HELIOSEISMIC CONSTRAINTS ON PHOTOSPHERIC ABUNDANCES

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ABSTRACT

Recent analyses of solar photospheric abundances suggest that the oxygen abundance in the solar atmosphere needs to be revised downwards. We investigate if solar models constructed with lower oxygen and other heavy element abundances are consistent with helioseismic results. We find that revised abundances along with the current OPAL opacity tables are not consistent with seismic data. A significant upward revision of the opacity tables is required to make solar models with lower heavy element abundances that are consistent with helioseismology.

Key words: Sun: Abundances; Sun: Oscillations; Sun: Interior.

1. INTRODUCTION

Recent analyses of spectroscopic data using 3D atmospheric models have suggested that the solar abundance of oxygen and other abundant elements needs to be revised downwards (Allende Prieto, Lambert & Asplund 2001 , 2002; Asplund et al. 2004). Asplund et al. (2004) claim that the oxygen abundance should be reduced by a factor of about 1.48 from the earlier estimates of Grevesse & Sauval (1998). The abundances of C, N, Ne and Ar too are lowered, to [C/H] = 8.41, [N/H] = 7.80, [O/H] = 8.66, [Ne/H] = 7.84, [Ar/H] = 6.18, i.e., reduced by 0.11, 0.12, 0.17, 0.24 and 0.22 respectively, compared to earlier estimate of Grevesse & Sauval (1998). This causes the ratio of heavy elements to hydrogen abundances, Z/X to reduce from 0.0231 to 0.0174.

The reduction in Z will reduce the opacity which in turn will reduce the depth of the convection zone in solar models computed using the new abundances. This is already seen in the solar model of Bahcall & Pinsonneault (2004), which has CZ base at $r_b = 0.726R_\odot$, while the helioseismic estimate is $(0.713 \pm 0.001)R_\odot$ (Christensen-Dalsgaard, Gough & Thompson 1991; Basu & Antia 1997). Basu & Antia (2004) have shown that helioseismic estimate of the convection zone depth or the hydrogen abundance in the convection zone are not affected by revision in heavy element abundances. They also find that the revised abundances along with the current OPAL opacity tables (Iglesias & Rogers 1996) are not consistent with seismic constraints. In this work we try to estimate how much reduction in heavy element abundances is permitted by seismic constraints, assuming that OPAL opacities are correct. We also attempt to study the effect of varying abundance of each heavy element separately.

2. THE TECHNIQUE

In order to test whether the revised abundances are consistent with helioseismic constraints, we construct solar envelope models with the seismically determined hydrogen abundance i.e., $X = 0.739$ (Basu & Antia 1995, 2004) and the depth of the convection zone, i.e., $r_b = 0.7133R_\odot$ (Basu 1998; Basu & Antia 2004). The advantage of using envelope solar models as opposed to evolutionary models is that the envelope models can be constructed with a prescribed value of X and the depth of the convection zone. Furthermore, the structure inside the convection zone is independent of other uncertainties like those due to opacities, nuclear reaction rates or treatment of diffusion. We use the revised heavy element abundances in these models and compare the density and sound speed profiles in the resulting models with those inferred from seismic inversions. These models are constructed using OPAL opacities (Iglesias & Rogers 1996) with appropriately modified mixture of heavy elements. We use the OPAL equation of state (Rogers & Nayfonov 2002). We find that the sound speed in resulting solar envelope models is quite close to the seismically inverted profile, but there are significant difference in the density profile. To match the density profile in the convection zone, we need to adjust the opacity or the heavy element abundances.

In order to determine the seismically allowed range of opacity and heavy element abundance, we construct envelope models with a specified value of Z/X (but keep-

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Table 1. Properties of different heavy element mixtures analysed and the required modifications in opacity or Z/X to satisfy seismic constraints. The last column gives the partial derivative of the required opacity with respect to the abundance of each element considered.

Mixture	Z/X	$\kappa/\kappa_{\rm OPAL}$	Z/X (req.)	$\partial \log \kappa / \partial \log X_i$
GS98	0.0231	1.000 ± 0.025	0.0231 ± 0.0008	
Asp04	0.0174	1.200 ± 0.030	0.0218 ± 0.0007	
GS98-C	0.0222	1.010 ± 0.025	0.0226 ± 0.0008	-0.04
GS98-N	0.0228	1.010 ± 0.025	0.0231 ± 0.0008	-0.04
GS98-O	0.0196	1.102 ± 0.028	0.0222 ± 0.0007	-0.25
GS98-Ne	0.0220	1.060 ± 0.025	0.0236 ± 0.0008	-0.11
GS98-Mg	0.0228	1.012 ± 0.022	0.0232 ± 0.0007	-0.03
GS98-Si	0.0228	1.010 ± 0.025	0.0230 ± 0.0007	-0.03
GS98-S	0.0229	1.008 ± 0.022	0.0231 ± 0.0007	-0.02
GS98-Fe	0.0226	1.055 ± 0.025	0.0242 ± 0.0008	-0.16

