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Perspectives on the Interior of the Sun

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Abstract. The interior of the Sun is not directly accessible to observations. Nonetheless, it is possible to infer the physical conditions inside the Sun with the help of structure equations governing its equilibrium and with the powerful observational tools provided by the neutrino fluxes and oscillation frequencies. The helioseismic data show that the internal constitution of the Sun can be adequately represented by a standard solar model. It turns out that a cooler solar core is not a viable solution for the measured deficit of neutrino fluxes, and the resolution of the solar neutrino puzzle should be sought in the realm of particle physics.

Key words. Sun: Oscillations, rotation, interior.

1. Introduction

The Sun has been aptly described as the Rosetta Stone of astronomy, and its internal layers provide an ideal cosmic laboratory for testing atomic and nuclear physics, high-temperature plasma physics, and neutrino physics and even general relativity. The interior of the Sun is shielded by the solar material beneath the visible surface, but, nevertheless, it is possible to study its internal constitution with the help of equations governing its structure together with the boundary conditions provided by observations. The outstanding question concerns the correctness of the theoretically constructed models of the Sun. It turns out the solar interior is transparent to neutrinos released in the energy-generating core, and also to seismic waves generated through the bulk of the solar body. These serve as complementary probes which furnish reasonably accurate information about the physical conditions prevailing inside the Sun.

The standard solar model (SSM) is the simplest possible configuration with a minimum number of assumptions and physical processes. The Sun is assumed to be a spherically symmetric object with negligible effects of rotation, magnetic fields, mass loss and tidal forces on its global structure. It is supposed to be in a quasi-stationary state maintaining hydrostatic and thermal equilibrium. The energy generation takes place in the central regions by thermonuclear reactions which convert hydrogen into helium mainly by the pp-chain. The energy is transported outwards principally by radiative processes, but the region extending over about a third of the solar radius below the surface is convectively unstable and in these layers the energy flux is carried largely by convection modelled in the framework of a local mixing length theory. There is supposed to be no mixing of nuclear reaction products outside the convection zone, except for the slow gravitational settling of helium and heavy elements by diffusion beneath this zone into the radiative interior. There is no transport of energy by any wave motion and the standard nuclear and neutrino physics is adopted for theoretical models satisfying the observed constraints, namely, mass, radius, luminosity and ratio of chemical abundances (Z/X). Here X and Z refer respectively, to the fractional abundance by mass of hydrogen and elements heavier than helium.

2. Solar neutrinos

The early investigations in solar physics were largely devoted to an extensive collection of spectroscopic data for studying the temperature, density and chemical composition in the surface layers of the Sun. Since the 1960s, there have been experiments set up to measure the flux of neutrinos generated by the nuclear reaction network operating in the solar core (Bahcall & Pinsonneault 1995). The neutrino fluxes are sensitive to the temperature and composition profiles in the central regions of the Sun, and it was hoped that the steep temperature dependence of some of the nuclear reaction rates would enable a determination of the Sun's central temperature to better than a few percent.

There have been valiant attempts since the 1960s to measure the flux of neutrinos released by the nuclear reaction network generating energy in the central regions of the Sun. The predicted capture rate for the Homestake experiment for the standard solar model (SSM) is 7.3 ± 1.2 SNU (1 SNU= 10^{-36} captures per target atom per second) (cf. Bahcall *et al.* 1998). Davis, however, reports measurement of the solar neutrino counting rate to be 2.56 ± 0.22 SNU which clearly shows a puzzling deficit by nearly a factor of 3 over the SSM prediction. The Superkamiokande experiment is sensitive only to the high-energy ^8B neutrinos released by the pp-chain of nuclear reactions. The measured neutrino flux from the Superkamiokande experiment again shows a deficit by about 50% of the flux predicted by SSM.

