WHAT IS THE NEON ABUNDANCE OF THE SUN?

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Received 2005 March 8; accepted 2005 May 15

ABSTRACT

We have evolved a series of 13 complete solar models that utilize different assumed heavy-element compositions. Models that are based upon the heavy-element abundances recently determined by Asplund and coworkers are inconsistent with helioseismological measurements. However, models in which the neon abundance is increased by 0.4–0.5 dex to log N(Ne) = 8.29 ± 0.05 (on the scale in which log N(H) = 12) are consistent with the helioseismological measurements even though the other heavy-element abundances are in agreement with the determinations of Asplund et al. These results sharpen and strengthen an earlier study by Antia & Basu. The predicted solar neutrino fluxes are affected by the uncertainties in the composition by less than their 1σ theoretical uncertainties.

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

1. INTRODUCTION

Solar models constructed with recently determined heavy-element abundances (Asplund et al. 2005; see also Lodders 2003) disagree by many times the quoted measuring errors with helioseismological determinations of solar properties (Bahcall et al. 2005b). This disagreement has led to a number of attempts to reconcile the solar models and the helioseismological measurements. So far there has not been a successful resolution of this problem (see, e.g., Bahcall & Pinsonneault 2004; Bahcall et al. 2004, 2005b; Basu & Antia 2004; Antia & Basu 2005; Turck-Chièze et al. 2004; Guzik & Watson 2004; Guzik et al. 2005; Seaton & Badnell 2004; Badnell et al. 2005; Montalban et al. 2004).

Revising the radiative opacity used in the solar models appeared initially to be the most promising avenue for reaching agreement (Bahcall et al. 2004, 2005a; Basu & Antia 2004). However, a recalculation and refinement by the Opacity Project (OP; Badnell et al. 2005) of the radiative opacity used in the solar models yielded values for the radiative opacity that were very close to the previously used values (OPAL; Iglesias & Rogers 1996), and therefore the revision is insufficient to explain the disagreement between solar modeling and helioseismology. Of course, there could still be inadequacies in the calculation of the opacity in the region of interest that are common to both OPAL and OP evaluations.

It is also natural to ask whether changing the theoretical diffusion rate from the standard estimates could remove the discrepancies. Guzik et al. (2005) have explored solar models with a variety of diffusion treatments and conclude that the required increases in diffusion rates are unphysically large (for example, an order of magnitude increase compared to the 15% uncertainty estimated by Thoul et al. 1994; see also Turcotte et al. 1998; Delahaye & Pinsonneault 2005; Seaton 2005). Moreover, none of the variations of the diffusion rates restored completely the good agreement between helioseismology and solar modeling that was obtained (e.g., Bahcall et al. 2005a) with the previously estimated (higher) heavy-element abundances of Grevesse & Sauval (1998).

We note that the excellent agreement between the helioseismological measurements and the solar model predictions made using the older Grevesse & Sauval (1998) abundances could be an accident. There are many uncertainties in the treatment of the external layers of the star. The discrepancies between solar model predictions made with the newer Asplund et al. (2005) abundances and helioseismological measurements represent a stimulating challenge to make further improvements.

Could the discrepancies between helioseismology and solar modeling be due to errors in one (or a few) poorly measured element abundances? Antia & Basu (2005) have constructed envelope models of the Sun that incorporate the seismologically determined profile of sound speeds and the seismologically inferred abundance of hydrogen and depth of the convective zone. They constructed a series of envelope models in which they changed the abundance of certain elements in order to test the effect of the abundance changes on the seismologically determined density profile. Antia & Basu (2005) inferred that (with OP opacities) an increase in the Ne abundance by 0.63 ± 0.06 dex relative to the Asplund et al. (2005) preferred value yielded agreement with the density profile. Thus they found that, with the assumptions made regarding the envelope model, an abundance of [Ne/H] = 8.47 reconciled the disagreement between envelope models and helioseismology. Moreover, Antia & Basu found that satisfactory agreement with the density profile could also be achieved by simultaneously increasing the C, N, O, and Fe abundances by 0.05 dex and the Ne by 0.40 dex relative to the Asplund et al. (2005) recommended values.

