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Helioseismic Search for Magnetic Field in the Solar Interior

H. M. Antia[1], S. M. Chitre[1] & M. J. Thompson[2]
[1]*Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India.*
[2]*Astronomy Unit, Queen Mary and Westfield College, Mile End Road, London E1 4NS, U.K.*

Abstract. The observed splittings of solar oscillation frequencies can be utilized to study possible large-scale magnetic fields present in the solar interior. Using the GONG data on frequency splittings an attempt is made to infer the strength of magnetic fields inside the Sun.

Key words. Sun: oscillations, magnetic field, interior.

The frequencies of solar oscillations are split due to departures from spherical symmetry caused by rotation, magnetic field or any other aspherical perturbations in solar interior. The odd splitting coefficients arise from rotation and can be inverted to infer the rotation rate in solar interior. The even splitting coefficients arise from second order effects of rotation, magnetic field or latitudinal temperature variations. In this work we attempt to infer the magnetic field strength in the solar interior using data from Global Oscillation Network Group (GONG).

Note that forces associated with rotation or magnetic field are much smaller than the gravitational forces in solar interior, and hence a perturbative treatment can be applied to treat these departures from spherical symmetry. We adopt the formulation due to Gough & Thompson (1990), with the difference that we include perturbation in the gravitational potential and also assume differential rotation in the interior, though the symmetry axis of magnetic field is taken to coincide with rotation axis. We use only the toroidal magnetic field taken to be of the form,

$$\mathbf{B} = \left[0, 0, a(r)\,\frac{dP_k}{d\theta}\,(\cos\theta)\right], \tag{1}$$

$$a(r) = \begin{cases} \sqrt{8\pi p_0 \beta_0}\left(1 - \left(\dfrac{r - r_0}{d}\right)^2\right) & \text{if} \quad |r - r_0| \le d \\ 0 & \text{otherwise} \end{cases}. \tag{2}$$

Here $P_k(x)$ is the Legendre polynomial of degree k, p_0 is the gas pressure, β_0 is a constant giving the ratio of magnetic to gas pressure, r_0 and d are constants defining the mean position and thickness of the layer where the field is supposed to be concentrated.

We use the rotation rate inferred from GONG data for the months 4–14 (Antia, Basu & Chitre 1998) to estimate second order contributions to the splitting coefficients a_2 and a_4. We incorporate all the second-order contributions arising from rotation, including those from the distortion of equilibrium state and perturbation to the eigenfunctions. These contributions can be subtracted from observed splitting coefficients obtained from the GONG data (Hill *et al.* 1996) to give residuals which may be due to magnetic field or any other aspherical perturbation in the solar interior. The resulting residuals can be compared with calculated splittings from magnetic fields concentrated in different regions of solar interior.

There have been some suggestions that a significant toroidal magnetic field may be concentrated in a layer around the base of the convection zone (Dziembowski & Goode 1992). We therefore first investigate splittings that are expected from such a field and the results are shown in Fig. 1(a). These splittings include both the direct and distortion contributions as defined by Gough & Thompson (1990). It is clear from this figure that the splitting coefficients from such a field have a characteristic signature for modes with turning point near the base of the convection zone; it should be possible to detect such a signal in the observed splittings if a strong enough magnetic field is, indeed, present in these layers. Unfortunately, the errors in observed splitting coefficients are too large to detect small features expected from such magnetic field. In order to reduce the errors we take averages over 30 modes with nearby values of the lower turning point r_t and the results, after subtraction of expected contribution from rotation, are shown in Fig. 1(b). There is no clear signature of any feature near the base of the convection zone and hence we can only set an upper limit on the strength of magnetic field in this layer. This will, of course, depend on the thickness of the magnetic layer. For a half-thickness of $0.02R_\odot$ the upper limit on magnetic field strength turns out to be 300 kG. This limiting value is close to what was obtained by Basu (1997) using a similar technique and is also consistent with the value independently inferred by D'Silva & Choudhuri (1993).

