SUBSURFACE MAGNETIC FIELDS FROM HELIOSEISMOLOGY

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ABSTRACT

Using even-order frequency splitting coefficients of global p-modes it is possible to infer the magnetic field in the solar interior as a function of radial distance and latitude. Results obtained using GONG and MDI data are discussed. While there is some signal of a possible magnetic field in the convection zone, there is little evidence for any temporal variation of the magnetic field in the solar interior. Limits on possible magnetic field in the solar core are also discussed. It is generally believed that the solar dynamo is located in the tachocline region. Seismic studies do not show any significant temporal variation in the tachocline region, though a significant latitudinal variation in the properties of the tachocline are found. There is some evidence to suggest that the latitudinal variation is not continuous and the tachocline may consist of two parts.

Key words: Sun: Interior; Sun: Magnetic field; Sun: Oscillations; Sun: Rotation.

1. INTRODUCTION

Helioseismology has been successful in probing the spherically symmetric structure (Gough et al. 1996) of the Sun as well as the rotation rate in its interior (Thompson et al. 1996; Schou et al. 1998). To the first order, rotation affects only the frequency splitting coefficients which represent odd terms in the azimuthal order m of the oscillation modes. The even terms in these splitting coefficients, can arise from second order effects of rotation, magnetic field or any latitudinal dependence in the structure. It is not possible to distinguish between the effects of a magnetic field and aspherical perturbations to the solar structure (Zweibel & Gough 1995).

The even order splitting coefficients are fairly small, and no definitive results have so far been obtained regarding the magnetic field strength in the solar interior. Dziembowski & Goode (1989) using data from the Big Bear Solar Observatory claimed to find evidence for a mega Gauss field near the base of the convection zone. Improved data from the Global Oscillation Network Group (GONG) project (Hill et al. 1996) and the Michelson Doppler Imager (MDI) instrument (Rhodes et al. 1997) on board the SOHO satellite has not confirmed these results (Antia et al. 2000).

Instead of a magnetic field one can invoke aspherical structure to explain the even coefficients of frequency splittings. In this case, it is possible to apply an inversion technique to determine the latitudinal dependence in solar structure variables like the sound speed and density (Antia et al. 2001a). The advantage of this approach is that it can give the location of perturbation giving rise to the observed even splitting coefficients.

The GONG and MDI instruments have been observing the Sun for the last 7 years and it is also possible to study possible temporal variation in the internal magnetic field. It is well known that the frequencies of solar oscillations vary with time and this variation is correlated with solar activity (Elsworth et al. 1990; Libbrecht & Woodard 1990). Similarly, the even splitting coefficients are also known to vary with time and their variation is correlated to the corresponding component of observed magnetic flux at the solar surface (Libbrecht & Woodard 1990; Woodard & Libbrecht 1993; Howe et al. 1999; Antia et al. 2001a). However, most of these temporal variations are found to arise from perturbation near the solar surface (Basu & Antia 2000; Antia et al. 2001a). There is little evidence for any significant temporal variations in the solar structure below the thin surface layers.

Inversions for rotation rate (Thompson et al. 1996; Schou et al. 1998) have shown that the observed differential rotation at the solar surface continues through the convection zone, while in the radiative interior the rotation rate is more or less independent of latitude. The transition takes place close to the base of the convection zone in a region which has been named as the tachocline (Spiegel & Zahn 1992). It is generally believed that the solar dynamo operates in the tachocline region. Hence it would be interesting to look at the temporal variations in the solar structure and rotation rate in the tachocline region. Howe et al. (2000) found a 1.3 year periodicity in the equatorial rotation rate at $r = 0.72R_\odot$. But other investigations (Antia & Basu 2000; Corbard et al. 2001) did not find any systematic variation in the same region. Helioseismic inversions are unreliable in the tachocline region and the properties of the tachocline have been studied using forward modelling approach (Kosovichev 1996; Antia et al. 1998; Charbonneau et al. 1999). These results have