In this paper we evolve a series of complete solar models, interior plus atmosphere, to test the effects of abundance changes upon the full set of helioseismologically determined parameters: sound speed profile, depth of the convective zone, surface...
helium abundance, and density profile. The complete solar models have three advantages over envelope models: (1) the complete models incorporate solar evolution and a full description of the solar interior; (2) the complete models can be tested against all of the helioseismologically determined parameters, not just the density profile; and (3) the complete models can be used to determine how a given composition affects the calculated solar neutrino fluxes.

Like Antia & Basu, we consider that the neon abundance could possibly change by much more than the quoted uncertainty, 0.06 dex (Asplund et al. 2005). The reason is that neon cannot be measured spectroscopically in the solar photosphere and must be determined in regions in which the physical conditions are less well understood (see, e.g., the discussion in Lodders 2003). For exactly the same reason, we consider that the argon abundance could possibly change by much more than the quoted uncertainty, 0.08 dex. In addition, it should be noted that the contribution of neon to the radiative opacity in the solar radiative interior is very important in the range of temperatures in the range (2–5) × 10^6 K, precisely in the region the opacity needs to be increased in order to solve the discrepancy between solar model predictions and helioseismology (Bahcall et al. 2005a).

We present in §2 and Table 1 our results for a series of 13 complete solar models with different chemical compositions, and in §3 and Table 2 we give the solar neutrino fluxes for each of these models. We describe our main results and discuss our conclusions in §4.

2. SOLAR MODELS WITH DIFFERENT COMPOSITIONS

In this section we compare the results obtained from a series of solar models that have different assumed heavy-element abundances with the depth of the solar convective zone, the surface helium abundance, and the sound speed and density distributions, all obtained from helioseismological measurements.

![Table 1: Solar Models with Different Compositions](image1)

| Model              | Ne  | Ar  | CNO | Si+ | Z/X | Z_i | Ysurf | R'BC | ((b'c'/c')^2)^1/2 | ((b'p'/p')^2)^1/2 |
|--------------------|-----|-----|-----|-----|-----|-----|-------|------|------------------|------------------|
| BS05(OP)........... | 6.01| 1.43| 7.96| 4.83| 5.57| 5.02| 2.18   | 1.89 | 3.33             | 4.33             |
| BS05(AGS, OP)...... | 6.00| 1.43| 7.98| 4.78| 5.47| 5.07| 2.25   | 1.87 | 4.27             | 4.84             |
| 4................... | 6.01| 1.43| 8.03| 4.70| 5.30| 5.20| 2.44   | 1.80 | 4.11             | 4.17             |
| 5................... | 6.02| 1.44| 8.04| 4.68| 5.23| 5.21| 2.42   | 1.80 | 4.26             | 4.17             |
| 6................... | 6.01| 1.44| 8.09| 4.64| 5.09| 5.14| 2.30   | 1.76 | 3.99             | 3.99             |
| 7................... | 6.00| 1.44| 8.10| 4.70| 5.23| 5.26| 2.42   | 1.80 | 4.11             | 4.17             |
| 8................... | 6.01| 1.44| 8.11| 4.83| 5.58| 5.51| 2.54   | 1.89 | 4.33             | 4.33             |
| 9................... | 6.02| 1.44| 8.06| 4.67| 5.20| 5.24| 2.42   | 1.80 | 4.11             | 4.17             |
| 10..................| 6.01| 1.44| 8.04| 4.70| 5.23| 5.21| 2.42   | 1.80 | 4.26             | 4.17             |
| 11..................| 6.02| 1.44| 7.99| 4.79| 5.46| 5.60| 2.55   | 1.89 | 4.56             | 4.56             |
| 12..................| 5.98| 1.43| 7.87| 4.99| 5.94| 5.99| 2.59   | 1.98 | 4.56             | 4.56             |
| 13..................| 6.01| 1.43| 8.03| 4.70| 5.30| 5.44| 2.44   | 1.83 | 4.16             | 4.16             |

