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Seismic View of the Solar Interior

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Abstract. The interior of the Sun is not directly observable to us. Nevertheless, it is possible to infer the physical conditions prevailing in the solar interior with the help of theoretical models coupled with observational input provided by measured frequencies of solar oscillations. The frequencies of these solar oscillations depend on the internal structure and dynamics of the Sun and from the knowledge of these frequencies it is possible to infer the internal structure as well as the large scale flows inside the Sun, in the same way as the observations of seismic waves on the surface of Earth help us in the study of its interior. With the accumulation of seismic data over the last six years it has also become possible to study temporal variations in the solar interior. Some of these seismic inferences would be described.

Key words. Sun: oscillations, interior, rotation.

1. Introduction

Until recently the only source of information about the solar interior were the so-called theoretical solar models constructed using the equations of stellar structure and evolution (cf., Christensen-Dalsgaard *et al.* 1996). These equations have been derived using a number of simplifying assumptions and it is not obvious if these are indeed valid. It is, therefore, necessary to verify the correctness of these models through observational constraints. Historically, the first probe of physical conditions in the solar core was supplied by the measurement of neutrinos generated in the thermonuclear reaction network operating in the central regions of the Sun. A complementary probe was provided by the detection of solar oscillations which have been identified to be superposition of global modes of oscillations of the Sun (cf., Deubner & Gough 1984). Just like a musical instrument, the Sun oscillates in a sequence of well-defined modes which are determined by its internal structure. These modes are characterised by three quantum numbers, n, ℓ, m, where n is the radial order which is the number of nodes along the radius in the corresponding eigenfunction, while ℓ, m are the degree and azimuthal order determined by the horizontal variations defined by the spherical harmonics $Y_\ell^m(\theta, \phi)$. These oscillations are studied using the Doppler shift caused by the motion of fluid elements at the solar surface. The measured Doppler shift at a grid of points on the solar surface is decomposed in terms of spherical harmonics to get the contribution to each spherical harmonic. The resulting time-series is then Fourier transformed to calculate the power spectra for each ℓ, m, which in turn determine the frequencies of oscillations.

Early study of solar oscillations (cf., Gough & Toomre 1991) established the importance of accurate measurement of oscillation frequencies. For this purpose we need to observe the Sun continuously for a long duration. From most sites on the surface of the Earth it is not possible to observe the Sun continuously for more than 15 hrs. Thus for longer duration there are mainly two alternatives, the first is to observe the Sun using a network of identical instruments located around the world. A number of such networks have been operating and most successful of these is the Global Oscillation Network Group (GONG) project (Harvey *et al.* 1996) with six instruments, which have been observing the Sun since May 1995. The second alternative is to observe from a suitably located satellite and most successful of these satellites is the Solar and Heliospheric Observatory (SOHO) which was launched in December 1995. The Michelson Doppler Imager (MDI) instrument on board SOHO (Scherrer *et al.* 1995) has been observing the Sun since then, except for some breaks during 1998–99. With the availability of high quality seismic data from GONG and MDI instruments it has become possible to study the solar interior with unprecedented precision.

Most of the observed modes of oscillations have been identified as the acoustic or p-modes, where pressure gradient is the dominant restoring force. These are essentially sound waves trapped in the solar interior. As these waves travel inwards they get refracted away from the radial direction due to increasing sound speed and at some depth they suffer a total internal reflection and turn back to the surface where they are reflected by the steeply falling density profile. Thus these modes are trapped in a layer below the solar surface. The lower turning point of the modes is determined by its horizontal wavelength and frequency. Thus different modes are trapped in different regions of solar interior and sample the properties of this region. Consequently, by examining a variety of modes it is possible to study the variation of solar structure and rotation rate in the interior. GONG has measured frequencies of some half a million modes which strongly constrain theories of stellar structure and evolution as well as those of angular momentum transport in stellar interior.

