TEMPORAL VARIATIONS IN THE ROTATION RATE IN THE SOLAR INTERIOR

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ABSTRACT

The frequency splittings obtained from GONG and MDI observations over the last 7 years are used to study how the rotation rate of the solar convection zone has evolved with time. The bands of faster and slower than average rotation rate are found to move towards the equator at low latitudes, while at high latitudes they move towards the poles. The low latitude bands also move upwards with time, and they extend almost to the base of the convection zone. We find no significant temporal variation in the rotation rate in the tachocline region.

Key words: Sun: oscillations; Sun: rotation; Sun: interior.

1. INTRODUCTION

With the accumulation of GONG and MDI data over the last seven years it is now possible to study the temporal variation in the rotation rate in the solar interior. The solar rotation rate is known to show temporal variations, with bands of faster and slower rotating regions moving towards the equator with time (Howe et al. 2000a; Antia & Basu 2000). This pattern is found to penetrate to a depth of about $0.1R_\odot$. Antia & Basu (2001) extended this study to higher latitudes to find that at high latitudes these bands move polewards. In this work we extend these studies to longer time interval and also investigate the radial variations in the zonal flow pattern.

The seat of the solar dynamo is believed to be near the base of the convection zone and one may expect some changes in this region during the solar cycle. Howe et al. (2000b) have reported 1.3 yr oscillations in the rotation rate in equatorial region at $r = 0.72R_\odot$. However, this periodicity has not been seen in other investigations (e.g., Antia & Basu 2000; Corbard et al. 2001), and hence, needs to be investigated further.

2. DATA SET

We have used data sets from GONG and MDI for this investigation. These sets consist of the mean frequency and the splitting coefficients. We use GONG data for months 1–68, which cover the period from 1995 May 7 to 2002 February 22. We have used the 68 temporally overlapping data sets each covering a period of 108 days with a spacing of 36 days between two consecutive data sets. The MDI data sets (Schou 1999) consist of 30 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2002 August 21 with some gaps during 1998–99 when contact with SOHO was temporarily lost.

We use a 2D Regularized Least Squares (RLS) inversion technique (Antia et al. 1998) to infer the rotation rate in solar interior from each of the available data sets.

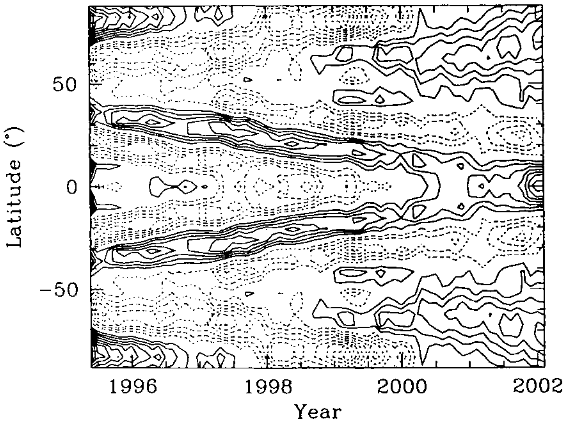

Figure 1. A contour diagram of the rotation-velocity residuals at $r = 0.98R_\odot$ obtained using 2D RLS inversion of GONG data. The solid contours are for positive $\delta v_{\rm rot}$, while dotted contours denote negative values. The contours are drawn at interval of 1 m/s. The zero contour is not shown.

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3. ROTATION RATE IN THE CONVECTION ZONE

The rotation rate in the outer layers of the Sun shows temporal variations with a pattern similar to the well known torsional oscillations at the surface. To study the temporal variations in the rotation rate we look at the residuals obtained by subtracting the temporal mean of the rotation rate from the rotation rate at any given time. The residuals at a depth of $0.02R_\odot$ below the surface from GONG data are shown in Fig. 1. This figure actually shows the linear velocity corresponding to the residual in rotation rate, i.e., $\delta v_{\rm rot} = \delta\Omega r\cos\theta$, where θ is the latitude. From this figure it can be seen that there are distinct bands of faster and slower than average rotation rate, and that these move towards the equator with time at low latitudes. At high latitudes, the bands seem to move towards the poles.

