SOLAR MODELS WITH REVISED ABUNDANCE

S. L. $\mathrm{Bi^{1,2}}$, T. D. $\mathrm{Li^1}$, L. H. $\mathrm{Li^3}$, & W. M. $\mathrm{Yang^{1,4}}$

ABSTRACT

We present new solar models in which we use the latest low abundances and we further include the effects of rotation, magnetic fields and extra-mixing processes. We assume that the extra-element mixing can be treated as a diffusion process, with the diffusion coefficient depending mainly on the solar internal configuration of rotation and magnetic fields. We find that such models can well reproduce the observed solar rotation profile in the radiative region. Furthermore the proposed models can match the seismic constraints better than the standard solar models, also when these include the latest abundances, but neglect the effects of rotation and magnetic fields.

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

1. Introduction

The standard solar models with the latest input physics are well known to yield the solar structure to an amazing degree of precision, and agree with the helioseismic inversions (see e.g., Christensen-Dalsgaard et al. 1996; Bahcall et al. 2001). Those models use the old abundance values (Grevesse & Savual 1998, hereafter GS98). However, the standard solar models with the new solar mixture AGS05 (Asplund et al. 2005, hereafter AGS05) disagree with helioseismic constraints, e.g., the position of the base of convection zone (CZ) is too shallow and the surface helium abundance is lower than in the Sun (Christensen-Dalsgaard et al. 1991; Basu 1998; Basu & Antia 2004). Larger discrepancies are in the sound-speed and density profiles between the Sun and the models with low Z (Bahcall & Pinsonneault 2004; Guzik et al. 2005). See Basu & Antia (2008) for a detailed review paper.

¹Department of Astronomy, Beijing Normal University, Beijing 100875, China; bisl@bnu.edu.cn

²Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences

³Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA

⁴School of Physics and Chemistry, Henan Polytechnic University, Jiaozuo 454000, Henan, China

A number of investigations have attempted to explain this discrepancy as a matter of improved physical inputs in the standard solar model such as: enhanced diffusivity, opacity increases, convective overshooting, low-Z accretion (Bahcall et al. 2005, 2006; Yang & Bi 2007; Christensen-Dalsgaard 2009; Serenelli et al. 2009; Guzik & Mussack 2010; Turck-Chièze et al. 2010) and revised solar composition (Asplund et al. 2009, hereafter AGSS09). The results of all of these analyses show that it is difficult reproduce the helioseismic constraints with the standard solar model also when it includes the latest abundances. This failure could be due to the fact that the standard solar model neglects rotation, magnetic fields and some extra-mixing processes. In this letter, we show that these effects can reduce the discrepancies.

2. Beyond the standard solar model

Helioseismology has revealed that the Sun is rotating differentially at the surface, slowly in the core and almost uniformly in the radiative region (Chaplin et al. 1999). The purely rotation-induced mixing has been considered in modeling rotating stars, as given in Zahn (1992), Maeder & Zahn (1998), Maeder & Meynet (2000), Palacios et al. (2003) and Mathis & Zahn (2004). However, these models appear insufficient to reproduce the helioseismically inferred internal solar rotation profile. This suggests that other effects should be considered in extracting angular momentum from the central core of the Sun.

Recently, two main mechanisms have been proposed to explain the solar flat rotation profile, namely internal gravity waves (e.g. Charbonnel & Talon 2005) and magnetic fields (e.g. Eggenberger et al. 2005). Here, we mainly describe the efficiency of the extra-mixing caused by rotation and magnetic fields, as prescribed by the Tayler-Spruit dynamo (Pitts & Tayler 1986; Spruit 2002). The theoretical formulation of this dynamo is still a matter of debate (Denissenkov & Pinsonneault 2007; Zahn et al. 2007), however, Eggenberger et al. (2005) found that the model with the Tayler-Spruit dynamo-type field successfully reproduces the observed solar rotation profile. Therefore, it is particularly interesting to investigate the effects of rotation and magnetic fields on the solar interior and global parameters.

