THE SOLAR ROTATION RATE FROM SOLAR MINIMUM TO MAXIMUM

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ABSTRACT

Frequency splittings obtained from GONG and MDI observations over the last 6 years are used to study how the rotation rate in the solar convection zone has evolved with time. The polar rotation rate is found to have had a minimum in 1999, distinctly before the maximum solar activity. The bands of faster and slower than average rotation rate are found to move towards the equator at low latitudes and towards the poles at high latitudes.

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

1. INTRODUCTION

With the accumulation of GONG and MDI data over the last six years it is now possible to study the temporal variation in the rotation rate in the solar interior. Inversions of rotational splittings (Thompson et al. 1996; Schou et al. 1998) have demonstrated that there is shear layer just below the solar surface and a more pronounced shear layer at the tachocline around the base of the convection zone.

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. Recently 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 1–60, which cover the period from 1995 May 7 to 2001 April 4. We have used the 58 temporally overlapping data sets each covering a period of 108 days. The MDI data sets (Schou 1999) consist of 26 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2001 November 6.

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

3. RESULTS

Figure 1 shows the time-averaged rotation rate in the solar interior obtained using 2D RLS inversion for GONG and MDI data. Although qualitatively the GONG and MDI results are similar, there is significant difference between the inferred rotation rate at high latitudes. The sharp peak around latitude of 75° in the MDI results is most probably due to the jet like feature which is known to arise in inversions of MDI data (Schou et al. 1998; Howe et al. 1998), and this may be influencing the inferred rotation rate at high latitudes.

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

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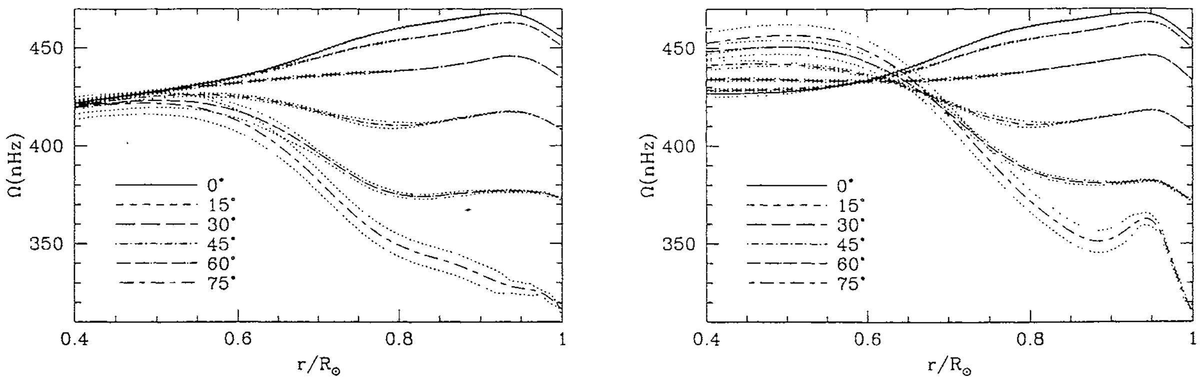

Figure 1. Temporal average of rotation rate in the solar interior obtained using 2D RLS inversion of GONG (left panel) and MDI (right panel) data. Various curves show the rotation rate at different latitudes as a function of radial distance, with dotted lines showing the error estimates.

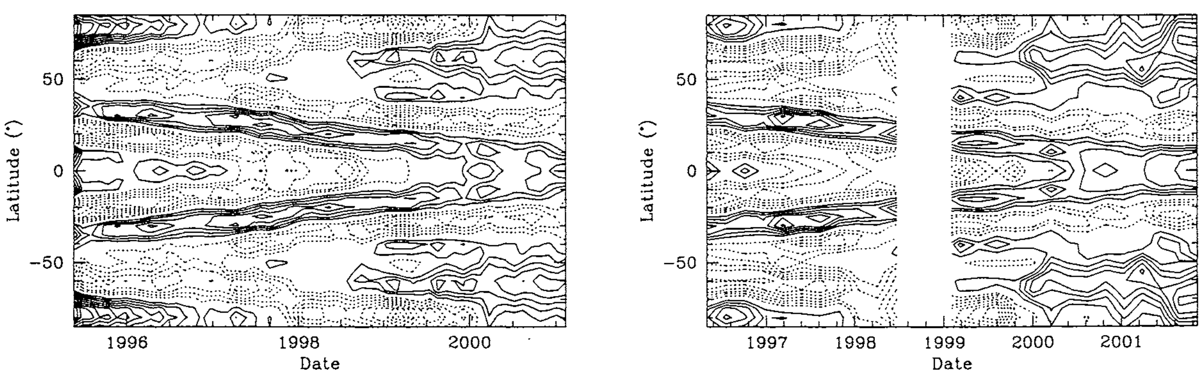

Figure 2. A contour diagram of the rotation-velocity residuals at $r = 0.98R_\odot$ obtained using 2D RLS inversion of GONG (left panel) and MDI (right panel) data. The continuous contours are for positive $\delta v_{\rm rot}$, while dotted contours denote negative values. The contours are drawn at interval of 1 m/s.

the 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 are shown in Fig. 2 for both GONG and MDI results. This figure actually shows the linear velocity corresponding to the residual in rotation, 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.