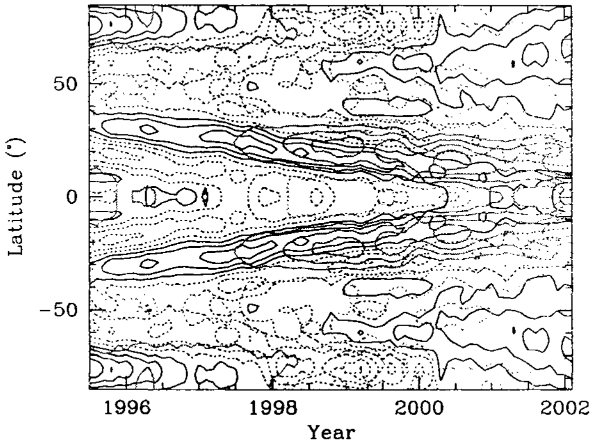

Figure 2. Superposed contour diagram of the rotation-velocity residuals (black contours) at $r = 0.98R_\odot$ and surface term in asphericity inversions (gray contours). The solid contours are for positive values, while dotted contours denote negative values.

Fig. 2 compares the temporal variation in zonal flows with those seen in the surface term of the inversion for asphericity. Antia et al. (2001) have demonstrated that the latter is well correlated with temporal variation in magnetic flux at solar surface. It can be seen that the band of positive zonal flow velocity is narrower than the surface term of asphericity. The equatorward edge of the two bands is roughly the same.

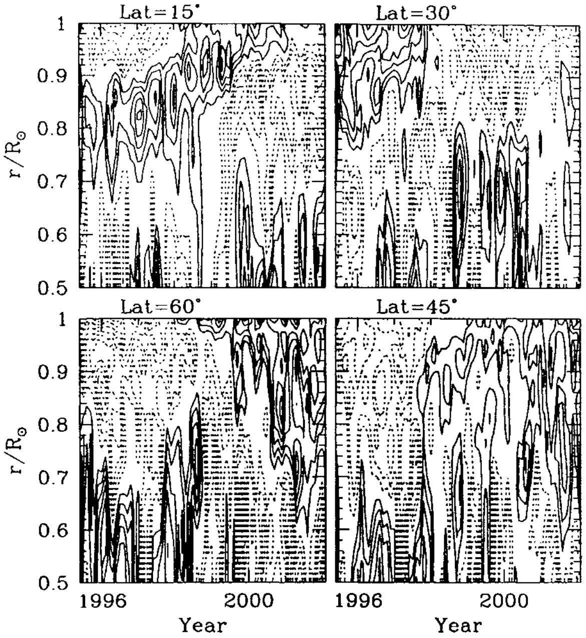

Figure 3. The rotation-velocity residuals from GONG data as a function of time and radial distance at selected latitudes. The contours of constant residual velocity are shown at intervals of 1 m/s, with solid contours showing positive values and dotted contours showing negative values.

Fig. 3 shows the rotation rate residuals from GONG data plotted as a function of time and radial distance at latitudes of 15°, 30°, 45° and 60°. At low latitudes there is a clear trend of contours moving upwards with time. From this we can deduce that the pattern rises upwards with time at a rate of about $0.05R_\odot$ per year or about 1 m/s. At 15° latitude, the pattern clearly penetrates to depths greater than $0.1R_\odot$ inferred in earlier works, reaching almost to the base of the convection zone. At other latitudes the depth of penetration cannot be discerned from these figures. At high latitudes the time evolution of pattern with depth is not clear either. Near the tachocline region there are many fluctuations which are probably due to errors in inversion and thus may not have any significance.

Fig. 4 shows the residual in rotation velocity at different latitudes as a function of time at $r = 0.98R_\odot$ from both GONG and MDI data. It is clear that different latitudes are at different phases of the pattern and the location of minima and maxima have strong latitudinal variations. The amplitude of variation is distinctly smaller around a latitude of 50° beyond which the shift in phase is gradual. If we assume that the zonal-flow pattern is periodic with a period of 11 years, the non-sinusoidal nature of variation implies the presence of higher harmonics of the period. We fit an expression of the form

$$\delta v_\phi(r,t,\theta) = \sum_{k=1}^{N} a_k(r,\theta)\sin(k\omega_0 t + \phi_k) \qquad (1)$$

where θ is the latitude and $\omega_0 = 2\pi/P_0$ is the basic solar cycle period, with $P_0 \approx 11$ years. Since the various terms are not orthogonal over the limited time period for which data are available the amplitudes of these terms also depends on the number of terms included. It is found that inclusion of $k = 2$ term tends to suppress the dominant $k = 1$ term. If this term is dropped then we can fit $k = 1$ and 3 terms. Fig. 5 shows the amplitudes of the $k = 1$ and $k = 3$

