SOLAR MODELS WITH REVISED ABUNDANCES AND OPACITIES

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Received 2006 November 9; accepted 2007 February 8; published 2007 February 27

ABSTRACT

Using reconstructed opacities, we construct solar models with low heavy-element abundance. Rotational mixing and enhanced diffusion of helium and heavy elements are used to reconcile the recently observed abundances with helioseismology. The sound speed and density of models in which the relative and absolute diffusion coefficients for helium and heavy elements have been increased agree with seismically inferred values at better than the 0.005 and 0.02 fractional levels, respectively. However, the surface helium abundance of the enhanced diffusion model is too low. The low-helium problem in the enhanced diffusion model can be solved to a great extent by rotational mixing. The surface helium and the convection zone depth of rotating model M04R3, which has a surface Z of 0.0154, agree with the seismic results at the levels of 1 \( \sigma \) and 3 \( \sigma \), respectively. M04R3 is almost as good as the standard model M98. Some discrepancies between the models constructed in accord with the new element abundances and seismic constraints can be solved individually, but it seems difficult to resolve them as a whole.

Subject headings: Sun: abundances — Sun: helioseismology — Sun: interior

1. INTRODUCTION

Recent analyses of the solar photospheric abundance have shown a significant reduction in the abundances of C, N, O, and other heavy elements (Lodders 2003; Asplund et al. 2004, 2005; Allende Prieto & Lambert 2005; Scott et al. 2006). As a result, the ratio of heavy-element abundance to hydrogen abundance, \( Z/X \), is reduced from 0.023 (Grevesse & Sauval 1998, hereafter GS98) to 0.0171 (Asplund et al. 2004, hereafter AGS), or 0.0177 (Lodders 2003), and the surface Z of the Sun decreases from 0.017 to 0.0126 (or 0.0133 ). Many solar models constructed in accord with this low Z disagree with the seismically inferred sound-speed and density profiles, convection zone (CZ) depth, and helium abundance of the CZ (Basu & Antia 2004a, 2004b; Montalbán et al. 2004; Turck-Chièze et al. 2004; Bahcall et al. 2005; Guzik et al. 2005).

Basu & Antia (2004a, hereafter BA04) and Bahcall et al. (2005) found that a 15\%–20\% increase in OPAL opacities at the base of the CZ can resolve the discrepancies between the solar models with low Z and helioseismology. However, Seaton & Badnell (2004) and Badnell et al. (2005) showed that the increase in the opacities is no more than 2.5\% near the base of the CZ. Antia & Basu (2005) and Bahcall et al. (2005) found that increasing the neon abundance can solve the discrepancies. However, Schmelz et al. (2005) and Young (2005) showed that the ratio of Ne to O is consistent with the value given by AGS. Another attempt to resolve the problem focuses on increasing the rates of diffusion in helium and heavy elements. Models with enhanced diffusion rates are in better agreement with helioseismology than the model without enhanced diffusion. However, the sound speed and the density are still far from the seismic results; the surface \( Z/X \) value is still too high, and the helium abundance of the CZ is too low (BA04; Montalbán et al. 2004; Guzik et al. 2005).

Using helioseismic data, Antia & Basu (2006) determined that the solar metal abundance is 0.0172 \( \pm \) 0.002. This is consistent with that of GS98. Delahaye & Pinsonneault (2006) found that both Fe/H and O/H are more consistent with the values of GS98 than with the values of AGS. Ayres et al. (2006) also found that the oxygen abundance is close to the value found in GS98. If these results are further confirmed, the problems induced by low Z will disappear. However, Asplund (2006) argued that the AGS results are trustworthy. Recently, Scott et al. (2006) also found that the low-carbon abundance is in good agreement with the findings based on entirely different indicators (AGS) and with the values determined by Ireland et al. (2006) from lunar grains irradiated by solar wind. Scott et al. (2006) claimed that their results are more reliable than those of Ayres et al. (2006). The answer to the problem is still an open question.

