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NEW SOLAR OPACITIES, ABUNDANCES, HELIOSEISMOLOGY, AND NEUTRINO FLUXES

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ABSTRACT

We construct solar models with the newly calculated radiative opacities from the Opacity Project (OP) and with recently determined (lower) heavy-element abundances. We compare the results from the new models with the predictions of a series of models that use OPAL radiative opacities, older determinations of the surface heavy-element abundances, and refinements of nuclear reaction rates. For all the variations we consider, solar models that are constructed with the newer and lower heavy-element abundances advocated by Asplund et al. disagree by much more than the estimated measuring errors with the helioseismological determinations of the depth of the solar convective zone, the surface helium composition, the internal sound speeds, and the density profile. Using the new OP radiative opacities, the ratio of the ^{8}B neutrino flux calculated with the older and larger heavy-element abundances (or with the newer and lower heavy-element abundances) to the total neutrino flux measured by the Sudbury Neutrino Observatory is 1.09 (0.87) with a 9% experimental uncertainty and a 16% theoretical uncertainty, 1 σ errors.

Subject headings: atomic processes — neutrinos — nuclear reactions, nucleosynthesis, abundances — Sun: abundances — Sun: interior

Recent, refined determinations of the surface heavy-element abundances of the Sun have led to lower than previously believed heavy-element abundances (see Asplund et al. 2005 and references therein). A number of authors have pointed out that these lower heavy-element abundances lead to solar models that conflict with different aspects of helioseismological measurements (e.g., Bahcall & Pinsonneault 2004; Basu & Antia 2004; Bahcall et al. 2005). If the radiative opacity in the temperature range of (2–4.5) $\times$ 10^6 K were to be increased by of order 10% relative to the standard OPAL opacity (Iglesias & Rogers 1996), then the discrepancy between new abundances and helioseismology could be resolved (Bahcall et al. 2005; see also Basu & Antia 2004).

The Opacity Project (OP) has recently performed more precise and more physically complete calculations of the radiative opacities with the goal of determining if these new calculations could eliminate the discrepancy between helioseismology and solar modeling that uses the new (lower) heavy-element abundances (see Badnell et al. 2004, Seaton & Badnell 2004, and Seaton 2004). The Opacity Project refinements result in only a small increase (less than 2.5% everywhere of interest) relative to the OPAL opacity.

In this Letter, we present a series of precise solar models that were calculated using the new OP opacities as well as the familiar OPAL opacities. We also present models that were constructed with the recently determined heavy-element abundances (Asplund et al. 2005) as well as with the previously standard abundances (Grevesse & Sauval 1998). In addition, we introduce refinements in the nuclear physics used in the solar models. We compare the results of each of our series of solar models with helioseismological and neutrino observations of the Sun. As a side product of this investigation, we determine the remarkable precision with which two very different stellar evolution codes reproduce the same solar model parameters.

Table 1 gives the principal characteristics of seven precise solar models that we use in this Letter to investigate the helioseismological and neutrino flux implications of the recent redeterminations of heavy-element abundances and of radiative opacities. Table 2 presents the neutrino fluxes calculated for each of the seven solar models represented in Table 1. At the end of the Letter, we summarize in Figure 1 and the related discussion the comparison between the helioseismologically determined sound speeds and densities and the predictions of the various solar models. We begin by describing the differences between the various solar models and by commenting on how these differences affect the calculated properties of the models, including the helioseismological parameters and neutrino fluxes.

The model BP04(Yale) was calculated by Bahcall & Pinsonneault (2004) and is their preferred standard solar model. BP04(Yale) uses the Grevesse & Sauval (1998) solar abundances and the best other input data available at the time the model was constructed. The model was constructed as described in Bahcall & Pinsonneault (1992) and Bahcall & Ulrich (1988) and uses the Yale–Ohio State–Princeton stellar evolution code (Pinsonneault et al. 1989; Bahcall & Pinsonneault 1992; Bahcall et al. 1995) as modified by iterations of the Bahcall-Ulrich nuclear energy generation subroutine. The model BP04(Garching) was derived using the Garching Stellar Evolution code (see, e.g., Schlattl et al. 1997 and Schlattl 2002 for details of the code) using the same procedures and input data as the BP04(Yale) solar model.