Notes.—The table gives the neutrino fluxes computed for the same models that are described in Table 1. The fluxes are presented in units of 10^18(pp), 10^18(Bc), 10^18(pep), 10^18(13N, 15O), 10^18(B, 17F), and 10^18(hep) cm^-2 s^-1.
The depth of the convective zone that is inferred from helioseismological measurements is (Basu & Antia 2004)

\[ \frac{R_{cz}}{R_\odot} = 0.7133 \pm 0.001, \text{ measurement.} \]  

(1)

The inferred surface abundance of helium is (Basu & Antia 2004)

\[ Y_{\text{surf}} = 0.2485 \pm 0.0034, \text{ measurement.} \]  

(2)

The sound speed and the density can be measured at a number of different radial depths in the Sun. Fortunately, the inferred distributions of sound speeds and densities are, to an excellent approximation, independent of the reference model used to derive the solar distributions. For example, making different choices for the reference model causes variations of only of order 0.03% in the profile of the sound speeds and of order 0.3% in the density profile (Basu et al. 2000). These changes are small compared to the variations in the profiles predicted by different solar models that have significantly altered surface abundances. Therefore, we compare all of the profiles reported in this section with the solar sound speed and density profiles inferred with the reference model BS(AGS, OP), which uses the Asplund et al. (2005) heavy-element abundances and the recently calculated (Badnell et al. 2005) radiative opacities.

Table 1 shows the calculated solar properties for a series of theoretical solar models that were evolved with different assumed heavy-element abundances. The first two rows in the table present results for models with the Grevesse & Sauval (1998) abundances (row 1) and the Asplund et al. (2005) abundances (row 2). In rows 3–13, we present the calculated solar quantities for solar models with compositions that differ from the Asplund et al. (2005) composition primarily by the addition of neon and argon (with, in some cases, a touch, 0.05 dex, of additional CNO elements and a dash, 0.02 dex, of the heavier elements whose abundances are well determined by meteoritic measurements; see Asplund et al. 2005; Lodders 2003).

We have used trial and error in order to find a composition mixture that fits well the helioseismological data without exceeding the quoted uncertainty (Asplund et al. 2005) in any of the abundance determinations except for neon and argon.

The model described in the third row of Table 1 fits very well all the helioseismological measurements. In fact, this model, which differs from the BS05(AGS, OP) model, based on Asplund et al. (2005), primarily by adding significant amounts of neon and argon, fits the helioseismological data essentially as well as the model that assumes the element abundances of Grevesse & Sauval (1998). The results for the other models in Table 1 show that there are a variety of satisfactory choices for the altered composition with the increase in the neon abundance between 0.4 and 0.6 dex. An increase of only 0.3 dex appears to be insufficient (see model 13); this model fits too shallow a depth for the convective zone. An increase of as much as 0.6 dex appears to be too much; the rms difference between the solar and the model sound speed is more than twice as large as for the BS05(OP) model.

![Graphs showing sound speed and density differences](image-url)