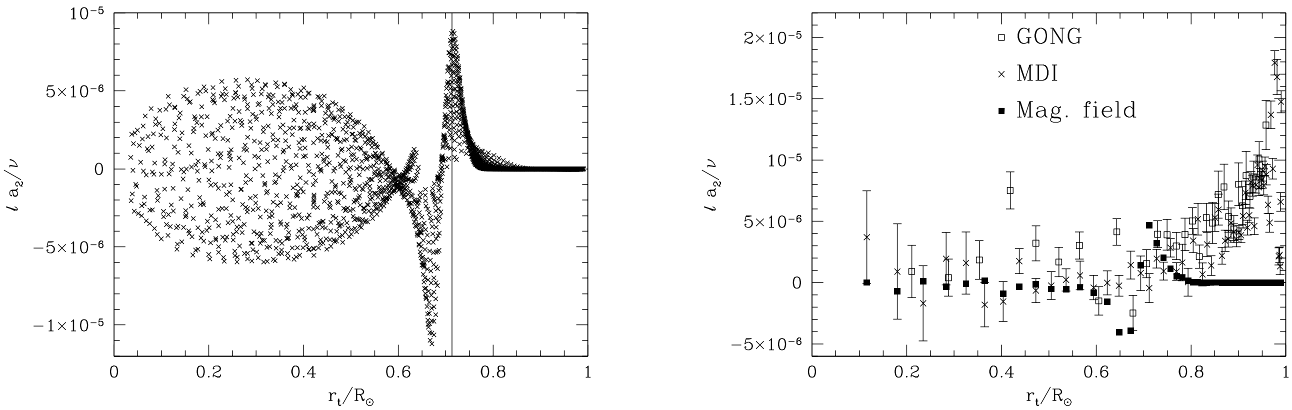

Figure 1. The left panel shows the splitting coefficients a_2 from a toroidal magnetic field concentrated near the base of the convection zone, plotted as a function of the lower turning point of the modes. The magnetic field is given by Eqs. (2,3) with $k = 2$, $\beta_0 = 10^{-4}$, $r_0 = 0.713R_\odot$ and $d = 0.02R_\odot$. In the right panel these coefficients are compared with observed values. Each point represents an average over 25 neighbouring modes. The estimated contribution from rotation has been subtracted from the observed splittings plotted in the figure.

also not shown any significant temporal variations in the tachocline properties (Basu & Antia 2001).

Although no temporal variations have been seen in the tachocline properties, there is a definite latitudinal variation in the position and possibly also in the thickness of the tachocline (Charbonneau et al. 1999; Basu & Antia 2001). On the other hand, there is no latitudinal variation in the depth of the convection zone or the solar structure in the tachocline region. These results appear to be contradictory as it is believed that the tachocline region is mixed by some rotationally induced instability (Richard et al. 1996; Brun et al. 1999). Hence, it would be interesting to study the latitudinal variation in the tachocline with accumulated data over the last seven years.

The global modes of oscillations used in these studies can only give information about the large scale structure and magnetic field in the solar interior. To study smaller features like active regions we need to use local helioseismic techniques, like the time-distance analysis (Duvall et al. 1993) or the ring diagram technique (Hill 1988). In this work we present some results obtained using the ring diagram technique, while the time-distance analysis of active regions is described by Kosovichev (2002).

2. EFFECT OF A MAGNETIC FIELD ON SOLAR OSCILLATIONS FREQUENCIES

In the absence of rotation or magnetic field the frequencies of solar oscillations are independent of the azimuthal order m. Rotation or magnetic field break this degeneracy leading to splitting of frequencies with the same radial order n and degree ℓ. The frequencies of solar oscillations can be expressed in terms of the splitting coefficients:

$$\nu_{n,\ell,m} = \nu_{n,\ell} + \sum_{j=1}^{J_{\max}} a_j^{n,\ell} \mathcal{P}_j^\ell(m), \qquad (J_{\max} \le 2\ell) \quad (1)$$

where $\mathcal{P}_j^\ell(m)$ are orthogonal polynomials of degree j in m (Ritzwoller & Lavely 1991; Schou et al. 1994). The odd coefficients $a_1, a_3, a_5, \ldots$, can be used to infer the rotation rate in the solar interior, while the even coefficients arise basically from second order effects due to rotation and magnetic field. Since forces due to rotation or magnetic field in the solar interior are smaller by about 5 orders of magnitude as compared to the gravitational forces, it is possible to apply a perturbative treatment to calculate their contribution to frequency splittings (Gough & Thompson 1990). Since the rotation rate in the solar interior can be inferred from the odd splitting coefficients, we can use this inferred profile to calculate the expected contributions to the even splitting coefficients from the second order effects of rotation. This calculated contribution can be subtracted out from the observed splitting coefficients to get the residuals which may be due to a magnetic field or other asphericities.

For simplicity we consider only a toroidal magnetic field, taken to be of the form,

$$\mathbf{B} = \left[0, 0, a(r)\frac{dP_k}{d\theta}(\cos\theta)\right], \quad (2)$$

with the axis of symmetry coinciding with the rotation axis. Here, $P_k(x)$ is the Legendre polynomial of degree k and

$$a(r) = \begin{cases} \sqrt{8\pi p_0 \beta_0}(1 - (\frac{r-r_0}{d})^2) & \text{if } |r - r_0| \le d \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where 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 half-thickness of layer where the field is concentrated.

2.1. The seismic data

We use data sets from both GONG and MDI for this study. The solar oscillations frequencies and the splitting coefficients from the GONG project (Hill et al. 1996) were obtained from 108 day time series. The MDI data were obtained from 72-day time series (Schou 1999). These data sets consists of the mean frequency and the splitting coefficients for each n, ℓ multiplet. We use the 62 data sets from GONG covering a period from May 7, 1995 to July 21, 2001. Each set covers data from 108 days with a spacing of 36 days between consecutive data sets. The MDI data sets (Schou 1999) consist of 28 non-overlapping sets covering a period from May 1, 1996 to March 30, 2002, with a break between July 1998 and January 1999 when the contact with SOHO was lost.