ing the relative abundances of various heavy elements the same), and adjust the opacity near the base of the convection zone to get density profile that is within 1.5% (which is the estimated error in density; Basu & Antia 2004) of seismically inverted profile. Repeating this procedure for different values of Z/X gives the allowed region in Z/X–opacity plane. For the purpose of modifying the opacity we multiply the opacity calculated from OPAL opacity tables by a constant factor for temperatures exceeding 1.5×10^6 K. Since we are not particularly interested in the structure below the convection zone base, the temperature range over which the opacity is modified is irrelevant. Only the depth of the convection zone is affected by opacity modification. We determine these allowed regions for different mixtures of heavy elements, like, the abundances as determined by Grevesse & Sauval (1998) (referred to as GS98); the recently determined abundances by Asplund et al. (2004) (referred to as Asp04). To study the effect of variation in abundance of individual element we also consider mixtures where the logarithmic abundances of only one element is reduced as compared to that in GS98. We have considered mixtures with abundances of C, N, O, Ne, Mg, Si, S and Fe reduced by 0.11, 0.12, 0.17, 0.24, 0.15, 0.15, 0.15 and 0.15 respectively, and these mixtures are referred to as GS98-C, GS98-N, GS98-O, GS98-Ne, GS98-Mg, GS98-Si, GS98-S and GS98-Fe.

3. RESULTS

Fig. 1 shows the relative differences in sound speed and density between different envelope models and the Sun as inferred from helioseismic inversions. All these envelope models have the correct X and CZ depth and differ only in the heavy element abundances. From Fig. 1 it can be seen that for the mixtures GS98, GS98-C, GS98-N the density profile is within limits of systematic errors and

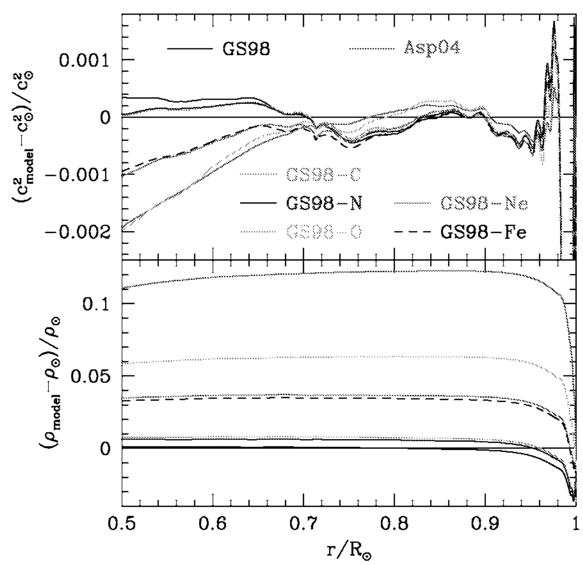

Figure 1. The relative difference in c^2 and ρ between envelope models constructed using different heavy element mixtures and the Sun. The results for mixtures GS98-Mg, GS98-Si and GS98-S are not shown as these are very close to those for GS98-C and GS98-N. It can be seen that the solar envelope model with GS98 composition agrees very well with the Sun. For other compositions the opacity needs to be increased by varying amounts (see Table 1) to get an envelope model which matches the inverted density profile.

in all these cases the sound speed below the CZ is also close to inverted profile. In other cases the sound speed deviates significantly below the CZ, which is due to low opacity.

Table 1, summarises the results for all mixtures that we have tried. The table lists the value of Z/X of the mixture as well as the Z/X required to get a seismically consistent solar envelope model. Similarly, the extent of opacity modification required to get seismically consistent solar envelope model using the Z/X value in the mixture is also given. Using the extent of opacity modification required for a given decrease in abundances we can calculate the partial derivative of required opacity with respect to the abundance of each element, $\partial \log \kappa / \partial \log X_i$. These values are also shown in Table 1.

It can be seen that the required opacity modifications are most sensitive to oxygen abundance. A decrease of just oxygen abundance by a factor of 1.48 suggested by Asplund et al. (2004) implies an increase of 10% in opacity to get a seismically consistent solar model. Thus any significant decrease in oxygen abundance is not consistent with seismic constraints and OPAL opacities, unless abundances of other elements are increased. In addition to oxygen, the required opacity modification is also somewhat sensitive to iron and neon abundances, while the abundances of other elements do not appear to be particularly relevant in this regard.

Fig. 2 shows the allowed regions for different mixtures compared with that for GS98. The allowed region shifts downwards when abundances of C or O are reduced, while it shifts upwards when abundances of Ne or Fe are reduced. Furthermore, GS98 mixture is consistent with seismic constraints as the point falls almost exactly at the centre of the allowed region. The results for variation in abundances of N, Mg, Si and S are not shown as in these cases there is very little difference in the allowed region as compared to that for GS98.

