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TEMPORAL VARIATIONS IN THE SOLAR ROTATION RATE DURING THE LAST ONE DECADE

Sarbani Basu[1] **and H. M. Antia**[2]

[1]*Astronomy Department, Yale university, P.O. box 208101, new Haven CT 06520-8101, U. S. A.*
[2]*Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*

ABSTRACT

With over a decade's worth of helioseismic data now available we study the temporal variation in rotation rate in the solar interior. Apart from the well known latitudinal shift in zonal flow pattern, we also find that at low latitudes the pattern shifts upwards with time. This pattern can be compared with predictions of solar dynamo theories. We also examine possible periodic variations in the rotation rate in the tachocline region.

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

1. INTRODUCTION

The solar rotation rate shows temporal variations. Bands of faster and slower than average rotating regions move towards the equator with time (Howe et al. 2000a; Antia & Basu 2000) at low latitudes, and towards the poles at high latitudes (Antia & Basu 2001). The low-latitude bands penetrate to the base of the convection zone and rise upwards with time (Basu & Antia 2003).

The tachocline at the CZ base is believed to be the seat of the solar dynamo, and changes may be expected 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 works (e.g., Antia & Basu 2000; Corbard et al. 2001) and hence needs to be investigated further.

With the accumulation of GONG and MDI data over the last ten years, it is possible to study the temporal variation in the rotation rate in the solar interior in more detail, which is what we do here.

2. DATA AND TECHNIQUE

We use 103 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 2005 August 5, with a spacing of 36 days between consecutive data sets. The MDI data consists of 47 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2005 December 27 (Schou 1999). Each set consists of the mean frequencies of different (n, ℓ) multiplets and the splitting coefficients.

We use 2D Regularised Least Squares (RLS) inversion technique (Antia et al. 1998) to infer the solar rotation rate for each data set. The time-variation of rotation is obtained by subtracting the time-averaged rotation rate from the rotation rate at each epoch:

$$\delta\Omega(r,\theta,t) = \Omega(r,\theta,t) - \langle\Omega(r,\theta,t)\rangle \ . \qquad (1)$$

where θ is the latitude. The residual is the time-varying component of the rotation rate. In early works on zonal flows (Howard & LaBonte 1980; Antia & Basu 2000), the residuals were calculated by subtracting the temporal average of smooth part $\Omega_S(r,\theta,t)$ of the rotation rate. This can be obtained by inverting only the a_1, a_3 and a_5 frequency splitting coefficients. Thus the residual are:

$$\delta\Omega_S(r,\theta,t) = \Omega(r,\theta,t) - \langle\Omega_S(r,\theta,t)\rangle \ . \qquad (2)$$

3. RESULTS

Fig. 1 shows the temporally varying component of rotation velocity using GONG data. The distinct bands of faster and slower than average rotation rate move towards the equator at low latitudes and towards the poles at high latitudes.

It is known that the surface term obtained from asphericity inversions correlate well with the magnetic flux at the solar surface (Antia et al. 2001). Comparing zonal flows with the surface term (Fig. 2), we see that the prograde bands seems somewhat narrower than the band in the surface term, however, The equatorward edge of the two bands is roughly the same. There also appears to be a phase offset between the two patterns, with surface term leading the zonal flow pattern by about 2 years. Further investigation is required to interpret the result.

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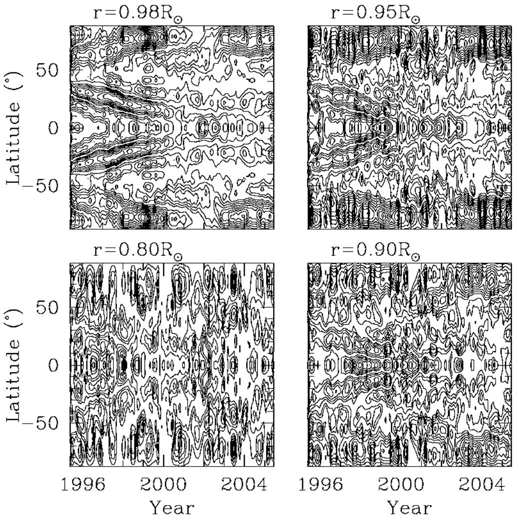

Figure 1. A contour diagram of the rotation-velocity residuals at a few representative depths, obtained using 2D RLS inversion of GONG data. We have plotted $\delta v_\phi = \delta\Omega r\cos\theta$. The red contours are for positive δv_ϕ, while blue contours denote negative values. The contours are drawn at intervals of 1 m/s; the contour for zero velocity is not shown.