2.2. Field near the base of the convection zone

Since there have been some suggestions that a toroidal magnetic field may be concentrated near the base of the convection zone (Dziembowski & Goode 1989) we consider splitting coefficients arising from such a field with $r_0 = 0.713R_\odot$, $d = 0.02R_\odot$, $\beta_0 = 10^{-4}$ and $k = 2$. Figure 1 shows the resulting splitting coefficients a_2 as a function of the lower turning point of the modes. These coefficients show a characteristic signature which should be detectable in the observed splittings if a strong enough magnetic field is indeed present in these layers. The errors in observed splitting coefficients is too large to show this signal and hence we take averages over neighbouring modes to reduce error bars. The resulting a_2 after subtracting out the contribution due to rotation is shown in the right panel of Fig. 1, which also shows the expected signal averaged in the same manner for a magnetic field with $\beta_0 = 10^{-4}$. The MDI data is from the first year of observation and the GONG data is from averaged spectrum for GONG months 4–14. Both these data sets are from observations around the minimum in solar activity. From this figure it can be seen that there is no clear signature of any feature near the base of the convection zone in the observed splittings. Thus we can only set an upper limit on the magnetic field in this layer, which will of course, depend on the thickness of the magnetic layer. For a layer with half-thickness of $0.02R_\odot$ the upper limit turns out to be $\beta_0 = 7\times10^{-5}$ or a magnetic field strength of 300 kG near the base of the convection zone (Antia et al. 2000). Similar limits have been obtained by Basu (1997). This limit is consistent with the value independently inferred by D'Silva & Choudhuri (1993).

2.3. Field in the upper convection zone

Looking at Fig. 1 it appear that there is no signature of a magnetic field in the radiative interior, as the observed splitting coefficients fall off smoothly with depth of the lower turning point. The only noticeable feature in the observed splitting coefficients is the peak around $r = 0.96R_\odot$. If this peak is solely due to a magnetic field, the field may be distributed around this depth. This is approximately the depth to which the outer shear layer in rotation profile extends (Antia et al. 1998; Schou et al. 1998). Comparison with expected splittings from magnetic field indicates that the observed peak may be due to a field with $\beta_0 = 10^{-4}$ (or $B \approx 20$ kG) concentrated around $r = 0.96R_\odot$ (Antia et al. 2000).

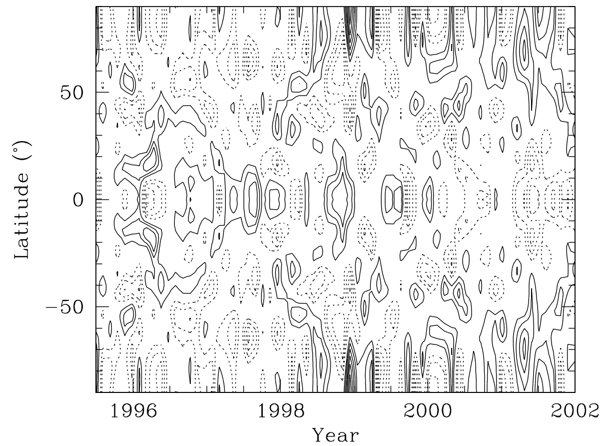

Figure 2. Contour diagram of the aspherical component of squared sound speed at $r = 0.96R_\odot$ as a function of time and latitude using the GONG data. The solid contours correspond to positive values, while dotted ones are for negative values. The contour spacing is 2×10^{-5}. The figure shows the residual obtained after subtracting out the temporal average at each latitude.

We do not expect an ordered large scale magnetic field inside the convection zone. It is possible that there is a concentration of randomised magnetic field at this depth which gives rise to the observed peak in the splitting coefficients. The splitting due to such a field will be quite different from what we have calculated and hence it is difficult to get the exact form or strength of the magnetic field from these calculations. Alternately, it is possible that this peak is due to departure from spherical symmetry in solar structure. This question is discussed in the next section. This feature is found to be present in all data sets and does not appear to depend significantly on the solar activity level.

