

CONSTRAINING SOLAR ABUNDANCES USING HELIOSEISMOLOGY

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ABSTRACT

Recent analyses of solar photospheric abundances suggest that the oxygen abundance in the solar atmosphere needs to be revised downward. In this study, we investigate the consequence of this revision on helioseismic analyses of the depth of the solar convection zone and the helium abundance in the solar envelope and find no significant effect. We also find that the 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 oxygen abundance consistent with seismic observations.

Subject headings: Sun: abundances — Sun: interior — Sun: oscillations

1. INTRODUCTION

Recent analyses of spectroscopic data using modern atmospheric models have suggested that the solar abundance of oxygen and other abundant elements needs to be revised downward (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 are also reduced. The measured ratio of oxygen to hydrogen abundance, $[O/H] = 8.66 \pm 0.05$, is different from earlier estimates at approximately the 3σ level. As a result, the ratio (by mass) of heavy-element to hydrogen abundance, Z/X , reduces from 0.023 to 0.0171, which causes the heavy-element abundance in the solar envelope to reduce from $Z = 0.017$ to 0.0126. This will cause the opacity of solar material to decrease, in turn reducing the depth of the convection zone (CZ) in solar models. Bahcall & Pinsonneault (2004) have constructed a solar model using these revised abundances to find that the depth of the CZ is indeed reduced significantly as the CZ base is found to be at $r_b = 0.726 R_\odot$, which is inconsistent with the seismic estimate of $0.713 \pm 0.001 R_\odot$ (Basu & Antia 1997, hereafter BA97; Basu 1998). Asplund et al. (2004) have argued that their estimate refers to the abundances near the surface, while because of diffusion the abundance could be much higher in the radiative interior. While this may be true, it should be noted that since the CZ is mixed on a rather small timescale, the abundances at the surface and above the base of the CZ should be the same. It is these abundances, coupled with the corresponding opacity tables, that determine the depth of the CZ in a solar model. It may be possible to increase the hydrogen abundance in the CZ by increasing diffusion, thereby increasing the CZ depth, but in that case the helium content of the CZ may decrease below the seismically estimated value.

Since the position of the CZ base, r_b , has been determined very accurately through seismic analysis (Christensen-Dalsgaard, Gough, & Thompson 1991; BA97), it provides a constraint on the heavy-element abundance or the opacities. In fact, BA97 have shown that the then accepted solar abundances along with the OPAL opacities (Iglesias & Rogers 1996) are consistent with the helioseismic data. Thus, it is of interest to test how the reduction in abundance affects the conclusions. Before we do

this, we examine whether a decrease in the abundances affects the seismic estimate of the CZ depth or the estimate of the helium abundance, Y .

2. THE TECHNIQUE

To estimate the depth of the CZ, we use the technique described by BA97. This technique requires the construction of solar envelope models with prescribed values of r_b and abundances along with the known input physics. Solar envelope models are more useful than full solar models because envelope models can be constructed with specific values of the CZ depth and X (or Y) and because the CZ of the models do not depend on other uncertainties like opacities, treatment of diffusion, etc., in the radiative interior. Since both the hydrogen abundance, X , and the depth of the CZ can be determined seismically, we can construct an envelope model with the seismic estimates of r_b and X , and we can then compare the sound-speed and density profiles of the model with the seismically obtained solar sound-speed and density profiles to check for consistency.

The relative abundances of heavy elements are modified by the reduction in the abundances of oxygen and other elements, and we need to reconstruct the OPAL opacity tables for this new mixture of heavy elements (with $[O/H] = 8.66$) that we refer to as MIX1. In this mixture, the logarithmic abundances of C, N, O, Ne, and Ar are reduced by 0.17 as compared with those given by Grevesse & Sauval (1998), while abundances of other elements are unchanged. It is possible that the abundances of some of these elements change by a slightly different factor, but that does not affect our conclusions. We use the OPAL equation of state (EOS; Rogers & Nayfonov 2002). In principle, the EOS tables also need to be modified in view of the change in mixture of heavy elements. We have not done that because the EOS is not particularly sensitive to the detailed breakup of heavy-element abundances. Opacity, on the other hand, needs recalculation since in regions of fully ionized H and He, the heavy elements are the predominant contributors to opacity, although their contribution to the EOS is small. Below the CZ, we use the X -profile determined from seismic data using the method of Antia & Chitre (1998) with the new heavy-element abundances. We construct solar envelope models with CZ base positions, r_b , at 0.709, 0.711, 0.713, 0.715, and 0.717 R_\odot to serve as calibration models for determining

r_b . All these models have $Z/X = 0.0171$ and $X = 0.74$, which is close to the estimated value of hydrogen abundance. To determine the helium abundance, we use calibration models with $r_b = 0.713 R_\odot$ and $X = 0.70, 0.72, 0.74, 0.76,$ and 0.78 and use the technique described by Basu & Antia (1995).