Our aim is to construct a solar model, using recently determined abundances, that can agree with the seismic constraints. We apply straight multipliers to the diffusion velocity to enhance the rates of element diffusion. Although the theoretical error of the gravitational settling rate is of the order of about 15\% (Thoul et al. 1994), there are some significant uncertainties in the treatment of the element diffusion (Guzik et al. 2005). Our multipliers of the diffusion coefficients are very high, despite the fact that there is no obvious physical justification for such high multipliers, as has been pointed out by BA04 and Guzik et al. (2005). However, the multipliers are required in our models for diffusion in order to reduce the heavy-element abundance of the CZ from the GS98 value to near the AGS value. In order to get the same helium in a rotating model as in a nonrotating model, a multiplier of the element diffusion is required because rotational mixing reduces the degree of gravitational settling. Other enhanced diffusion rate models have been discussed by BA04, Montalbán et al. (2004), and Guzik et al. (2005). The main difference between our models and those of others is that we include rotational effects in order to resolve the low-helium problem of the CZ. We compare our results with those of BA04 and Guzik et al. (2005) in Table 1.

2. SOLAR MODELS

2.1. Properties of Our Solar Models

We use the Yale Rotation Evolution Code (YREC7) to construct our solar models. However, we modify the code to in-
TABLE 1
MODEL PARAMETERS

| Model                   | \(Y_{\text{out}}\) | \(Z_{\text{out}}\) | \(\alpha\) | Multiplier | \(R_c\) \((R_\odot)\) | \((ZX)\) | \(Y_s\) | \(Z_s\) |
|------------------------|---------------------|---------------------|-------------|-------------|----------------------|---------|---------|---------|
| M98                    | 0.2794              | 0.0201              | 2.166       | 1.0(1.0)\(^a\) | 0.7151\(^b\) | 0.0247  | 0.2487  | 0.01809 |
| M04                    | 0.26066             | 0.0148              | 1.608       | 1.0(1.0)    | 0.7335              | 0.0174  | 0.2294  | 0.01322 |
| M04D                   | 0.28618             | 0.019619            | 1.7827      | 2.4 (3.8)   | 0.7168              | 0.0176  | 0.2225  | 0.01347 |
| M04R1                  | 0.265803            | 0.019497            | 1.71799     | 2.4 (3.8)   | 0.7206              | 0.0177  | 0.2368  | 0.01350 |
| M04R2                  | 0.2836              | 0.018892            | 1.67555     | 2.0 (2.5)   | 0.7206              | 0.01976 | 0.2454  | 0.01462 |
| M04R3                  | 0.28358             | 0.01886             | 1.6889      | 2.0 (2.0)   | 0.7167              | 0.0208  | 0.2450  | 0.015396|
| FULL1M\(^d\)           | ...                 | ...                 | ...         | 1.65        | 0.7233              | 0.0171  | 0.2244  | 0.0130  |
| FULL2M\(^d\)           | ...                 | ...                 | ...         | 1.65        | 0.7138              | 0.0218  | 0.2317  | 0.01639 |
| Enhanced Diffusion\(^e\)| 0.2626              | 0.0197              | 1.944       | 3           | 0.7022              | 0.0196  | 0.1926  | 0.01552 |
| Intermediate Enhanced Diffusion\(^e\)| 0.2705              | 0.0197              | 1.763       | 1.5; 4      | 0.7175              | 0.0206  | 0.2269  | 0.01561 |

\(^a\) The multiplier for the diffusion coefficient of the helium
\(^b\) The multiplier for the diffusion coefficient of the heavy elements.
\(^c\) Using OPAL EOS96, Bahcall et al. (2004) obtained \(R_c = 0.7155 R_\odot\).
\(^d\) Full solar model (see BA04).
\(^e\) Guzik et al. (2005) model 3.
\(^f\) Guzik et al. (2005) model 5.