4. SUMMARY AND DISCUSSION

The revised abundances of heavy elements as calculated by Asplund et al. (2004) are not consistent with seismic constraint if the OPAL opacity tables are assumed to be correct. In order to satisfy the seismic constraint the opacities need to be increased by about 20% over the OPAL values, near the base of the convection zone. The required opacity modification is most sensitive to the oxygen abundance and a reduction by more than 12% in oxygen abundance is not favoured by seismic constraints.

Alternatively, a reduction in oxygen abundance may be compensated by increase in abundance of neon or iron. Thus a logarithmic reduction by 0.17 in Oxygen abundance can be compensated by an increase by 0.39 in neon abundance or an increase by 0.27 in iron abundance. Increase in abundance of other elements will not be very effective in this matter.

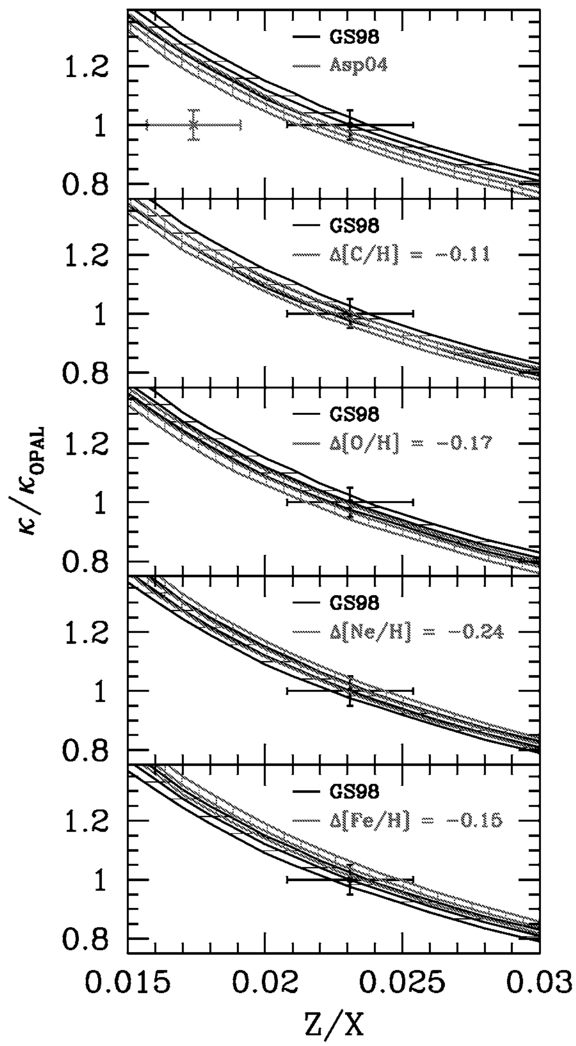

Figure 2. The allowed region in the Z/X–opacity plane for different heavy element mixtures is compared with that for GS98. The point with error bars mark the observed values for GS98 or Asp04. We can see that the mixture Asp04 is not consistent with helioseismic constraint if OPAL opacities are assumed to be correct. The point marking this mixture is well outside the allowed region in Z/X–opacity plane.

Recently, Seaton & Badnell (2004) have computed the revised opacities using data from OP project to find that opacities near the base of the convection zone increases by 6%. This increase in opacity will improve the agreement with seismic data, but is not sufficient to solve the problem. Even with this increased opacities the revised abundances would not be consistent with seismic constraint.

Bahcall et al. (2004a) have applied the constraint of seismically determined convection zone depth to standard solar models constructed using an evolutionary code to find that a 21% increase in opacity would be required near the base of the convection zone to get the correct convection zone depth. This agrees with our estimate even though it is based on completely different constraint using evolutionary standard solar models. Bahcall et al. (2004b) have tried different levels of opacity modification in evolutionary solar models and compared the resulting models with seismically determined sound speed and density profiles. They find that if the opacities for $2 \times 10^6 < T < 5 \times 10^6$ K are increased by 11% over the OPAL values, then it is possible to get a solar model that is in reasonable agreement with seismically determined sound speed and density profiles. However, this model has a slightly low helium abundance of 0.243 in the convection zone and the abundance profiles just below the base of the convection zone are also not in agreement with seismic results (Antia & Chitre 1998). These differences may explain the somewhat lower opacity modification required by Bahcall et al. (2004b) as compared to our work. If we construct solar envelope models with $Y = 0.243$ the value in model of Bahcall et al. (2004b), then the required opacity modification reduces to 16%. Some of the remaining difference could be due to differences in composition profile just below the base of the convection zone and other uncertainties in input physics.

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