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Implications of revised solar abundances for helioseismology

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Abstract. Recent solar photospheric abundance analyses (Asplund et al. 2005; Lodders 2003) revise downward the abundances of C, N, O, Ne, Ar, and other elements, which reduces the solar Z/X to 0.0165 (0.0177 Lodders), and Z to 0.0122 (0.0133 Lodders). Solar models evolved with standard physics including diffusive settling that give good agreement with helioseismology were calibrated to previous higher abundance determinations, e.g., the Grevesse & Noels (1993) values of Z/X = 0.0245 and Z ~0.018. However, many studies conclude that solar models evolved with the new lower abundances give worse agreement with the helioseismically-inferred sound speed profile, convection zone base radius, and convection zone helium abundance. We review the solar abundance analysis improvements, compare standard solar models calculated using the old and new abundances against helioseismic constraints, and review suggestions to restore agreement.

Key words. Sun: abundances – Sun: oscillations – Sun: evolution

1. Revised solar abundances

It seems very important for stellar astrophysics to consider the surprisingly large change in solar abundances obtained recently by reanalysis of the solar spectrum using updated physics (Asplund et al. 2005; Lodders 2003). Solar abundances are given in a base 10 logarithmic scale (dex) relative to hydrogen, where the log of the number of hydrogen atoms ≡ 12.00. There are two sources of solar system abundance determinations–the solar spectrum and meteorites. The abundant volatile elements He, C, N, O, Ne, and Ar are depleted in meteorites. The agreement between photospheric and meteoritic abundances for non-volatile elements is surprisingly good, to within 0.01 ± 0.06 dex. The quoted accuracy of individual abundance determinations is about 10%, or 0.04 dex.

Photospheric abundance determinations depend on a model atmosphere (either theoretical or semi-empirical), and atomic and molecular data. Traditional model atmospheres have been static and one-dimensional, and have assumed hydrostatic equilibrium and local thermodynamic equilibrium. The new abundance analyses are based on three-dimensional dynamical model atmospheres resolving ~10 granules (e.g., Stein & Nordlund 1998), taking spatial and temporal averages of the simulations, with self-consistent convection and radiation transport. In addition, the atomic and molecular data have been updated, and non-LTE corrections are included for many elements. With these new model atmosphere treatments, the line shapes, flux distribution, high-degree *p*-mode frequencies, and other solar properties now agree with observations. Moreover, the abundances obtained using atomic or molecular lines for a given element are in agreement.

As a case in point, consider the oxygen abundance determination. Asplund et al. (2004) reanalyzed the [OI] forbidden line, removing a blend with Ni, and including a revised gf transition probability. They also reanalyzed the OI lines taking into account NLTE corrections and 3D effects. In addition, they reanalyzed the OH molecular transitions, which are susceptible to surface inhomogeneities such as granulation. Whereas previous determinations ranged from 8.87 for the OH molecular transitions to 8.64 for the OI lines, the new abundances fall between 8.61 and 8.68 for all indicators. The Asplund et al. (2005) oxygen abundance is 8.66 ± 0.05, a 48% decrease compared to the widely-used determination of Grevesse & Sauval (1998; GS98). Similar decreases are derived for C (35%), N (27.5%), Ne (74%), and Ar (66%), with other elements such as Na to Ca lower by 12 to 25%, and Fe decreased by 12%. The cumulative effect of these new determinations is that the mass fraction of elements heavier than H and He at the Sun's photosphere is reduced to 0.0122 instead of ~ 0.018 for the GS98 mixture.

2. Helioseismology results

While the new abundance analyses are based on improved physics treatment and give more consistent results, they have posed a challenge for helioseismology (Basu & Antia 2004; Bahcall & Pinsonneault 2004; Turck-Chiéze et al. 2004; Guzik et al. 2005). Models calibrated using the new solar abundances with standard physics including diffusive settling give much worse agreement with the inferred sound speed profile, convection zone (CZ) depth, and CZ helium abundance.

Figure 1 compares the sound-speed profiles to the inference of Basu et al. (2000) for models using codes, input physics and calibration method discussed in Guzik et al. (2005). The models are calibrated either to the Grevesse & Noels (1993, GN93) or Asplund et al. (2005, AGS05) mixtures. Figure 2 shows the observed minus calculated vs. calculated frequencies for two models calibrated using the GN93 mixture and OPAL (Iglesias & Rogers 1996) opacities, and either the Alexander & Ferguson (1995, private communication) or Ferguson et al. (2005) low-temperature opacities. The third model uses both OPAL and Ferguson et al. (2005) opacities based on the AGS05 mixture. An interesting result is that the improved low-temperature opacities of Ferguson et al. (2005) including more lines are higher by up to a factor of ~1.5, for the same GN93 mixture. This increase improves agreement (flattens the slope of the O-C curve) for the higher-frequency modes. Such a factor was shown to have this effect by Guzik et al. (1996). The GN93 models have CZ Y=0.2418, and CZ base radius 0.7133 $R_\odot$, whereas the AGS05 model has CZ Y=0.2273, and CZ base radius 0.7306 $R_\odot$. These results are to be compared with the helioseismic inferences of Basu & Antia (2004) of Y=0.248 ± 0.003 and CZ base radius 0.7133 ± 0.0005 $R_\odot$.