2. Seismic inference of solar structure

If the Sun were strictly spherically symmetric the frequencies of oscillations would be independent of azimuthal order m, and the frequencies $\nu_{n\ell}$ would depend on the internal structure. But the Sun is rotating and hence, the frequencies $\nu_{n\ell m}$ can be expressed in terms of the mean frequency $\nu_{n\ell}$ of the multiplet and a series of splitting coefficients. The mean frequency is determined by the horizontally averaged structure of the Sun, while the splitting coefficients depend on the aspherical perturbations to solar structure as well as rotation rate and magnetic field in the solar interior. In this section, we will consider the spherically symmetric solar structure which controls the mean frequencies of a n, ℓ multiplet. These frequencies have been determined to an accuracy of 10^{-5}. Since the frequencies of p-modes depend on the sound speed and density profile in the solar interior, these profiles can be determined from the observed frequencies. A number of inversion techniques have been developed for this purpose (Gough & Thompson 1991). An outstanding achievement of these inversion techniques is determination of sound speed profile in most of the solar interior to an accuracy of better than 0.1%, which provides a strong constraint on solar models.

From early inversion for sound speed it was demonstrated that there is a significant diffusion of helium and heavy elements from the convection zone into the radiative interior (Christensen-Dalsgaard *et al.* 1993). These elements being heavier than hydrogen slowly diffuse towards the centre, thus reducing the helium abundance in the solar

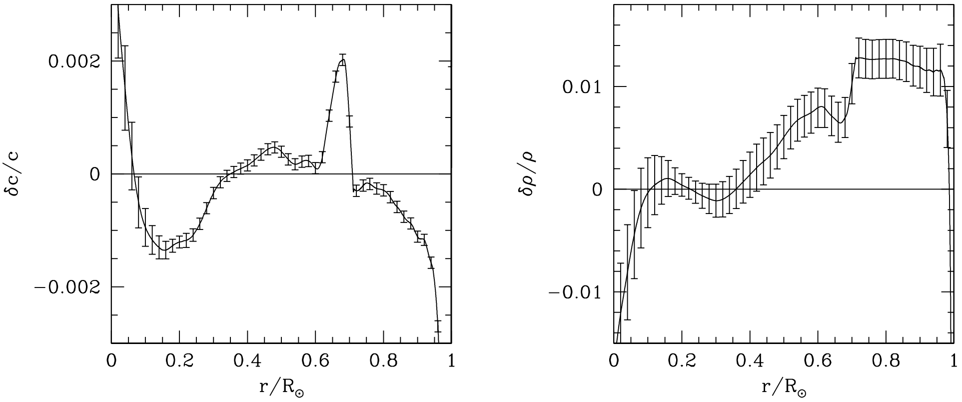

Figure 1. Relative difference in sound speed and density profiles between the Sun (as inferred by seismic inversions) and the standard solar model from Christensen-Dalsgaard *et al.* (1996).

envelope. Such a diffusion of helium and heavier elements should occur in interior of other stars as well. During the main sequence phase of stellar evolution hydrogen burning supplies the required energy to sustain the stellar luminosity; the diffusion of helium in the interior decreases the hydrogen abundance in the core, which in turn will reduce the main sequence life-time of stars. The ages of globular clusters are determined by calibrating against theoretical calculations of stellar evolution. The inclusion of the diffusion of helium would naturally reduce the estimated age of globular clusters. This should help in resolving the age problem in standard big bang model of cosmology.

Apart from diffusion it was also demonstrated that the opacity of solar material near the base of the convection zone needs to be revised upwards. This was later confirmed by revised OPAL opacities (Rogers & Iglesias 1992). The incorporation of revised opacity tables and diffusion of helium and heavy elements in solar interior improved the solar models significantly. Fig. 1 shows the plots of the relative difference in sound speed, and density between the Sun as inferred from helioseismic inversions and a standard solar model (Christensen-Dalsgaard *et al.* 1996). The agreement between the model and the Sun is fairly good except for a noticeable discrepancy near the base of the convection zone and a smaller discrepancy in the energy-generating core. The bump below $0.7R_\odot$ could be attributed to a sharp change in the gradient of helium abundance profile arising from diffusion in the reference model. This discrepancy occurs just below the base of the convection zone and a moderate amount of turbulent mixing (induced by say, a rotationally induced instability) in this region can alleviate this discrepant feature (Richard *et al.* 1996; Brun *et al.* 1999). This also happens to be the region where inversions for the rotation rate (cf., Schou *et al.* 1998) show the presence of a strong shear layer, which is referred to as the tachocline (Spiegel & Zahn 1992). The shearing motion in the tachocline is probably responsible for a certain amount of mixing in this region. This mixing also resolves the outstanding problem of low lithium abundance in the solar envelope, since the lithium can be destroyed by nuclear reactions near the base of the mixed layer.