We present a simple scheme for dealing with angular momentum transport and element mixing in the solar interior. It is based on the stellar structure equations which include rotation and magnetic fields (Pinsonneault et al. 1989; Li et al. 2003). The detailed derivation is given in Yang & Bi (2006, 2008). This formulation allows us to estimate the effects of rotation and magnetic fields on the Sun properties. The angular momentum transport and elements mixing can be described with two diffusion equations as follows:

$$\rho r^2 \frac{\partial \Omega}{\partial t} = f_{\Omega} \frac{1}{r^2} \frac{\partial}{\partial r} \left[\rho r^4 \left(D_{rot} + D_m \right) \frac{\partial \Omega}{\partial r} \right], \tag{1}$$

$$\frac{\partial X_{i}}{\partial t} = f_{C} \frac{1}{\rho r^{2}} \frac{\partial}{\partial r} \left[\rho r^{2} (D_{rot} + D'_{m}) \frac{\partial X_{i}}{\partial r} \right] + \left(\frac{\partial X_{i}}{\partial t} \right)_{nuc} + \left(\frac{\partial X_{i}}{\partial t} \right)_{micro}, \tag{2}$$

where the adjustable parameters f_{Ω} and f_{C} are introduced to represent some inherent uncertainties in the diffusion equations. The second and third terms on the right-hand-side of Equation (2) are the nuclear and gravitational settling terms, respectively. In our model, the diffusion coefficient D_{rot} is associated with the rotational instability as described by Chaboyer et al. (1995). In the case of a Tayler-Spruit dynamo-type field, the diffusion coefficient for the angular momentum transport can be written as (Maeder & Meynet 2003):

$$D_m = r^2 \Omega q^2 \left(\frac{\Omega}{N_\mu}\right)^4 \tag{3}$$

and the one for chemical element transport as:

$$D'_{m} = r^{2} \Omega q^{4} \left(\frac{\Omega}{N_{\mu}}\right)^{6}. \tag{4}$$

Equations (3) and (4) are valid in the regime of negligible thermal diffusion, namely $N_{\mu} \gg N_{T}$, where N_{T} (N_{μ}) represents the thermal (μ -) gradients associated with buoyancy frequency. When this condition is violated, we should replace Equations (3) and (4) with

$$D_m = r^2 \Omega \left(\frac{\Omega}{N_T}\right)^{1/2} \left(\frac{K}{r^2 N_T}\right)^{1/2} \tag{5}$$

and

$$D'_{m} = r^{2}\Omega |q| \left(\frac{\Omega}{N_{T}}\right)^{3/4} \left(\frac{K}{r^{2}N_{T}}\right)^{3/4}, \tag{6}$$

respectively, where $q=-\frac{\partial \ln \Omega}{\partial \ln r}$ and $K=4acT^3/3\kappa \rho^2 c_p$ is the thermal diffusivity.

Additionally, in order to reproduce the solar surface angular velocity, we adopt the Kawaler (1988) braking law:

$$\frac{dJ}{dt} = f_K K_\Omega \left(\frac{R}{R_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2} \Omega^3,\tag{7}$$

where $K_{\Omega} \simeq 1.13 \times 10^{47} \text{ g cm}^2 \text{ s}$ and f_K is an adjustable parameter related to the magnitude of the magnetic fields.

3. Calculations and results

Our solar models are obtained from the one-dimensional Yale Rotating Stellar Evolution Code (YREC; Guenther et al. 1992; Li et al. 2003; Yang & Bi 2006), by including rotation, magnetic fields and relevant extra-mixing processes. In addition, we use the following updated physical quantities: OPAL equation of state tables EOS2005 (Rogers & Nayfonov 2002), the opacities (GS98, AGS05 and AGSS09) supplemented by the low-temperature opacities (Ferguson et al. 2005), diffusive element settling (Thoul et al. 1994) and the Krishna-Swamy Atmosphere $T - \tau$ relation.

In order to investigate the influence of rotation and magnetic fields, we constructed these solar models in accord with different physical processes corresponding to different solar compositions. In the numerical calculations, all models are calibrated from the initial zero-age main sequence (ZAMS) to the present solar-age models, for which the radius is 6.9898×10^{10} cm, the luminosity 3.8515×10^{33} erg/g, the mass 1.9891×10^{33} g and the adopted photospheric Z/X ratio. The free variables are the initial helium abundance Y, the initial metallicity Z and the mixing-length parameter, all of which are adjusted to match these observational constraints. In addition, we assumed that the convective region rotates rigidly, as proposed by Pinsonneault et al. (1989). The initial angular velocity is another free parameter that can be tuned so that the surface velocities of solar-age models match the observed values.