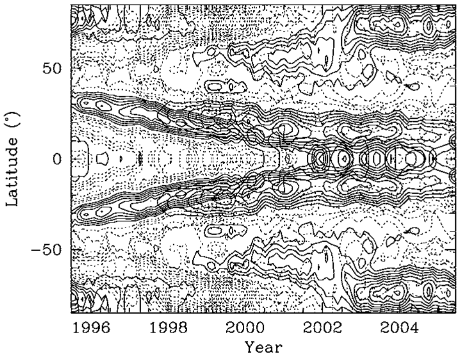

Figure 2. Superposed contour diagrams of the rotation-velocity residuals (blue contours) at $r = 0.98R_\odot$ and surface term in asphericity inversions (red contours). The positive contours are shown by solid lines, and negative ones by dotted lines.

Fig. 3 shows the zonal flow pattern as a function of time and radius at a fixed latitude. We can see that the zonal flow pattern at 15° latitude penetrates to at least a depth of $0.2R_\odot$, which is about a factor of two higher than earlier estimates (Howe et al. 2000a; Antia & Basu 2000). The pattern probably extends to the base of the convection zone (see also Vorontsov et al. 2002; Basu & Antia 2003). The fluctuations near the tachocline are most likely caused by data errors and hence, may not be significant. The bands seem to move upwards with time at a rate of about $0.05R_\odot$ per year i.e., about 1 m/s. The upward movement is does not appear to be uniform.

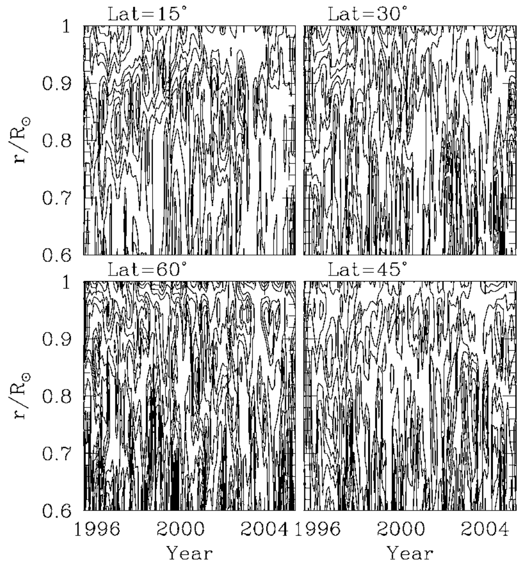

Figure 3. The rotation-velocity residuals as a function of time and radial distance at selected latitudes. The contours of constant residual velocity are shown at intervals of 1 m/s, with red contours showing positive values and blue contours showing negative values. The zero-velocity contour is not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

In order to check for correlations between the zonal flows and solar activity, we determined the correlation ceoficient between the average magnitude of the rotation-rate residuals calculated over the latitude range of 0–60°, $\langle|\delta\Omega|\rangle$, and the 10.7 cm radio flux (See Fig. 4). Rotation-rate residuals calculated using Eq. (1) show no significant correlation with activity, but those calculated using Eq. (2) show strong correlation at all radii in the outer part of the CZ. The correlation reduces as one approaches the base of the CZ. This shows the significant variation of the higher order frequency splitting coefficients with solar cycle. We can also conclude that the zonal flow pattern penetrates to a depth of at least $0.8R_\odot$.

Fig. 5 shows the rotation velocity residuals at fixed radius and latitude plotted as a function of time. Different latitudes appear to be at different phases of the zonal-flow pattern (see Fig. 5). The magnitude of the flow is distinctly smaller around 50° than at other latitudes. This is also the latitude beyond which the shift in phase is less marked and gradual. If we assume that the zonal-flow pattern is periodic with a period of 11 years, the non-sinusoidal nature of variation in Fig. 5 implies the presence of higher harmonics of the period. To the current data we can fit an expression of the form

$$\delta v_\phi(r,t,\theta) = \sum_{k=1}^{N} a_k(r,\theta)\sin(k\omega_0 t + \phi_k) \qquad (3)$$

where, $\omega_0 = 2\pi/P_0$ is the basic solar cycle period, with $P_0 \approx 11$ years to predict the zonal flow pattern at any time. Fig. 6 shows the pattern obtained by fitting only the first four terms at two representative radius and latitudes. These can be compared with those from theoretical dynamo models.

