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Problems for the standard solar model arising from the new solar mixture

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Abstract. The solar photospheric abundances have been revised downward after reanalysis of the solar spectrum using improved atomic physics and three-dimensional dynamical model atmospheres (Asplund et al. 2005). The revised photospheric Z/X is now 0.0165±0.0017 (Z ∼ 0.0122), lower than the previous determination of Grevesse & Sauval (1998) of 0.0230±0.0023 (Z ∼ 0.0171). Adopting these new abundances results in solar models that have sound speed discrepancies of about 1.4% below the convection zone base, as well as a too-shallow convection zone, and too-low convection zone helium abundance compared to those inferred from helioseismic data. Here we review attempts to restore agreement, e.g., enhanced diffusive settling, increased opacities below the convection zone, increased neon abundance, and accretion of lower-Z material early in the sun's main-sequence lifetime. While these proposed solutions mitigate the effects of the new abundances, no single change that restores agreement is physically justified, and a solution invoking combinations of changes seems contrived. The questions remain of whether we should adopt these new abundances, and, if they are confirmed, what are the implications for solar model physics and consequences for modeling the interiors of other stars.

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

1. Introduction

Until 2004, we thought we knew very well the interior structure of the sun and how it reached its present state. Evolved solar models with the latest input physics (including diffusive settling) reproduced the sound speed profile determined from seismic inversions to within 0.4%, as well as the seismically-inferred convection zone (CZ) depth and CZ helium abundance.

However, new analyses of the sun's spectral lines revise downward the abundances of elements heavier than H and He, particularly the abundances of carbon, nitrogen, and oxygen that are contributing to the opacity just below the CZ (Asplund et al. 2005; AGS05). Compared to the older Grevesse & Savual (1998; GS98) abundances, the AGS05 abundance of C is lower by 35%, N by 27.5%, O by 48%, and Ne by 74%. The abundances of elements from Na to Ca are lower by 12 to 25%, and Fe is decreased by 12%. For the GS98 abundances, the ratio of the element to hydrogen mass fraction Z/X = 0.023, and Z ∼ 0.018, while, for the new abundances, Z/X = 0.0165, and Z∼0.0122.

Models evolved with the new abundance mixture give worse agreement with helioseismic constraints; the sound-speed discrepancy is 1.4% below the CZ base, and the CZ depth is shallow and CZ helium abundance low compared to those derived from seismic inversions. We are reluctant to dismiss these new abundances because of the many improvements in physics and models included, namely 3D dynamical atmosphere models, non-local thermodynamic equilibrium corrections for important elements, and updated atomic and molecular data. Line profile shapes now agree nearly perfectly with observations. Also, it is impressive that abundances derived from several different atomic and molecular lines for the same element now are consistent.

Here we review the input and assumptions for standard one-dimensional evolved solar models, results of helioseismic tests using the old and new abundances, and ongoing attempts to resolve these discrepancies. This is an update to an earlier review by Guzik (2006).

2. Solar evolution modeling

Until recently, solar interior modelers have had little impetus to progress beyond one-dimensional spherical models of the sun, with perhaps the exception of introducing some additional mixing below the CZ to deplete surface lithium and reduce the small remaining sound-speed discrepancy at the CZ base. For the Grevesse & Noels (1993; GN93) or GS98 abundances, the simplest 'spherical sun' assumptions appeared nearly adequate for solar modeling. These include one-dimensional zoning (concentric shells in hydrostatic equilibrium), initial homogeneous composition, negligible mass loss or accretion, neglecting rotation and magnetic fields, simple surface boundary conditions, mixing-length theory of convection (e.g., Bohm-Vitense 1958), and no additional mixing or structural changes from convective overshoot, shear from differential rotation, meridional circulation, waves, or oscillations.

In addition, the latest physical data applied without modification produced good agreement with helioseismology. Examples of these data include opacities (e.g., OPAL (Iglesias & Rogers 1996) or OP (Seaton & Badnell 2004)) supplemented by low-temperature opacities (e.g., Ferguson et al. 2005); equation of state (e.g., OPAL (Rogers et al. 1996), MHD (Däppen et al. 1988), or CEFF (Christensen-Dalsgaard & Däppen 1992)), nuclear reaction rates (e.g., Angulo et al. 1999), and diffusive element settling (e.g., Burgers 1969; Cox, Guzik, & Kidman 1989; Thoul, Bahcall, & Loeb 1994). The solar models produced by the Los Alamos group shown here use the OPAL opacities, Ferguson et al. (2005) or Alexander & Ferguson (private communication, 1995) low-temperature opacities, SIREFF EOS (see Guzik & Swenson 1997), and Burgers' diffusion treatment as implemented by Cox, Guzik, & Kidman (1989; CGK89).