The first two rows of Table 1 and Table 2 show that the principal characteristics of solar models are independent, to practical accuracy, of the evolutionary code used for their calculation. For example, the initial helium abundance is the same in the BP04(Yale) and BP04(Garching) models to an accuracy of $\pm 0.04\%$, and the depth of the convective zone is the same to $\pm 0.01\%$. In a more stringent test, the ^{7}Be, ^{8}B, ^{17}F, and pep neutrino fluxes in the two models agree to $\pm 0.4\%$ or better and the *p-p*, hep, ^{13}N, and ^{15}O neutrino fluxes to better than

TABLE 1
CHARACTERISTICS OF SEVEN SOLAR MODELS

Model	α_{convec}	Y_i	Z_i	$R_{CZ}/R_\odot$	Y_{surf}	Z_{surf}	Y_c	Z_c
BP04(Yale)	2.07	0.2734	0.0188	0.7147	0.243	0.0169	0.640	0.0198
BP04(Garching)	2.10	0.2736	0.0188	0.7146	0.243	0.0170	0.641	0.0196
BS04	2.09	0.2742	0.0188	0.7148	0.244	0.0169	0.641	0.0202
BS05(^{14}N)	2.09	0.2739	0.0188	0.7153	0.244	0.0170	0.635	0.0202
BS05(OP)	2.11	0.2725	0.0188	0.7138	0.243	0.0170	0.634	0.0202
BS05(AGS, OP)	1.98	0.2599	0.0140	0.7280	0.229	0.0126	0.620	0.0151
BS05(AGS, OPAL)	1.96	0.2614	0.0140	0.7289	0.230	0.0125	0.622	0.0151

NOTES.—This table lists the principal model characteristics for a series of precise solar models that are defined in the text. Here α_{convec} is the usual convective mixing-length parameter, Y_i and Z_i are the initial helium and heavy-element abundances by mass, R_{CZ} is the radius at the base of the convective zone, Y_{surf} and Z_{surf} are the present-day surface abundances of helium and heavy elements, and Y_c and Z_c are the present-day abundances at the center of the Sun. The first five models use the Grevesse & Sauval (1998) abundances; the last two models use the Asplund et al. (2005) abundances. The first four models use OPAL opacities.

$\pm 0.1\%$. This important result, which demonstrates that two different stellar evolution codes yield the same answers to high precision, shows that we have to take seriously discrepancies between solar model predictions and observations even when the discrepancies are very small.

The small differences between the BS04 and the BP04(Garching) solar models can be summarized as follows. First, in the BS04 model, individual metals diffuse at the different velocities implied by the Thoul et al. (1994) analysis, whereas in the BP04 calculation, all the metals are assumed to diffuse at the same velocity (usually taken to be that of the iron). The changes in abundances induced by using individual velocities are very small, parts per thousand. Second, in the BS04 model, the increase in metallicity caused by the burning of ^{12}C that is out-of-CN equilibrium into ^{14}N is accounted for in the evaluation of the radiative opacities. Two protons are included together with ^{12}C in the conversion to ^{14}N. In the Garching code, this increase in Z is taken into account, whereas in the Yale code, the change in composition is added to the helium abundance. Third, because ^{17}O burns slowly at the solar center temperatures, the ^{17}O abundance is not assumed to be in equilibrium in the BS04 model and is essentially unmodified after it is produced by ^{16}O(p, γ)^{17}F and the β-decay of ^{17}F. In the Yale code, the reaction ^{17}O(p, α)^{14}N is assumed to occur very fast because of a resonant reaction.

The refinements in physics between the BS04 and the BP04(Garching) models do not change significantly the computed astronomical characteristics that are summarized in Table 1. For example, the initial helium abundances inferred from the BP04(Yale), BP04(Garching), and BS04 models all agree to about $\pm 0.1\%$, and the other astronomical characteristics are, in nearly all cases, the same in all three models to comparable or better accuracy. The neutrino fluxes are practically the same in all three models, with the most important change, $\pm 1\%$, occurring for the ^{8}B neutrino flux.

In what follows, we will discuss solar models constructed with the Garching code and will denote the different models by BS05 (plus specifications). Each successive improvement will be incorporated in all subsequent models except where noted otherwise.

The model BS05(^{14}N) is the same as the model BS04, except that in the newer model we use the recently measured value of $S_{1,14} = 1.7 \pm 0.2$ keV barns for the low-energy cross section factor of the ^{14}N(p, γ)^{15}O fusion reaction (Formicola et al. 2004). Again, this improvement makes no practical change in the traditional astronomical characteristics of the models that are shown in Table 1. However, BS05(^{14}N) has ^{13}N and ^{15}O solar neutrino fluxes that are almost a factor of 2 lower than

TABLE 2
PREDICTED SOLAR NEUTRINO FLUXES FROM SEVEN SOLAR MODELS

Model	*pp*	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
BS05(AGS, OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
BS05(AGS, OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

NOTE.—This table presents the predicted fluxes, in units of 10^{10}(*pp*), 10^{9}(^{7}Be), 10^{8}(pep, ^{13}N, ^{15}O), 10^{6}(^{8}B, ^{17}F), and 10^{3}(hep) cm^{-2} s^{-1} for the same solar models whose characteristics are summarized in Table 1.

