TEMPORAL VARIATIONS OF THE SOLAR ROTATION RATE AT HIGH LATITUDES

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ABSTRACT

Frequency splitting coefficients from Global Oscillation Network Group and Michelson Doppler Imager observations covering the period 1995–2001 are used to study temporal variations in the solar rotation rate at high latitudes. The torsional oscillation pattern in the Sun is known to penetrate to a depth of about $0.1\ R_\odot$ with alternate bands of faster and slower rotating plasma. At lower latitudes, the bands move toward the equator with time. At higher latitudes, however, the bands appear to move toward the poles. This is similar to the observed poleward movement of large-scale magnetic fields at high latitudes. This also supports theoretical results of poleward-moving bands at high latitudes in some mean field dynamo models. The polar rotation rate is found to decrease between 1995 and 1999, after which it has started increasing.

Subject headings: Sun: interior — Sun: oscillations — Sun: rotation

1. INTRODUCTION

The rotation rate of the solar interior can be determined by inverting observed rotational splittings of solar oscillation frequencies (Thompson et al. 1996; Schou et al. 1998). With the accumulation of Global Oscillation Network Group (GONG) and Michelson Doppler Imager (MDI) data over the last 6 years, it is now possible to study the temporal variation of the rotation rate in the solar interior. The rotation rate is known to show temporal variations, with bands of faster and slower rotating regions moving toward the equator with time (Schou 1999; Howe et al. 2000; Antia & Basu 2000) similar to torsional oscillations observed at the solar surface (Howard & LaBonte 1980; LaBonte & Howard 1982; Snodgrass 1992). This pattern is found to penetrate to a depth of about $0.1\ R_\odot$. Torsional oscillations are believed to arise from nonlinear interactions between magnetic field and differential rotation. As such, they should provide a constraint on theories of solar dynamo. Covas et al. (2000) considered an axisymmetric mean field dynamo model to study temporal variations in rotation rate and magnetic field in the solar interior. They find temporal variation in the rotation rate, which shows a pattern similar to torsional oscillations at low latitudes, with bands of faster and slower rotating regions moving toward the equator with time. But at high latitudes they find that these bands migrate poleward. As far as surface observations go, some magnetic features are seen migrating poleward at high latitude (Leroy & Noens 1983; Makarov & Sivaraman 1989). This poleward movement may be crucial for magnetic field reversal during the solar cycle. Thus, it is of interest to check if the observed zonal flow pattern also moves poleward at high latitudes. Inverters thus far have largely ignored the variation of the rotation rate near the polar regions, where the measurement of the rotation rate is likely to be less reliable. Preliminary helioseismic work by Howe et al. (2001) and Basu & Antia (2001) suggests that there could be a poleward flow at high latitudes. In this work, we attempt to study the temporal variations of the rotation rate near the poles. We first test the ability of inversion techniques to resolve the rotation rate near the poles using artificial data. We then apply

these techniques to study the temporal variations in the rotation rate using observed splitting coefficients.

2. DATA AND TECHNIQUE USED

We have used data sets from GONG and MDI for this investigation. These sets consist of the mean frequency and the splitting coefficients for each (n, l) multiplet. We use the GONG data for months 1–55, which cover the period from 1995 May 7 to 2000 October 6. We use all available 54 data sets, each covering a period of 108 days with a spacing of 36 days between consecutive data sets. The first data set covers only 36 days (a GONG month being 36 days). The MDI data (Schou 1999) consist of 23 nonoverlapping data sets, each covering a period of 72 days, starting from 1996 May 1 and ending on 2001 April 4, with some gap in between when the *Solar and Heliospheric Observatory* (*SOHO*) satellite was out of contact.

We use a two-dimensional regularized least-squares (RLS) inversion technique to infer the rotation rate in the solar interior from each of the available data sets. The details of the inversion technique are described by Antia, Basu, & Chitre (1998). Since in this work we are mainly interested in the rotation rate at high latitudes where the inversion technique is somewhat uncertain, we first perform a series of tests using artificial data sets to ascertain the reliability of the inversion procedure. For this purpose, we use a model rotation profile and calculate the splitting coefficients for the assumed rotation rate. Then we add random errors with the same standard deviation as the estimated errors in observed data sets and perform inversion using the same regularization as that used for the real data. We construct artificial data sets using test profiles of the form