We also examine the consistency of similar models that have a smaller reduction (by 0.03) in the logarithmic abundances ($[O/H] = 8.80$ for these models). We refer to this mixture of heavy-element abundances as MIX2. The changes in abundances result in $Z/X = 0.0218$ for these models. We also construct a few full solar models to check how they compare with seismic data.

For this work, we use the observed frequencies obtained by the Global Oscillations Network Group (GONG; Hill et al. 1996) between months 4–14 as well as frequencies obtained by the Michelson Doppler Imager (MDI) from the first 360 days of its observation (Schou et al. 1998).

3. RESULTS

Using the technique described by Basu & Antia (1995), we first estimate the helium abundance in the solar envelope using models with MIX1 abundance. We find $X = 0.7392 \pm 0.0034$ using GONG data and $X = 0.7385 \pm 0.0034$ using MDI data, or $Y = 0.2482$ and 0.2489 , respectively. The error bars include systematic errors, including those caused by uncertainties in the EOS (see Basu & Antia 1995 and Basu 1998 for details of uncertainties). These results are consistent with earlier estimates that used models with completely different heavy-element abundances (Däppen et al. 1991; Basu & Antia 1995; Richard et al. 1996; Basu 1998). We repeat the same exercise using MIX2 abundances to find $X = 0.7394$ (GONG) and 0.7386 (MDI). Thus, it appears that the inferred hydrogen abundance is insensitive to the heavy-element abundance of the calibration models, while the helium abundance changes slightly due to the change in Z .

To estimate the depth of the CZ, we use the technique described by BA97 that requires the decomposition of the frequency differences between the calibration models and the Sun in terms of two functions, $H_1(w)$ and $H_2(\nu)$, that depend on the sound-speed differences and surface structure, respectively (Christensen-Dalsgaard, Gough, & Thompson 1989). Here, ν is the frequency, and $w = \nu/(\ell + 1/2)$, where ℓ is the degree of the mode. The function $H_1(w)$ can be used to determine the position of the CZ base. Figure 1a shows the function $H_1(w)$ for calibration models using MIX1 abundances. From this, we can estimate the position of the base of the CZ to be $r_b = 0.7133 \pm 0.0005$ (GONG) and $0.7132 \pm 0.0005 R_\odot$ (MDI). The error bars here include systematic errors as determined by Basu (1998). These values are in good agreement with earlier estimates and are evidently not affected by the revision of abundances. The function $H_1(w)$ is a measure of the sound-speed differences between the models and the Sun, and Figure 1a shows that although the sound-speed differences are small in the CZ, there are significant systematic differences below the CZ. There is a small difference in the sound speed even within the CZ. This figure can be compared with Figure 10 of BA97 in order to compare $H_1(w)$ for higher Z models. The difference is most likely due to a reduction in opacities because of a reduced Z .

Although the seismic estimate of X or the CZ depth is not affected by the revision in abundances, solar models constructed using the current abundances may not have the correct depth of the CZ or the correct density profile in the CZ. To