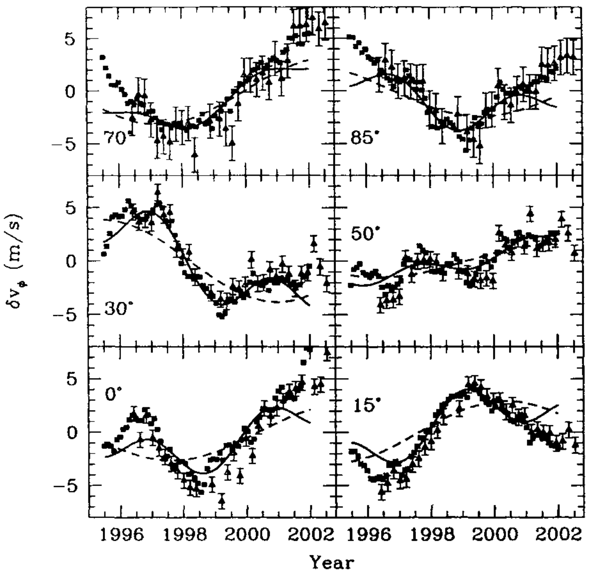

Figure 4. The zonal flow velocity as a function of time at different latitudes at $r = 0.98R_\odot$. The open triangles with error bars show the results using MDI data, while the filled squares show the GONG results. For clarity the error bars are omitted from GONG points. The lines show the fits to GONG data with period of 11 yr using Eq. 1 with only $k = 1$ term (dashed line) and $k = 1$ and 3 terms (solid line).

components as a function of radial distance and latitude. It is clear that the first term dominates and the amplitude of higher harmonic is less than half of the basic frequency. Similar results have been found by Vorontsov et al. (2002). The higher harmonic is found to be significant only near the surface. Furthermore, from the amplitude of $k = 1$ term it is clear that the pattern penetrates to a good fraction of the convection zone depth at low latitudes and possibly at high latitudes too. The pattern is not well defined at intermediate latitudes of around 40°.

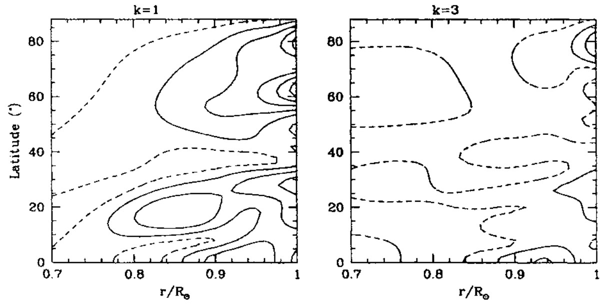

Figure 5. The contours of constant amplitude of $k = 1$ and 3 terms in the fit to zonal flow velocity. The contours are shown at intervals of 1 m/s, with dashed contour showing the 1 m/s level.

To check for possible periodic oscillations near the tachocline region, we calculate the residual in the rotation rate at different depths and latitudes. Some of the results are shown in Fig. 6, which can be compared with Fig. 2 of Howe et al. (2000b). We do not see any significant periodic signal in either the GONG or the MDI results at any latitude or depth. Even in inversion results of Howe et al. (2000b), the periodicity is not clear in MDI data and appears to show up only in GONG data.

