TEMPORAL VARIATIONS IN ZONAL FLOWS

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ABSTRACT

With more than half a solar-cycle worth of helioseismic data now available, we revisit the question of how solar rotation rate changes 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: Rotation; Sun: Oscillations; Sun: Interior.

1. INTRODUCTION

With the accumulation of GONG and MDI data over the last nine years, it is possible to study the temporal variation in the rotation rate in the solar interior. The rotation rate is known to change with time, with bands of faster and slower than average rotating regions moving towards the equator with time (Howe et al. 2000a; Antia & Basu 2000) at low latitudes. These bands move towards the poles at high latitude (Antia & Basu 2001). At low latitudes these bands rise upwards with time and penetrate to the base of the convection zone (Basu & Antia 2003).

The seat of 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 the equatorial region at $r = 0.72R_\odot$. However, this periodicity has not been seen in other works (e.g., Antia & Basu 2000; Corbard et al. 2001) and hence needs to be investigated further. In this work we investigate possible temporal variations in the rotation rate in the convection zone as well as in the tachocline region.

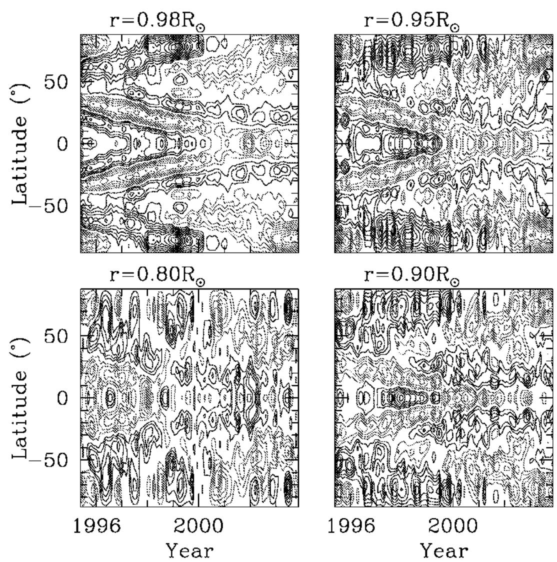

Figure 1. A contour diagram of the rotation-velocity residuals obtained using 2D RLS inversion of GONG data shown at a few representative depths. The red contours are for positive δv_ϕ, while blue contours denote negative values. The contours are drawn at intervals of 1 m/s; the contour for zero velocity is not shown.

2. DATA AND TECHNIQUE

We use 87 temporally overlapping data sets from GONG (Hill et al. 1996) each covering a period of 108 days, starting from 1995 May 7 and ending on 2004 January 7, with a spacing of 36 days between consecutive data sets. The MDI data consists of 38 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2004 March 19 (Schou 1999). Each set consists of the mean frequencies of different (n, ℓ) multiplets and the splitting coefficients. We use 2D Regularized Least Squares (RLS) inversion techniques (Antia et al. 1998) to infer the rotation rate in the solar interior from each of the available data sets.

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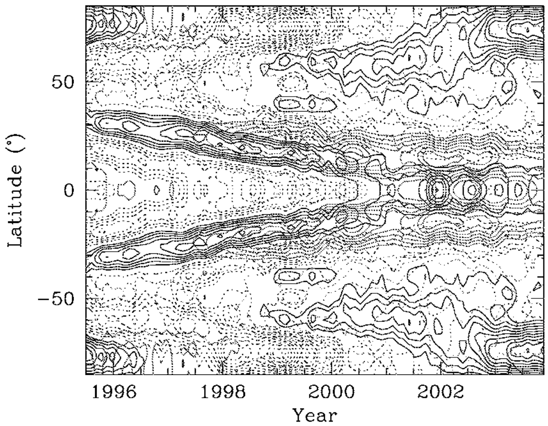

Figure 2. Superposed contour diagrams of the rotation-velocity residuals (blue contours) at $r = 0.98R_\odot$ and surface term in asphericity inversions (red contours). Positive contours are shown as solid lines, and negative ones as dotted lines.