The models are calibrated to the present solar radius 6.9599×10^{10} cm (Allen 1973), luminosity 3.846×10^{33} erg/g (Willson et al. 1986), mass 1.989×10^{33} g (Cohen & Taylor 1986), age 4.54 ± 0.04 Gyr (Guenther et al. 1992), and adopted photospheric Z/X ratio. For evolution models, the initial helium abundance Y, initial element mass fraction Z, and mixing length to pressure scale height ratio α are adjusted so that the final luminosity, radius, and surface Z/X match the observational constraints.

Helio- and asteroseismology has turned out to be an excellent way to test the physics of stellar models. See the paper by Christensen-Dalsgaard for an introduction to stellar seismology. Basu & Antia (2004a), Bahcall & Pinsonneault (2004), and Turck-Chièze et al. (2004) authored some of the first papers to examine the effects of the new abundances on solar models. Table 1 compares the calibrated evolution models of Guzik, Watson, & Cox (2004, 2005; GWC04 and GWC05) using the GN93 and AGS05 mixtures. For the AGSO5 model, the CZ Y abundance is low (0.2273) and the CZ base radius 0.7306 $R_\odot$ is shallow compared to the seismically inferred CZ Y abundance of 0.248 ± 0.003 and CZ base radius of 0.713 ± 0.001 $R_\odot$ from Basu & Antia (2004a).

Figure 1 shows the differences between inferred and calculated sound speed for calibrated evolved models using the old and new abundances, and Fig. 2 shows the observed minus calculated frequency differences. The inferred sound speed is from Basu et al. (2000). The discrepancy with the new abundances is much larger than with the old abundances.

Table 1. Calibrated model properties for GN93 and AGS05 mixtures

Model	GN93	AGS05
Y_o	0.2703	0.2570
Z_o	0.0197	0.0135
α	1.770	1.995
Z_{CZ}	0.0181	0.0124
Y_{CZ}	0.2418	0.2273
R_{CZB} ($R_\odot$)	0.7133	0.7306

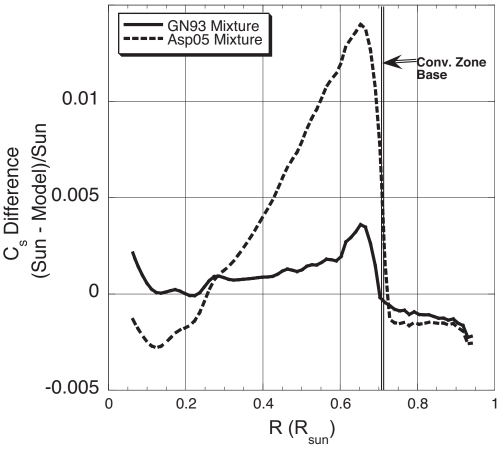

Fig. 1. Difference between inferred and calculated sound speeds for models with the GN93 and AGS05 abundances.

The uncertainties in sound speed inversions are much smaller than the differences between these curves, at most a few widths of the plotting line. The observational uncertainties for the modes of Fig. 2 are less than 0.1 μHz

3. Attempts to restore agreement

We are aware of the following changes applied to solar models to attempt to mitigate the discrepancy with seismic constraints for the new abundances: Increased opacities below the CZ (11-21%); neon abundance increase ($\times\sim$4); increased abundances (within uncertainty limits, or using alternative determinations); enhanced diffusive settling rates ($\times$1.5 or more); accretion of lower-Z material early in the sun's lifetime; structure modification below the CZ base due to radiative damping of gravity waves; tachocline mixing (also used with old abundances); convective overshoot; combinations of the above. The conclusion has been that it is difficult to match simultaneously the new Z/X and helioseismic constraints for CZ depth, sound speed and density profiles, and CZ helium abundance by applying these changes.