These two experiments are sensitive only to the intermediate and high energy neutrinos. There are currently two radiochemical experiments using the gallium detector which have a low threshold of 0.233 MeV and are capable of measuring the low-energy pp-neutrinos. The GALLEX and SAGE experiments report measurement of the solar neutrino counting rate of 72.5 ± 6.0 SNU, while the SSM prediction of the neutrino capture rate for the gallium experiment is 129 ± 8 SNU. There is evidently a clear discrepancy between the measured and calculated neutrino fluxes. There have been a number of ingenious suggestions (cf. Chitre 1995) proposed to lower the central temperature of the Sun, in the process causing a depletion of the expected fluxes of medium and high energy neutrinos. But such a cooler solar core is inconsistent with the current experimental measurements, as this leads to even larger suppression of high energy ^8B neutrino flux to which the Superkamiokande experiment is sensitive. The Homestake experiment that detects the intermediate as well as high energy neutrinos shows even a larger reduction in the counting rate. We are thus faced with a paradoxical situation!

One of the primary goals of contemporary solar neutrino experiments is to probe the physics of thermonuclear reactions operating in the central regions of the Sun and, importantly, to constrain the properties of neutrinos. It has been demonstrated by Hata *et al.* (1994) and Castellani *et al.* (1997) that none of the existing solar neutrino experimental measurements are consistent with each other, provided we make the assumptions that neutrinos have standard properties, namely, no mass and hence no magnetic moment and no flavour-mixing during transit, and that the Sun is in thermal equilibrium with a constant luminosity, $L_\odot$. These deductions based on fairly general considerations are independent of any underlying solar model and in fact, they lead to an unphysical situation in that the ^7Be neutrino flux turns out to be negative. A cooler solar core, therefore, does not seem like a viable solution for the missing solar neutrino problem. A possible resolution of this paradox is the operation of propagation effects (cf. Bahcall & Bethe 1990) which would permit the electron neutrinos, by virtue of their tiny mass, to get transformed, during their transit through the solar body or through the space between the Sun and Earth, into neutrinos of a different flavour and as a result a fraction of them go undetected in the current solar neutrino experiments. This has been the conundrum plaguing the community over the past four decades which has prompted solar physicists to look for an independent, complementary tool to probe the thermal conditions inside the Sun.

3. Solar seismology

The surface of the Sun undergoes a series of mechanical vibrations which manifest themselves as Doppler shifts oscillating with a period centred around 5 minutes (Leighton *et al.* 1962). These have now been identified as acoustic modes of pulsation of the entire Sun (Ulrich 1970; Leibacher & Stein 1971; Deubner 1975) representing a superposition of millions of standing waves with amplitude of an individual mode of the order of a few cm/s. The frequencies of many of these modes have been determined to an accuracy of better than 1 part in 10^5. The accurately measured oscillation frequencies provide very stringent constraints on the admissible solar models. The determination of the mode frequencies to a high accuracy, of course, requires continuous observations extending over very long periods of time and this is achieved with the help of ground-based networks observing the Sun almost continuously. The most prominent amongst these networks is the Global Oscillation Network Group (GONG) which comprises six stations located in contiguous longitudes around the world (Harvey *et al.* 1996). Satellite-borne instruments have also been observing the solar oscillations and particularly, the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) with its higher spatial resolution has been able to study solar oscillations with small associated length scales. The accurate helioseismic data of oscillation frequencies may be analyzed in two ways: i) Forward method, ii) Inverse method. In the Forward method, an equilibrium standard solar model is perturbed in a linearized theory to obtain the eigenfrequencies of solar oscillations, and these are compared with the accurately measured mode frequencies (Elsworth *et al.* 1990). The fit is naturally seldom perfect, but comparison indicated the thickness of the convection zone to be close to 200,000 km and the helium abundance, Y in the solar envelope was found to be 0.25. The direct method has had only a limited success, although it led to an improvement of the input microphysics like opacities and equation of state and emphasized the role of diffusion of helium and heavy elements into the radiative interior (Christensen-Dalsgaard *et al.* 1993). A number of inversion techniques (Gough & Thompson 1991) have, therefore, been developed using the equation of mechanical equilibrium to infer the acoustic structure of the Sun.

