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To cite this article: Sarbani Basu and H M Antia 2013 J. Phys.: Conf. Ser. 440 012017

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Revisiting the Issue of Solar Abundances

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Abstract. We revisit the issue of solar abundances and examine whether the updated abundances result in solar models that have structures that agree with the structure of the Sun as determined by helioseismology. We quantify the changes in opacity required to bring the models constructed with the newer solar abundances in agreement with the Sun.

1. Introduction

The solar heavy element abundance, both total and relative, is still an unsettled quantity. For a considerable period of time, solar heavy element abundances as determined by Grevesse & Sauval (1998; henceforth GS98) were used. Solar models constructed with these abundances, that yield Z/X = 0.023, matched the helioseismically determined structure of the Sun quite well (see e.g., Basu & Antia 2008 and references therein).

Following updated analysis techniques that included the use of 3D model atmosphere, the solar metallicity was revised downwards by Asplund et al. (2005; henceforth AGS05) to Z/X = 0.0165. These changes resulted in solar models that did not match the structure of the Sun (Basu & Antia 2008 and references therein). With further improvement in analysis, abundances were updated by Asplund et al. (2009; henceforth AGSS09) to Z/X = 0.018. These abundances were quickly adopted by some members of the stellar astrophysics community since the 3D model atmospheres were considered to be better than the 1D atmospheres used earlier. Additionally, the oxygen and carbon abundances derived from different lines were consistent with each other, and brought the solar abundance in line with some of the young stars in the solar neighbourhood. However, others in the stellar astrophysics community did not adopt these abundances because they could not be used to model the Sun properly; additionally they argued that the difference between solar abundances and those in the young nearby stars could be a result of the fact that the Sun was not born in what is the current solar neighbourhood and hence a difference in abundances is not surprising.

An independent calculation using a different 3D model atmosphere found Z/X = 0.0209(Caffau et al. 2010, 2011; henceforth CAF10). Another compilation by Lodders (2010; henceforth LOD10) resulted in Z/X = 0.019

We have constructed models with the different heavy element abundances and compared the results with the helioseismically determined structure of the Sun. We have relied on a mix of full solar models obtained by evolving the Sun from the zero-age main sequence, as well as envelope models of the Sun. Envelope models of the Sun have the advantage that they can be constructed with a specified position of the convection-zone (CZ) base and a specified helium abundance.



Figure 1. The sound-speed and density differences between the Sun and standard solar models constructed with different heavy-element abundances. The differences are shown by the lines and the ticks show 1σ errorbars. For the sake of clarity, errorbars are shown only for one result.

These envelope models were used to estimate the extent by which current opacities need to be changed to make models constructed with different metallicities yield the correct convection zone depth.

2. Results

In Fig. 1 we show the sound-speed and density differences between the Sun and solar models constructed with the different heavy element abundances mentioned above. These models were constructed with the Yale Stellar Evolution Code, YREC (Demarque et al. 2008) with OPAL equation of state (Rogers & Nayfonov 2002) and OPAL opacities (Iglesias & Rogers 1996) that were supplemented by low-temperature opacities of Ferguson et al. (2005). Nuclear reaction rates from Adelberger (1998) were used, except for the $^{14}N(p,\gamma)^{15}O$ reaction for which the rates of Formicola et al. (2004) were used. Note from the figure that the lower-metallicity models do not match the Sun very well. The GS98 and CAF10 models show a similar degree of agreement with the Sun despite the fact that the CAF10 abundance is lower, this is because the heavy element mixture of CAF10 is such that the opacity of the CAF10 model is similar to that of the GS98 model. Table 1 lists main properties of models. Note that the lower-abundance models have shallower convection zones compared with the Sun. They also have lower helium abundances.

We have also constructed a model with the CAF10 abundances, but with the abundance of Ne increased by a factor of 1.4. An increased Ne abundance has been suggested as a means to get low-Z models in concordance with the Sun (Antia & Basu 2005; Bahcall et al. 2005). In Fig. 2 we compare the sound-speed and density differences between the Sun and the CAF10 model with the Ne abundance enhanced by a factor of 1.4. Note that increasing Ne by this factor improves the density profile of the model, but over-corrects the sound-speed profile. A smaller Ne enhancement, say by a factor of 1.2 will be better as far as the sound-speed profile is concerned.