3. ASPHERICITY IN THE SOLAR STRUCTURE

Apart from second order contributions from rotation, which can be easily estimated, the even splitting coefficients can arise from either a magnetic field or departures from spherical symmetry in solar structure. We have discussed the first possibility in the previous section. In this section we consider the other possibility. The departure from spherical symmetry can arise due to magnetic field (in which case this is included in the calculations described in the previous section) or may arise because the Sun may not be in strict hydrostatic equilibrium as is the case inside the convection zone. There could be other contributions to pressure, e.g., turbulent pressure, which are not isotropic and these may cause departure from spherical symmetry. Leaving aside the origin of asphericity we attempt to generalise the structure inversion technique to include departures from spherical symmetry. The splitting coefficients are sensitive only to the north-south symmetric component of asphericity and hence only this component can be determined. The differences in the sound speed, c, and the density, ρ, with respect to a spherically symmetric solar model can be cal-

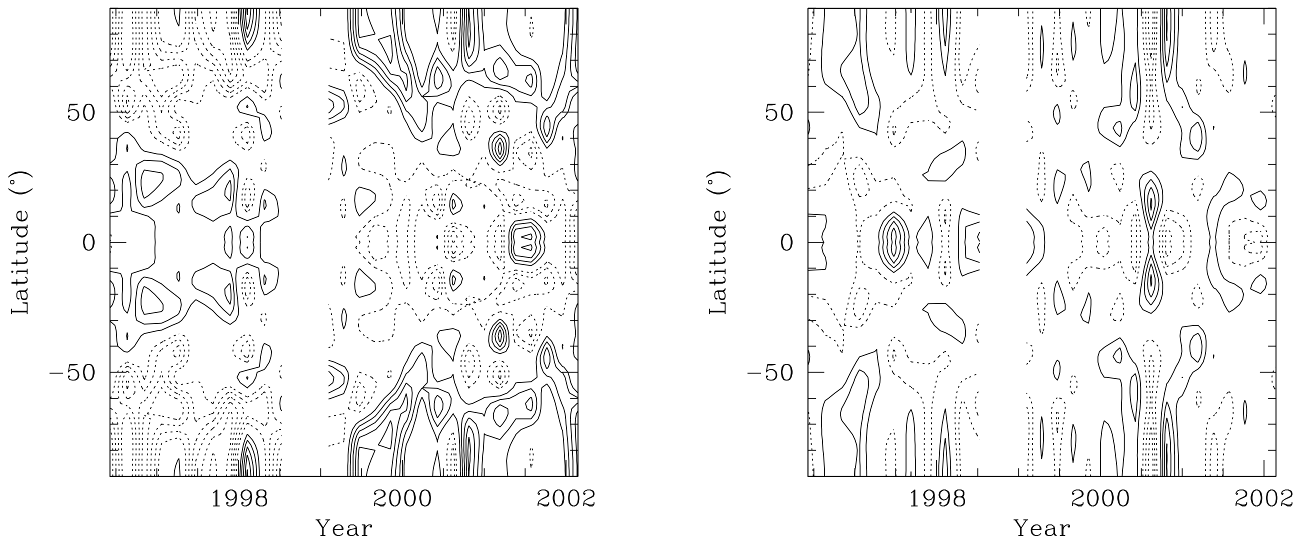

Figure 3. Contour diagram of the aspherical component of squared sound speed at $r = 0.96R_\odot$ as a function of time and latitude using the MDI data. This figure shows the residual obtained by subtracting out the temporal average at each latitude. The solid contours correspond to positive values, while dotted ones are for negative values. The contour spacing is 2×10^{-5}. The left panel shows the results obtained using all modes with $1.5 \le \nu \le 3.5$ mHz, while the right panel shows the results using modes with $1.5 \le \nu \le 3.0$ and $\ell < 110$.

culated using (Antia et al. 2001a)

$$\frac{\ell a_{2k}(n,\ell)}{\nu_{n\ell}} = Q_{\ell k}\frac{F_k(\nu_{n\ell})}{E_{n\ell}} + \frac{Q_{\ell k}(4k+1)}{2}\times \quad (4)$$
$$\int_0^R dr \int_0^\pi \sin\theta\, d\theta \left(\mathcal{K}^{n\ell}_{c^2,\rho}\frac{\delta c^2}{c^2} + \mathcal{K}^{n\ell}_{\rho,c^2}\frac{\delta\rho}{\rho}\right) P_{2k}(\cos\theta)$$

where $E_{n\ell}$ is the mode inertia (Christensen-Dalsgaard & Berthomieu 1991) and $Q_{\ell k}$ is a geometric factor as defined by Antia et al. (2001a). Here $F_k(\nu)$ are the surface terms which accounts for uncertainties in the treatment of surface layers.

3.1. Temporal variations in asphericity

Eq. 4 can be used for inversion to determine the sound speed and density as a function of radial distance and latitude. Using seismic data at different times it is also possible to study temporal variations in the solar structure. It is well known that the frequencies and even order splitting coefficients vary with solar activity. Thus it would be interesting to study if this implies any variations in the solar structure. The spherically symmetric component has been well studied and will not be considered in this work.

Fig. 2 shows the results for aspherical component of squared sound speed obtained using GONG data at $r = 0.96R_\odot$ as a function of time and latitude. To see the temporal variations more clearly, the figure shows the residuals obtained after subtracting the temporal average at each latitude. There is no pattern in the residuals, thus suggesting that there is no significant temporal variation. Similar results are obtained at other depths also. The aspherical component of density also shows a similar result and does not show any significant temporal variation. Thus it is clear that all the temporal variation in the splitting coefficients is accounted for by that in the surface term. In fact the surface term is well correlated with the corresponding component of the observed magnetic flux at the solar surface (Antia et al. 2001a).