**Fig. 1.** —Relative sound speed differences, \( \frac{\delta c}{c} = (c_{\text{obs}} - c_{\text{obs}}) / c_{\text{mod}} \) (top panels), and relative density differences, \( \frac{\delta \rho}{\rho} = (\rho_{\text{obs}} - \rho_{\text{obs}}) / \rho_{\text{mod}} \) (bottom panels), between some selected solar models and helioseismological results from MDI data. All panels show the BS05(OP) and BS05(AGS, OP) standard solar models for reference. In the two left panels, models 3, 4, and 5 (see Table 1 for details on the composition changes) show an agreement with helioseismology data that is comparable to that of our preferred standard solar model, BS05(OP). In the right top panel, models 12 and 13 show a better agreement with the helioseismological sound speed profile than the BS05(AGS, OP) model, but they are still a factor of 2 worse than BS05(OP). Note in particular the effect in the sound speed of adding too much neon (+0.6 dex; model 12). This is the result of an excessive enhancement in the opacity, to which neon is a main contributor in the solar interior between 0.4 – 0.7 R_\odot. Model 12 predicts, on the contrary, an acceptably good density profile (a similar result for the density profile was found by Antia & Basu 2005 using envelope models).
Figure 1 shows the fractional differences between the sound speeds and densities calculated with selected solar models and those inferred with the aid of the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO). In particular, we use frequencies obtained from MDI data that were collected for the first 360 days of its observation (Schou et al. 1998). For reference, we show in all four panels of Figure 1 the BS05(OP) solar model (model 1 of Table 1, made using the older Grevesse & Sauval 1998 higher heavy-element abundances) and the BS05(AGS, OP) solar model (model 2 of Table 1, made using the Asplund et al. 2005 lower heavy-element abundances). The three other models that are illustrated in the left-hand panels of Figure 1 (models 3–5 of Table 1) were selected in order to illustrate that by a judicious choice of the neon abundance it is possible to obtain agreement with the helioseismological sound speed and density profiles that is comparable to what is obtained with our preferred solar model, BS05(OP).

The top right panel shows that adding neon is not a panacea. The panel establishes this result with the aid of two solar models from Table 1, model 12 (+0.6 dex of neon with respect to Asplund et al. 2005) and 13 (+0.3 dex of neon with respect to Asplund et al. 2005). Both models 12 and 13 yield a factor of 2 worse agreement with the helioseismological sound speed profile than BS05(OP) [although they are in better agreement with the profile than BS05(AGS, OP); see also Table 1].

Model 12 is particularly instructive. The agreement with the helioseismologically determined density profile is acceptable. A similar result was found by Antia & Basu (2005) in their study of envelope models. The Antia-Basu envelope models could only be tested against the density profile since their models had by construction the correct sound speed profile. However, the predicted sound speed profile of model 12 is much worse than for BS05(OP), and Figure 1 shows that the sound speed profile is unacceptable. The principal reason that the profile of the sound speed is unacceptable while the density profile is acceptable is that the sound speed is measured much more accurately than the density.

We note that the successful composition changes are essentially a way of increasing the opacity in the region in which the model predictions differ from the measured helioseismological properties. The required corrections in the opacity must extend from $2 \times 10^6$ K ($R = 0.7 R_\odot$) to $5 \times 10^6$ K ($R = 0.4 R_\odot$), with opacity increases of order 10% (Bahcall et al. 2005a).

3. NEUTRINO FLUXES FOR DIFFERENT ASSUMED COMPOSITIONS

We present in this section the neutrino fluxes computed for each of the solar models that we have discussed in the previous section. The main purpose of this discussion is to show that the predicted neutrino fluxes are insensitive to the composition changes that are being considered.

Table 2 presents the calculated solar neutrino fluxes for all 13 of the solar neutrino models that are listed in Table 1. The fluxes predicted by models 3–13 fall between the extremes for the first two models, BS05(OP) [which assumes the Grevesse & Sauval 1998 abundances] and BS05(AGS, OP) [which assumes the Asplund et al. 2005 abundances].

In the absence of a definitive reason for choosing between the Grevesse & Sauval (1998) abundances and the Asplund et al. (2005) abundances, it is reasonable to consider for each flux the average of the value predicted by BS05(OP) and the value predicted by BS05(AGS, OP). For all the models listed in Table 2, each of the neutrino fluxes differs by less than the $1 \sigma$ theoretical uncertainty from the average flux predicted by the BS05(OP) and BS05(AGS, OP) models, where the theoretical uncertainties are given in Bahcall & Serenelli (2005) and Bahcall et al. (2005b). We conclude that the variations in composition discussed in this paper do not significantly affect the predicted solar neutrino fluxes.