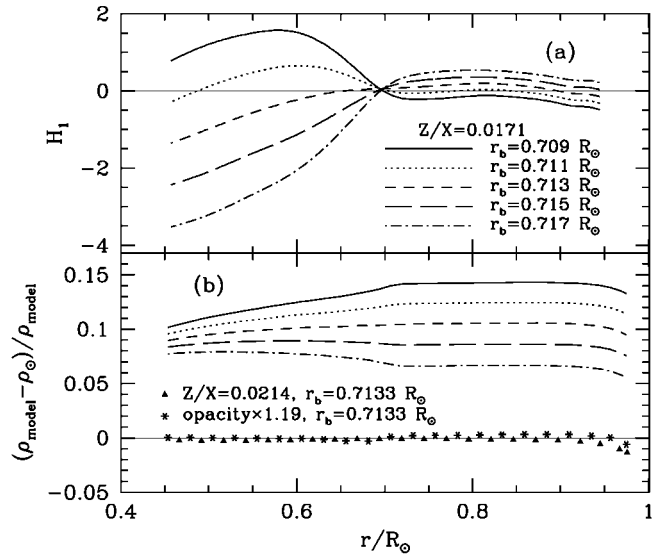


FIG. 1.—(a) Function $H_1(w)$ obtained from frequency differences between envelope models with MIX1 composition and the MDI frequencies plotted as a function of the lower turning point of the acoustic modes. (b) Relative difference in density between the solar envelope models with MIX1 composition and the Sun. The different line styles are the same as in (a). The panel also shows the density differences for two other models, one with $Z/X = 0.0214$ and the other with opacities increased by 19%.

check for this, we compare the density profiles in these envelope models with that obtained through seismic inversions; the results are shown in Figure 1b. It is clear that the differences are very large. The estimated error in density inversion in most of the CZ is about 0.005. In addition to this, there could be systematic errors due to uncertainties in X , r_b , and the EOS. An error of 0.0034 in X causes $\delta\rho/\rho \approx 0.012$, and an error of $0.0005 R_\odot$ in r_b yields $\delta\rho/\rho \approx 0.005$, while uncertainties in the EOS also give $\delta\rho/\rho \approx 0.005$. Assuming that these errors are uncorrelated, we get a total error of 0.015 in $\delta\rho/\rho$. Other uncertainties, like the treatment of convection, turbulence, and the atmosphere, etc., only affect the outermost layers and hence are not included. We have not included the effect of uncertainties in Z and opacities since we use seismic data to constrain these quantities by matching the density profile (BA97) in a model with the correct X and r_b . To get the correct density profile, we need to increase the opacity near the CZ base. We find that if the opacities are increased by 19%, then a MIX1 model with $r_b = 0.7133$ and $X = 0.739$ has the correct density profile (see Fig. 1b). Alternately, as in BA97, we can estimate the value of Z/X for the same relative abundances as MIX1 that will give the correct density assuming that the OPAL opacities are correct (i.e., we increase the opacity by increasing Z). We find that we need $Z/X = 0.0214$ to get the correct density profile (see Fig. 1b). We can also determine the range of opacities that give the density profile within acceptable limits for each value of Z/X , and Figure 3 below shows the result. Only the Z/X and opacity values in the hatched region are consistent with seismic constraints. The point with error bars shows the measured values assuming an uncertainty of 5% in the opacity at the CZ base.

We have repeated the analysis using models with MIX2 composition. The results are shown in Figure 2. The position of the base of the CZ estimated using GONG and MDI data is 0.7135 and $0.7134 R_\odot$, respectively. Thus once again the r_b estimate is not significantly affected by Z . From Figure 2b, it

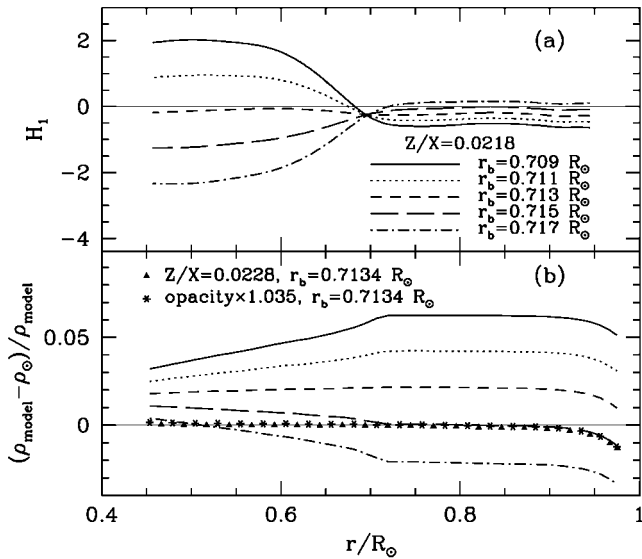


FIG. 2.—Same as Fig. 1, but for models with MIX2 composition. Panel *b* also shows the density differences for two other models, one with $Z/X = 0.0228$ and another with opacities increased by 3.5%.

is clear that now we have better agreement with solar density in the CZ. The function $H_1(w)$ is also essentially flat in the CZ. However, the model with the correct CZ depth does not have the correct density. In this case, increasing the opacity by 3.5% or increasing Z/X to 0.0228 makes it possible to get the correct density profile (see Fig. 2*b*). This value of Z/X is close to that found by Grevesse & Sauval (1998). The allowed region in the Z/X -opacity plane for the MIX2 mixture is also shown in Figure 3 by the vertically hatched region. The allowed region is just above that for the MIX1 mixture.