We construct the following six models: (1) M98, a standard model with GS98 mixture opacities; (2) M04, a model with AGS mixtures; (3) M04D, which is the same as model M04, but with the element diffusion enhanced (Thoul et al. 1994); (4) M04R1, which is the same as model M04D, but with rotation (Pinsonneault et al. 1989) and a diffusion coefficient of 0.285803 \(\alpha\) = 0.019497 \(R_\odot\) = 1.71799 \(Y_s\) = 2.4 (3.8) \(Z_s\) = 0.7206 \(Y_s\) = 0.0177 \(Z_s\) = 0.2368 \(Y_s\) = 0.01350 \(Z_s\) = 0.01350.

We therefore use the OPAL EOSs (Rogers et al. 1996) in all our models. Element diffusion is included for helium and metals (Thoul et al. 1994). Energy transfer by convection is treated according to the standard mixing-length theory, and the boundaries of the convection zones are determined by the Schwarzschild criterion. We take the solar age to be 4.57 Gyr. The sound-speed and density differences between model M04 and the Sun are shown in Figure 1, where those of the Sun were given by Basu et al. (2000). Model M04 is in strong disagreement with the seismically inferred value of 0.2485 \(R_\odot\) = 0.2454 \(Y_s\) = 0.01322 \(Z_s\) = 0.01322.

We construct the following six models: (1) M98, a standard model with GS98 mixture opacities; (2) M04, a model with AGS mixtures; (3) M04D, which is the same as model M04, but with the element diffusion enhanced (Thoul et al. 1994); (4) M04R1, which is the same as model M04D, but with rotation (Pinsonneault et al. 1989) and a diffusion coefficient of 0.285803 \(\alpha\) = 0.019497 \(R_\odot\) = 1.71799 \(Y_s\) = 2.4 (3.8) \(Z_s\) = 0.7206 \(Y_s\) = 0.0177 \(Z_s\) = 0.2368 \(Y_s\) = 0.01350 \(Z_s\) = 0.01350.

Some of the parameters of the models are summarized in Table 1. The mixing-length parameter \(\alpha\), \(Z_{\text{out}}\), and \(Y_{\text{out}}\) are free parameters adjusted to obtain the observed solar radius, solar luminosity, and surface element abundances, respectively. Finally, \(R_c\), (\(RX\)) \(Y_s\), and \(Z_s\) are the results of calculations at the age of 4.57 Gyr.

2.2. Results

Some of the calculation results are shown in Table 1. The base of the CZ is at 0.7335 \(R_\odot\) for M04 and is different (by 20 \(\sigma\)) from the seismically inferred value of 0.713 \(\pm 0.001\) \(R_\odot\) (Basu & Antia 1997). The surface helium abundance of 0.2294 is 6 \(\sigma\) away from the seismically inferred value of 0.2485 \(\pm 0.0034\) (BA04). The sound-speed and density differences between M04 and the Sun are shown in Figure 1, where those of the Sun were given by Basu et al. (2000). Model M04 is in strong disagreement with the seismically inferred sound-speed and density profiles, the depth of the CZ, and the envelope helium abundance.

AGS suggested that increased diffusion might be able to resolve these disagreements. Thus, we construct the model M04D by multiplying the diffusion coefficients for helium and heavy elements by factors of 2.4 and 3.8, respectively. However, we have no physical justification for these multipliers. This method was first proposed by Guzik et al. (2005). The base of the CZ of model M04D is at 0.7168 \(R_\odot\), which agrees with the seismically inferred value (Basu & Antia 1997) at about the 3 \(\sigma\) level. The sound-speed and density of model M04D are more consistent with the seismic data than that of model M04. The difference of the sound-speed and density between model M04D and the Sun, \(\delta v/c\) and \(\delta \rho/\rho_s\), is less than 0.005 and 0.02, respectively. These values are close to those of the standard model M98. In fact, the density profile of model M04D is even slightly better than that of model M98. However, the surface helium abundance of 0.2225 is too low, which disagrees with the seismically inferred value of 0.2485 (BA04) at the level of 8 \(\sigma\).

