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Helioseismic inferences from the GONG data

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Abstract. The accurately measured frequencies of solar oscillations provide a powerful tool to study the solar interior in sufficient detail to test theories of stellar structure and evolution. A primary inversion of these frequencies yields the profiles of sound speed and density throughout the solar interior. Using the seismically inferred sound speed and density profiles alongwith the equations of thermal equilibrium and input physics, it is possible to calculate the temperature and helium abundance profiles inside the Sun. The resulting composition profile is essentially flat in the region just below the convection zone indicating the operation of turbulent diffusion in this region. Such a turbulent mixing may explain the observed low Lithium abundance in the solar envelope. These inferred profiles can also be used to test input physics like the equation of state, opacities and nuclear energy generation rates.

Key words: sun: oscillations, sun: interior, sun: rotation

1. Introduction

The observed frequencies of solar oscillations offer an unique opportunity to study the solar interior. The most precise of these frequencies are known to a relative accuracy of better than 10^{-5}, which is better than the accuracy to which global quantities like mass, radius and luminosity are known. With the operation of Global Oscillation Network Group (GONG) a large amount of helioseismic data is becoming available (Harvey et al. 1996; Hill et al. 1996) and some of the inferences obtained from these seismic data are described here. By comparing the frequencies obtained from GONG data with those from other observations, it is possible to estimate systematic errors in these frequencies. Similarly, comparison of results obtained using different data allows us to estimate systematic errors in these inferences.

2. The f-mode

The f-mode is essentially a surface mode that is confined in regions immediately below the solar surface and as such the properties of these modes should give us information about the immediate subsurface layers. Since frequencies of f-modes are essentially independent of the stratification in the solar interior, they can provide a diagnostic of velocity fields, magnetic fields etc., present in the surface layers. The amplitudes of f-modes are very low, and consequently, the frequencies have so far been measured only at high degree where there is sufficient power. Earlier measurements of these frequencies (Libbrecht et al. 1990; Bachmann et al. 1995) indicated that there is a significant discrepancy between the observed f-mode frequencies and those computed with a solar model.

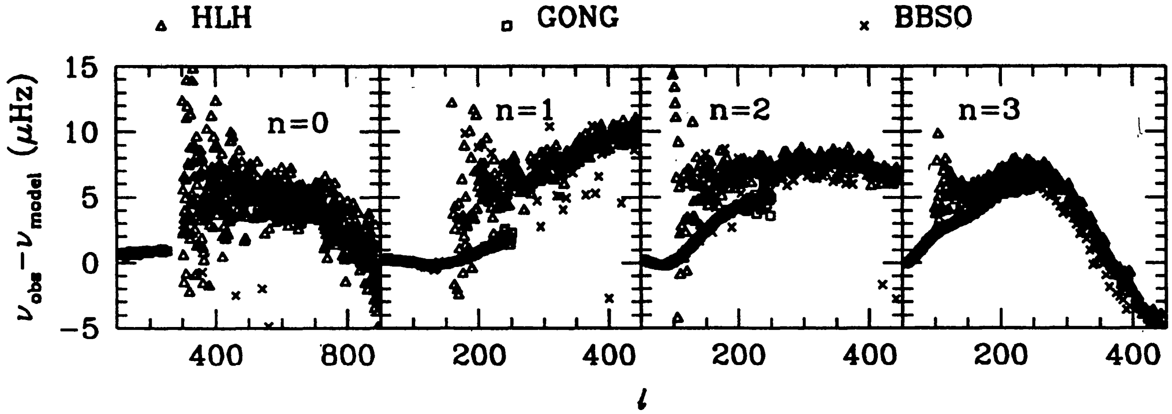

Figure 1. Difference between various observed frequencies and those of a standard solar model for n = 0-3 as a function of degree l.

A comparison of GONG frequencies with those from earlier observations should give an estimate of systematic errors in these frequencies. The GONG frequencies were computed using the rotationally corrected m-averaged spectra for GONG month 4. The results for modes with radial harmonic number n = 0-3 are shown in Figure 1 which displays the difference between various observed frequencies and those of a standard solar model. The BBSO data (Libbrecht et al. 1990) falls in two categories: one for $l \leq 140$ where the frequencies have been determined by fitting individual peaks, and second set for higher l where the frequencies have been computed by ridge fitting technique. The HLH frequencies (Bachmann et al. 1995) have all been computed using ridge fitting, while the GONG frequencies have been calculated by fitting individual peaks (Anderson et al. 1990). From the figure it is clear that for n=0 and 1, there are significant systematic differences between the frequencies computed by fitting individual modes and those from ridge fitting techniques. The difference reduces as one goes to higher values of n.

