) have used independent 3D models to determine an oxygen abundance of $8.76 \pm 0.07$ which lies between the GS98 and AGS05 values, the Asplund group has revised their value to $8.69 \pm 0.05$ (Grevesse et al. 2010; henceforth GASS10), which is only slightly higher than their earlier, AGS05 value. While the GASS10 value is consistent with Caf10 within 1\sigma of uncertainties, the Caf10 value is consistent with the abundance of GS98.
Because of the revisions, the ratio of heavy element to hydrogen abundance, \( Z/X \) in the Sun has changed too: it was 0.023 for GS98, 0.0165 (AGS05) 0.0209 (Caf10) and 0.0181 (GASS10).

In this work we check whether models constructed with the latest estimates of abundances are consistent with helioseismic constraints. One of the solutions that had been proposed to alleviate the problem with the solar models constructed with AGS05 abundances was to increase the abundance of Neon since its photospheric abundance is uncertain (Antia & Basu 2005; Bahcall et al. 2005), we take a second look at this suggestion. We first look at density differences in solar envelope models with different \( Z/X \) to determine how much opacity modifications will be needed to get a model that agrees with seismic constraints, we then look at full, evolutionary solar models to look at discrepancies in all parts of the Sun and lastly, we try to see if the ionisation-zones can tell us something about which of the abundance estimates is closer to the Sun.

2. Results using envelope models

Following the approach of Antia & Basu (2005), we determine the convection-zone density differences between solar envelope models constructed with different abundances and the Sun. The envelope models were constructed with the seismically determined value of \( X = 0.739 \) (Basu & Antia 2004) and the position of the convection-zone base \( r_b = 0.7133R_\odot \) (Basu & Antia 1997, 2004). With these constraints, the sound-speed profile in the convection zone is very similar to the seismically determined solar profile, differences in structure caused by differences in abundance show up as density differences and the results are shown in Fig. 1. As expected from earlier results, the GS98 model agrees well with the Sun, the AGS05 model does not. What we find is that while the GASS10 model fares better than AGS05, it is still very discrepant. The convection-zone density in Caf10 models is 6% larger than that in the Sun. If neon abundance is increased by a factor of 2, the density profile in the corresponding envelope model matches the seismic profile in the convection zone. If the neon abundance is increased by a factor of \( \sqrt{2} \) the results are in between as shown in Fig. 1. It should be noted that all models were constructed with OPAL opacities (Iglesias & Rogers 1996) that were calculated for the respective mixtures. Since Caf10 do not give abundances of all required elements, abundances from Lodders et al. (2009) were used for the remaining elements.

By comparing differences in the density profile in the lower convection zone between the envelope models with the seismically derived solar density profile, it is possible to estimate the opacity change needed near the base of the convection zone to get an envelope model with a given density profile.
value of $Z/X$ and a given relative abundance to match the Sun. For this purpose we multiply OPAL opacities by a fixed factor and determine the factor needed to give density profile within 1.5% of the seismic value. This error includes systematic errors in inversions and solar models. The results for different mixtures are shown in Fig. 2. The actual value of $Z/X$ of the respective mixture is marked by the points with errorbars. It is clear that GS98 abundances are consistent with seismic constraint, while the AGS05 values are well outside the constraints. The errorbars for the recent abundances of Caf10 graze the allowed region.

3. Results with full models
Since solar envelope models do not satisfy constraints in the inner parts of the Sun very well, we have also used full, evolutionary solar models to study the effect of the abundances. The models with different abundances were constructed using YREC the Yale Rotating Evolutionary Code in its non-rotating configuration (Demarque et al. 2008). We compare the sound-speed and density profiles of these models with those of the Sun in Fig. 3. As can be seen from Fig. 3, the best agreement is obtained with GS98 abundances, but the model using Caf10 abundances is also fairly close. On the other hand, models with AGS05 and GASS10 abundances are significantly worse.

All these models have been constructed using the OPAL opacities for the respective mixtures. If we construct a model using the $Z/X$ value of Caf10 but using opacities calculated for the GS98 mixture, the resulting model is significantly worse. This can be seen in Fig. 4 as the model...
marked Caf10(GS). Thus it is clear that not only the total abundance, but the heavy element mixture also makes a significant difference and hence consistent opacities are a must. As in the case of envelope models, we have also constructed a neon-enhanced Caf10 model where the neon abundance is increased by a factor of $\sqrt{2}$. This model is also shown in Fig. 4 and as can be seem it is in better agreement with the Sun than even the GS98 model. All these models were constructed using OPAL opacities for the respective mixtures. Models with OP opacities (Badnell et al. 2005) will give slightly better agreement.