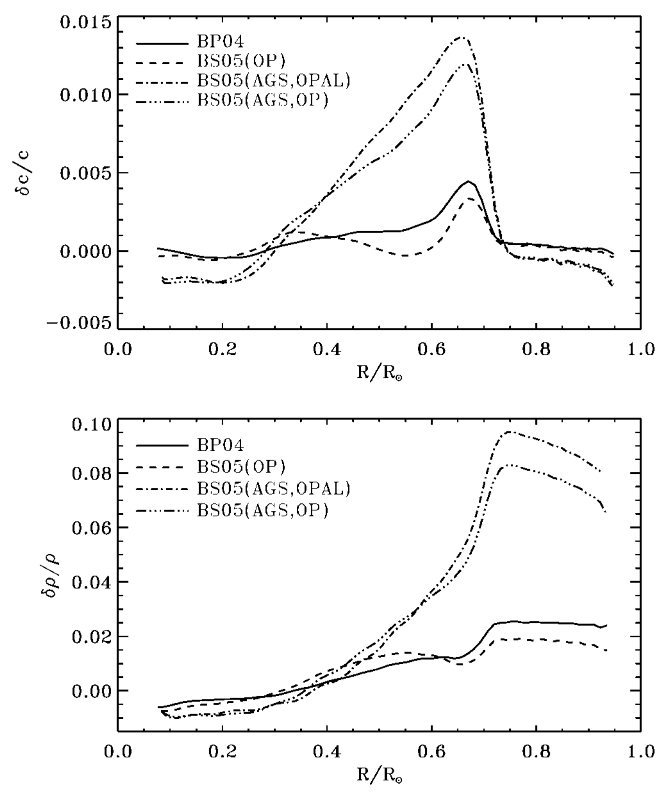

FIG. 1.—Relative sound speed differences, $\delta c/c = (c_\odot - c_{model})/c_{model}$, and relative densities, $\delta\rho/\rho$, between solar models and helioseismological results from Michelson Doppler Imager data.

the corresponding fluxes obtained from the BS04 solar model. The CNO contribution to the solar luminosity is also reduced compared to BS04, BP04(Garching), and BP04(Yale). The latter models have a CNO contribution of 1.55% to the solar luminosity, while for BS05(^{14}N) the CNO contribution is only 0.8%.

The next two solar models are the first in the series to use OP opacities. BS05(OP) and BS05(AGS, OP) differ in that BS05(AGS, OP) uses the heavy-element abundance taken from Asplund et al. (2005). Like all the preceeding models, BS05(OP) uses Grevesse & Sauval (1998) abundances. Comparing BS05(OP) with BS05(^{14}N), we see that the new OP opacities do not change significantly the neutrino fluxes nor do they change the other principal model characteristics.

The lower heavy-element abundances used in BS05(AGS, OP) cause the computed depth of the convective zone to be too shallow and the surface helium abundance to be unacceptably low, as compared with the helioseismologically measured values. The depth of the solar convective zone and the helium surface abundance have recently been redetermined by Basu & Antia (2004) using the best-available helioseismological data. Comparing the values calculated using BS05(AGS, OP) with the measured values (given in parentheses), we have

$$\frac{R_{CZ}}{R_\odot} = 0.728(0.713 \pm 0.001, \text{ exp.}); \qquad (1)$$

$$Y_{surf} = 0.229(0.249 \pm 0.003, \text{ exp.}). \qquad (2)$$

For BS05(AGS, OP), the disagreements between helioseismological measurements and the computed values of R_{CZ} and Y_{surf} are many times the quoted errors. By contrast, all of the models in Table 1 that use the Grevesse & Sauval (1998) abundances [BP04(Yale), BP04(Garching), and BS04 and BS05(^{14}N) and BS05(OP)] have values for these parameters, $R_{CZ} \sim 0.715$ and $Y_{surf} \sim 0.244$, that are in much better agreement with helioseismological measurements.

