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HELIOSEISMOLOGY AND THE SOLAR NEUTRINO PROBLEM

H. M. ANTIA AND S. M. CHITRE
Tata Institute of Fundamental Research
Homi Bhabha Road, Mumbai 400005, India

The precisely measured frequencies of solar oscillations provide us with a unique tool to probe the solar interior with sufficient accuracy. These frequencies are principally determined by the dynamical quantities like sound speed, density or the adiabatic index of the solar material and a primary inversion of the observed frequencies yields the sound speed and density profiles inside the Sun (Gough et al. 1996). The equations of thermal equilibrium enable us to determine the temperature and chemical composition profiles, but for this additional prescriptions regarding the input physics (i.e., opacities, equation of state and nuclear energy generation rate) are required (Shibahashi 1993; Antia & Chitre 1995; Shibahashi & Takata 1996; Kosovichev 1996). This information in turn can be used to calculate the neutrino fluxes, and the seismic models can thus be used to explore the possibility of an astrophysical solution to the solar neutrino problem (Roxburgh 1996; Antia & Chitre 1997).

The sound speed and density profiles inside the Sun are inferred from the observed frequencies using a regularized least squares technique (Antia 1996). The primary inversions based on the equations of hydrostatic equilibrium, however, provide us with the ratio T/μ, where μ is the mean molecular weight. In order to separately determine T and μ it is necessary to use the equations of thermal equilibrium. Once the temperature, density and composition are known we can calculate the integrated luminosity and the neutrino fluxes. However, the computed luminosity will not necessarily match the observed solar luminosity because of possible errors in the primary inversions as well as the uncertainties in the nuclear reaction rates. This difference in luminosity will give an estimate of uncertainties in the nuclear reaction rates and also the inversions.

We have used the nuclear reaction rates from Bahcall & Pinnsoneault (1995, hereinafter BP95), except for the pp reaction for which we have used the older reaction rate from Bahcall (1989). These inversions have been obtained using a Z profile including diffusion of heavy elements, with surface $Z = 0.018$. A comparison between the X profile in the Sun obtained using GONG months 4–10 data and that in the Model S of Christensen-Dalsgaard et al. (1996) shows the inverted profile to be distinctly flat for $r > 0.68R_\odot$ (Fig. 1). It thus appears that the region just below the convection zone is probably mixed (Richard et al. 1996; Basu 1997) and this may explain the observed low lithium abundance in the solar envelope.

The helioseismically estimated cross-section for the pp nuclear reaction should be $(4.15 \pm 0.25) \times 10^{-25}$ MeV barns, if we admit 5% error in integrated luminosity that incorporates all systematic errors including those arising from a factor of 2 uncertainty in Z. This value is consistent with 4.07×10^{-25} MeV barns (Bahcall 1989), but slightly

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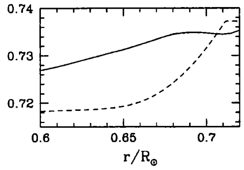

Figure 1. The continuous line shows the hydrogen abundance profile in the Sun as inferred using the GONG months 4–10 data, while the dashed line shows the X profile in Model S of Christensen-Dalsgaard et al. (1996).

higher than the value of 3.89×10^{-25} MeV barns adopted by BP95. However, an increase in the pp nuclear reaction rate by a factor of 2.9 as recently suggested by Ivanov et al. (1997) is certainly unacceptable, because the computed luminosity for seismic models then turns out to be $2.7L_\odot$. Even if opacities are reduced arbitrarily in an attempt to get the correct luminosity, the temperature is correspondingly lowered and in order to maintain the sound speed the hydrogen abundance X needs to be increased to a value exceeding unity! Clearly, such an increase in the pp reaction rate is totally unphysical and in fact, even an increase by a factor of 1.65 can be ruled out from helioseismic data.

It can be readily seen that the neutrino fluxes in seismic models, computed assuming thermal equilibrium, are not very different from those in the standard solar model and evidently these are inconsistent with the observed fluxes. In order to explore the possibility that a relaxation of thermal equilibrium may alter the neutrino fluxes, we use arbitrary X profiles and even after allowing for arbitrary modifications in opacities (or equivalently in the heavy element abundances Z) it turns out to be difficult to construct seismic models which are simultaneously consistent with any two of the three solar neutrino experiments (Antia & Chitre 1997). This is true even when the Sun is not assumed to be in thermal equilibrium and the deductions are freed from any assumptions about input opacity and specific mode of energy transport in the central regions of the Sun. The only premise that is required for the analysis is that the sound speed and density in the solar interior can be prescribed from primary inversions of the helioseismic data and that the nuclear reaction rates are known and neutrinos have standard properties. These results are consistent with those obtained by Heeger & Robertson (1996) from more general considerations, independent of any solar model. The solution to the solar neutrino problem should therefore be sought in terms of nonstandard neutrino properties (e.g., MSW effect).

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