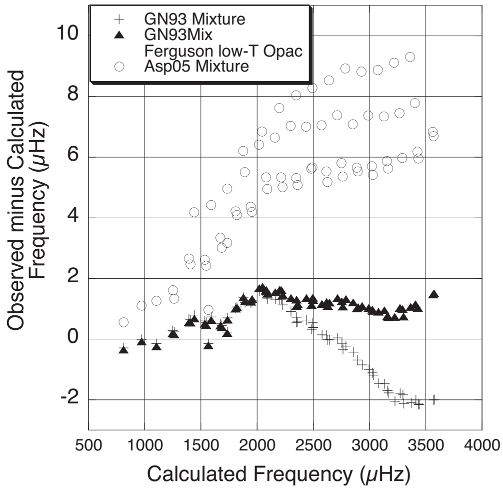

Fig. 2. Observed minus calculated versus calculated ℓ=0, 2, 10, & 20 frequencies for models with GN93 (triangles, pluses) and AGS05 (open circles) abundances. The triangle-labeled model uses the Ferguson et al. (2005) low-temperature opacities for the GN93 mixture, whereas the model labeled with pluses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

4. Opacity increases

Serenelli et al. (2005), Basu & Antia (2004b), Montalban et al. (2004), Bahcall, Serenelli, & Pinsonneault (2004), Bahcall et al. (2005), and Bahcall, Serenelli, & Basu (2005) investigated the effects of increasing the opacities below the CZ. They find that opacity increases of up to 21% from the OPAL values in a localized region below the CZ reduce the sound-speed discrepancy and improve the CZ depth. The sound-speed discrepancies are a little smaller with a broader constant opacity increase of 11% applied over the 2 to 5 million K region below the CZ.

Although improvements to the solar model can be made by *ad hoc* opacity increases, there is little justification for such large enhancements, at least as judged by the opacity differences from independent groups producing solar opacity data. Badnell et al. (2005) find that the OP opacities are higher than the OPAL opacities by at most 2.5% just below the CZ. The Los Alamos LEDCOP opacities (see Neuforge-Verheecke et al. 2001) are lower than the OPAL opacities below the CZ by about 3%, in the wrong direction to improve agreement.

5. Neon and other element abundance increases

For awhile, it was thought that an increase in the solar neon abundance provided the most plausible resolution to this problem. Neon is not measured in photosphere due to lack of suitable spectral lines. Instead, its abundance is determined relative to oxygen using lines formed in the solar corona, XUV and gamma ray spectroscopy of quiet and active regions, and solar wind particle collections. AGS05 adopt a Ne/O abundance ratio of 0.15, and apply this ratio to the photospheric oxygen abundance to derive the Ne abundance. The neon abundance has been revised downward by 74% from the GS98 value, for the most part due to the oxygen abundance reduction

This Ne/O ratio was questioned by Drake & Testa (2005), who determined a ratio from x-ray spectra of 21 nearby stars of 0.4, or 2.7× greater than AGS05 value. However, Schmelz et al. (2005) examine x-ray spectra for the full-disk sun and for active regions, and find a Ne/O ratio of 0.15, the same as used by AGS05. Young (2005) finds 0.17±0.05 from EUV lines in the quiet sun, in good agreement with Schmelz et al. For α Cen, Liefke & Schmitt (2006) find a coronal Ne/O ratio of 0.28. The debate about the sun's Ne/O abundance, and whether it is anomalous compared to nearby or solar-like stars, continues.

Several groups explored models with enhanced neon. Antia & Basu (2005) suggest an increase of about 0.67±0.06 dex for OPAL opacities, or more than a factor of four. Bahcall, Basu, & Serenelli's (2005) model with a 0.6 dex increase has an acceptable CZ Y abundance of 0.244 and CZ base radius of 0.712 $R_\odot$. Turck-Chièze et al. (2005) find that a slightly smaller Ne enhancement of 0.5 dex over the AGS05 value nearly restores the sound speed agreement. Delahaye & Pinsonneault (2005) increase Ne by 0.64 dex to restore the agreement with the CZ depth. However, their resulting model has large sound speed discrepancies in the deeper interior, leading them to conclude that a Ne enhancement alone will not restore agreement.

More modest Ne enhancements, combined with increases in the other element abundances of ~0.05 dex, at the limit of the AGS05 uncertainties, have also been considered. Bahcall, Basu, & Serenelli's best model has Ne enhanced by 0.45 dex (2.8×), Ar by 0.4 dex, and C, N, and O by 0.05 dex. This model produces reasonably good agreement with the inferred sound speed and density profile, and has CZ base radius 0.715 $R_\odot$, and acceptable CZ Y= 0.2439.