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. 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.

In addition to the well known bands of torsional oscillations we can also see that the rotation rate in the polar region has been varying with time. The polar rotation rate reached a minimum during 1999 after which it started increasing. This minimum is distinctly before the phase of maximum activity. Similarly, the maximum velocity must have been before the GONG network started operating, i.e., before the minimum activity epoch. Fig. 4 shows the rotation-velocity residuals at a latitude of 85° as a function of time at a few selected depths. It is clear that in the outer region there is a systematic variation in the rotation velocity with time and this variation persists up to a depth of $0.1R_\odot$. Below that the errors are too large and it is not clear if the pattern persists.

To check for possible periodic oscillations near the tachocline region, we calculate the residual in the

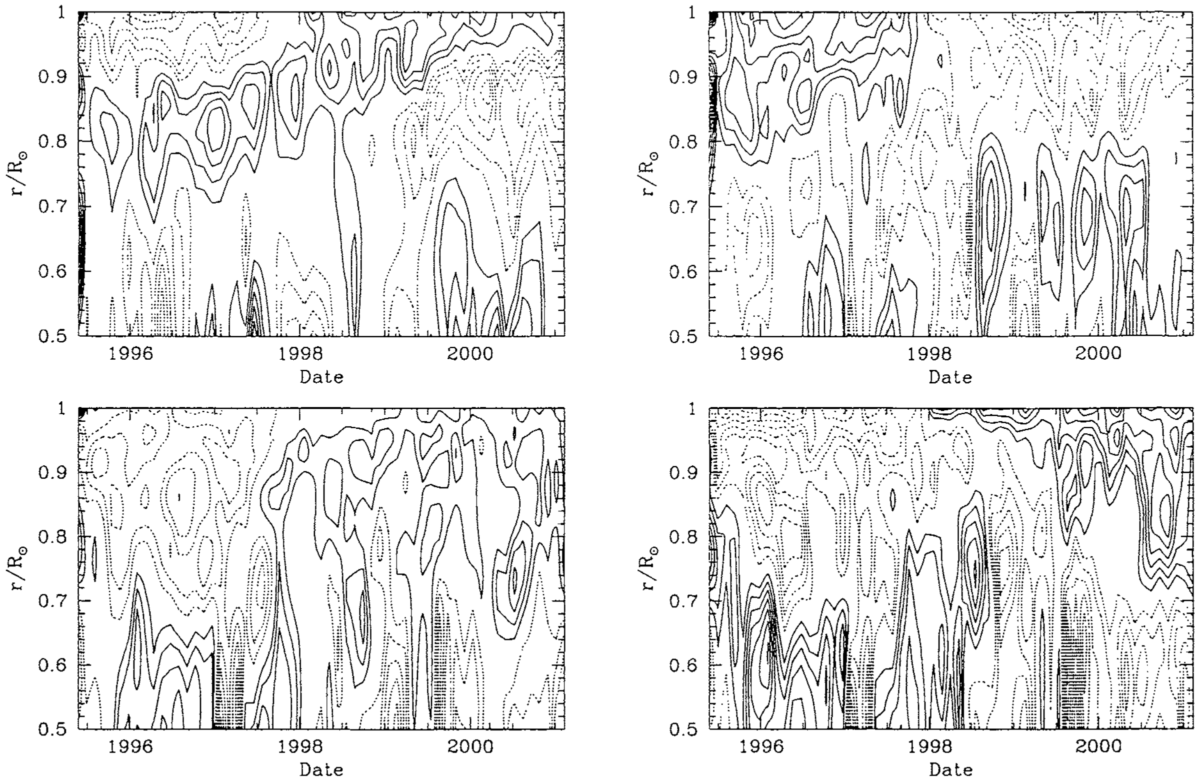

Figure 3. The rotation-velocity residuals from GONG data as a function of time and radial distance at selected latitudes. The contours of constant residual velocity are shown at intervals of 1 m/s, with continuous contours showing positive values and dotted contours showing negative values.

rotation rate at different depths and latitudes. Some of the results are shown in Fig. 5, 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. To test for possible periodicities in these results we take the Fourier transform of these data. The resulting power spectrum does not show any significant peak at any latitude or depth that we tried. Fig. 6 shows the results for equatorial region at $r = 0.72R_\odot$, where Howe et al. (2000b) find 1.3 year period. For calculating the Fourier transform of MDI results the missing points due to data gap are treated as zeros. From Fig. 6 it is clear that we do not see any significant peak in the power spectra. All the peaks in Fig. 6 are less than 1σ error estimates. 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.