Fig. 3 shows the residuals in sound speed at $r = 0.96R_\odot$ as determined by the MDI data. The left panel which shows the results using full data shows a distinct temporal variation in contrast to the GONG results. However, a careful look at the figure suggests that most of the temporal variation occurs between July 1998 and January 1999, when the contact with SOHO satellite was lost. This period is marked by the gap in the contour diagram. Before the gap there is positive asphericity at low latitudes and negative values at high latitudes. This is reversed after the gap and in fact there is very little systematic variations in the results before or after the gap. Thus there are two possibilities, either the Sun has had some interesting transition exactly when the MDI instrument was not operational, or the apparent variation is due to systematic errors introduced due to instrumental variations during recovery of the SOHO satellite. Considering the fact that the GONG data does not show any abnormality during this period, the second possibility appears to be more likely. This seems to be confirmed by the right panel which shows the same results but using only modes with $\ell < 110$. In this case there is no temporal variation in asphericity. Thus it appears that the systematic errors in MDI data are predominantly in the high degree modes.

These systematic errors in MDI data are likely to affect other conclusions too. For example, from the observed variation in the solar f-mode frequencies Dziembowski et al. (2001) have concluded that the solar radius is reducing at the rate of 1.5 km per year. Looking at their Fig. 2 (results with γ_f included) it appears that most of the variation has occurred between 1998.5 and 1999.2, the same period when MDI was not operational. There is very lit-

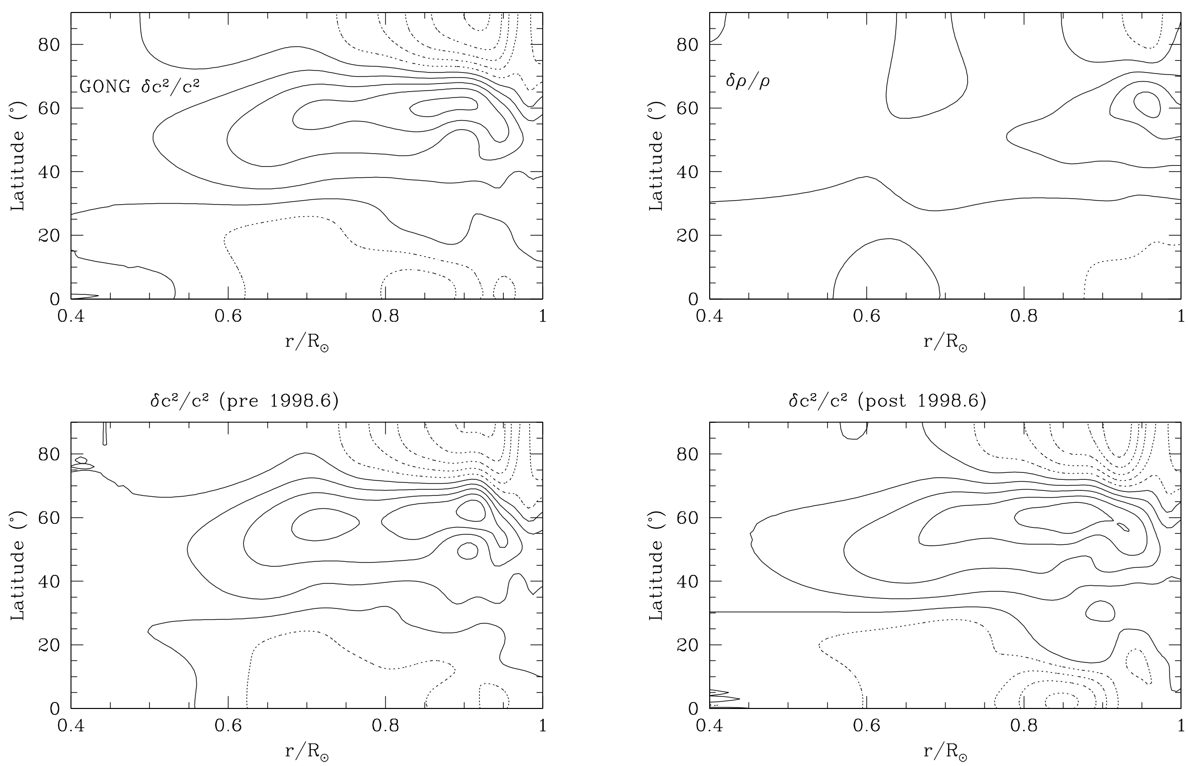

Figure 4. *Contour diagram of the temporal average of aspherical component of squared sound speed (top left panel) and density (top right panel) as a function of radial distance and latitude using the GONG data. The solid contours correspond to positive values, while dotted ones are for negative values. The contour spacing is* 2×10^{-5}*. The lower panels show the temporal average over pre 1998.6 and post 1998.6 data.*

tle variation in estimated radius before or after the break. This becomes more clear if additional data that has now become available is added. Thus once again the claimed radius variation is probably an effect of systematic errors. In fact, using an independent analysis Antia et al. (2001b) did not find any significant variation in the solar radius.