After addressing the issue of a possible magnetic field at the base of the convection zone, where theory suggests a field might be stored, we consider where else the data might indicate the presence of a magnetic field. There is no signature for the presence of significant magnetic field in the radiative interior, since the averaged residual splittings after correcting for rotation do not show any variation with r_t. However, within the convective envelope there is some significant residual splitting, which could be due to a moderately strong magnetic field. This residual appears, interestingly, to rise towards the surface. If it is due solely to magnetic field, the field may be distributed around a depth of ≈ 30000 km. It may be noted that this is approximately the depth to which the surface shear layer seen in solar rotation profile extends (Antia, Basu & Chitre 1998; Schou *et al.* 1998). Fig. 2 shows the splittings due to a few magnetic field configurations which are concentrated in the upper part of the convection zone. A comparison of these with the observed splittings indicates that there may be an azimuthal magnetic field with $\beta \approx 10^{-4}$ (i.e., $B \approx 20$ kG), with peak around $r = 0.96R_\odot$. The non-zero value of these coefficients for $r_t < 0.7R_\odot$ could be easily explained by magnetic field in outer layers as can be seen from the computed splittings.

In this study we have assumed a smooth toroidal magnetic field, but in practice we do not expect such a field inside the convection zone. Turbulence may be expected to randomize the magnetic field and such a field may not be expected to produce any significant distortion in the equilibrium state. The direct effect of a magnetic field will still be felt though the contribution would be different. Thus our results may be treated as indicating an order of magnitude of field that may be expected if the observed splitting coefficients are indeed due to the presence of a magnetic field. If

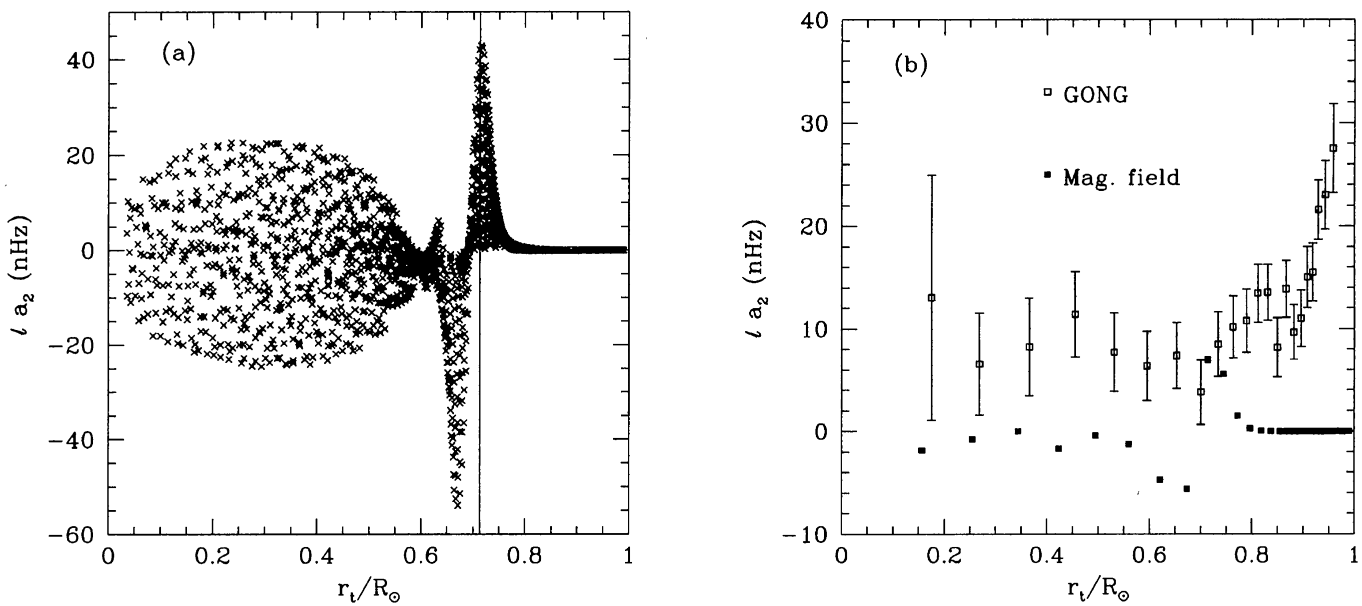

Figure 1. The splitting coefficient a_2 from a toroidal magnetic field concentrated near the base of the convection zone, plotted as a function of the lower turning point for the mode. Magnetic field is given by equations (1,2) with $k = 2$, $\beta_0 = 10^{-4}$, $r_0 = 0.713R_\odot$ (shown by the vertical line in the figure) and $d = 0.02R_\odot$. The left panel shows the splitting coefficients from each mode separately, while the right panel shows the results after averaging over 30 neighboring modes. The right panel also includes the observed splittings averaged over the same set of modes.