Figure 1 shows the angular velocity as a function of radius r at the ages of 2.0 Gyr and 4.57 Gyr. For the purely rotating model, the Ω -gradient clearly appears in the radiative region. In the solar interior, the angular velocity increases with increasing age during the main sequence, while in the surface it is just the opposite. As a consequence of this at the present age the core rotation velocity is about four times as large as the surface one. On the other hand, the angular velocity profile for the model with magnetic fields is significantly different. During the main-sequence stage, the Sun is a quasi-solid body. It is interesting to note that at the age of 4.57 Gyr, the surface rotation velocity predicated by both models is approximately 2.9×10^{-6} rad/s. However, the total angular momentum is quite different. For the calibrated models, the total angular momentum of the rotating model at the age $4.57~{\rm Gyr}$ is $8.97\times10^{48}~{\rm g~cm^2~s^{-1}}$, which is about five times as large as the seismic result $(1.94 \pm 0.05) \times 10^{48} \text{ g cm}^2 \text{ s}^{-1}$ (Komm & Howe 2003); while for the model with magnetic fields at the same age, the total angular momentum is 2.02×10^{48} g cm² s⁻¹, which is in good agreement with the result obtained by helioseismology at 1σ level. The magnetic field thus constitutes a more efficient process to transport angular momentum because it enhances the coupling between the radiative zone and convective one.

Rotation and magnetic fields have important consequences on the chemical composition

profile of the outer convective envelope, as shown in Figure 2. By comparing the models with and without rotation and magnetic fields, we find that the extra-mixing process counteracts the effect of diffusive settling in the outer envelope. Hence, the model with rotation and magnetic fields has a smoother helium abundance profile than the standard solar model with the same abundance. This leads to a change in the CZ structure, as well as improvements in the sound speed and density profiles.

For further investigation of the magnetic field's role, Figure 3 shows in detail the differences between the calculated and inferred sound-speed and density profile (Basu et al. 2009). The different lines refer to calibrated evolved models at the age of 4.57 Gyr, each using a different abundance, indicated as GS98, AGS05 and AGSS09. It is clearly visible that the discrepancy between seismic inferences and solar models with the new lower abundances is much larger than one with the old abundance. As illustrated by the different curves, the effects of rotation and magnetic fields on the stellar structure equations change the hydrostatic equilibrium and thermodynamic variables on the solar interior, and therefore also have a significant impact on the solar models. Table 1 summarizes the main characteristics of our calibrated models. Interestingly, among all the models listed in the table, model AGSS09c shows the best agreement with the inversions. This model reproduces the sound speed and density profiles in within 0.5%, while for model GS98a the discrepancy is about 0.3%. Furthermore, model AGSS09c predicts the position of the CZ base at $R_{CZ} = 0.721R_{\odot}$ which shows a 8σ discrepancy, while AGSS09a model shows a 10σ one. For the surface helium abundance the situation is analogous: model AGSS09c predicts $Y_s = 0.243$ with a 1.5 σ discrepancy, while model AGSS09a shows the discrepancy at 3.6σ level. Although the models including rotation and magnetic fields show some improvements with respect to the standard solar model, they still disagree with the seismic constraints.

4. Conclusions

We have investigated the effects of rotation and magnetic fields on the solar models, and have found that when these effects are included, alongside the new abundances, the revised solar models can better reproduce the helioseismic constraints. However, we see that it is difficult to match simultaneously the new abundances and helioseismology data for sound speed, density profiles, convection zone depth and surface helium abundance. Although the Tayler-Spruit dynamo type magnetic field still needs to be studied further, our results show that it does provide a possible explanation for the solar abundance problem. We have neglected turbulence, which may feed the differential rotation and sustain magnetic fields in the convection zone, and other interactions. These physical processes will be considered

in our future work. The results obtained in this paper are encouraging and we intend to apply our model to solar-type stars to get a proper interpretation of the existing helioseismic observations and the coming asteroseismic ones.