Of course any increase in abundances from the AGS05 value will mitigate the problem. Turck-Chièze et al. (2004) show the effects of adopting the Lodders (2003) abundances with a different normalization to meteoritic abundances and Z~0.0133. They also try the Holweger (2001) solar abundances, with a Z/X of 0.021, intermediate between GS98 and AGS05. The Holweger abundances are derived with a different approach than that of AGS05, using 1D semi-empirical rather than 3D theoretical model atmospheres.

6. Enhanced diffusion

Several groups, e.g., Basu & Antia (2004a), Montalban et al. (2004), GWC05, and Yang & Bi (2007) considered the effects of enhanced diffusion. At first this idea might seem promising, because the solar interior could have higher abundances that give good sound speed agreement, while the CZ elements could be depleted to the AGS05 photospheric values. In practice, the requred diffusion increases are quite large (factors of 1.5 to 2 on absolute rates), and enhanced diffusion also depletes the

CZ Y abundance to well below the seismic determination, and leaves the CZ too shallow.

The diffusion coefficients themselves should not be in error by as much as factors of 1.5 or 2; estimates of diffusion velocity uncertainties for Fe and O, the main contributors to opacity below the CZ, are at most 35% (Montalban et al. 2006). In particular, the gravitational settling that depends mainly on the gravitational force should not be in error by such a large factor. GWC05 investigated varying the thermal diffusion coefficients alone apart from gravitational settling (see Section 9 below); thermal diffusion contributes about 40% to the diffusion velocity below the CZ (CGK89; Turcotte et al. 1998).

7. Gravity waves and dynamical effects

Arnett, Meakin, & Young (2006, private communication) have been investigating, following Press (1981) and Press & Rybicki (1981), the effects of gravity waves excited and launched inward at the CZ base. The radiative damping of these waves as they travel inward deposits energy and changes the solar structure in the same way as would an opacity enhancement. The expected wave spectrum and amplitudes still need to be worked out, but could remove as much as half of the sound-speed discrepancy.

8. Combinations of effects

Finally, several groups considered combinations of changes, such as diffusion, opacity, and abundance enhancements. Basu & Antia (2004a) find that agreement can nearly be restored with diffusion plus abundance increases, as is seen for their FULL2M model, calibrated to Z/X = 0.0218. This model has the abundances of C, N, O, Ne, and Ar reduced by 0.03 dex from the GS98 abundances. For this model, the Y abundance is still a little low (0.2317), but the CZ base radius agrees well with the seismic value (0.7138 $R_\odot$). Montalban et al. (2004) present several models with combinations of opacity, diffusion, and abundance modifications. Their best model (D3) with a diffusion rate increase of 1.5 and opacity increase of about 7% at the CZ base has Y = 0.239, and CZ base radius 0.715 $R_\odot$.

9. Examination of three attempts to restore agreement

Here we discuss three of our attempts to restore agreement: enhanced thermal diffusion, accretion, and convective overshoot Table 2 summarizes the properties of these models compared to models with AGS05 and GN93 abundances.

Enhanced thermal diffusion. Enhanced diffusion models have the attraction of retaining higher Z in the core, while producing the observed lower photospheric abundances. GWC05 investigated lowering the binary thermal resistance coefficients (enhancing thermal diffusion) for elements and He by different amounts. Figure 3 shows the sound speed discrepancy for a model with resistance coefficients $\times 1/4$ for C, N, O, Ne, Mg and $\times 2/3$ for He. For this model, the CZ depth is still a little shallow, 0.718 $R_\odot$, and the CZ Y is still a little low, 0.227. But there is no justification for these *ad hoc* changes in thermal diffusion coefficients.

Accretion. GWC04 and GWC05 proposed accretion of material depleted in heavier elements as another way to keep the interior structure more like that obtained using higher abundances. In this scenario, the pre-main sequence sun would have ~98% of its present mass, and a higher Z with a mixture similar to the GN93 or GS98 abundances. The last ~2% of material accreted would have lower Z, and be accreted after the sun begins core hydrogen burning and is no longer fully convective.