3. RESULTS

To study the temporal variations in the rotation rate we look at the residuals of the rotation rate obtained by subtracting the temporal mean of rotation rate from the rotation rate at any given time. The residuals at a few representative depths below the surface are shown in Fig. 1 for GONG data. This figure actually shows the residual rotation velocity, $\delta v_\phi = \delta\Omega r \cos\theta$, 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, which move towards the equator with time at low latitudes. This pattern continues till a depth of at least $0.2R_\odot$, though the phase is varying with depth. At high latitudes, the bands seem to move towards the poles.

Fig. 2 compares the temporal variation in the zonal flows with those seen in the surface term obtained from asphericity inversions. Antia et al. (2001) have demonstrated that the latter is well correlated with changes in the magnetic flux at the 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.

Fig. 3 shows the rotation rate residuals plotted as a function of time and radius at latitudes of 15°, 30°, 45° and 60°. At low latitudes there is a clear trend — the bands seem to move 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 is clearly seen to penetrate to a depth of at least $0.2R_\odot$, which is about a factor of two higher than the earlier estimates of penetration depth (Howe et al. 2000a; Antia & Basu 2000). The pattern probably extends to the base of the convection zone. Vorontsov et al. (2002) also found the zonal flow pattern to penetrate to the base of the convection zone at high latitudes. The

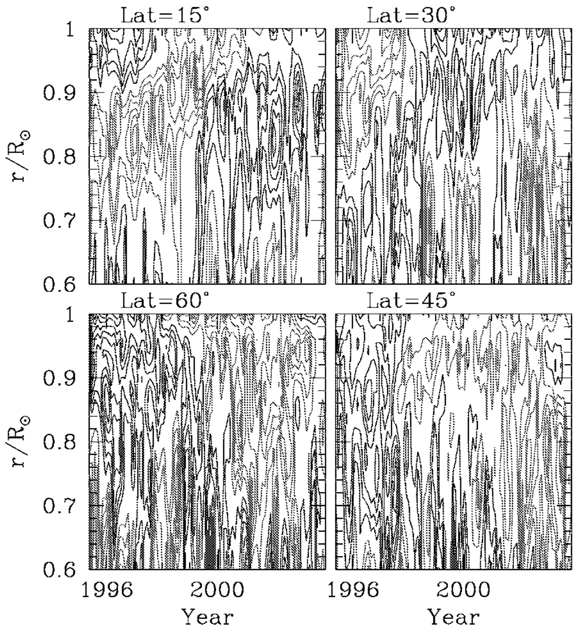

Figure 3. The rotation-velocity residuals as a function of time and radial distance at selected latitudes. The contours of constant residual velocity are shown at intervals of 1 m/s, with red contours showing positive values and blue contours showing negative values. The zero-velocity contour is not shown.

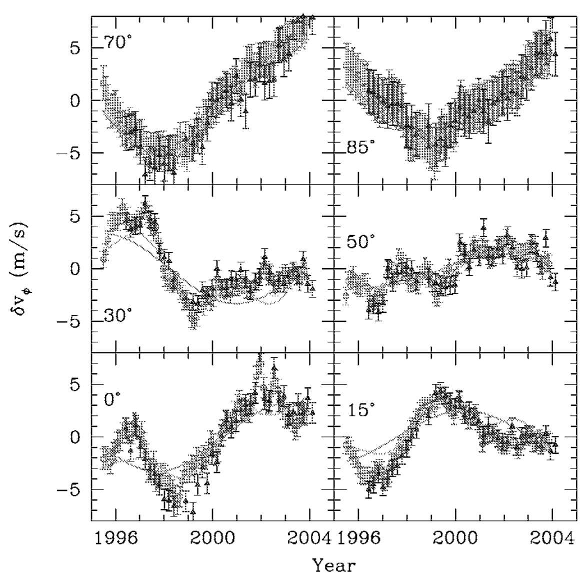

Figure 4. The zonal flow velocity as a function of time at different latitudes at $r = 0.98R_\odot$. The red and blue points show the results using GONG and MDI data while the lines show the fits to GONG data with period of 11 yr using Eq. 1 with only the $k = 1$ term (green) and with $k = 1$ and $k = 3$ terms (cyan).