S.L.B. acknowledges grant 2007CB815406 of the Ministry of Science and Technology of the Peoples Republic of China and grants 10773003 and 10933002 from the National Natural Science Science Foundation of China. L.H.L. acknowledges the financial support of Grant ATM 073770 by NSF and the Vetlesen Foundation of USA.

REFERENCES

Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser.336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes, III & F. N. Bash (San Francisco, CA: ASP), 25

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Bahcall, J. N., Pinsonneault, M. H., & Basu, S. 2001, ApJ, 555, 990

Bahcall, J. N., & Pinsonneault, M. H. 2004, Phys. Rev. Lett., 92, 121301

Bahcall, J. N., Basu, S., & Serenelli, A. M. 2005, ApJ, 631, 1281

Bahcall, J. N., Serenelli, A. M., & Basu, S. 2006, ApJS, 165, 400

Basu, S. 1998, MNRAS, 298, 719

Basu, S., & Antia, H. M. 2004, ApJ, 606, L85

Basu, S., & Antia, H. M. 2008, Phys. Rep. 457, 217

Basu, S., Chaplin, W. J., Elsworth, Y., New, R., & Serenelli, A. M. 2009, ApJ, 699, 1403

Chaboyer, B., Demarque, P., & Pinsonneault, M. H. 1995, ApJ, 441, 865

Chaplin, W. J., Elsworth, Y., Isaak, G. R. et al., 1999, MNRAS, 300, 1077

Christensen-Dalsgaard, J., Gough, D. O., & Thompson, M. J. 1991, ApJ, 378, 413

Christensen-Dalsgaard, J., et al. 1996, Science, 272, 1286

Christensen-Dalsgaard, J., Di Mauro, M. P., Houdek, G., & Pijpers, F. 2009, A&A, 494, 205

Denissenkov, P. A., & Pinsonneault, M. 2007, ApJ, 655, 1157

Eggenber, P., Maeder, A., & Meynet, G. 2005, A&A, 440, L9

Ferguson, J. W., Alexander, D. R., Allard, F., et al. 2005, ApJ, 623, 585

Grevesse, N, & Sauval, A. J. 1998, Space Sci. Rev., 85, 161

Guenther, D. B., Demarque, P., Kim, Y.-C., & Pinsonneault, M. H. 1992, ApJ, 387, 372

GuziK, J. A., Watson, L. S., & Cox, A. N. 2005, ApJ, 627, 1049

GuziK, J. A., & Mussack, K. 2010, ApJ, 713, 1108

Kawaler, S. D. 1988, ApJ, 333, 236

Komm, R., Howe, R., Durney, B. R. et al., 2003, ApJ, 586, 650

Li, L. H., Basu, S., Sofia, S., et al. 2003, ApJ, 591, 1267

Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143, 1063

Maeder, A., & Meynet, G. 2003, A&A, 411, 543

Maeder, A., & Zahn, J.-P. 1998, A&A, 344, 1000

Mathis, S., & Zahn, J.-P. 2004, A&A, 425, 229

Palacios, A., Talon, S., Charbonnel, C., & Forestini, M. 2003, A&A, 399, 603

Pinsonneault, M. H., Kawaler, S. D., Sofia, S., & Demarque, P. 1989, ApJ, 338, 424

Pitts, E., & Tayler, R. J. 1986, MNRAS, 216, 139

Rogers, F. J., & Nayfonov, A. 2002, ApJ, 576, 1064

Serenelli, A. M., Basu, S., Ferguson, J. W., & Asplund, M. 2009, ApJ, 705, L123

Spruit, H. C. 2002, A&A, 381, 923

Thoul, A. A., Bahcall, J. N., & Loeb, A. 1994, ApJ, 421, 828

Turck-Chièze, S., Palacios, A, Marques, J. P., & Nghiem, P. A. P. 2010, ApJ, 715, 1539

Yang, W. M., & Bi, S. L. 2006, A&A, 449, 1161

Yang, W. M., & Bi, S. L. 2007, ApJ, 658, L67

Yang, W. M., & Bi, S. L. 2008, ChJAA, 8, 677

Zahn, J.-P. 1992, A&A, 265, 115

Zahn, J. -P., Brun, A. S., & Mathis, S. 2007, A&A, 474, 145

This preprint was prepared with the AAS LATEX macros v5.2.