To test this possibility, a model was evolved starting with Z=0.0197 on the zero-age main sequence, and material was progressively added that reduced the CZ Z by 0.001 over six steps of about six million years, giving the model time to equilibrate to a new shallower CZ depth and leave behind the higher-Z composition gradient after each step (Guzik 2006). The final accretion episode left the CZ with Z=0.0137. After 36 million years, the model was evolved normally (including diffusive settling), and calibrated as usual to the

Table 2. Structure results for several models

Model	Max Sound Speed Δ%	Photosphere Z/X	R_{CZB} ($R_\odot$)	Y_{CZ}
GN93	0.004	0.0244	0.7133	0.2419
AG05	0.014	0.0163	0.7306	0.2273
Enhanced diffusion	0.006	0.0206	0.7175	0.2269
Low-Z accretion	0.012	0.0170	0.7235	0.2407
Convective overshoot	0.012	0.0164	0.7038	0.2292

observed luminosity, radius, and AGS05 Z/X value.

Figure 3 shows the sound speed differences, with some improvement in sound speed agreement, except near the CZ base. Compared to the AGS05 model, the accretion model has a less shallow CZ base radius of 0.7235 $R_\odot$, and a nearly acceptable CZ Y abundance of 0.2407. The very steep Z abundance gradient at the CZ base in the accretion model (see Guzik 2006) might have a detectable signature in the seismic frequencies. Basu (1997) finds that inversions appear to rule out such steep composition gradients at the CZ base.

Castro et al. (2007) also approximated an accretion model by instantaneously decreasing the Z abundance in the CZ in an early main-sequence model (age 74 My). They do not find an improvement in the CZ depth, as we did for our model, but find about the same CZ Y abundance, 0.240, and improved sound speed agreement except near the CZ base.

Convective overshoot. It is possible that the CZ depth predicted using standard mixing-length theory is too shallow, and convective motions are extending the nearly adiabatically stratified part of the CZ to the depth inferred seismically. Some recent work on this subject has been published by Rempel (2004). To examine this possibility, we evolved models with AGS05 abundances, but extending the CZ that follows the adiabatic gradient to a depth that optimizes agreement with the sound speed inversions. We hoped that a deeper CZ would also inhibit diffusion and keep the CZ Y abundance higher.

For the first overshoot model, the CZ depth is 0.704 $R_\odot$, deeper than inferred seismically. The sound speed agreement is improved only

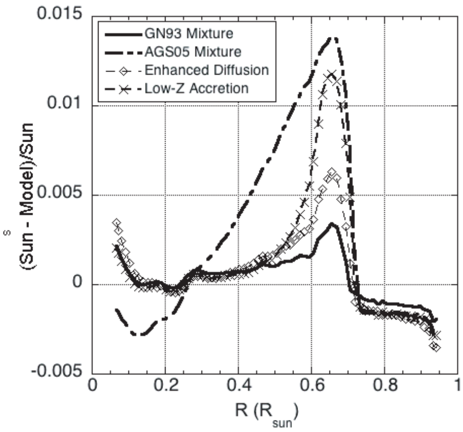

Fig. 3. Difference between inferred and calculated sound speeds for models with the GN93 and AGS05 abundances, and with enhanced diffusion or low-Z accretion.

within the CZ, but not much below it (Fig. 4). The deeper CZ does not inhibit Y diffusion as hoped. For the second model, we decided to extend the CZ even deeper, to 0.64 $R_\odot$ (Fig. 4). The sound speed gradient at the base of this adiabatically stratified CZ clearly does not agree with the seismically-inferred one. It appears that overshooting alone is not a solution to this problem.

10. Assessment and alternatives

The new photospheric element abundances give worse agreement with helioseismology. Simple single changes in the input physics of solar models do not restore agreement and are not physically justified. Combinations of effects (increased opacities, abundances, and dif-

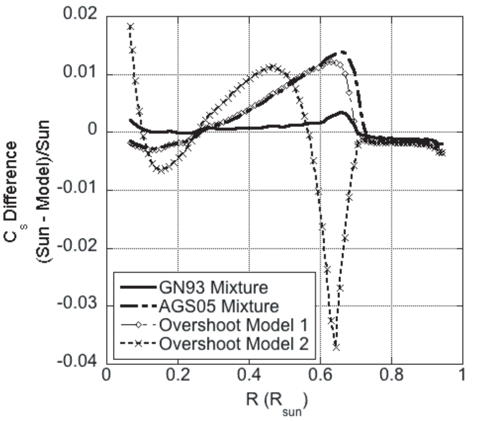

Fig. 4. Difference between inferred and calculated sound speeds for models with the GN93 and AGS05 abundances, and with convective overshoot.