4. DISCUSSION

Table 1 shows that solar models with a variety of chemical compositions, but all with an increase in [Ne/H] by 0.4–0.5 dex (a factor of 2.5–3.2) relative to the Asplund et al. (2005) recommended value, yield helioseismological parameters that are in satisfactory agreement with all the helioseismological measurements. For example, BS05(OP) and models 3, 4, 5, and 10 all predict helioseismological parameters in good agreement with what is measured. We are unable to find solar models with an increase of neon abundance larger than 0.6 dex, or as small as 0.3 dex, that are consistent with helioseismological (see, e.g., models 11, 12, and 13 of Table 1).

We see from the preceding paragraph that different methods yield different values for the solar neon abundance. One of the reasons for these discrepant values is that neon does not have any suitable photospheric lines, and therefore to obtain a “photospheric” abundance for neon it is necessary to measure neon relative to an element that does have good photospheric lines. Different authors chose to normalize the neon abundance with respect to different elements (e.g., Lodders normalizes relative to oxygen and Feldman & Widing normalize relative to magnesium). In addition, all methods for determining the neon abundance are uncertain because the environments (like the solar corona or upper atmosphere) are imperfectly understood.

We have no idea whether the suggestion of a neon abundance in the range [Ne/H] = 8.29 ± 0.05 dex is the correct solution to the conundrum posed by the conflict between helioseismology and solar models constructed with the Asplund et al. (2005) abundances. Only new observations with a variety of techniques and
increased robustness can decide this question. The main reason for this paper to make clear that further measurements of the neon abundance, accompanied by careful analyses of the systematic uncertainties in the measurements, are of great importance for solar physics.

If the correct solution to the conflict between solar modeling and helioseismology is to increase the neon abundance $4.5 \pm 0.05$ dex, then this will be the first determination of a heavy-element abundance via helioseismology. Of course, this determination depends upon the assumption that there are no relevant and important errors in other input parameters to the solar model calculations and that we have not left out, as a result of an unjustified approximation, a significant physical process.

The recent investigations of solar abundances (Asplund et al. 2000, 2001, 2002; Asplund et al. 2004) employ more powerful techniques than previous used (see Grevesse & Sauval 1998) and therefore command respect. However, it would be very valuable if different groups would analyze the solar abundances using different computer codes and different data. The comparison between the results of different groups would permit a more robust estimation of the systematic uncertainties.

Table 2 shows that the neutrino fluxes for all 13 of the solar models considered in this paper lie within $\pm 1 \sigma$ theoretical uncertainties of each other, where the theoretical uncertainties are summarized in Table 8 of Bahcall & Serenelli (2005). Thus the uncertainty regarding the abundances of heavy elements does not affect in an important way the predicted solar neutrino fluxes.

After this paper was posted on the astrophysics archive, but before it was submitted to the *Astrophysical Journal*, we received a copy of a very interesting paper by Drake & Testa (2005). These authors determine the neon-to-oxygen abundance ratio from X-ray measurements of coronal lines in 21 nearby stars (median distance $\sim 30$ pc) with the *Chandra X-Ray Observatory*. The X-ray observations indicate a neon-to-oxygen ratio 2.7 times larger than the Asplund et al. (2005) value. The larger value from the X-ray observations is in good agreement with the increase by a factor of 2.8 $\pm$ 0.4 that we require to fit the helioseismological data. Drake & Testa (2005) also cite supporting data from other X-ray and gamma-ray observations.

J. N. B. and A. M. S. are supported in part by NSF grant PHY0070928 to the Institute for Advanced Study. S. B. is partially supported by NSF grants ATM 0206130 and ATM 0348837.

J. N. B. thanks Marc Pinsonneault for repeatedly pointing out over the past decade the potential importance and possible uncertainty of the solar neon abundance.

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