The above results were obtained with envelope models, and it could be argued that full solar models obtained from evolutionary calculations may give better results. To check this, we construct two full solar models, FULL1 and FULL2, with Z/X and a relative heavy-element abundance as in MIX1 and MIX2, respectively. In these models, as with other standard solar models, the surface X and the mixing-length parameter are adjusted to match the present-day solar radius and luminosity at an age of 4.6 Gyr. These models were constructed with the Yale Rotating Evolution Code in its nonrotating configuration (Guenther et al. 1992) and includes diffusion of helium and heavy elements as per Thoul, Bahcall, & Loeb (1994). The sound-speed and density differences between these models and the Sun are shown in Figure 4. The sound-speed differences are dominated by differences in the CZ depth. The density differences are also affected by the differences in composition. We can see that these models are worse than the envelope models. Models FULL1 and FULL2 have $r_b = 0.7320$ and $0.7217 R_\odot$ and surface X of 0.7505 and 0.7422, respectively. We can see that the model with the higher Z/X is closer to the Sun, and we can argue that the agreement improves with an even higher oxygen abundance and a higher overall Z/X , which is in fact the case (see, for example, model STD of Basu, Pinsonneault, & Bahcall 2000 or model 20 of Winnick et al. 2002). Unlike models with higher Z/X , these models do not reproduce the seismically determined value of X in the solar envelope either.

Since Asplund et al. (2004) have suggested that increased diffusion may yield seismically consistent solar models with the revised abundances, we have constructed two models, FULL1M

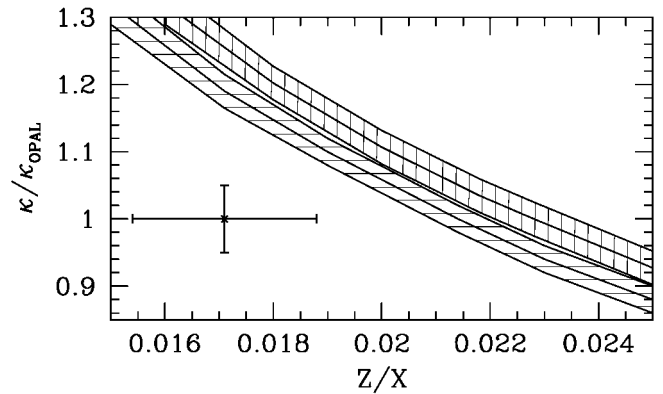


FIG. 3.—Hatched area: Allowed region in Z/X -opacity plane that is consistent with seismic constraints. The horizontal and vertical hatched regions show the region for MIX1 and MIX2 mixtures, respectively. The point with error bars shows the current values of the opacity and the abundances.

and FULL2M, with diffusion coefficients increased by a factor of 1.65, and these models are also shown in Figure 4. The positions of the CZ bases are 0.7233 and 0.7138 R_\odot for FULL1M and FULL2M, respectively, and the envelope X is 0.7626 and 0.7519, respectively. Thus, FULL2M has the observed value of r_b , but the value of X in the envelope is more than 3 σ beyond the seismically measured value. It should be noted that we have increased the diffusion coefficients without any physical justification. We have also constructed static, full models of the Sun using the seismically determined abundance profile (Antia & Chitre 1998), and these are labeled INV1 and INV2 for MIX1 and MIX2 abundances, respectively. These models have surface X of 0.7680 and 0.7447, respectively, and are also shown in Figure 4. Despite having the correct CZ depth, the X -values in these models are, respectively, about 9 σ and 2 σ away from the seismically inferred value. Thus, with the new abundances, we could not simultaneously get correct values of X and the CZ depth in a full solar model. Models FULL1M, FULL2M, INV1,