$$\Omega(r, \theta) = 460 - 55\cos^2\theta - 55\cos^4\theta$$
$$+ A\exp\left[-\left(\frac{r - r_0}{w_r}\right)^2\right]\exp\left[-\left(\frac{\cos^2\theta - c_0}{w_c}\right)^2\right],$$
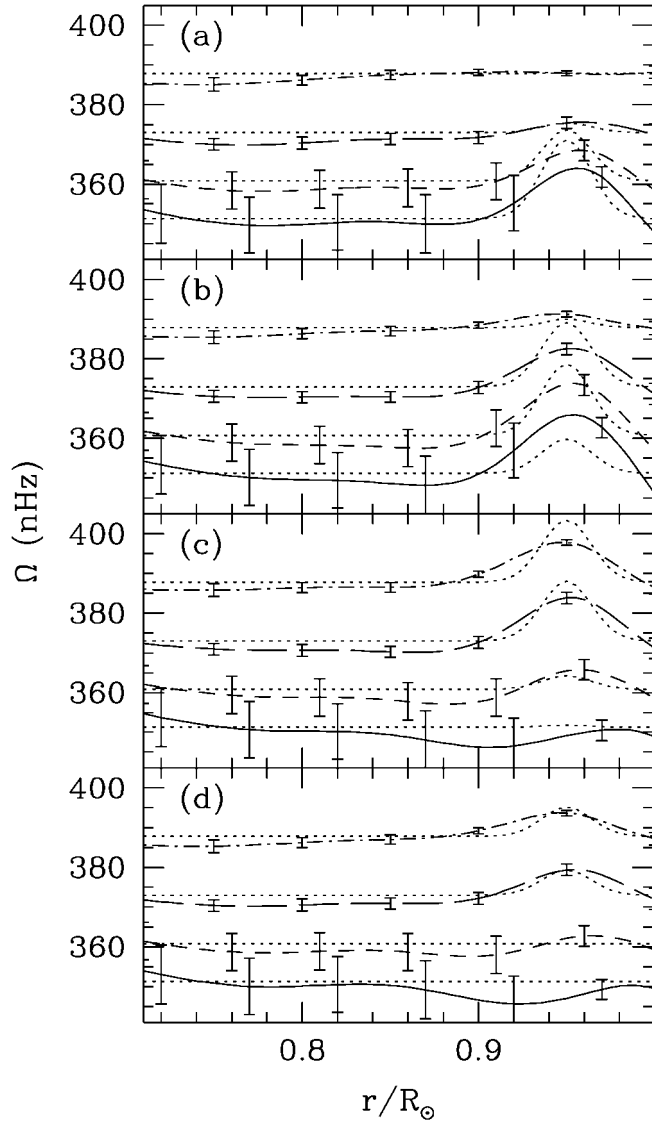(1)

Fig. 1.—Artificial data inversion results for several different model rotation profiles. In each panel, the dotted lines show the true rotation rate, while other lines show the inverted profiles at different latitudes. The solid line is for 85°, the short-dashed line for 75°, the long-dashed line for 67°.5, and the dot-dashed line for 60° latitudes. All the artificial profiles are for $r_0 = 0.95\ R_\odot$, $w_r = 0.02\ R_\odot$, and $A = 20$ nHz in eq. (1). (a) $c_0 = 1$, $w_c = 0.1$. (b) $c_0 = 0.9$, $w_c = 0.1$. (c) $c_0 = 0.8$, $w_c = 0.1$. (d) $c_0 = 0.8$, $w_c = 0.05$.

where $\Omega(r, \theta)$ is the rotation rate in units of nanohertz and A, r_0, w_r, c_0, and w_c are suitably chosen constants. In Figure 1, the inverted profiles are compared with the actual ones for a few of these sets using errors in MDI data sets. It is clear that inversions are able to reproduce relatively sharp peaks at high latitudes, too, although the exact shape may not match the actual peak. The radial extent of the peak is reasonably well reproduced by the inversions. Thus, the inversion results appear to be reliable even at high latitudes.

