Abstract

We discuss the current Standard Solar Model conflict between helioseismology and photospheric abundances, a speculation that connects this anomaly to formation of the gaseous giant planets, and a possible neutrino measurement to directly test solar core metalicity.

Key words: standard solar model, CN cycle, neutrinos, gaseous giant planets

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1. Helioseismology and Photospheric Abundances

This talk summarizes some recent work [1] on a discrepancy in the Standard Solar Model (SSM) – a conflict between helioseismology and the new metal abundances that emerged from improved modeling of the photosphere – and on a possible connection to a key SSM assumption, that the early Sun was chemically homogeneous due to its passage through the fully convective Hayashi phase. We suggest a speculative mechanism – planetary formation – that could invalidate this assumption, and an opportunity, CN-cycle neutrinos, for independently determining the Sun’s central metallicity.

The SSM assumes local hydrostatic equilibrium and proton burning by the pp chain and CN cycle, with the latter accounting for about 1% of energy generation. The Sun’s evolution from zero-age on the main sequence is constrained by various boundary conditions (initial mass, present luminosity, etc.), including the initial composition. Assuming a homogeneous proto-Sun, the initial core metalicity (Z) is fixed to today’s surface abundances under the assumption that these have changed little over the past 4.6 b.y. of solar evolution, while the He/H ratio is adjusted to produce the correct modern luminosity. Small corrections due to diffusion of heavy elements are made in the model.

Photospheric absorption lines are the only practical way to fix the abundances of certain volatile elements such as C, N, and O. Metals influence the SSM through bound→free transitions that affect the opacity, with O and Ne being important for temperatures char-
characteristic of the upper radiative zone. Until recently, metallicities determined from interpretations of photospheric absorption lines, e.g., the 1998 work of Grevesse and Sauval [2], led to SSM sound speed profiles that agreed with helioseismology. These earlier line analyses were based on 1D models of the photosphere, despite known stratification, convection, and inhomogeneities. To address these deficiencies, parameter-free 3D models were developed. These more complete models markedly improved line shapes and the consistency of line sources. The new analyses [3], however, led to a significant reduction in Z, 0.0169 → 0.0122, altering SSM sound speeds and destroying the once good agreement between helioseismology and the SSM (see Fig. 1).

The reduced Z also affects the SSM 8B neutrino flux, due to the sensitivity of this prediction to core temperature. The change from GS98 [2] to AGS05 [3] abundances lowers the 8B flux prediction from 5.95 to 4.72 × 10^6/cm^2/s. The 391-day SNO NCD-phase result is 5.54 ± 0.32 ± 0.35 × 10^6/cm^2/s [4].

2. Metals in the Early Solar System

The convective zone extends over the outer 30% of the Sun by radius and contains about 3% of the Sun’s mass. The change from GS98 to AGS05 abundances lowers the total metal content of this zone by 50 M_☉. Interestingly, the one known example of large-scale metal segregation in the solar system, the formation of the gaseous giant planets, concentrates a similar amount of metal, ~ 40-90 M_☉, depending on modeling uncertainties. The conventional picture (see [1] for references) places planetary formation late in the development of the solar nebula, when the last few percent of the gas has formed into a disk, with metal-rich grains and ice concentrated in the disk’s midplane. In the core accretion model, midplane interactions allow rocky planetary cores to grow until ~ 10 M_☉, after which the gravitational potential is sufficient to capture gas. Envelope formation is thought to be rapid, requiring perhaps as little as 1My. This process produced
metal enrichments of Jupiter and Saturn of $\sim 3-7$ [5].

The process of planetary formation, by scrubbing metals from an initially homogeneous gas cloud, would produce enough metal-depleted gas to dilute the convective zone. This could lead to a two-zone Sun – a core higher in Z than the surface – contradicting a key SSM assumption and possibly accounting for the apparent discrepancy between helioseismology and photospheric abundances.

This conjecture passes some simple tests connected with the total budget of metals and the total mass of gas that a Jupiter could perturb gravitationally during planetary formation. It requires 1) planetary formation to occur after the Sun developed a radiative core (separating the interior from the exterior) and 2) deposition of a significant fraction of the metal-poor gas onto the Sun. These assumptions do not appear unreasonable [1].

There are several variables in this picture, including the amount of gas processed, the efficiency of the fractionation, whether the fractionation affects all elements equally, and the dynamics of the depleted gas. The constraints include the photospheric abundances and partial abundances for Jupiter and Saturn, determined from Galileo, Cassini, and subsequent modeling [5]. One would need to explore this parameter space to test whether this scenario could quantitatively account for observations.

3. Can Neutrinos Help?

It would be helpful to test the SSM assumption of a homogenous Sun by directly comparing abundances on the surface and in the core. We noted earlier that the $^8$B neutrino flux responds to changes in metalicity due to the influence of metals on core temperature. But the change is modest and not characteristic: many of the 19 parameters of the SSM can be adjusted to produce similar core temperature changes. Changes in fluxes due to parameter variations that alter core temperature will be termed “environmental.”

But CN solar neutrino sources have a linear dependence on core metalicity, in addition to the environmental sensitivity. The BPS08(GS) SSM [6] predicts a modest 0.8% CN-cycle contribution to solar energy generation but measurable neutrino fluxes, e.g.,

$$^{15}O(\beta^+)^{15}N \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8 \text{ cm}^2\text{s}.$$ (1)

Because the CN and $^8$B neutrinos have a similar dependence on the core temperature, environmental uncertainties (solar age, opacity, luminosity,...) produce correlated changes in these fluxes. This correlation (see Fig. 2) allows one to use the measured $^8$B flux [4,7] to largely eliminate environmental uncertainties affecting the CN flux, yielding

$$\frac{R^{\text{SNO+}}(\text{CN})}{R^{\text{SSM}}(\text{CN})} = \frac{X(C+N)}{X_{\text{SSM}}(C+N)} \left( \frac{R^{\text{SK}}(8B)}{R^{\text{SSM}}(8B)} \right)^{0.828} \times [1 \pm 0.03(\text{SK}) \pm 0.026(\text{res env}) \pm 0.049(\text{LMA}) \pm 0.071(\text{nucl})]$$ (2)

The ratio of the CN-neutrino rate R measured in a future deep scintillator detector (e.g., SNO+ [8], Borexino [9], or Hanohano [10]) to that calculated in the SSM appears on the left side. The quantity of interest, the ratio of the primordial core C+N metalicity X to the SSM value, appears as the first term on the right. The proportionality between these ratios can be expressed in terms of the ratio of the measured and SSM rates for Super-Kamiokande (SK). Residual uncertainties include the SK $^8$B measurement
error, remaining environmental dependences (after use of the SK constraint), neutrino oscillation parameters, and nuclear cross sections. Further details are given in [1].

Thus the current overall theoretical uncertainty in relating a future CN neutrino flux measurement to core metalicity is about 9.6%. The dominate uncertainties, those due to flavor physics and nuclear cross sections, can be reduced by future laboratory measurements. SNO+, a deep scintillator experiment that will be constructed in SNOLab, may be able to measure the CN flux to an accuracy of about 10% [8]. Given that recent changes in core metalicity are $\sim 30\%$, it appears that future neutrino experiments may be able to constrain core metalicity at an interesting level of precision.

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