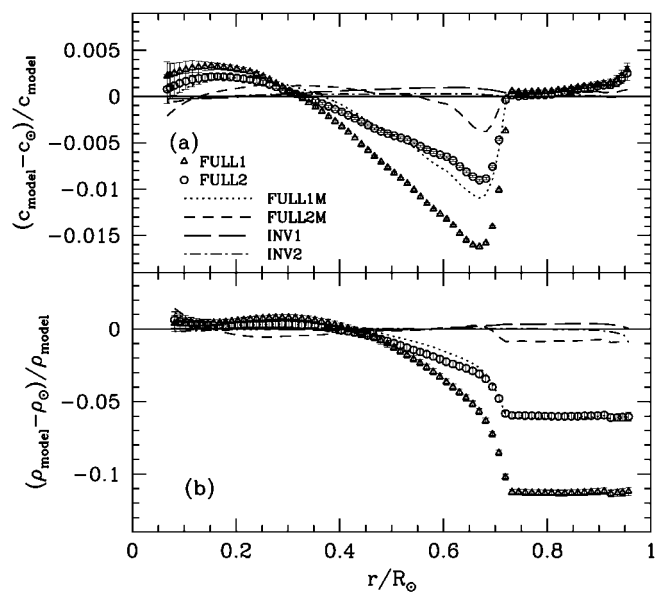


FIG. 4.—Relative sound-speed and density differences between different full solar models and the Sun. The different symbols represent the different standard solar models, while the different line styles represent the different nonstandard models. Models FULL1, FULL1M, and INV1 have an MIX1 composition, and models FULL2, FULL2M, and INV2 have an MIX2 composition.

and INV2 are not standard solar models because the X -profile has been calculated using nonstandard procedures.

4. CONCLUSIONS

We have investigated the effects that the revision of the abundance of oxygen and related elements in the solar atmosphere may have on seismic estimates of the solar helium abundance and the depth of the CZ. We find neither of these estimates to be sensitive to variations in Z . We find that solar envelope models that have reduced abundances of oxygen and related elements do not have the correct density profile in the CZ despite having the seismically determined CZ depth and surface X . The density difference is about 10%, which is more than 6 times the estimated uncertainties in density. In order to get a seismically consistent solar model, it is necessary to increase either the abundances of heavy elements or the computed opacities for a given abundance ratio. Even for a much smaller reduction in the oxygen abundance ($[O/H] = 8.80$, the MIX2 abundances), it turns out that Z/X needs to be increased from 0.0218 to 0.0228 to match the sound speed and density in the solar CZ. The region in the Z/X -opacity plane for both mixtures that is consistent with seismic constraints is shown in Figure 3. The allowed region is not too sensitive to variations in the oxygen abundance, but to match the seismic constraints, either the opacity or the heavy-element abundances, or both, need to be increased. From seismic constraints, it is not possible to decide between these possibilities.

We find that the recent estimate of the value of the oxygen abundance by Asplund et al. (2004) along with the OPAL opacities are not consistent with seismic data. In fact, if current opacity tables are accepted, no significant reduction in the ox-

xygen abundance from the values of Grevesse & Sauval (1998) is favored by helioseismology. Models constructed with the new abundances have either an incorrect CZ depth, an incorrect X , or an incorrect density profile in the CZ. Increasing the diffusion of heavy elements below the CZ base to compensate for a reduction in the atmospheric abundance does not work; the models fail to satisfy the X constraint in the solar envelope, even though they may have the correct CZ depth. If the new values of abundances are confirmed, then opacity sources in the Sun will need to be reinvestigated. The intrinsic opacities will need to be increased to counteract the decrease in opacity due to the reduction in heavy-element abundances. It could be argued that the abundances in the atmosphere where the spectral lines are formed is different from those in the CZ because of some fractionation. This could resolve the problem we face now. However, we will be faced with the more fundamental problem of having no way of determining the CZ abundances of the Sun.

This work utilizes data obtained by the Global Oscillation Network Group project, managed by the National Solar Observatory, which is operated by AURA, Inc., under a cooperative agreement with the NSF. This work also utilizes data from the Solar Oscillations Investigation/ Michelson Doppler Imager (SOI/MDI) on the *Solar and Heliospheric Observatory (SOHO)*. *SOHO* is a project of international cooperation between ESA and NASA. MDI is supported by NASA grants NAG5-8878 and NAG5-10483 to Stanford University. We thank the OPAL group for the opacity tables for the different heavy-element mixtures. This work was supported by NSF grant ATM 0206130 to S. B.

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