Unlike in envelope models, the convection-zone depth and envelope helium abundance in full models cannot be specified a priori. These are determined by the constraint that the models have the correct radius and luminosity at the current age of the Sun, and hence test how close to the Sun the models are and provide additional tests. Recently, Serenelli & Basu (2010) found that the initial abundance that the Sun was born with is $Y_{\text{ini}} = 0.273 \pm 0.006$ (random) $\pm 0.002$ (systematic). In models, $Y_{\text{ini}}$ is adjusted to satisfy the luminosity constraint, and thus $Y_{\text{ini}}$ is another test of the models. In Table 1, we compare the position of the convection-zone base, the current surface helium abundance and the initial helium abundance of the models shown in Figures 3 and 4 with the seismically derived quantities for the Sun. It can be seen that while models using GS98 or Caf10 abundances are in reasonable agreement with the seismic values, the model with AGS05 and GASS10 abundances have values which are significantly different from seismic constraints.

4. The ionisation zones
The effect of abundances on solar models is primarily due to change in opacities. Nevertheless, the change in Equation of State (EOS) also makes a small difference, which can be noticed in the convection zone, where stratification is determined by the EOS. In the ionisation zones of various elements the adiabatic index, $\Gamma_1$ is reduced below its ideal gas value of 5/3 and this can be measured by inverting oscillation frequencies. A similar technique has been used to determine the helium abundance in the solar convection zone (see Basu & Antia 2008 for a review). In addition to $\Gamma_1$ it is also possible to use the dimensionless sound speed gradient (Gough 1984),

$$W(r) = \frac{r^2 \frac{dc^2}{dr}}{Gm},$$  \tag{1}$$

where, $G$ is the gravitational constant and $m$ is the mass enclosed in a sphere of radius $r$. $W(r)$ has the ideal-gas value of $-2/3$ everywhere in the convection zone except at the ionisation
Table 1. The position of the base of the convection zone, $r_b$, and the helium abundance in the convection zone, $Y_{CZ}$, and the initial helium abundance, $Y_{ini}$, in solar models with different abundances.

| Abundances | $Z/X$ | $r_b/R_\odot$ | $Y_{CZ}$ | $Y_{ini}$ |
|------------|-------|---------------|----------|----------|
| Observed   |       | 0.7133 ± 0.0005 | 0.2485 ± 0.0035 | 0.273 ± 0.006(rand) ± 0.002(syst) |
| GS98       | 0.0230 | 0.7154 | 0.2464 | 0.2768 |
| AGS05      | 0.0165 | 0.7272 | 0.2296 | 0.2601 |
| Caf10      | 0.0209 | 0.7166 | 0.2425 | 0.2725 |
| GASS10     | 0.0181 | 0.7225 | 0.2363 | 0.2666 |
| Caf10+Ne*1.4 | 0.0219 | 0.7127 | 0.2460 | 0.2756 |
| Caf10(GS)  | 0.0209 | 0.7181 | 0.2395 | 0.2696 |

zones of different elements. The deviation from $-2/3$ caused by the HeII ionisation zone has been used to determine the solar helium abundance (e.g., Antia & Basu 1994). The ionisation zones of different heavy elements overlap making it almost impossible to separate out the effect of individual elements, However, the combined effect of all heavy elements is discernible in inversion results (Antia & Basu 2006). Figure 5, shows $W(r)$ for a few solar models with different abundances. Also shown are $W(r)$ values for the Sun as inferred from inversions of GONG and MDI data sets. We show solar results for all available data sets from both projects and the resulting lines combine to give bands which give an estimate of errors in the inversion results. Since the OPAL EOS is not available for different mixtures, we use the CEFF EOS (Christensen-Dalsgaard & Dæppen 1992) in these calculations. As expected, the GS98 model agrees quite well with the observations, while AGS05 does not. The Caf10 model is close to observations, though there are some differences. Increasing neon abundance helps in improving the agreement of the Caf10 model near the base of the convection zone, a neon increase also helps the AGS05 model. It is unfortunate that none of the more sophisticated EOSs are available with different mixtures. Since the detailed structure of $\Gamma_1$ and $W(r)$ depend on the EOS for a given set of abundances, availability of the the better EOSs for more mixture will allow a more reliable tests for models constructed with different abundances.

Figure 5. The dimensionless sound speed gradient, $W(r)$ in the convection zone in solar envelope models with various abundances is compared with that inferred from observed data from GONG and MDI. The model AGS05+Ne is with neon abundance increased by a factor of 2, while model Caf10+Ne is with neon abundance increased by a factor of $\sqrt{2}$. 
5. Summary
We have compared the structure of models constructed using different heavy-element abundances with the seismically determined structure of the Sun. In particular, we have compared the sound-speed and density profiles, the position of the convection-zone base, the current and initial helium abundances, as well as signatures of the ionisation zones.

We find that although the Caf10 abundances are lower than the GS98 abundances, the solar models constructed with Caf10 abundances show almost as good an agreement with the Sun as do models constructed with GS98 abundances. This is a result of the very different relative abundances of heavy elements in the two mixtures which results in a different opacity at the same temperature and density. In fact, a model constructed with the Caf10 value of $Z/X$ but with the relative abundances of GS98 [the model we call Caf10(GS)] fares much worse. This shows that it is extremely important to use opacities calculated for the correct mixture before constructing a solar model. A marginal increase in neon abundance by a factor of $\sqrt{2}$ can improve the agreement still further. Models with abundances from AGS05 or GASS10 are not consistent with seismic constraints even if neon abundance is increased by a factor of 2.

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