Table 1. Characteristics of the Calibrated Solar Models

Model	$(Z/X)_s$	Z_s	Y_s	R_{cz}/R_{\odot}	$<\delta c/c>$	$<\delta ho/ ho>$	Y_c	Z_c	Y_{ini}	Z_{ini}	α_{MLT}
GS98a	0.0229	0.0169	0.246	0.715	0.0012	0.008	0.644	0.0198	0.277	0.0188	2.12
AGS05a	0.0165	0.0125	0.230	0.728	0.0030	0.034	0.623	0.0148	0.261	0.0140	2.08
AGS05b	0.0165	0.0124	0.239	0.727	0.0028	0.035	0.622	0.0146	0.269	0.0139	2.04
AGS05c	0.0165	0.0124	0.237	0.726	0.0028	0.033	0.621	0.0146	0.260	0.0139	2.05
AGSS09a	0.0181	0.0136	0.236	0.723	0.0020	0.022	0.631	0.0160	0.267	0.0152	2.12
AGSS09b	0.0181	0.0134	0.245	0.722	0.0019	0.023	0.630	0.0158	0.268	0.0150	2.07
AGSS09c	0.0181	0.0135	0.243	0.721	0.0017	0.021	0.630	0.0158	0.266	0.0150	2.09

^aSolar models with diffusion.

 $^{{}^{\}rm b}{\rm Solar}$ models with diffusion and rotation.

 $^{^{\}rm c}{\rm Solar}$ models with diffusion, rotation and magnetic fields.

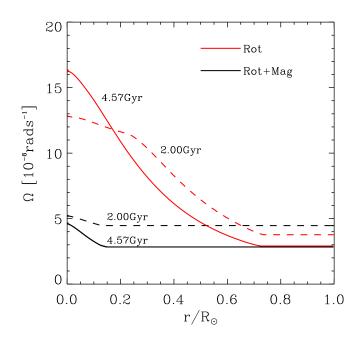


Fig. 1.— Comparison of angular velocity profiles for the two cases: (1) purely rotating models; and (2) models with rotation and the Tayler-Spruit dynamo-type field. The dashed and solid lines refer to different ages: 2.0 Gyr and 4.57 Gyr, respectively.

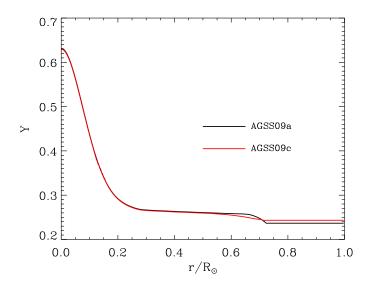


Fig. 2.— Helium abundance profiles for the calibrated solar models at the age of 4.57 Gyr, computed with and without rotation and magnetic fields.

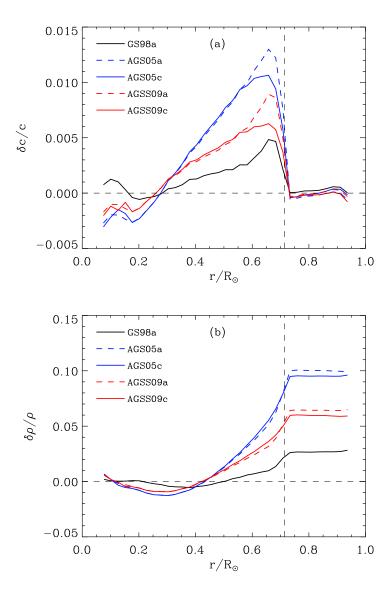


Fig. 3.— Differences between inferred and calculated sound speeds and densities for models with and without rotation and magnetic fields at the age of 4.57 Gyr, corresponding to the GS98, AGS05 and AGSS09 abundances. Sound speed and density inversions are from Basu et al. (2009).