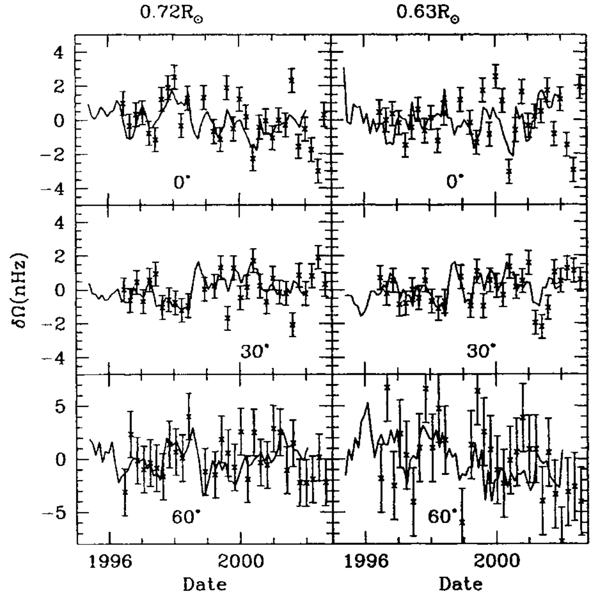

Figure 6. The rotation-rate residuals as a function of time at a few selected radii and latitudes. The radii are marked at the top of the figure, while latitudes are marked in each panel. The continuous line shows the results obtained using GONG data, while the points show the results from MDI data using 2D RLS inversion technique.

4. THE TACHOCLINE

Since the rotation rate in the tachocline region is steeply varying function with radius, inversions may not give reliable results in this region. To study the properties of the tachocline we use the three techniques described by Antia et al. (1998). These are: (1) a calibration method in which the properties at each latitude are determined by direct comparison with models; (2) a one dimensional (henceforth, 1d) annealing technique in which the parameters defining the tachocline at each latitude are determined by a nonlinear least squares minimisation using simulated annealing method and (3) a two-dimensional (henceforth, 2d) annealing technique, where the entire latitude dependence of the tachocline is fitted simultaneously, again using simulated annealing. To improve the accuracy we take weighted average of these three results.

In all techniques the tachocline is represented by a model of the form (cf., Antia et al. 1998),

$$\Omega_{\rm tac} = \frac{\delta\Omega}{1+\exp[(r_t - r)/w]}, \qquad (2)$$

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. Here, $\delta\Omega$, r_t and w are functions of latitude. The properties we are interested in are the position and the thickness of the tachocline, and the change in rotation rate across the tachocline. No significant temporal variation is seen in any of these properties (Basu & Antia 2001).

Table 1. Mean properties of the tachocline at different latitudes

Lat. (°)	$\delta\Omega$ (nHz)	r_t ($R_\odot$)	w ($0.01R_\odot$)
0	20.60 ± 0.42	0.6920 ± 0.0018	0.67 ± 0.13
15	17.68 ± 0.23	0.6912 ± 0.0018	0.75 ± 0.12
45	-30.32 ± 0.52	0.7096 ± 0.0018	1.16 ± 0.10
60	-67.62 ± 0.72	0.7103 ± 0.0022	1.47 ± 0.19

Since there is no significant temporal variation in any of the properties of the tachocline, we take temporal average over all data sets and techniques to improve the accuracy and the results are shown in Table 1. There is clearly a systematic variation in the position of tachocline with latitude while the variation in thickness is less clear. From Table 1, it appears that there is little difference between depth and thickness of tachocline between latitudes of 0° and 15° and between latitudes of 45° and 60°. It could be hypothesised that latitudes 0° to 30° and > 30° form two parts of tachocline which are distinct with different depths and thicknesses, while there is very little variation with latitude within each part.

5. CONCLUSIONS

The rotation-rate residuals, obtained by subtracting the time-averaged rotation rate from that at each epoch, show a pattern of temporal variation similar to the well known torsional oscillations observed at the surface, with bands of faster and slower rotation moving towards the equator with time. At high latitudes the bands appear to move towards the pole. This is quite similar to what is seen in theoretical results of Covas et al. (2000). At low latitudes the bands of faster and slower rotation appear to move upwards at a rate of about 1 m/s and the pattern penetrates almost to the base of the convection zone. Assuming that the zonal flow pattern has a fundamental period of 11 years we find that in addition to the fundamental period, the third harmonic is also significant in outer layers.

We do not find any evidence for the 1.3 year periodicity in equatorial regions at $r = 0.72R_\odot$, reported by Howe et al. (2000b). There is no significant temporal variation in the position, width or the extent of jump across the tachocline. The position of tachocline shows a significant variation with latitude, and the tachocline is found to be prolate, with a difference of $(0.018 \pm 0.003)R_\odot$ in position between the equator and a latitude of 60°, which is consistent with results obtained by Charbonneau et al. (1999).

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