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Helioseismology and solar neutrinos

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1. Introduction

The Sun has been verily described as the Rosetta Stone of astronomy, as this is the one cosmic laboratory which is readily available for studying a variety of physical processes operating both inside and outside the solar body. The internal layers of the Sun are clearly not accessible to direct observations. Nonetheless, it is possible to construct a reasonable theoretical picture of its interior with the help of mathematical equations governing the mechanical and thermal equilibrium of the Sun, together with the appropriate boundary conditions provided by observations. The main issue is about checking the correctness of these numerically constructed solar models. It turns out the Sun is nearly transparent to neutrinos released in the nuclear reaction network operating in the energy-generating core and to wave motions generated in the solar body. Both these probes enable us to 'see' inside the Sun and to infer the physical conditions occurring throughout the solar interior (Chitre 1995).

2. Standard solar Model

The Standard Solar Model (SSM) is constructed using a variety of simplifying approximations. The Sun is assumed to be spherically symmetric with negligible effects of rotation, magnetic field, mass loss and tidal forces on its overall structure and maintaining mechanical and thermal equilibrium. The energy generation is by thermonuclear reactions converting hydrogen into helium mainly by the proton-proton chain and the energy is transported by radiative processes, except in the outer layers which are unstable against convection. There is gravitational settling of helium and heavy elements below the base of the convection zone. The standard nuclear and neutrino physics is adopted for constructing theoretical models to maintain the observational constraint of the present radius and luminosity of the Sun. The broad description of the solar interior that emerges from such a standard solar model. (cf. Bahcall and Pinsonneault 1995) may be essentially valid, but one would like to test how far the theoretical models are tenable.

There have been valiant attempts to measure the flux of neutrinos released by the nuclear reaction network operating in the solar core. The event rates reported by various solar neutrino experiments are shown in Table 1; clearly the observed neutrino fluxes are significantly lower than those predicted by SSM (Bahcall, Basu & Pinsonneault 1998).

Table 1.

Experiment	Threshold energy	Observed ν flux	SSM flux
HOMESTAKE (^{37}Cl)	0.814 MeV	2.56 ± 0.22 SNU	7.70 ± 1.2 SNU
SUPERKAMIOKANDE (H_2O)	7 MeV	2.42 ± 0.07 ($10^6 cm^{-2} s^{-1}$)	5.15 ± 0.72 ($10^6 cm^{-2} s^{-1}$)
GALLEX/SAGE (^{71}Ga)	0.233 MeV	72.5 ± 6.0 SNU	129 ± 8 SNU

1 SNU = 10^{-36} events per target atom per second.

There have been, of course, a number of ingenious suggestions to account forthediscrepancy between theoretical and experimentally measured neutrino fluxes. These include partial mixing of nuclear products in the solar core, presence of rapid rotation / magnetic field and of WIMPS in the central regions, the reductioin of opacity (equivalently, lowering of the metal abundance), alteration of nuclear cross - sections etc. Most of these proposals were intended to reduce the expected flux of medium and high energy neutrinos by lowering the central temperature. But such a cooler solar model is inconsistent with the neutrino experimental data, as it leads to a larger suppression of high energy ^{8}B neutrino flux to which the SUPERKAMIOKANDE experiment is sensitive. The HOMESTAKE experiment that detects the intermediate and high energy neutrinos shows even a larger reduction and we have the paradoxical situation that there is far less, if any of the ^{7}Be neutrino flux seen. The intriguing question is : where are the ^{7}Be neutrinos ? It has also been demonstrated by Hata, Bludman & Langacker (1994) and Castellani et al. (1997) that none of the existing experimental measurements are consistent with each other if the neutrinos are assumed to have standard properties, i.e. no mass, no magnetic moment, no flavour mixing in transit, and the Sun is asssumed to be in thermal equilibrium with constant luminosity, $L_\odot = 3.846 \times 10^{33}$ erg s^{-1}. These deductions based on fairly general considerations are independent of any underlying solar model and in fact, lead to an unphysical situation in that the ^{7}Be neutrino flux turns out to be negative! A cooler solar core thus does not appear to be a viable solution for the solar neutrino puzzle. This has prompted solar physicists to look for an independent, complementary probe to determine the thermal conditions inside the Sun and to explore the solar neutrino problem within the framework of models constrained by helioseismic data.

3. Seismic sun

The surface of the Sun is like a churning ocean; it undergoes a series of mechanical vibrations which manifest as Doppler shifts oscillating with a period centred around 5 minutes (Leighton et al. 1962). These global oscillations are a superposition of millions of standing waves which sample the physical conditions in different layers of the Sun. In much the same way that seismic tremors enable geophysicists to study the internal layers of the Earth, the helioseismic tool provided by a rich spectrum of velocity fields observed at the solar surface, can probe the Sun's interior with extraordinary precision. The accurately measured acoustic frequencies (to better than 1 part in 10^5) provide very stingent constraints on the admissible solar models which clearly have important implications for the predicted solar neutrino fluxes.