The f-mode frequencies from GONG data are very close to those computed for a standard solar model and various mechanisms invoked (Murawaski & Roberts 1993; Rosenthal & Gough 1994; Ghosh et al. 1995) in the past to explain the reported differences between the observed and computed frequencies may not be necessary. Of course, we still do not have reliable frequencies at high degree and only better data from SOHO or a reanalysis of HLH data would be able to resolve the question whether there is indeed any significant difference between the observed and computed frequencies. From Figure 1, it appears that there is still a small difference between the observed and computed frequencies, but it is not clear if this difference is significant as there are liable to be some systematic errors in the frequencies inferred from GONG data too.

From the behaviour of systematic error with n it appears that the neglect of horizontal velocity in spatial filtering is a possible cause for the systematic differences. From the computed eigenfunctions we find that the ratio of the horizontal to vertical velocity at the photosphere is unity for $n = 0$, between 0.4–0.5 for $n = 1$, between 0.24–0.32 for $n = 2$ and between 0.15–0.25 for $n = 3$. The influence of horizontal velocity on ridge fitting techniques needs to be further studied. The horizontal velocity will also affect the peak fitting techniques because of the presence of m leaks, but the effect will be much smaller, of the order of 0.5μHz, and it is quite possible that the existing discrepancy between the GONG f-mode frequencies and those of a solar model is due to this effect.

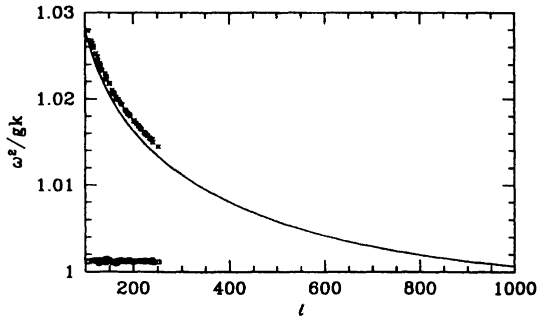

Figure 2. ω^2/gk for the f-mode in a solar model (solid line) are compared with observed values represented by crosses. The open squares display the ratio $(\omega_{obs}/\omega_{mod})^2$.

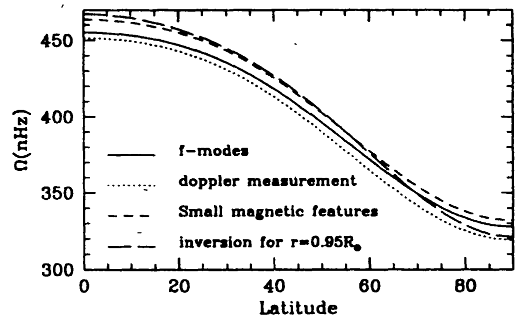

Figure 3. The solar surface rotation rate as inferred from the f-mode splittings (solid line) is compared with other measurements.

The frequencies of f-modes are asymptotically expected to satisfy the simple dispersion relation, $\omega^2 = gk$, where g is the acceleration due to the gravity at the surface and $k = \sqrt{l(l+1)}/r$ is the horizontal wave number. Figure 2 shows the quantity ω^2/gk for a solar model and for the corresponding GONG frequencies. The systematic trend away from unity at lower degree is most probably due to the fact that the peak in kinetic energy density associated with f-mode shifts inwards with decreasing degree and thus these modes are effectively localized somewhat below the solar surface, where gk would be larger. This figure also shows the ratio $(\omega_{\mathrm{obs}}/\omega_{\mathrm{model}})^2$ and it is clear that the ratio is more or less constant. This could be due to systematic errors or alternatively, due to an error in the assumed radius in the solar model. In order to explain the observed discrepancy the solar radius will need to be decreased by 0.03% or about 210 km, which is perhaps more than the expected uncertainties in the radius. The observed discrepancy in frequencies is likely to be due to systematic errors in peak fitting techniques. With better data on the f-mode at higher degree becoming available we may be able to estimate the value of solar radius more accurately as also its possible variation with solar cycle. Since the frequencies of these modes can be determined to a relative accuracy of 10^{-5}, neglecting any systematic effects it would be possible to determine the solar radius to similar accuracy.