In Fig. 3 we have compared the dimensionless sound-speed gradient of the models with that of the Sun. This quantity, W(r) defined as

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

Mixture	Z/X	$R_{ m CZ}$	$Y_{\rm CZ}$	Y_0
Helioseismic	-	0.713 ± 0.001^{a}	0.2485 ± 0.0034^{b}	0.273 ± 0.006^c
GS98	0.023	0.7139	0.2456	0.2755
AGS05	0.0165	0.7259	0.2286	0.2586
AGSS09	0.018	0.7205	0.2352	0.2650
CAF10	0.0209	0.7150	0.2415	0.2711
LOD10	0.019	0.7136	0.2412	0.2665
CAF10 LOD10	$0.0209 \\ 0.019$	$0.7150 \\ 0.7136$	$0.2415 \\ 0.2412$	$0.2711 \\ 0.2665$

Table 1. Properties of models with different heavy-element mixtures

 a Basu & Antia (1997); b Basu & Antia (2004); c Serenelli & Basu (2010)



Figure 2. The sound-speed and density differences between the Sun and standard solar models. One model was constructed with the CAF10 heavy element abundance and the other with the CAF10 et al. abundances, but with the Neon abundance increased by a factor of 1.4. Again the differences are shown by the lines and the ticks show 1σ errorbars.

is sensitive to the changes in the adiabatic index in ionization zones of various elements. Here we use solar envelope models that were constructed to have the observed solar CZ base and the observed helium abundance. The envelope models were used to ensure that differences in convection zone depth does not contribute to the difference in W(r). The solar value was obtained by inverting solar oscillation frequencies obtained by the GONG project (Hill et al. 1996) to determine the solar sound-speed and density profiles. As can be seen in the figure, the GS98 model shows the best agreement. The CAF10 model does not fare badly either, though enhancing Ne does not help as far as W(r) is concerned. The other, lower-Z, models are not in agreement with the Sun.

The envelope models are constructed with the observed CZ depth and helium abundance and hence the sound speed profile in these models agrees well with that in the Sun, but the density profile in general doesn't match (see Fig. 4). By modifying the opacity near the base of the convection zone, it is possible to make the density profiles of the models also agree with that of the Sun (Basu & Antia 2004). We used the models shown in Fig. 4 to determine the factor by which opacity must change for any given composition so that the density profiles match that of the Sun. We modified opacity by a constant factor till the density of the model matched the inverted density profile in the lower part of the CZ. There is an error of about 2% in estimating



Figure 3. The dimensionless sound-speed gradient of models constructed with different compositions compared with the solar value as determined using GONG data.

this factor. The factors are listed in Table 2. We find that GS98 and CAF10 models can be made to agree with the Sun with very little change in opacities. The AGS05 models need a large change (26.5%) while even the updated AGSS09 models need a fairly large change (16.5%).



Figure 4. The density difference between solar envelope models and the Sun. All models have the correct CZ base and helium abundance and hence the sound-speed profiles match that of the Sun by construction. The density profiles can be made to match the Sun's by modifying the opacity.

3. Summary

We find that solar models constructed with the GS98 abundances continue to have the best match with helioseismically determined solar properties. Of the more recent solar abundance determinations, the CAF10 abundances result in models that have reasonable properties in terms of the position of the convection-zone base, the convection-zone helium abundances and initial helium abundances. The sound-speed and density profiles are comparable to those of the GS98 models. We also find that enhancing the Neon abundance by a factor of 1.4 in the CAF10

Model	Opacity factor
GS98	1.005
AGS05	1.265
AGSS09	1.165
CAF10	1.060
LOD10	1.125
CAF10+1.4Ne	1.010

Table 2. Factor by which OPAL opacities have to be multiplied to bring density profiles of models shown in Fig. 4 to match that of the Sun

models improves the density profile and other properties, however, the sound-speed profile in the radiative zone is over-corrected. A smaller enhancement, by a factor of about 1.2 will probably work better as far as the sound-speed profile is concerned. GS98 and CAF10 models can be made to match solar properties better with very little change in opacities. The other abundances require a larger change. Increasing the amount of Neon in the CAF10 mixture decreases the need to modify opacities.

Acknowledgements

This work utilizes data obtained by the Global Oscillation Network Group (GONG) project managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofísico de Canarias, and Cerro Tololo Inter-American Observatory. This work was supported by NSF grant AST 1105930 to SB.

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