3. RESULTS

To identify the time-varying component of the rotation rate, we take the time average of all the results obtained from the
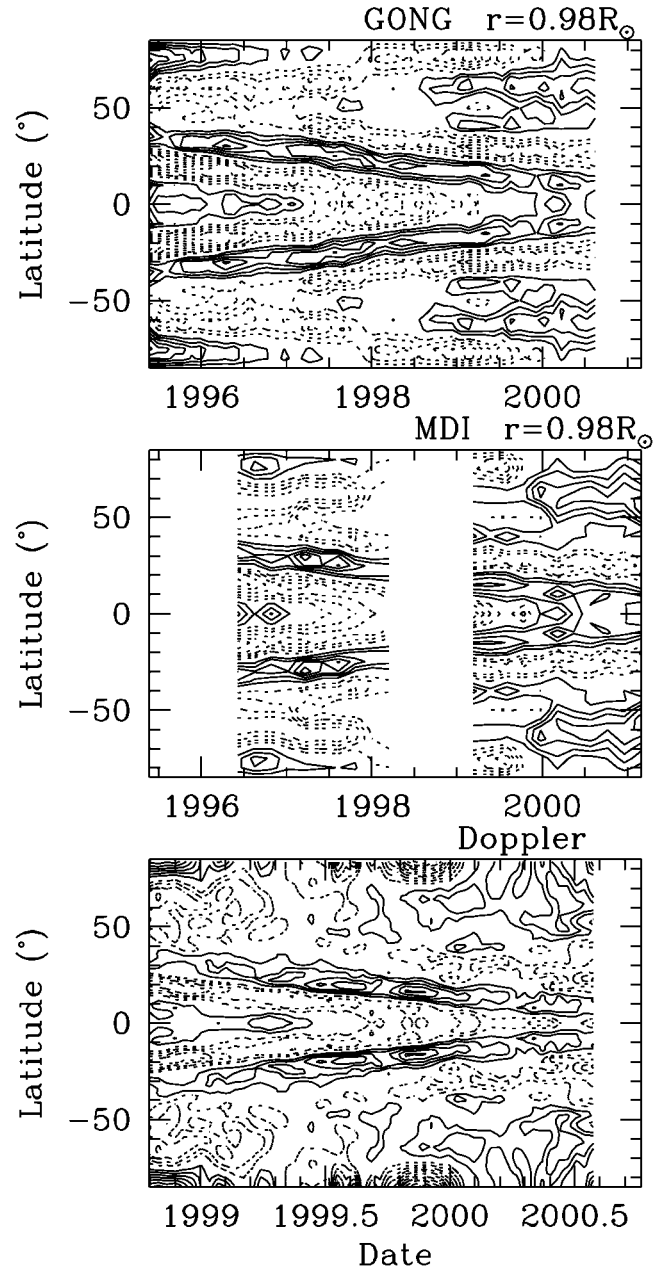

Fig. 2.—Contour diagrams of constant rotation velocity residuals at $r = 0.98\ R_\odot$ obtained using two-dimensional RLS inversion of GONG and MDI data. Also shown are the residuals for surface Doppler observation of Ulrich (2001). The solid contours are for positive δv_ϕ, while dotted contours denote negative values. The contours are drawn at intervals of 1 m s^{-1}.

different GONG (or MDI) data sets and then subtract this mean from the rotation rate at each epoch to get the residual. This residual, $\delta\Omega$, contains the time-varying part of the rotation rate. Figure 2 shows the contours of constant residual as a function of time and latitude at a depth of $0.02\ R_\odot$ below the solar surface as obtained from both GONG and MDI data. The MDI results have a gap during 1998–1999 when no data were available due to problems with the *SOHO* spacecraft. In order to facilitate comparison of the inversion results with surface observations, we show the rotation velocity $v_\phi = r\Omega \cos\theta$, where θ is the latitude. Also shown in the figure are the contours obtained for surface rotation velocity using Doppler measurements from Mount Wilson (Ulrich 2001). For the figure with
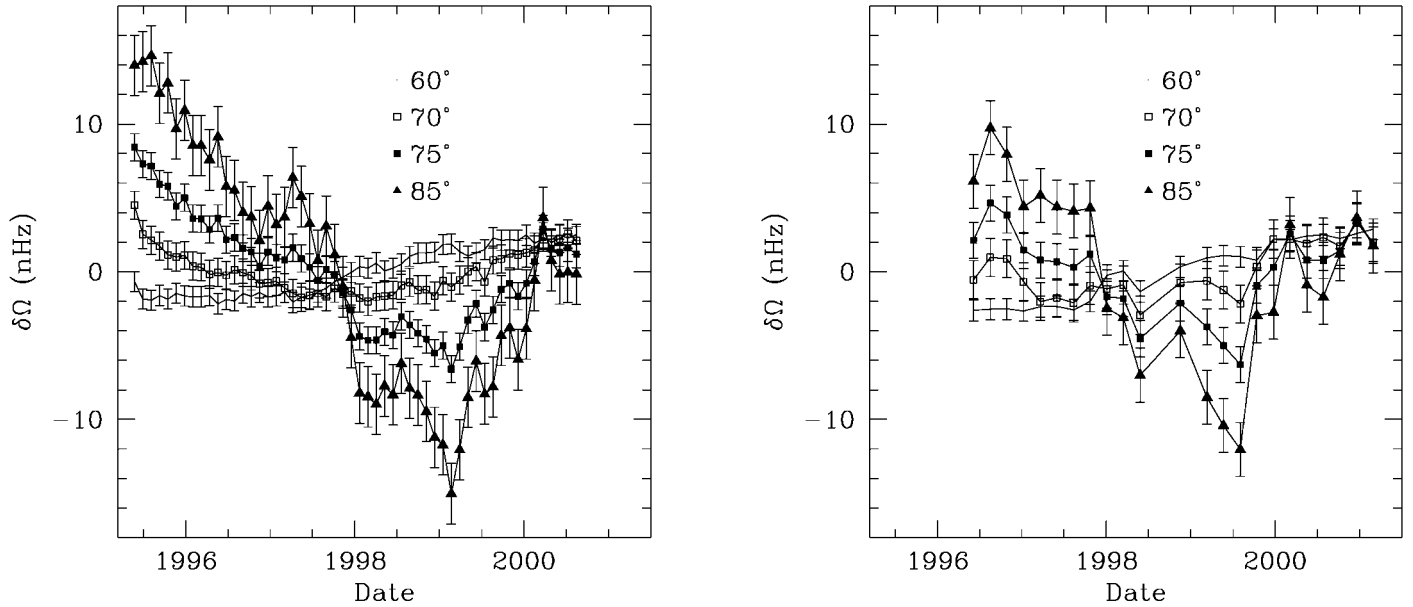
Fig. 3.—Rotation rate residuals at $r = 0.98\ R_{\odot}$ plotted as a function of time for different latitudes. The latitudes are marked in the figure. The results were obtained using two-dimensional RLS inversion of GONG (*left*) and MDI (*right*) data.