4. 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.

The rotation rate in the polar regions in the outer layers decreased with time during 1995–1999, after which it started increasing. This decrease extends to a depth of at least $0.1R_\odot$ from the surface, similar to the penetration depth of the zonal flow pattern. 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).

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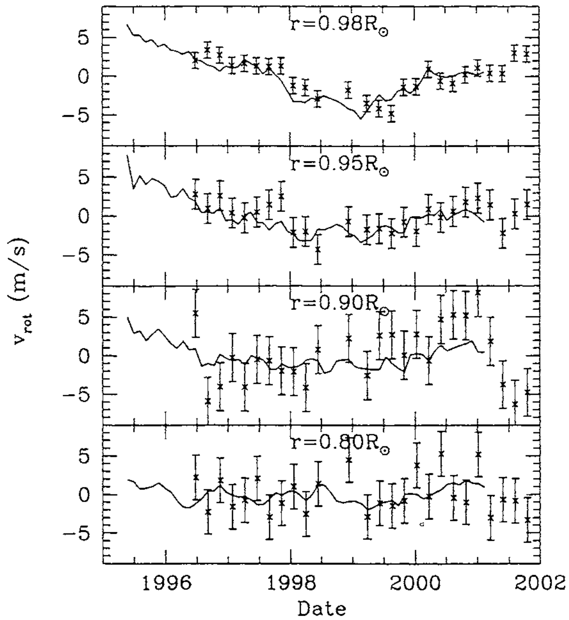

Figure 4. The rotation-velocity residuals in the polar region plotted as a function of time at a few selected radii. The results were obtained using 2d RLS inversion of GONG and MDI data. The continuous lines are GONG results and points with errorbars are MDI results.

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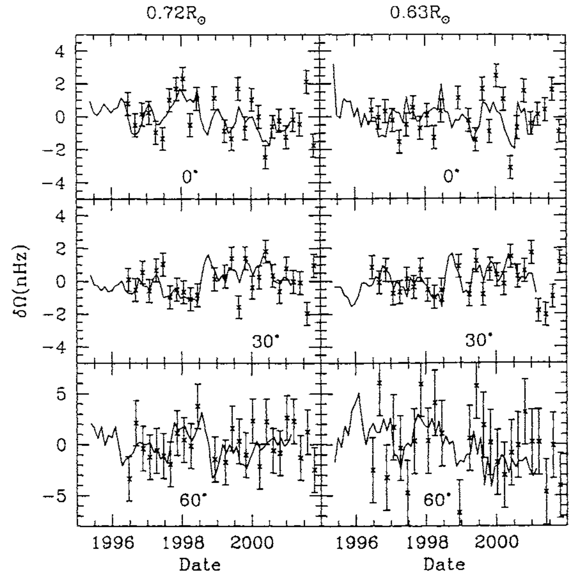

Figure 5. The rotation-rate residuals as a function of time at a few selected radii and latitudes. The radii are marked at the top of the figure, while latitudes are marked in each panel. The continuous line shows the results obtained using GONG data, while the points show the results from MDI data using 2D RLS inversion technique.

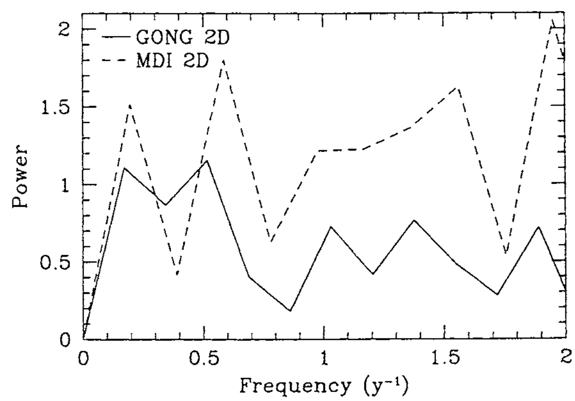

Figure 6. Power spectra obtained from various results for residual rotation rate in equatorial region at $r = 0.72R_{\odot}$.

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