The measured frequencies of solar oscillations are in reasonable agreement with those predicted for a standard solar model by forward method (Elsworth et al. 1990). In fact, over the years the agreement has improved with more refined input microphysics like opacities and the equation of state, as well as inclusion of diffusion of helium and heavy elements (Christensen-Dalsgaard, Proffitt & Thompson 1993). The inverse method has been effectively used with the help of equations governing the mechanical equilibrium for inferring the acoustic structure of the Sun by inverting the currently available seismic data. The primary inversions can determine the sound speed through the solar interior to an accuracy of better than 0.1 per cent and the internal density profile to a slightly lower accuracy (Antia & Basu 1995, Gough et al. 1996, Basu 1999).

In order to obtain the temperature and chemical composition profiles, however, we need to supplement the seismically inferred structure (namely, radial distribution of sound speed and density) with equations of thermal equlibrium and mode of energy transport, along with the auxiliary input physics such as opacity, equation of state and nuclear reaction rates (Antia & Chitre 1995; Shibahashi & Takata 1996; Kosovichev 1996). The inverted sound speed, density, temperature and composition profiles constitute seismic solar models which turn out to be pretty close to SSM. The resultant neutrino fluxes computed with the seismic models are, therefore, expected to be in reasonable accord with those predicted by SSM (Bahcall et al. 1997). On the other hand, Roxburgh (1996) has explored the possibility of reducing the neutrino fluxes in seismic models by varying the hydrogen abundance profile as well as by altering certain nuclear reaction rates. Antia & Chitre (1995, 1997) adopted both the sound speed and density profiles from primary inversions to estimate the central temperature of the Sun to be $(15.68 \pm 0.03) \times 10^6$K and to obtain the temperature and helium abundance profiles in the solar core. It turns out that it is possible to determine only one parameter specifying the composition and we, therefore, assume the heavy element abundance to be known and attempt to surmise the helium abundance profile. We then use these seismic models to compute the integrated luminosity which may not necessarily match the observed, $L_\odot$. The variance may be due to uncertainities in primary inversions, assumed heavy abundance profile, input microphysics etc., but the dominant contribution arises from the nuclear reaction rates and opacities. The computed luminosity is very sensititve to the nuclear reaction rate, but depends only weakly on the heavy elemental abundance, Z. It should, therefore, be possible to limit the nuclear reaction rates using the observed solar luminosity. Since the nuclear energy generation in the solar interior is largely controlled by the pp-reaction rate, it is found that in order to satisfy the observed luminosity constraint the proton-proton reaction cross-section should be in the range, $S_{11} = (4.15 \pm 0.25) \times 10^{-25}$ MeV barns (Antia & Chitre 2000). This estimate is based on the assumption that opacities are known to reasonable accuracy with an uncertainity of upto 50% in Z and that there is only upto 3 % uncertainity in the computed luminosity. It can be readily shown that the current best estimates for S_{11} and Z are only marginally consistent with the helioseismic constraints and probably need to be increased slightly by a few percent. The remarkable feature that emerges from these computations is that even if we allow for arbitrary variations in the input opacities and relax the thermal equlibrium requirement, but assume standard properties for neutrinos, it may be feasible to reduce individual neutrino fluxes to the measured values. But it turns out to be very difficult to construct a seismic model that is simultaneously consistent with any two of the three existing solar neutrino experiments within 2σ of the measured fluxes (Antia & Chitre 1995). This clearly suggests that a resolution of the solar neutrino puzzle should be sought in the framewok of non-standard neutrino properties such as the MSW effect.

One of the primary goals of contemporary solar neutrino experiments is to test the physics of nuclear reactions operating inside the Sun and possibly to constrain the properties of neutrinos. An intriguing paradox in the measurement of solar neutrino fluxes is the bahaviour of ^{7}Be neutrinos. The recent measurements from GALLEX/SAGE together with the experimental data from HOMESTAKE and SUPERKAMIOKANDE and the observed solar luminosity constraint lead to a severe suppression of ^{7}Be! The sensitive BOREXINO experiment is, therefore, crucial for a reliable measurement of the total 7Be neutrino flux, but also for its possible time - variations namely, diurnal, indicative of matter oscillations and seasonal, representing a signature of vacuum oscillations.

In conclusion, the accurate helioseismic measurements go beyond providing a basic understanding of the solar structure by turning the Sun into a precision laboratory for studying the physics of high temperature plasmas and neutrino oscillations. It is, tempting to speculate that we are probably poised to witness an overture to another revolutionary discovery in neutrino physics, in which our Sun seems to be playing a modest role.

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