Doppler results, we show the north-south symmetric part of the rotation velocity since that is what the inversion results determine. In addition, we bin the Doppler data over the time intervals covered by the GONG data for a better comparison. In all these results, we can see that bands of faster and slower rotation move toward the equator at low latitudes. But beyond about 50°, the bands appear to move toward the poles. Theoretical results of Covas et al. (2000) based on a mean field dynamo model also show this feature. The latitude at which the transition from equatorward to poleward movement takes place is also similar in their models. The poleward drift is clear in the GONG results, which do not have any gap. The surface rotation rate as measured using Doppler techniques (Ulrich 2001) also shows similar features, although the poleward migration of bands at high latitude is not as clear as in the helioseismic results, probably due to difficulties of making Doppler measurements at high latitudes. Helioseismic data represents an average rotation rate over the period of observations, and this averaging smooths out variations on short timescales in the rotation rate, which have been observed both in Doppler measurements at the solar surface (Ulrich et al. 1988; Hathaway et al. 1996) and in results from local helioseismic techniques (Basu & Antia 2000). To test the robustness of the pattern, we have tried many different regularization parameters for inversion, and all results show these bands. The GONG and MDI patterns will not match exactly, as the temporal mean, which is subtracted to calculate the residuals, is taken over different time intervals.

In addition to having these bands, the rotation rate in the polar region has been decreasing with time during the period 1995–1999. To show this variation clearly, we show in Figure 3 the rotation rate residuals at constant latitude as a function of time at a depth of 0.02 $R_{\odot}$ below the solar surface. It is clear that there is a good agreement between the GONG and MDI results. At a latitude of 85°, which is the highest latitude for which we have tried to calculate inversion results, both GONG and MDI results show a clear decrease in the rotation rate residuals from 1995 to 1999, after which the residuals start

increasing. The minimum in polar rotation rate is found to be in early 1999 in GONG data and slightly later in MDI data. At a latitude of 75°, the pattern of variation is similar, but the amplitude of variation is much lower. The amplitude decreases rapidly as we move away from pole. It may be noted that in this figure we have plotted the rotation rate Ω rather than the rotation velocity v_{ϕ}. The amplitude of v_{ϕ}-variation does not increase as we approach the pole.