Apart from frequencies it is also possible to determine the splitting coefficients (Ritzwoller & Lavely 1991) from the GONG data. The splitting coefficients for the f -mode should give a measure of near surface rotation rate, which can be compared with other measurements. Figure 3 shows the solar surface rotation rate as a function of latitude as measured using different techniques, including the doppler measurements (Ulrich et al. 1988) and using small magnetic features (Komm et al. 1993). It can be seen that there is a reasonable agreement between different measurements. This figure also shows the rotation rate inferred from helioseismic inversions at $r = 0.95\ R_\odot$ and it can be seen that this value is close to that determined using small magnetic features thus suggesting that magnetic features are possibly anchored somewhat below the solar surface.

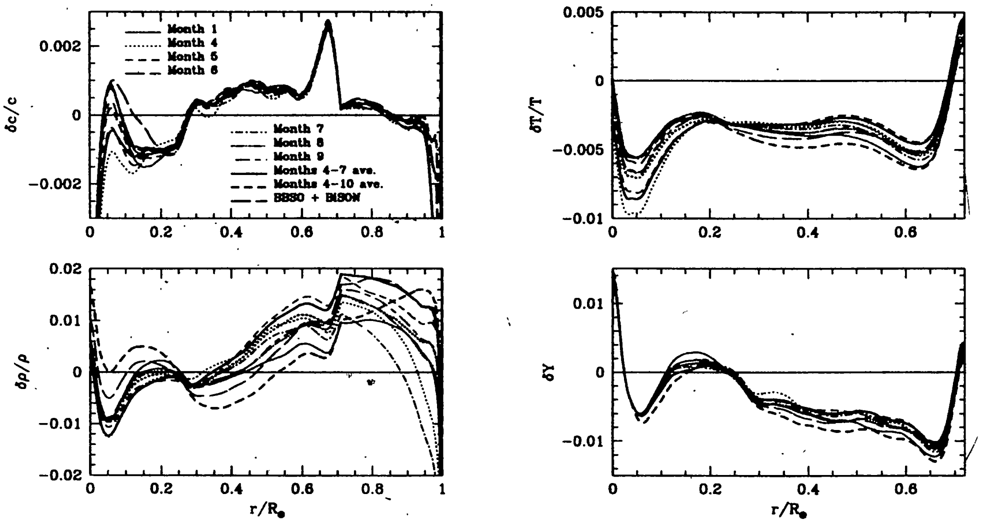

Figure 4. Relative difference in sound speed, density, temperature and absolute difference in helium abundance between the Sun and the Model S of Christensen Dalsgaard et al. (1996) using various sets of observed frequencies.

3. Inversion for solar structure and rotation rate

The observed frequencies of solar oscillations have been successfully used to infer the internal structure of the Sun (Gough et al. 1996). The primary inversions of known frequencies yield the profiles of sound speed, density, adiabatic index and other related quantities through most of the solar interior. On the other hand, in order to infer the temperature and chemical composition profiles additional assumptions regarding input physics and thermal equilibrium are required (Antia & Chitre 1995; Shibahashi & Takata 1996; Kosovichev 1996). In order to study the influence of systematic errors in observed frequencies, we use different versions of GONG frequencies as well as the observed frequencies from BBSO data combined with the frequencies of low degree modes form BiSON (Elsworth et al. 1994). For inferring the sound speed and density inside the Sun we use the regularized least squares technique (Antia 1996). These inverted sound speed and density profiles along with the equations of thermal equilibrium and input physics are then used to infer the temperature and helium abundance profiles in the radiative interior (Antia & Chitre 1996). The results are shown in Figure 4, where the spread between different inverted profiles gives an estimate of errors expected from uncertainties in the observed frequencies. Apart from this, additional errors arising from uncertainties in our knowledge of opacities would be introduced in inversion for temperature and chemical composition profiles (Antia & Chitre 1996). These systematic errors are probably much large than those arising from errors in observed frequencies.