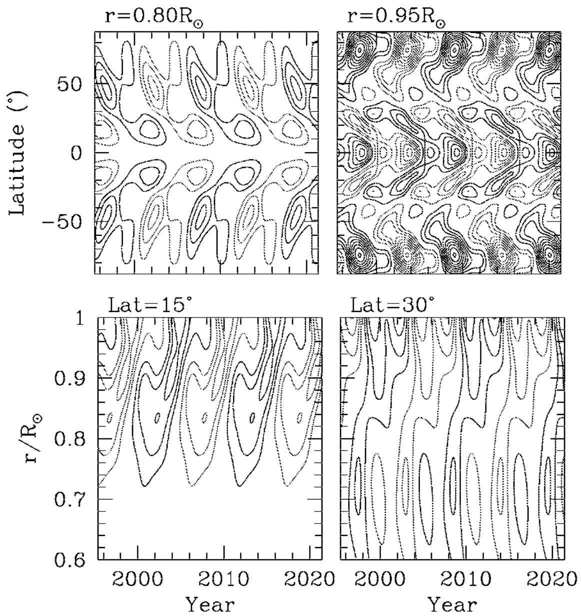

Figure 5. The rotation-velocity residuals as a function of time and latitude (top) and radial distance (bottom) at a few selected depths (or latitudes) as obtained from fits using $k = 1$ and 3 terms in Eq. 1. Contour levels are the same as in Fig. 1.

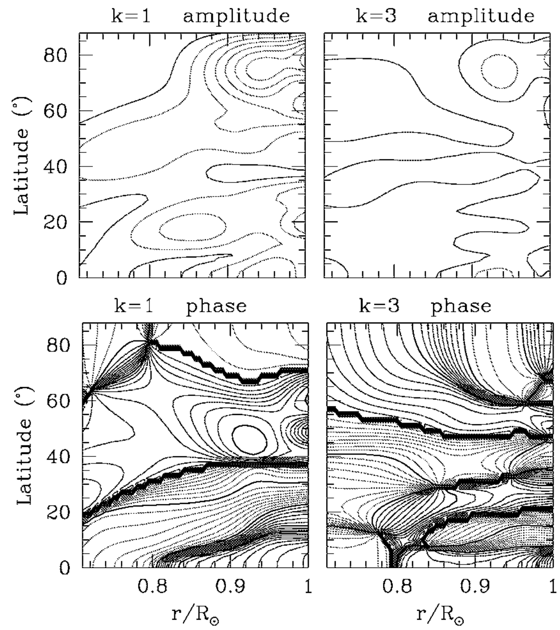

Figure 6. Contours of constant amplitude (or phase) of $k = 1$ & 3 terms in the fit to zonal flow velocities. Amplitude contours are at intervals of 1 m/s, with blue contours marking the 1 m/s level. Phase contours are at intervals of 10° (red positive, blue negative). Black contours are at intervals of 90°. The bunching of the black contours mark the transition between ±180°, and is artificial.

fluctuations near the tachocline region are probably due to errors, and hence, are not statistically significant.

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°, which is also the latitude 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 frequency, with $P_0 \approx 11$ years. We use the $k = 1$ and 3 terms to obtain the fits and Fig. 5 shows the pattern obtained over a period of 26 years at different depths and latitudes. This can be regarded as 'prediction' of the pattern over the solar cycle. It can be seen that at $r = 0.8R_\odot$ the pattern is quite feeble and is almost opposite in phase as compared to that near the surface in the equatorial region.