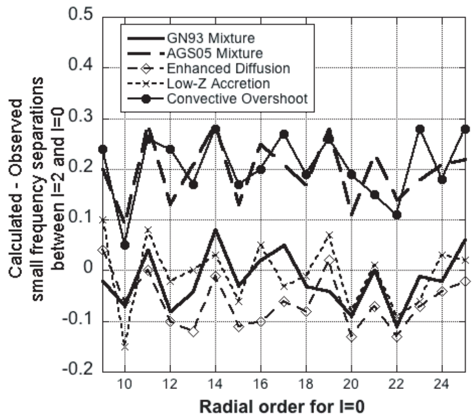

Fig. 5. Difference between calculated and observed small separations for ℓ=0 and 2 modes for five models.

fusion) are more physically plausible, but seem contrived and do not completely restore agreement.

What else should be considered? Perhaps the new AGS05 abundance determinations are not correct. The abundance determinations are being reviewed carefully by Asplund et al. and other groups. Socas-Navarro & Norton (2007) recently derived a NLTE photospheric oxygen abundance consistent with the Asplund et al. values. As noted by Pinsonneault & Delahaye (2006) and Stein (2007, private communication), 3D atmospheres don't reproduce the solar center-to-limb intensity variation, so radiation transport model improvements are being pursued.

Some of the proposed solutions would be more successful if the CZ Y abundance as determined from inversions could be reduced. The CZ Y inference depends on the EOS in the solar convection zone. However, the EOS does not seem to be very uncertain, with the CEFF, OPAL, MHD, or SAHA-S EOSs not giving very similar results, and not able to accommodate a Y of 0.22 to 0.23 as required (Boothroyd & Sackmann 2003; Basu & Antia 2004a; Lin and Däppen 2005; Ayukov et al. 2006).

Ideally, one would like to infer the convection zone Z abundance or even individual element abundances directly from their seismic signature, which also depends on the EOS of the elements ionizing in the CZ. Antia & Basu (2006) use the ionization signature in the sound speed derivative to infer CZ Z = 0.0172±0.002, closer to the old abundances. Lin et al. (2007) show that a lower Z increases the discrepancy with inversions for the adiabatic index Γ_1. Lin & Däppen (2005) find, however, that a reduction in carbon abundance, in the direction of the new AGS05 abundances, can improve the sound speed inference. It seems that it would be worthwhile to continue to pursue EOS improvements to better infer the CZ abundances.

The small frequency separations between low-degree modes that are sensitive to the core structure have been used to constrain the core Z abundance. Chaplin et al. (2007) find Z = 0.0187-0.0239; see also Basu et al. (2007); Zaatri et al. (2007). These results don't rule out the accretion or enhanced diffusion options which can retain high core Z, but disfavor the prospect that the new abundances were present initially throughout the sun. Figure 5 shows the small frequency separation differences of the Guzik et al. models minus the solar-cycle corrected frequency differences from the BiSON group (Chaplin et al. 2007). The AGS05 model and the overshoot model where the core Z is low do not agree as well with data.

11. Implications for other stars

A few papers are appearing that consider whether observations and models of other stars support or disfavor the new abundances. Alecian et al. (2007) find that the new abundances improve calibration of the pre-main sequence binary system RS Cha. VandenBerg et al. (2007) find that isochrone fits to M67 favor old abundance mixture. Perhaps missing pieces to this puzzle will be more apparent in light of comparing models and observations of other stars.

12. Conclusions

A resolution to the new solar abundance problem is not obvious. Most seismic evidence disfavors the new abundances, and stellar models cannot be plausibly adjusted to restore agreement. But the improvements in the physics of new abundance determinations, and successes in line profile matching and self-consistency of abundance determinations cannot be easily dismissed. The helioseismic match with observations wasn't perfect even with the old abundances, and may have been fortuitous, a result of compensating errors. We know that some physical effects are being neglected, and now is a good time to re-examine all of our assumptions and input physics. It may be that nonspherical and dynamical effects need to be included in evolutionary models of the sun to resolve this problem.

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