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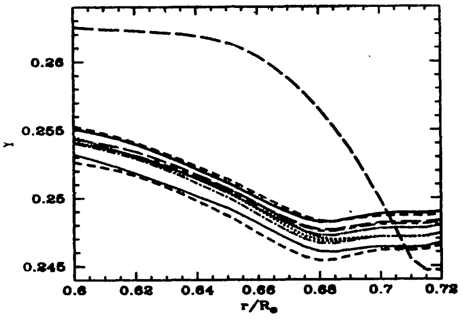

Figure 5. The helium abundance profile as inferred from different observed frequencies. The various line styles have the same significance as in Figure 4. The thick long dashed line shows the helium abundance profile in the Model S of Christensen-Dalsgaard et al. (1996)

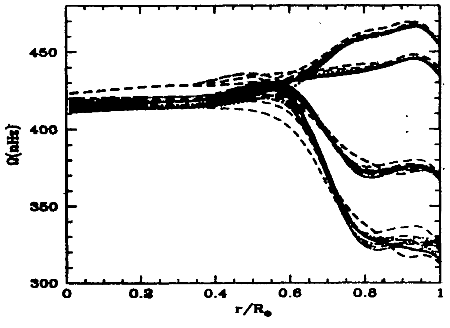

Figure 6. The solar rotation rate at latitudes of 0°, 30°, 60° and 90° as inferred from various observed splittings. The various line styles have the same significance as in Figure 4.

From Figure 4 it is clear that the inverted profiles are fairly close to those in the standard solar model and the major departure occurs just below the base of the convection zone. In this region the helium abundance profile in the Sun appears to be smooth, while that in the model has a sharp change in gradient arising from diffusion. Figure 5, shows the profiles in this region and the difference is very clear. It can be readily seen that the inverted profiles are almost flat for $r > 0.68\ R_\odot$ and it appears that this region is probably kept mixed by some turbulent mixing process arising from rotation or any other effect. Similar conclusions are also reached by looking at the oscillatory signature in the frequencies as a function of n (Basu & Antia 1994). At $r = 0.68\ R_\odot$, the temperature in the Sun is around 2.5×10^6 K which is sufficient to burn lithium and hence such a mixing could be responsible for the observed low lithium abundance in the solar envelope (Richard et al. 1996). From Figure 5 it can be seen that the helium abundance in the convection zone appears to be between 0.246-0.249, which is consistent with other helioseismic estimates (Basu & Antia 1995) obtained using completely independent techniques.

The inverted profiles can also be used to test the input physics. Thus from the derivation in sound speed in the lower part of the convection zone it appears that the OPAL equation of state (Rogers et al. 1995) underestimates the adiabatic index Γ_1 by about 0.0005. A detailed study of the base of the convection zone as well as inversion for thermal and composition prodiles suggests that there is no significant uncertainty in the OPAL opacities (Iglesias & Rogers 1996). But the nuclear energy generation rates would need to be increased by a few percent over the values adopted by Bahcall & Pinsonneault (1995).

The measured splittings of solar oscillation frequencies offer us a valuable tool for studying the rotation rate inside the Sun. It is possible to infer both the radial and latitudinal variation in the rotation rate (Thompson et al. 1996). We have used the 1.5D inversion technique for inverting the rotation rate from the measured splitting coefficients (Ritzwoller & Lavely 1991) using the regularized least squares technique with iterative refinement (Antia et al. 1996) and the results are shown in Fig. 6. It is clear from the figure that the surface differential rotation persists through the solar convection zone, while below the base of convection zone the rotation rate appears to be relatively independent of latitude. The core appears to be rotating slower than the surface equatorial rotation rate. Further, there is a distinct shear layer just underneath the surface where the rotation rate increases with depth. There is a hint of this shear layer becoming less pronounced with latitude, in the sense that the radial variation of the rotation rate tends to diminish with increasing latitude.

4. Conclusions

Accurately measured frequencies of solar oscillations provide us a unique diagnostic to probe subtle aspects of input physics and provide stringent tests for the theories of stellar structure and evolution. Reasonable agreement between the inverted profiles and those in a standard solar model gives us some confidence in current theories of stellar structure and evolution. However, the remaining discrepancies clearly indicate that improvements are required and continued efforts to improve the agreement will provide better insight into the theory of stellar evolution as well as properties of matter under the solar conditions.

Acknowledgements

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