Similar results are obtained with models that use OPAL opacities [see the row labeled BS05(AGS, OPAL) in Table 1]. Solar models constructed with the AGS05 composition disagree with the helioseismological measurements of R_{CZ} and Y_{surf}, independent of whether one uses OPAL or OP radiative opacities.

Figure 1 shows that, for four representative models, the sound speeds and densities inferred from solar models that use the Grevesse & Sauval (1998) solar abundances are in excellent agreement with the helioseismological measurements (Schou et al. 1998) of sound speeds and densities. Solar models that use the new Asplund et al. (2005) abundances are in disagreement with the helioseismological measurements. For models that use the Grevesse & Sauval (1998) abundances and OPAL, the rms differences between the solar model predictions for sound speeds and densities are, respectively, 0.0015 ± 0.0001 and 0.015 ± 0.002, where we quote the range that spans the values for the first four models that appear in Table 1. The results with OP opacities are even better: 0.00097 and 0.012, respectively. By contrast, the rms differences for models that use the AGS05 abundances are larger by more than a factor of 3, 0.0053 ± 0.0005 and 0.047 ± 0.003, respectively.

How do the adopted element abundances and the radiative opacity affect the predicted solar neutrino fluxes? Figure 2 shows the solar neutrino energy spectrum that is calculated using the BS05(OP) solar model, which may be taken as the currently preferred solar model. The fractional uncertainties for the neutrino fluxes are given in Table 8 of Bahcall & Serenelli (2004).

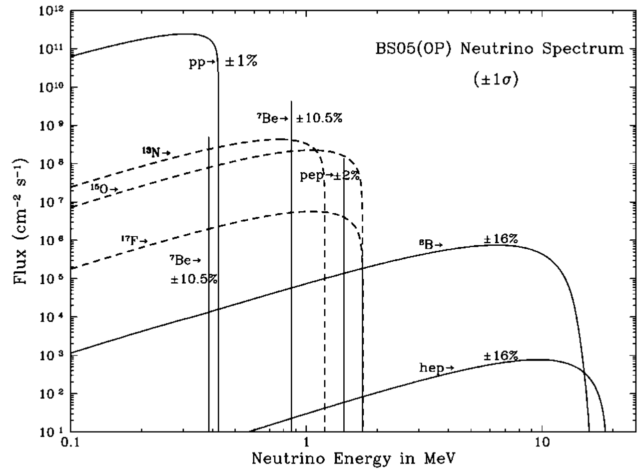

FIG. 2.—Solar neutrino energy spectrum for the solar model BS05(OP). The uncertainties are taken from Table 8 of Bahcall & Serenelli (2004).

Using OP opacity, the ratio of the ^{8}B neutrino flux calculated with the older (larger) heavy-element abundances [or with the newer (lower) heavy-element abundances] to the total ^{8}B neutrino flux measured by the Sudbury Neutrino Observatory (Ahmed et al. 2004) is (see Table 2)

$$\frac{\text{solar model } ^8\text{B } \nu \text{ flux}}{\text{measured } ^8\text{B } \nu \text{ flux}} = 1.09\ (0.87), \qquad (3)$$

with a 9% experimental error (Ahmed et al. 2004) and a 16% theoretical uncertainty (Bahcall & Serenelli 2004), with 1 σ uncertainties. If we adopt OPAL opacities, the coefficients on the right-hand side of equation (3) become 1.12 (0.88), very similar to the values for OP opacities. Turck-Chièze et al. (2004) found a 9% lower ^{8}B neutrino flux for a model similar to BS05(AGS, OPAL). Their lower flux is accounted for by the fact that Turck-Chièze et al. did not use the recent and more accurate *pp* cross section calculated by Park et al. (2003) and that Turck-Chièze et al. did use intermediate screening for fusion reactions instead of the more accurate approximation of weak screening (see Bahcall et al. 2002).

Comparing the calculated to the measured (Bahcall et al. 2004) *p-p* neutrino flux, assuming OP opacities, we have

$$\frac{\text{solar model } p\text{-}p \ \nu \text{ flux}}{\text{measured } p\text{-}p \ \nu \text{ flux}} = 0.99\ (1.00), \qquad (4)$$

with a 2% experimental uncertainty (Bahcall et al. 2004) and a 1% theoretical uncertainty (Bahcall & Serenelli 2004). The agreement is similarly good if we adopt OPAL opacities. The CNO contribution to the solar luminosity is only 0.5% for the models BS05(AGS, OP) and BS05(AGS, OPAL).

We conclude that the agreement between solar model predictions and solar neutrino measurements is excellent and is not significantly affected by the choice of heavy-element abundances or the radiative opacity.

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