One of the major accomplishments of the inversion methods was an effective use of the accurately measured solar oscillation frequencies for a reliable inference of the internal structure of the Sun (Gough *et al.* 1996; Kosovichev *et al.* 1997). The profile of the sound speed, $c = \sqrt{\Gamma_1 P/\rho}$ (where $\Gamma_1 = (\partial \ln P/\partial \ln \rho)_s$ is the adiabatic index) can now be determined through the bulk of the solar interior to an accuracy of better than 0.1% and the profiles of density and adiabatic index to somewhat lower accuracy (Gough *et al.* 1996). The agreement between the sound speed profile deduced from helioseismic inversions and SSM is remarkably close except for a pronounced discrepancy near the base of the convection zone and a noticeable difference in the energy-generating core. The hump below $0.7R_\odot$ may be attributed to a sharp change in the gradient of helium abundance profile on account of diffusion. A moderate amount of rotationally-induced mixing immediately beneath the convection zone can smooth out this feature. The dip in the relative sound speed difference around $0.2R_\odot$ may be due to ill-determined composition profiles in the SSM, possibly resulting from the use of inaccurate nuclear reaction rates.

From the recently available seismic data, the helium abundance in the solar envelope is deduced to be 0.249 ± 0.003 (Basu & Antia 1995) and the depth of the convection zone is estimated to be $(0.2865 \pm 0.0005)R_\odot$ (Basu 1998). It has also been possible to surmise the extent of overshoot of convective eddies beneath the base of the convection zone. The measured oscillatory signal is found to be consistent with no overshoot, with an upper limit of $0.05H_p$ (H_p being the local pressure scale height) (Monteiro *et al.* 1994; Basu *et al.* 1994).

The seismic structure of the Sun which we have discussed so far is based on the equations of mechanical equilibrium. The equations of thermal equilibrium have not been used because on oscillatory time scales of several minutes, the modes are not expected to exchange significant amount of energy. The frequencies of solar oscillations are, therefore, largely unaffected by the thermal processes in the interior. However, in order to determine the temperature and chemical composition profiles we need to supplement the seismically inferred structure obtained through primary inversions by the equations of thermal equilibrium, together with the auxiliary input physics such as the opacity, equation of state and nuclear energy generation rates (Gough & Kosovichev 1990; Antia & Chitre 1998; Takata & Shibahashi 1998). It turns out that the inverted sound speed, density, temperature and composition profiles, and consequently the neutrino fluxes, come pretty close to those given by the SSM. In general, the computed total luminosity resulting from these inverted profiles would not necessarily match the observed solar luminosity. The discrepancy between the computed and observed solar luminosity, $L_\odot$ can, in fact, be effectively used to provide a test of the input nuclear physics; in particular, it can be demonstrated that the cross-section for the proton-proton reaction needs to be increased slightly to $(4.15 \pm 0.25) \times 10^{-25}$MeV barns (cf. Antia & Chitre 1998). Note this cross-section has a crucial influence on the nuclear energy generation and neutrino fluxes, but it has never been measured in the laboratory. Indeed, it can be readily shown that the current best estimates for the proton-proton reaction cross-section and metallicity, Z are only marginally consistent with the helioseismic constraints and probably need to be increased slightly by a few per cent (Antia & Chitre 1999).

The seismic models enable us to estimate the central temperature of the Sun which is found to be $(15.6 \pm 0.4) \times 10^6$K, if we allow for upto 10% uncertainty in the opacities (Antia & Chitre 1995). It turns out that it is possible to determine only one parameter specifying the chemical composition and we assume the heavy element abundance, Z, to be known and attempt to surmise the helium abundance profile, *Y*. The inferred helium abundance profile is in fairly good agreement with that in the SSM which includes diffusion, except in the regions just beneath the convection zone where the profile is essentially flat (Antia & Chitre 1998). This is suggestive of some sort of a mixing, possibly arising from a rotationally-induced instability. Interestingly, the temperature at the base of the solar convection zone is $\lesssim 2.2 \times 10^6$ K, which is not high enough to burn lithium. However, if there is some amount of mixing that extends a little beyond the base of the convection zone to a radial distance of $0.68R_\odot$, temperatures exceeding 2.5×10^6 K will be attained for the destruction of lithium by nuclear burning, and this may explain the low lithium abundance.