3.2. Temporal average of asphericity

Since we do not find any significant temporal variation in asphericity in the solar interior, it is possible to improve the accuracy of inversions by taking temporal average over all data sets. The average asphericity from GONG data as a function of radius and latitude is shown in Fig. 4. The MDI results obtained using only modes with $\ell < 110$ are similar to this. The typical errors in low latitude region inside the convection zone is about 10^{-5} which is half the contour spacing. The errors increase with depth and latitude. The most striking feature is the broad peak around $r = 0.9R_\odot$ and a latitude of $60°$. This is similar to the feature seen in section 2.3 in the splitting coefficients. The peak has shifted downwards when the surface term is removed for inversion. The maximum asphericity in sound speed is 10^{-4}. The perturbation in density is significantly smaller than that in squared sound speed. This may imply that a major part of this perturbation is coming from a magnetic field. A thermal perturbation will affect the density and squared sound speed (which is essentially temperature) to a comparable extent. Of course, this is not essential and there could be thermal perturbation which don't affect the density significantly. As noted earlier this feature could be due to a random magnetic field in the convection zone. If that is the case we can argue that the propagation speed is altered due to magnetic field and we may expect $\delta c^2/c^2 \approx v_A^2/c^2$, where v_A is the Alfven speed. This will translate to a field of about 70 kG at $r = 0.9R_\odot$.

Near the base of the convection zone $\delta c^2/c^2 \approx 5 \times 10^{-5}$ around a latitude of $60°$. If this is due to a magnetic field the field strength would be about 250 kG, comparable to the upper limit obtained in Section 2.2. It should be noted that in Section 2.2 we only considered field concentrated near the base of the convection zone, while the feature seen in Fig. 4 is spread over a broad region. Thus the earlier limit does not apply to this. From Fig. 4 if we try to put a limit on the magnetic field concentrated near the tachocline, then it will be of the order of $v_A^2/c^2 \sim 2 \times 10^{-5}$ (twice the estimated error in $\delta c^2/c^2$), which will correspond to a field strength of about 150 kG, close to the value inferred by D'Silva & Choudhuri (1993). Thus it is not clear if any significant field as required by dynamo theories is concentrated in this region.

To study the possibility of small temporal variation in inferred asphericity in sound speed, we divide the data sets into two parts around middle of 1998 and take averages separately over these parts. The results are shown in Fig. 4. There is a distinct increase in asphericity in post 1998.6 set as compared to earlier times. The increase appears to be up to 2×10^{-5} in some regions and is spread over a wide region.

Table 1. Distortion at solar surface due to a toroidal magnetic field located at different layers in the solar interior.

$r_0/R_\odot$	$d/R_\odot$	$\lvert\Delta r/r\rvert$
0.2	0.1	2×10^{-4}
0.4	0.1	6×10^{-5}
0.6	0.1	1×10^{-5}
0.8	0.1	6×10^{-6}

4. MAGNETIC FIELD IN THE SOLAR CORE

The inversions for asphericity become unreliable in the solar core ($r<0.3R_\odot$) since very few p-modes penetrate into this region. Further, the few modes that penetrate have large errors in the splitting coefficients and since the sound travel time in the core is fairly small the splitting coefficients are not very sensitive to the magnetic field in this region. As a result, it is difficult to get much information about possible magnetic field or asphericity in the solar core from these even order splitting coefficients. However, most of the solar mass is in the core and any significant perturbation to spherical symmetry in that region will cause significant distortion which will be visible even at the surface, unless it is compensated by suitably large distortions in the outer layers. From the temporal average of asphericity shown in Fig. 4, we can conclude that for $r>0.3R_\odot$, $\delta c^2/c^2<10^{-4}$ except possibly close to the peak in asphericity around $r=0.9R_\odot$ and latitude of 60°. It would be interesting to examine if this limit is applicable to possible asphericity in the solar core also.

Using the formalism developed by Gough & Thompson (1990) it is possible to calculate the distortion due to a large scale magnetic field in the solar interior. If we assume that the magnetic field is toroidal and given by Eqs. 2,3, with $\beta_0=10^{-4}$ and $k=2$ we can calculate the resulting distortion at the solar surface and the results for a few different values of r_0 are summarised in Table 1. It is clear that a magnetic field in the core produces distortion at the solar surface which is comparable to β_0, while if the field is located in the outer regions, the distortion is much less. This may be expected because the fractional mass affected by the magnetic field is small when the field is in outer regions.