To study the depth dependence of the changes in the polar rotation rate, we show, in Figure 4, the rotation rate residuals at a latitude of 85° at different depths. At $r = 0.98\ R_{\odot}$, the errors are small and both GONG and MDI data show a clear time variation with a minimum in early 1999, as discussed earlier. This panel also shows the north-south symmetric component of the surface rotation rate as inferred from Mount Wilson Doppler measurements (Ulrich 2001). It is clear that although the Doppler measurements have larger fluctuations, the basic trend is similar to the helioseismic results, and in particular, these measurements also show the minimum at around the same period. The results for deeper layers have larger errors, but even so, a similar variation is seen at $r = 0.95\ R_{\odot}$. At even deeper layers, there is no clear temporal variation. Thus, it seems possible that the depth to which the temporal variation extends is similar to the 0.1 $R_{\odot}$ found for the zonal flow pattern at low latitudes (Howe et al. 2000; Antia & Basu 2000).

4. CONCLUSIONS

The solar rotation rate obtained from inversions of different sets of GONG and MDI data are used to study the time evolution of the rotation rate. The rotation rate residuals, obtained by subtracting the time-averaged rotation rate from that at each epoch, show the well-known pattern of temporal variation similar to the torsional oscillations observed at the surface, with
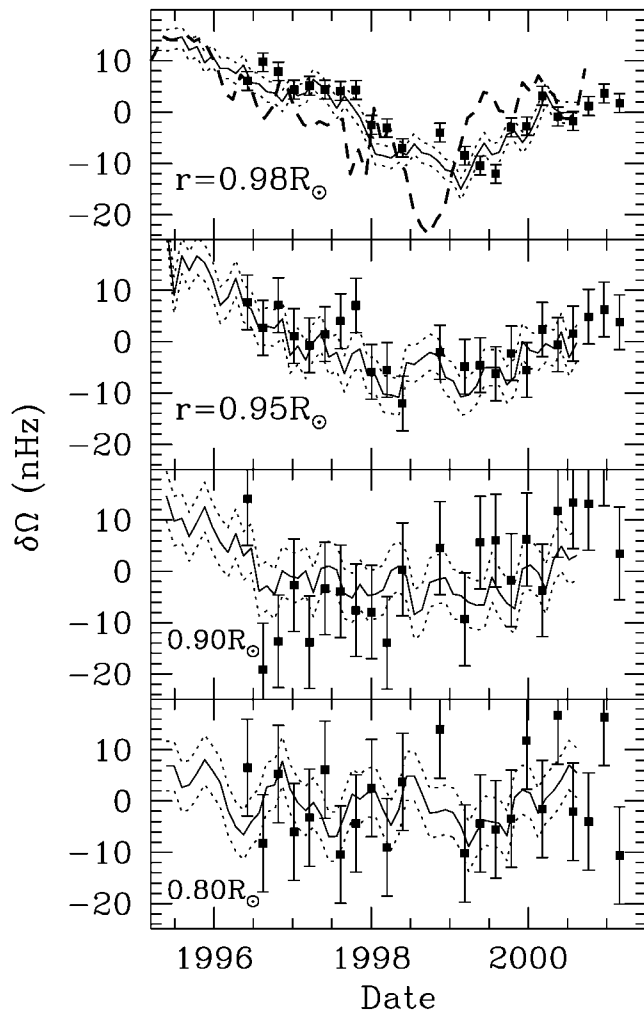
FIG. 4.—Rotation rate residuals at a latitude of 85°, plotted as a function of time at a few selected radii as marked in each panel. The results were obtained using two-dimensional RLS inversion of GONG and MDI data. The solid lines show the GONG results, with dotted lines showing the 1 σ error estimates, while the filled squares with error bars show the MDI results. The thick dashed line in the top panel shows the results from Doppler measurements at the solar surface.

bands of faster and slower rotation moving toward the equator with time at low latitudes. At high latitudes, it appears that the bands move toward the pole instead; the transition between equatorward and poleward movement appears to be around a latitude of 50°. Observations of magnetic features also show such poleward movement at high latitudes (see Leroy & Noens 1983; Makarov & Sivaraman 1989; Erofeev & Erofeeva 2000; Benevolenskaya, Kosovichev, & Scherrer 2001). Theoretical results of Covas et al. (2000) using a mean field dynamo model also show this feature. Our inversion results therefore reinforce the link between zonal flows and the solar magnetic cycle. Earlier works, too, have shown connections between zonal flows and the solar activity cycle (Antia & Basu 2000).

The rotation rate in the outer layers of the polar regions varies with time, reaching a minimum in early 1999, after which it has started increasing. The time of minimum rotation rate at the poles is distinctly before the maximum in solar activity. Similarly, it appears that the maximum rotation rate was achieved before the minimum in activity. These changes appear to persist until a depth of about 0.1 $R_\odot$, similar to the depth of penetration of zonal flow pattern at low latitudes. The observed temporal variations in the rotation rate should provide constraints on dynamo models.

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