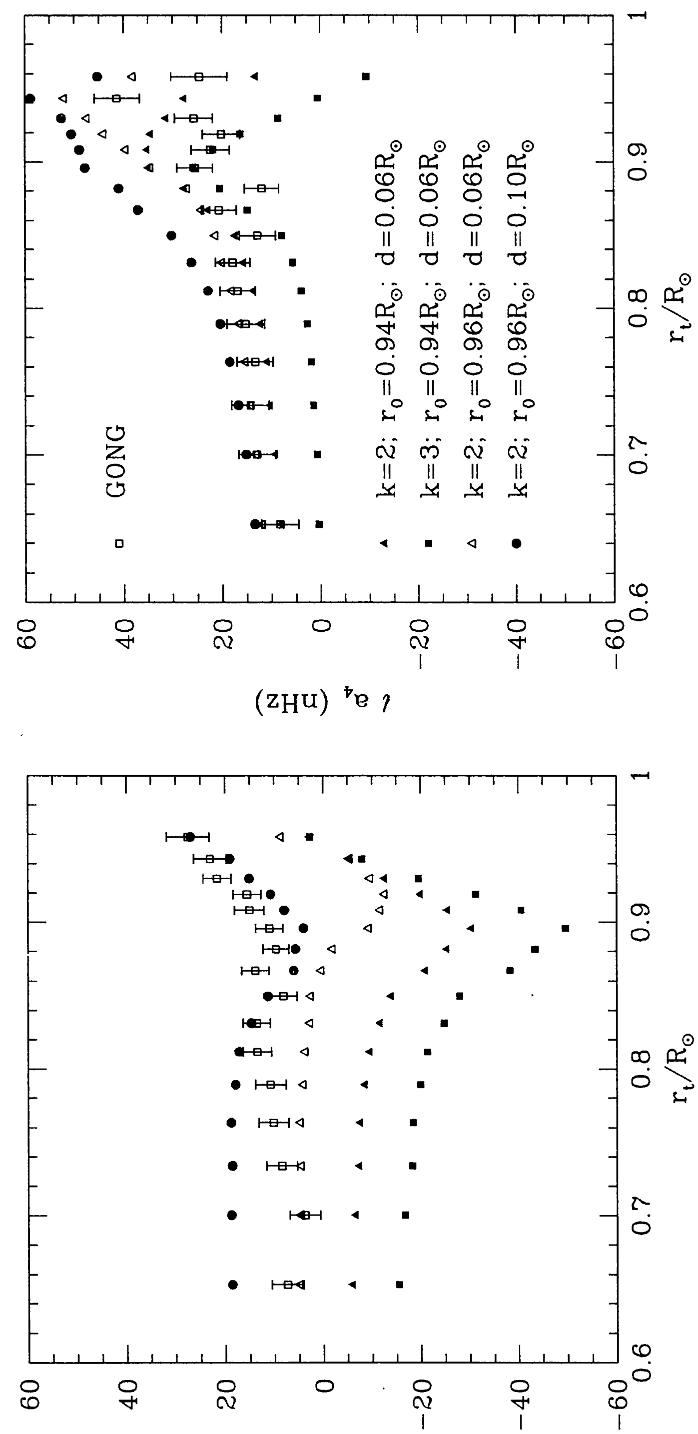

Figure 2. The splitting coefficients a_2 and a_4 from a toroidal magnetic field concentrated in the upper part of the convection zone, plotted as a function of the lower turning point. The estimated contribution from rotation has been subtracted from the observed splittings plotted in the figure. Magnetic field is given by equations (1,2) with $\beta_0 = 10^{-4}$, and the value of r_0, d and k as marked in the figure.

the field is concentrated in flux tubes which occupy only a small fraction of the volume, then the required magnetic field could be correspondingly larger. If we assume that the flux tubes occupy a fraction f of the total volume, the magnetic field strength should increase by $1/\sqrt{f}$. Alternately, a nonmagnetic latitudinally-dependent perturbation to the wave propagation speed might be responsible for the signal we have detected (cf. Gough & Zweibel 1995). Once again we may expect a perturbation of order 10^{-4} located in the region around $r = 0.96R_{\odot}$ for accommodating the observed splittings. Using the splitting coefficients alone it is not possible to distinguish between these two possibilities.

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