2006ESASP.617E..49B

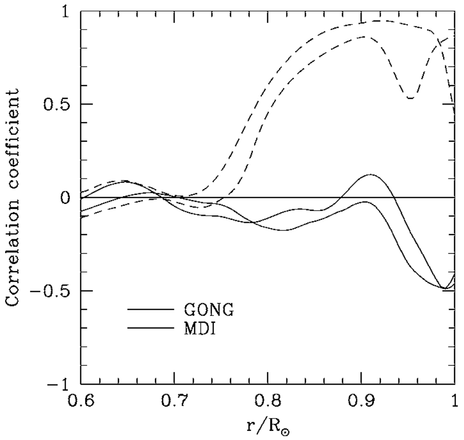

Figure 4. The correlation coefficient between the 10.7 cm radio flux and the mean magnitude of residual rotation rate in the latitude range of 0–60° plotted as a function of radial distance. The solid lines show the result using $\delta\Omega$ (Eq. 1) and the dashed lines are for $\delta\Omega_s$ (Eq. 2).

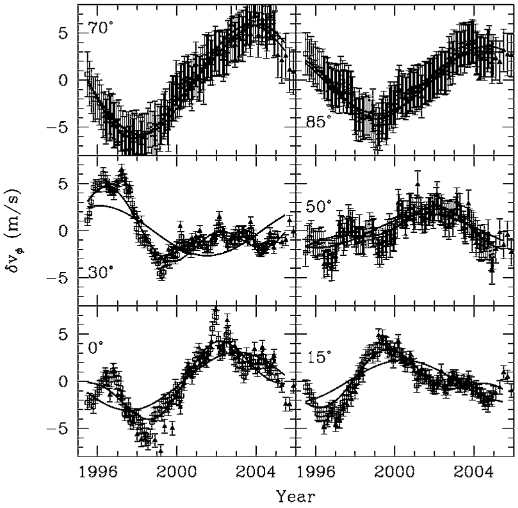

Figure 5. The zonal flow velocity as a function of time at different latitudes at $r = 0.98R_\odot$. The red and blue points show the results using GONG and MDI data while the lines show the fits to GONG data with period of 11 yr using Eq. 3 with only $k = 1$ term (green) and $k = 1, 2$ terms (cyan).

The amplitudes and phase of the $k = 1$ and $k = 2$ components as a function of radial distance and latitude can be seen in Fig. 7. It is clear that the first term dominates and the amplitude of higher harmonics is a small fraction of basic frequency (similar to results of Vorontsov et al. 2002 and Basu & Antia 2003). Higher-order terms other than $k = 2$ are not significant, a fact that was not very clear from earlier, limited data. Furthermore, the amplitude of the $k = 1$ term makes it 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°.

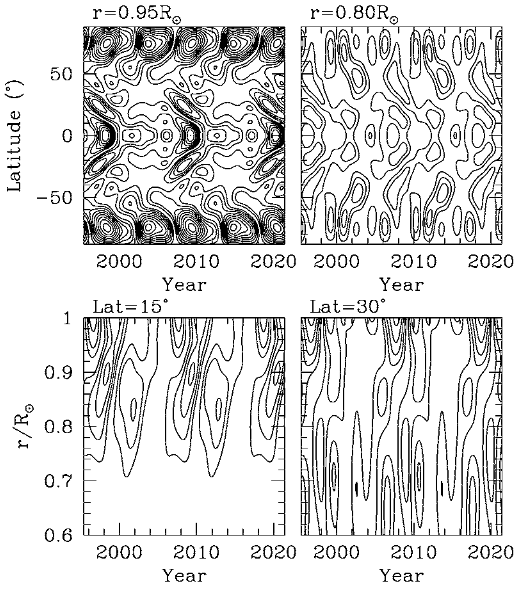

Figure 6. The rotation-velocity residuals as a function of time and latitude at two representative radius and latitudes. The contours of constant residual velocity are in the same format as in Figs. 1.

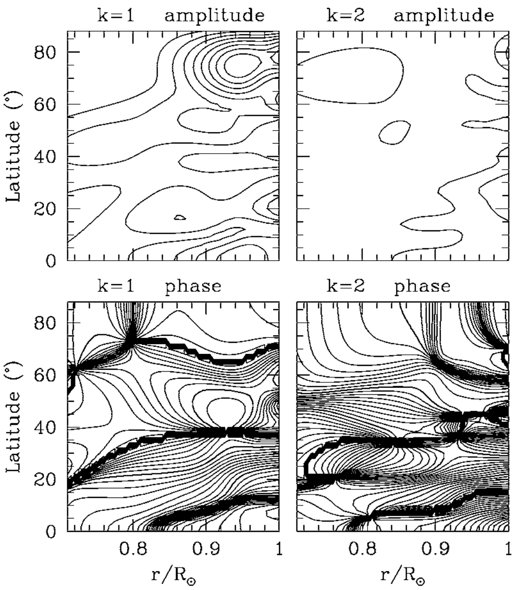

Figure 7. The contours of constant amplitude and phase of $k = 1$ and 2 terms in the fit to zonal flow velocity. The amplitude contours are shown at intervals of 1 m/s, with blue contour showing the 1 m/s level. The phase contours are at interval of $10°$ with red contours showing positive values and blue ones negative values. The black contours are at interval of $90°$.