The expected distortion at the solar surface can be compared with the observed distortion of $-(5.4\pm0.5)\times10^{-6}$ (Kuhn et al. 1998). Of this the seismically inferred rotation profile accounts for a distortion of -5.8×10^{-6} (Antia et al. 2000). Thus the residual distortion at the surface is at a level of 10^{-6}. This will imply that the magnetic field in the core should be such that $\beta_0<10^{-6}$. The actual distortion will depend on the form of the magnetic field and thickness of region where it is located. To allow for all these factors we can increase the upper limit by an order of magnitude. Thus we can put a conservative upper limit of 10^{-5} on the ratio of magnetic to gas pressure in the solar core.

Table 2. Properties of the tachocline at a few selected latitudes.

Lat. ($^\circ$)	$\delta\Omega$ (nHz)	r_t ($R_\odot$)	w ($R_\odot$)
0	20.8 ± 0.3	$.6917\pm.0023$	$.0062\pm.0012$
15	17.8 ± 0.2	$.6910\pm.0021$	$.0076\pm.0010$
45	-30.6 ± 0.4	$.7097\pm.0021$	$.0103\pm.0012$
60	-67.8 ± 0.6	$.7104\pm.0027$	$.0151\pm.0015$

5. THE TACHOCLINE

Using the forward modelling technique described by Antia et al. (1998) we study the properties of the tachocline as a function of time using the GONG and MDI data. The rotation rate in the tachocline is modelled by (Antia et al. 1998)

$$\Omega_{\rm tac}=\frac{\delta\Omega}{1+\exp[(r_t-r)/w]},\qquad(5)$$

where $\delta\Omega$ is the jump in the rotation rate across the tachocline, w is the half-width of the transition layer, and r_t the radial distance of the mid-point of the transition region. No significant temporal variation is found in any of these properties of the tachocline (Basu & Antia 2001). Thus we can take temporal average to improve the accuracy and the results are shown in Table 2.

From Table 2 it is clear that there is significant latitudinal variation in the position and thickness of the tachocline, which is consistent with the earlier results (Charbonneau et al. 1999; Basu & Antia 2001; Corbard et al. 2001). However, from the table it appears that the latitudinal variation is not continuous. The position and thickness for latitudes of 0° and 15° are the same within errorbars. Similarly, those for latitudes of 45° and 60° are close to each other, but they are significantly different from the values for low latitudes. Thus it appears that the tachocline actually consists of two parts, one at low latitudes where $\delta\Omega>0$ and another at high latitudes where $\delta\Omega<0$. This two parts are located at different depths and have different thicknesses, but there may be no significant latitudinal variation within each part. Thus the tachocline may cover the shaded region in Fig. 5, where we have used a half-thickness of $2.5w$, which would cover about 85% of the variation in the rotation rate.

It is believed that large shear in the tachocline region gives rise to some instabilities which cause mixing in the tachocline region. This mixing accounts for low observed lithium abundance at the solar surface and also yields sound speed profile in better agreement with seismic inversions (Richard et al. 1996; Brun et al. 1999). If the tachocline has a significant latitudinal dependence, then we would expect the mixed region also has a latitudinal dependence giving rise to asphericity in solar structure. However, there is no evidence for significant asphericity in this region as seen from Fig. 4 and further the depth

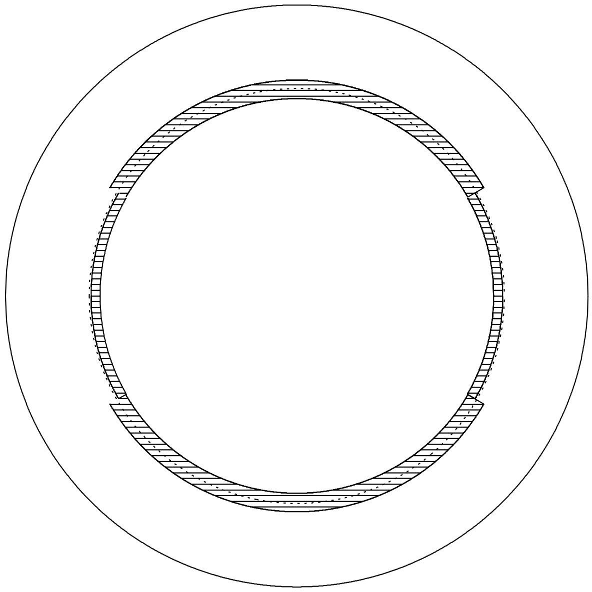

Figure 5. A section of the Sun showing the position of the tachocline (shaded area) and the base of the convection zone (dashed line). The solar rotation axis is assumed to be vertical.

of the convection zone also does not have any significant latitudinal variation (Basu & Antia 2001). This will appear to suggest that the tachocline may not be responsible for the mixing below the base of the convection zone. Another alternative is that the thickness of the tachocline varies in such a manner that the lower boundary of the mixed region does not have significant latitudinal dependence. This appears to be the case in Fig. 5. Of course, we have chosen the width of $2.5w$ to achieve this. Nevertheless, this is a reasonable estimate for extent of mixing due to the tachocline. It may be argued that it is a coincidence that variation in position and thickness match each other. If there is no mixing in the tachocline, as in the standard solar model (Christensen-Dalsgaard et al. 1996), the deviation in squared sound speed is of order of 0.5%, while the asphericity in the tachocline region is of order of 5×10^{-5}. Thus the agreement between position and thickness variations in the tachocline should be at level of 1%. A part of asphericity seen inside the convection zone may be due to latitudinal variation in the tachocline.