With the knowledge of the sound speed and density profiles in the solar interior deduced through inversions, it is possible to employ the equations of thermal equilibrium to determine the temperature and chemical composition profiles inside the Sun (Gough & Kosovichev 1990; Takata & Shibahashi 1998; Antia & Chitre 1998) provided input physics like the opacity, equation of state and nuclear energy generation rates are known. In general, the computed luminosity resulting from these inferred profiles would not necessarily match the observed solar luminosity. The discrepancy between the computed and measured solar luminosity can, in fact, provide a test of input physics, and using these constraints it has been demonstrated that the nuclear reaction cross-section for the proton-proton reaction needs to be increased slightly (Antia & Chitre 1998; Degl'Innocenti *et al.* 1998; Schlattl *et al.* 1999). This cross-section has a controlling influence on the rate of nuclear energy generation and neutrino fluxes, but it has never been measured in the laboratory and all estimates are based on theoretical computations.

Using the inverted profiles for temperature, density and chemical composition it is possible to calculate the neutrino fluxes in the seismic model, which turn out to be close to those in the standard solar model. This suggests that the known discrepancy between the observed and predicted neutrino fluxes is likely to be due to non-standard neutrino physics. It can be shown that even if we allow for arbitrary variations in opacity or heavy element abundance in solar interior, it is not possible to construct any solar model satisfying the seismic constraint, which also matches the observed neutrino fluxes (Antia & Chitre 1997). Thus helioseismology has turned the Sun into a precision laboratory to study neutrino properties. Recent results from the Sudbury Neutrino Observatory (SNO) have confirmed (Ahmad *et al.* 2001) that the observed deficit in solar neutrinos is, indeed, due to oscillations between different neutrino species. A reliable estimate of neutrino fluxes from the Sun is required to distinguish between different possible mechanisms for oscillations between different species of neutrinos and seismic constraints have played a central role in improving these theoretical estimates of neutrino fluxes.

3. Rotation rate in the solar interior

Since the Sun is rotating, the frequencies of solar oscillations depend on m and the frequency splittings between different modes of same n, ℓ multiplet depends on rotation rate in the region where the mode is trapped. Thus from the observed frequency splittings it is possible to infer the rotation rate as a function of radial distance and latitude using a suitable inversion technique (Schou *et al.* 1998). The most striking feature of inferred rotation rate is that the differential rotation observed at the solar surface continues through the convection zone, while near the base of the convection zone there is a sharp transition to almost solid body rotation in the radiative interior (cf., Fig. 2). This region of intense shear has been named as tachocline (Spiegel & Zahn 1992). The origin of tachocline is not understood and provides a strong challenge to the theory of angular momentum transport in stellar interior.

Further, contrary to early expectation, the solar core is found to be rotating slower than the equatorial region at the surface. If the solar core were rotating much faster it could distort the Sun thus increasing its quadrupole moment. This could cause conflict with the test of general relativity based on the precession of orbit of planet mercury, since distorted Sun could produce a part of the precession by purely Newtonian effects. From the inverted rotation rate in solar interior we can estimate the quadrupole moment