The remarkable feature that emerges from these computations is that even if we allow for arbitrary variations in the input opacities and relax the requirement of thermal equilibrium, but assume standard properties for neutrinos, it turns out to be 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 (Roxburgh 1996; Antia & Chitre 1997). This suggests that the persistent discrepancy between measured and predicted solar neutrino fluxes is likely to be due to non-standard neutrino physics. In this sense, helioseismology may be regarded to have highlighted the importance of the Sun as a cosmic laboratory for studying the novel properties of neutrinos.

We have been hitherto discussing the spherically symmetric structure of the Sun. It is also possible to determine helioseismically the rotation rate in the interior from the accurately measured rotational splittings. The first order effect of rotation yields splittings which depend on odd powers of the azimuthal order. These odd splitting coefficients can be used to infer the rotation rate as a function of depth and latitude. It is found that the surface differential rotation persists through the solar convection zone, while in the radiative interior the rotation rate appears to be relatively uniform (Thompson *et al.* 1996). The transition region near the base of the convection zone (the tachocline) is centred at a radial distance, $r = (0.7050 \pm 0.0027)R_\odot$ with a half-width of $(0.0098 \pm 0.0026)R_\odot$ (Basu 1997). There is distinct evidence of a shear layer just beneath the solar surface extending to $r \simeq 0.95R_\odot$ where the rotation rate increases with depth.

The helioseismically inferred rotation rate is, indeed, consistent with the measured solar oblateness of approximately 10^{-5} (Kuhn *et al.* 1998). The resulting quadrupole moment turns out to be $(2.18 \pm 0.06) \times 10^{-7}$ (Pijpers 1998), implying a precession of perihelion of the orbit of planet Mercury by about 0.03 arcsec/century, which is clearly consistent with the general theory of relativity.

The even order terms in the splittings of solar oscillation frequencies reflect the Sun's effective acoustic asphericity and can provide a valuable handle to probe the presence of a large-scale magnetic field or a latitude-dependent thermal fluctuation in the solar interior. Further, the local helioseismic techniques like ring diagrams or time-distance helioseismology provide a powerful tool for studying large-scale meridional flows inside the Sun (Kosovichev & Duvall 1999).

It has now been well demonstrated that the frequencies of solar oscillations vary with time and that these variations are correlated with the solar activity (Elsworth *et al.* 1990; Libbrecht & Woodard 1990; Dziembowski *et al.* 1998; Bhatnagar *et al.* 1999). It is expected that these frequency variations should result from structural changes in the layers close to the solar surface in order to show fluctuations over timescales of order 11 years. With accumulating GONG and MDI data over nearly five years during the rising phase of solar cycle 23, it has, indeed, been possible to study temporal variations of the solar rotation rate and other characteristic features associated with the solar envelope. In fact, helioseismic inversions have revealed small temporal variations of the rotation rate in the subsurface layers. These alternating bands of fast and slow rotational bands appear to migrate towards the equator as the solar cycle progresses, reminiscent of the torsional oscillations detected at the solar surface (Howard & LaBonte 1980; Snodgrass 1984), but extending to a depth of some 60 Mm (Howe *et al.* 2000; Antia & Basu 2000).

The frequencies of fundamental, or *f*-modes which are surface modes, are largely determined by the surface gravity and thus provide a valuable tool to probe the near-surface regions as well as an accurate measurement of the solar radius. (Schou *et al.* 1997; Antia 1998). The temporal variations in solar radius by a few kms have also been found to be correlated with solar activity indices (Antia *et al.* 2000). An important application of the accurately measured *f*-mode frequencies is their potential use as a diagnostic of solar oblateness and of magnetic fields just beneath the solar surface, in addition to studying the solar cycle variations of these quantities.

The ongoing efforts in helioseismology will hopefully, reveal the nature and strength of magnetic fields present inside the Sun and will also help in highlighting the processes that drive the cyclical magnetic activity and also locate the seat of the solar dynamo. The accumulating seismic data during the ascending and descending phases of cycle 23 will enable us to study the temporal variation of mode frequencies and amplitudes which should be indicative of the changes in the solar cycle and dynamics. In the process we may also learn how the magnetic field of the Sun changes with the solar cycle and what causes the solar irradiance to vary synchronously with the sunspot cycle. Finally, an unambiguous detection of buoyancy driven gravity modes would furnish a powerful tracer of the energy-generating regions of our Sun!

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