6. MAGNETIC FIELD IN ACTIVE REGIONS

To study the subsurface magnetic field in active regions we use the ring diagram technique (Hill 1988) which involves study of 3d spectra from observations over a part of the solar disk. We use the available spectra from the MDI data for this study. Each spectra covers a region of 15° in heliographic longitude and latitude. Each spectra is fitted following the procedure explained by Basu et al. (1999) and Basu & Antia (1999) to calculate the mode parameters. To study the influence of active region on mode properties, we choose a pair consisting of a quiet and an active region at the same latitude. The difference in mode properties between these two regions will give the effect of magnetic field in the active region (Rajaguru et al. 2001). It is found that frequencies increase with surface magnetic field. This frequency difference cannot be accounted by the surface term, which shows that the difference between active and quiet region persists to a depth of at least few Mm. Further, the frequency shift in f-modes is comparable to those in p-modes of similar frequency, which probably implies that the difference is arising from a magnetic field rather than thermal perturbation. The thermal perturbations are not expected to affect the f-modes significantly. But it is difficult to infer the form or location of the field from the seismic data. It is possible that Wilson depression associated with the Sunspot can account for the frequency differences between active and a quiet regions. It may be noted that because of spatial resolution of 15° on the solar surface we can only study average properties over regions much larger than sunspots. Time-distance analysis (Kosovichev 2002) is better suited to study the magnetic field in active region because of higher spatial resolution.

7. SUMMARY

Using the even order splitting coefficients it is possible to study the magnetic field and departures from spherical symmetry in the solar interior. Unfortunately, it is not possible to distinguish between these two possibilities. The seismic data from GONG and MDI covering the last 7 years does not show any signal from possible toroidal magnetic field concentrated near the base of the convection zone. An upper limit on such a concentrated field is about 150 kG. The seismic data shows a broad feature around $r = 0.9R_\odot$ and a latitude of 60° which may be due to a magnetic field or aspherical perturbation to the solar structure. The aspherical perturbations to the sound speed are at the level of 10^{-4} in this region and if these are due to a magnetic field we may expect a field strength of 70 kG. We do not expect large scale ordered magnetic field inside the convection zone but it is possible that some randomised magnetic field is present. This feature extends to the base of the convection zone where it has a magnitude of 5×10^{-5}, which will correspond to a field strength of 250 kG. The observed splitting coefficients do not yield a tight constraint on the magnetic field in the solar core as very few modes penetrate to the core. However, any magnetic field in this region will yield significant distortion at the solar surface. From the observed distortion we can put an upper limit of $B^2/(8\pi p_0) < 10^{-5}$ in the solar core ($r < 0.4R_\odot$). This corresponds to a field strength of 7 MG at the centre, or 3MG at $r \approx 0.2R_\odot$ or 0.8 MG at $r \approx 0.4R_\odot$.

There is no significant temporal variation in aspherical component of sound speed or density in the solar interior. This also applies to possible temporal variations in magnetic field. Thus any temporal variation in solar interior is less than about 5×10^{-5}, which is the error estimate inside the convection zone at low latitude. By taking temporal average over the high activity and low activity data sets it appears that there may be a small increase in sound speed asphericity with activity at the level of 10^{-5} in a broad region centred at latitude of 60°. This is comparable to the error estimate and its significance is not clear. The MDI data do show some temporal variation, but a closer look shows that most of the temporal variation has occurred during the time when SOHO had lost contact. Thus this is likely to be an artifact of systematic error introduced during recovery of SOHO. This systematic error will also affect other inferences about temporal variation obtained using the MDI data. This systematic error appears to be predominantly in high degree ($\ell > 110$) modes.

It is generally believed that the solar dynamo is operating in the tachocline region. But no significant temporal variation is seen in properties of the tachocline. Nevertheless, the tachocline is known to be prolate and there is indeed a significant latitudinal variation in the position and thickness of the tachocline. However, this latitudinal variation may not be continuous and it appears that the tachocline may consist of two parts one at low latitude where the rotation rate increases with radius and second one at high latitude where the rotation rate decreases with radius. These two parts may be located at different depths and have different thicknesses. But there may be no significant variations within each part. The thickness difference between the two parts should match the depth variation to ensure that the lower limit of mixing due to the tachocline is essentially independent of latitude.

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