The rotational mixing can reduce the degree of gravitational settling (Chaboyer et al. 1995; Yang & Bi 2006). We thus construct a rotating model, M04R1, to study the low-helium problem of model M04D. The rotational mixing in all our models is treated as a diffusion process (Pinsonneault et al. 1989), and the rotational mixing processes include the Eddington circulation, the Goldreich-Schubert-Fricke instability, and the secular shear instability (Zahn 1993). In all our rotating models, the surface rotation rate is about 2.86 \(\times 10^{-6}\) rad s\(^{-1}\) at the age of 4.57 Gyr. The sound-speed and density differences between model M04R1 and the Sun are shown in Figure 1. They are almost the same as those in model M04D. The surface helium abundance of model M04R1 is 0.2386, which is 3 \(\sigma\) away from 0.2485 (BA04) but agrees with that of Kosovichev (1997). However, the base of the CZ is at 0.7206 \(R_\odot\) and disagrees with the seismically inferred value at about the 7 \(\sigma\) level.

In order to get a model that is more consistent with seismic constraints than model M04R1, we relax the constraint of the heavy elements determined by AGS and construct model M04R2 with \(Z/X = 0.01976\) and model M04R3 with \(Z/X = 0.0208\). The sound-speed and density differences between model M04R2 and the Sun are less than 0.004 and 0.01, respectively, and the surface helium abundance of model M04R2 is 0.2454 within the constraint of observation (BA04). However, the depth of the CZ in model M04R2 disagrees with the
Fig. 1.—(a) Sound-speed difference between the Sun and the model. (b) Density difference between the Sun and the model. The solar values were derived from SOHO/MDI data (Basu et al. 2000). The long-dashed line refers to M98. The solid line indicates M04. The triple-dot-dashed line shows the results of M04D. The dotted line is given for M04R1. The dash-dotted line and the thick solid line correspond to M04R2 and M04R3, respectively.
the rotating model can thus be enhanced by the rotational mixing, and the surface helium abundance of settling of the helium abundance can thus be partly counteracted can smooth out the gradient of the element abundances. The weight (Pinsonneault et al. 1989), and the rotational mixing by element settling at the base of the CZ. The rotational secular dance of the CZ is too low in such models. In enhanced dif-

3. DISCUSSION AND CONCLUSIONS

In this study, we assume that the diffusion coefficients for helium and heavy elements can be enhanced, respectively. Thus, the discrepancies between the models with low Z and helioseismological theory can be reduced, but the helium abundance of the CZ is too low in such models. In enhanced diffusion models, there is a gradient of element abundances caused by element settling at the base of the CZ. The rotational secular shear is highly sensitive to the gradients of the mean molecular weight (Pinsonneault et al. 1989), and the rotational mixing can smooth out the gradient of the element abundances. The settling of the helium abundance can thus be partly counteracted by the rotational mixing, and the surface helium abundance of the rotating model can thus be enhanced.

After relaxing the constraint of $Z/\mathcal{X}$ in model M04R3, the sound-speed profile, density profile, depth of the CZ, and surface helium abundance are almost the same as those in the standard model M98, but the surface $Z$ of 0.0154 is higher than the value found in AGS. The difference in the sound speed and density in our models can be improved by enhancing the diffusion coefficients for helium and heavy elements. Thus, the maximum difference in the sound speed decreases from 0.014 in model M04 to 0.0045 in models M04D and M04R1. The density profiles of the enhanced diffusion models are even slightly better than that in model M98. The surface helium abundance of 0.2225 in model M04D is too low and is different (by 8 $\sigma$) from that of BA04. The surface helium abundance of the rotating model M04R1 is 0.2368, which agrees with that of Lodders (2003) and Kosovichev (1997), but the position at the base of the CZ in this model is 7 $\sigma$ away from the seismically inferred position (Basu & Antia 1997). The surface helium abundance and the base position of the CZ in model M04R3 are in agreement with seismic results at the levels of 1 $\sigma$ and 3 $\sigma$, respectively, but the surface heavy-element abundance of 0.0154 is higher than the value found in AGS. Some problems between the new element abundances and helioseismological theory can be solved individually, but it seems difficult to resolve them as a whole.

We thank Daniel Kister for his help, the anonymous referee for his/her useful remarks, and the NSFC through projects 10473021 and 10433030 for their support.

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