3. Attempts to restore agreement

While these discrepancies seem small (only 1-2% in sound-speed for the AGS05 mixture, compared to 0.4% for the GN93 models), it is very difficult to modify the physical input to restore agreement to the level obtained with the earlier abundances. Bahcall et al. (2004) and Montalban et al. (2004) consider opacity increases below the convection zone. However, increases of 11 to 20% are needed, whereas the uncertainties in calculated opacities are likely to be small, given that opacities of three groups, OPAL, Los Alamos LEDCOP (Neuforge et al. 2001), and the OP project (Badnell et al. 2005), agree to within 5%. The abundances themselves could be un-

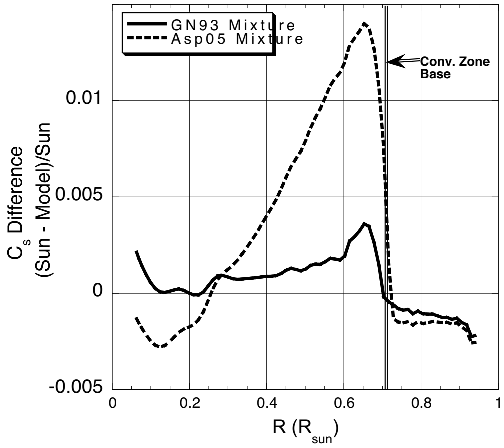

Fig. 1. Sound speed profile differences between inference of Basu et al. (2000) and models calibrated using the GN93 (solid) and AGS05 (dashed) solar mixtures.

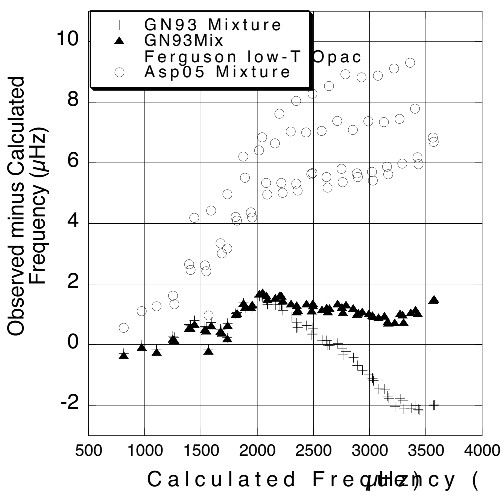

Fig. 2. Observed minus calculated versus calculated ℓ=0, 2, 10, & 20 frequencies for models with GN93 (solid triangles, pluses) and AGS05 (open circles) abundances. The solid triangle model frequencies use the Ferguson et al. (2005) low-temperature opacities for the GN93 mixture, whereas the model with pluses uses the 1995 Alexander & Ferguson opacities.

certain; however, Antia & Basu (2005) find that, in order to restore agreement, the C, N, and O abundances must be increased to the limits of their uncertainties, and the neon abundance must be increased by a factor of 2.5, well beyond the quoted uncertainties. Diffusive element settling could be underestimated; however, Basu & Antia (2004) and Montalban et al. (2004) find that factors of 1.5 or 2 increases in diffusion rates are needed to improve the sound-speed agreement, but the CZ Y abundance and/or CZ depth are still too low. Guzik et al. (2005) considered adjusting the thermal diffusion rates for He separately from C, N, O, Ne, and Mg; for the most promising model, the He thermal diffusion rate was increased by ×1.5, and the element thermal diffusion rate by a factor of 4. While the sound-speed CZ depth are improved, the CZ Y abundance is slightly low, and there is no physical justification for such large thermal diffusion increases. Combinations of effects could also be invoked, e.g. smaller abundance increases, combined with increased opacities, or with enhanced diffusion, as shown by Montalban et al. (2004), Turck-Chiéze et al. (2004), and Basu & Antia (2004), but are contrived and unsatisfying.

Antia & Basu (2005) and Bahcall et al. (2005) investigate an increase in neon abundance. The neon abundance is not derived from photospheric lines, but rather is measured in relation to the oxygen abundance in the solar corona, and same ratio is assumed for the photospheric value. A high Ne abundance has been derived based on x-ray spectra for nearby stars (Drake & Testa 2005), but is only a factor of 2.7 higher than the AGS05 value (not ×4 as required). Whether the Ne abundance of nearby stars is appropriate to the Sun, and also why the coronal O/Ne ratio for the Sun would be so different from the photospheric ratio, would need to be explained.

4. Other considerations

We could consider other possibilities, such as late accretion of surface material depleted in heavier elements. Perhaps the first ∼98% of the Sun's mass acccumulated could have had higher Z, similar to the GN93 mixture, while the last ∼2% had a lower-Z and accreted after the Sun began core hydrogen burnng and was no longer fully convective. Another possibility is that the seismically-inferred convection zone depth is not correctly reproduced by the mixing-length theory. Perhaps there are physical effects missing in the models that could mimic opacity enhancements, such as entropy generation by seismic waves, as discussed by Press (1981).

5. Conclusions

Perhaps the new abundance determinations should be reconsidered in light of the difficulties of fitting helioseismology. However, Asplund et al. (2005) remark: " . . . we consider it unlikely that our derived abundances are as far from the real values as suggested by these helioseismology studies. It would be a remarkable conspiracy of factors if this were the case, considering that the atomic and molecular based abundances now finally agree, the lack of any significant trends in derived abundances with line strength or excitation potential and the almost perfect match between observed and predicted line profiles, including their asymmetries. . . . a great deal of fine-tuning would be necessary to simultaneously bring the C, N, and O abundances up by some 0.2 dex if at all possible." Even if the solution for helioseismology is a revised upward Ne abundance, the solar C, N and O abundances are still much lower than previously believed. This result alone would have implications for stellar and galactic chemical evolution, and interpretation of cluster HR diagrams. Since we do not understand fully the origin of the present interior structure of the Sun, any missing or incorrect physical effects in our models might have a larger effect in interpreting asteroseismic data and determining the structure of other types of stars.

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