To check for possible periodic oscillations near the tachocline region, we show $\delta\Omega$ at two radii in Fig. 8. This figure can be directly 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 these latitudes or depths. To test for periodicities in our results we calculate the discrete Fourier transform of $\delta\Omega$ and the results are shown in Fig. 9. It can be seen that none of the panels

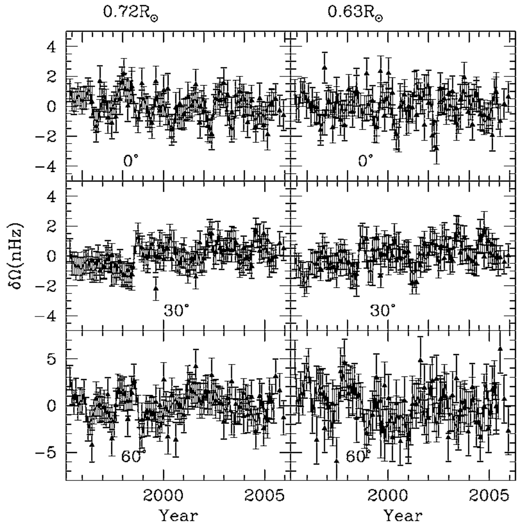

Figure 8. The rotation-rate residuals as a function of time at a few selected radii and latitudes. The radii are marked at the top of the figure, while latitudes are marked in each panel. 2D RLS inversion results from GONG are in red, MDI in blue.

show any dominant peak.

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. At low latitudes the bands move 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 zonal flow pattern penetrates almost to the base of the convection zone. The mean magnitude of zonal-flow velocities defined by Eq. (2) are extremely well correlated with solar activity indices till 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 second 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).

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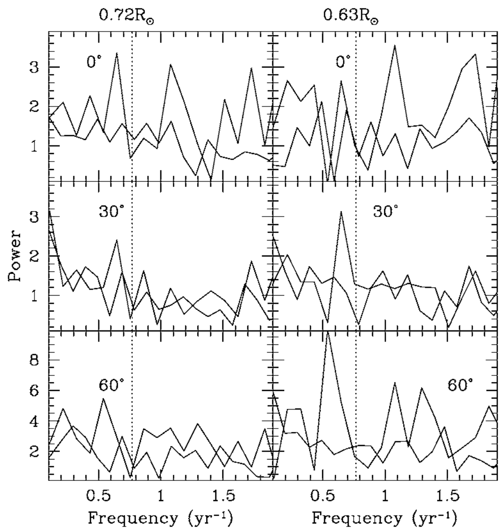

Figure 9. The discrete Fourier transform of the rotation-rate residuals at two radii (marked on top) and a few latitudes (as marked in each panel). GONG results are in red, MDI in blue. The dotted vertical line marks the 1.3 year period.

REFERENCES

Antia H. M., Basu S., 2000, ApJ 541, 442

Antia H. M., Basu S., 2001, ApJ 559, L67

Antia H. M., Basu S., Chitre S. M., 1998, MNRAS 298, 543

Antia, H. M., Basu, S., Hill, F., Howe, R., Komm, R. W., & Schou, J. 2001, MNRAS 327, 1029

Basu S., Antia H. M., 2003, ApJ 585, 553

Corbard, T., Jiménez-Reyes, S. J., Tomczyk, S., Dikpati, M., Gilman, P., 2001, in Helio- and Astero-seismology at the Dawn of the Millennium, ed. A. Wilson (ESA SP-464; Noordwijk: ESA), 265

Covas E., Tavakol R., Moss D., Tworkowski A., 2000, A&A 360, L21

Hill F., et al., 1996, Science 272, 1292

Howard R., LaBonte B. J. 1980, ApJ 239, L33

Howe R., Christensen-Dalsgaard J., Hill F., Komm R. W., Larsen R. M., Schou J., Thompson M. J., Toomre J., 2000a, ApJ 533, L163

Howe R., Christensen-Dalsgaard J., Hill F., Komm R. W., Larsen R. M., Schou J., Thompson M. J., Toomre J., 2000b, Science 287, 2456

Schou J., 1999, ApJ 523, L181

Vorontsov S. V., Christensen-Dalsgaard J., Schou J., Strakhov V. N., Thompson M. J., 2002, Science 296, 101