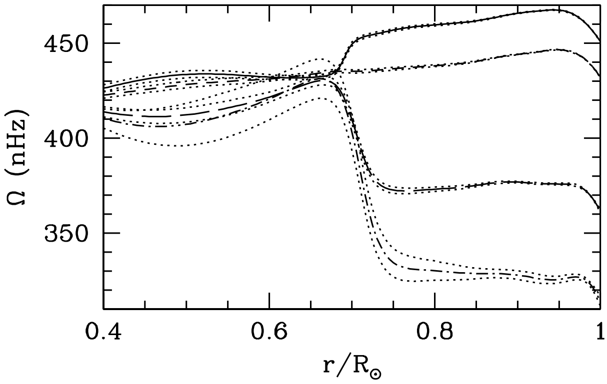

Figure 2. Rotation rate at various latitudes as a function of radial distance inferred from GONG data (Antia *et al.* 1998). The continuous, short-dashed, long-dashed and dot-dashed lines show the rotation rate at latitudes of 0°, 30°, 60°, 90° respectively. The dotted lines show the respective 1σ error limits.

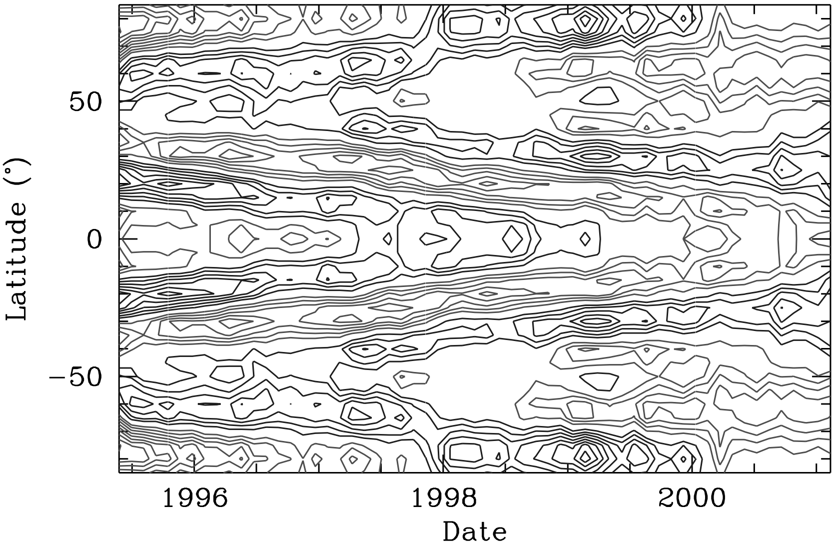

Figure 3. The contours of time varying component of rotation velocity, $v_{\rm zon} = \delta\Omega r\cos\theta$ (θ is the latitude) at a depth of $0.02R_\odot$ below the solar surface obtained using the GONG data are shown as a function of latitude and time. The contours are drawn at interval of 1 m/s.

(Pijpers 1998) and it turns out that this results in negligible precession of orbit of mercury thus validating general relativity.

With the accumulation of seismic data over the last 6 years it is possible to study the temporal variations in the solar interior associated with the well-known 11 year solar cycle. From the measured variation in p-mode frequencies it should be possible to infer temporal variations in solar structure. But all the observed variation can be accounted for by variations in the outer surface layers (Basu & Antia 2000). In contrast the rotation rate shows significant variation in outer 10% of solar radius (Howe *et al.* 2000; Antia & Basu 2000). In order to study the temporal variation in rotation rate we subtract the temporal average of rotation rate at each latitude and radial distance from that determined at each epoch to obtain the residual. Fig. 3 shows the contours of constant residual of rotation velocity as a function of latitude and time at $r = 0.98R_\odot$. This shows a characteristic pattern with bands of faster and slower than average rotation velocity moving towards the equator at low latitude and towards the pole at higher latitude (Antia & Basu 2001). Similar pattern has been observed at the solar surface also (Howard and LaBonte 1980) and is referred to as torsional oscillations. These temporal variations in rotation rate would play a crucial role in the operation of solar dynamo, which is still not understood. The dynamo is generally believed to operate in the region near the base of the convection zone, but so far there is no evidence of any temporal variation in this region from seismic data.

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