Fig. 6 shows the amplitudes and phases of the $k = 1$ and $k = 3$ components as a function of radial distance and latitude. It is clear that the first term dominates. Similar results have been found by Vorontsov et al. (2002). 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°. The phase of the pattern shows a more complicated behaviour. In regions where the amplitude is small, and at high latitudes, the phase can not be determined reliably. At low latitude the contours of constant phase tend to move towards the equator in deeper layers.

To check for possible periodic oscillations near the tachocline region, we calculate the rotation-rate residuals at different depths and latitudes. Some of the results are shown in left panel in Fig. 7, 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 check for possible periodic oscillations we take the discrete Fourier transform of the rotation rate residuals shown in left panel of Fig. 7 and the results are shown in the right panel of Fig. 7. It can be seen that none of the spectra show any dominant peak. In all cases the highest peak is of order of 2σ and are not likely to be significant and there is no peak near 1.3 year period.

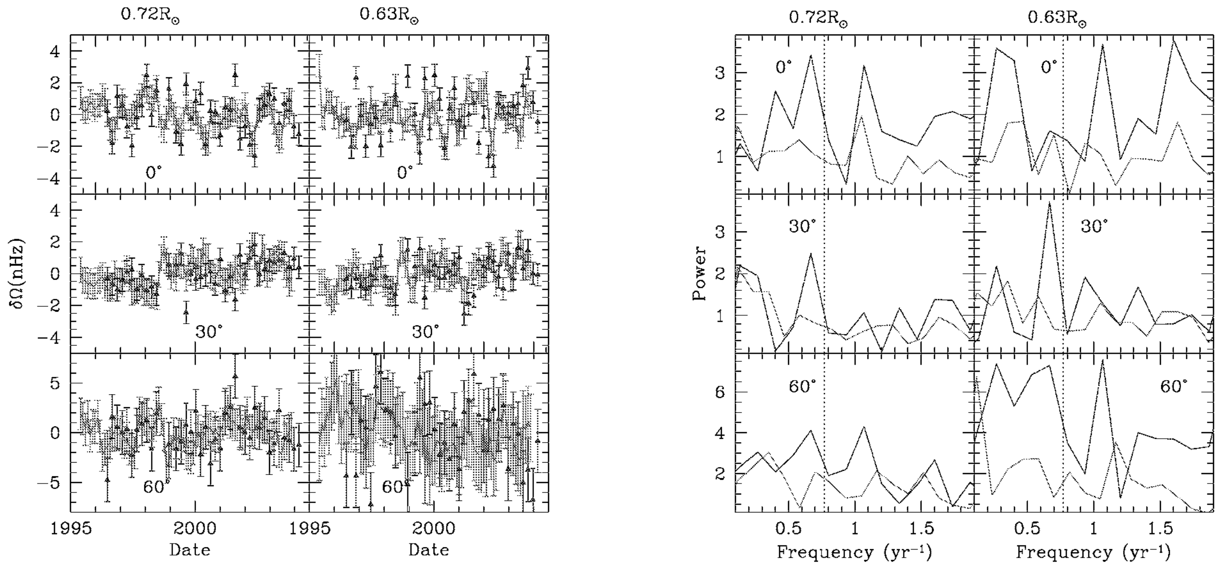

Figure 7. The rotation-rate residuals as a function of time at a few selected radii and latitudes. The radii are marked at the top of the figure, while latitudes are marked in each panel. The red points show the results obtained using GONG data, while blue points show the results from MDI data using 2D RLS inversion technique. The right panel shows the discrete Fourier transform of the rotation rate shown in the left panel. The dotted line is the right panels mark the 1.3 year period.

4. CONCLUSIONS

The rotation-rate residuals (obtained by subtracting the time-averaged rotation rate from that of each epoch) show the well known pattern of temporal variation that is similar to the torsional oscillations observed at the surface. It shows 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. Further, the zonal flow 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 $r = 0.72 R_\odot$, reported by Howe et al. (2000b).

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