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# Implications of the new solar abundances for the late evolution of the Sun

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**Abstract.** Evolved solar models based on the recent abundance determination of Asplund et al. (2005) have shown poor agreement with helioseismic inferences in an area near the convection zone base. Multiple ad hoc methods have been attempted to reconcile these abundance determinations with helioseismic measurements, but no satisfactory resolution has yet been reached. Although the agreement is worsened just below the convection zone, the core and surface structure derived using the new abundances is not as discrepant with helioseismology at the present stage of the Sun's evolution. Evolution depends most heavily on the core values, with the radius depending more upon the abundances in the convection zone. Thus, it may be possible to get an indication of the Sun's future evolution with the new abundances despite the helioseismic disagreement occurring for the present Sun near the convection zone base. Here we compare models of the Sun evolved through core hydrogen exhaustion that are calibrated to the present luminosity, mass, and radius at age 4.54 Gyr using the Asplund et al. (2005) and Grevesse & Noels (1993) abundances.

**Key words.** Sun: abundances – Sun: interior – Sun: evolution

## 1. Introduction

The models presented here were calculated using the Iben stellar evolution code updated to include modern nuclear reaction rates, abundances, opacities, equation of state, and diffusive settling. Details of the evolution code and calibration parameters used are described in Guzik et al. (2005) and references therein. The solar abundances tested here are the Grevesse & Noels (1993, hereafter GN93) and Asplund et al. (2005, hereafter AGS05) mixtures. OPAL opacity tables used for the solar interior (Iglesias & Rogers 1996) and low-temperature opacities important near the surface (Alexander & Ferguson 1995; Ferguson et al. 2005) have been produced for both the GN93 and AGS05 mixtures. Once calibrated to current solar conditions at 4.54 Gyr, the model evolution is continued until core hydrogen is depleted at ∼ 10 Gyrs.

## 2. Comparison of Solar Evolutions

Three models were evolved, the first model (GN93old) from OPAL opacity tables using the GN93 mixture as well as low-temperature opacities calculated by Alexander & Ferguson (1995). The second model (GN93new) uses the same GN93 opacities but replaces the low-

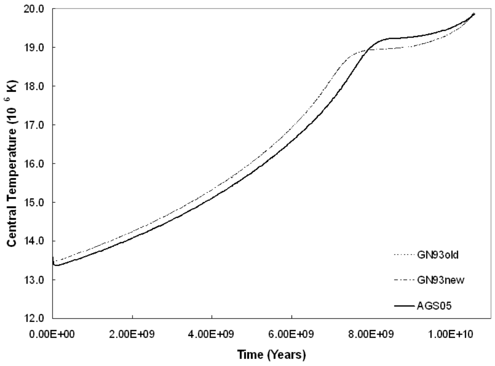


**Fig. 1.** With drastically reduced amounts of C, N and O to burn at temperatures above ~ 18 million K, model AGS05 must burn hotter in order to maintain hydrostatic equilibrium.

temperature opacities with a newly calculated table described in Ferguson et al. (2005). The third model (AGS05) was calculated with OPAL and low-temperature opacity tables constructed from AGS05 abundances. The models were calibrated to the correct mass, radius, luminosity and age for a current surface abundance ratio of $Z/X = 0.0245$ for the GN93 mixture or $Z/X = 0.0165$ for the AGS05 mixture.

Although the agreement between helioseismology and solar models is worsened just below the convection zone, where properties are largely dependent upon abundance choice, the core and surface structure derived from the new abundances are comparable to the GN93 models. Since evolution depends most heavily on the core values, with the radius depending upon the abundances in the convection zone near the surface, a good indication of the Sun's future evolution can be predicted regardless of the current helioseismic disagreement occurring directly below the convection zone base. The GN93 models share virtually identical evolutionary properties and the AGS05 model follows the expected trend; evolving slower than the GN93 models due to the lower central density and opacity resulting from lower metal abundances. In terms of evolution, the lower metal abundances, specifically the reduced C, N and O become increasingly important in late main sequence evolution when the Sun's core temperature rises above ~ 18 million K. Here the CNO cycle becomes the dominant source of energy production and the lower central density leads to hotter burning in order to maintain hydrostatic equilibrium. Thus, the central temperature rises faster than in the more metal rich models above ~ 18 million K, as seen in Figure 1. The implications of these evolutionary differences are important for the assumptions about stellar evolution that extend from our knowledge of solar evolution. If a star of a given mass turns off the main sequence at a later time, as with the AGS05 model, it will affect the interpretation and comparison of synthetic cluster diagrams with data. The result is a different age interpretation for both old globular clusters and also younger open clusters.

## 3. Conclusions

A favored solution to the discrepancy between helioseimology and the AGS05 abundances is that Ne is underestimated in AGS05 by ~ 2.5x (Drake & Testa 2005). Even if this is the case, the C, N and O abundances are still much lower than previously believed. If these abundances are lower everywhere, then stars doing any nuclear burning by the CNO cycle will all be affected and the isochrones used for producing synthetic cluster HR diagrams must be different than previously believed.

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