SEISMIC INVESTIGATION OF CHANGES IN THE ROTATION RATE IN THE SOLAR INTERIOR

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

Frequency splitting coefficients from Global Oscillation Network Group (GONG) and Michelson Doppler Imager (MDI) data obtained during the period 1995–2000 are used to study temporal variations in the solar rotation rate. The torsional oscillation pattern in the Sun is known to penetrate to depths greater than the subsurface shear layer seen in rotation inversions. We study temporal and latitudinal variations in the properties of this shear layer. We also investigate the reported periodic variations of the rotation rate in the tachocline region in an attempt to test the results independently.

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

1. INTRODUCTION

With the accumulation of GONG and MDI data over the last five years, it is now possible to study the temporal variation in the rotation rate in the solar interior. Inversion of rotational splittings (Thompson et al. 1996; Schou et al. 1998) has demonstrated that there is shear layer just below the solar surface where the rotation rate increases with depth. In this work, we investigate possible temporal and latitudinal variations in the properties of the subsurface shear layer.

The 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 $0.1R_\odot$. However, these studies have not included the variation in rotation rate near the polar regions, where the rotation rate is likely to be less reliable. In this work we make an attempt to study the temporal variations of the rotation rate near the poles.

The seat of the solar dynamo is believed to be near the base of the convection zone and since rotation is expected to play a crucial role in the operation of solar dynamo, one may expect some changes in the rotation rate in this region during the solar cycle. Recently 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) and hence needs to be investigated further.

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 the GONG data for months 1–47, which cover the period from 1995 May 7 to 1999 December 23. We use all available 46 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. The MDI data (Schou 1999) consists of 19 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2000 June 20.

We use both 1.5D and 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 inversion techniques are described by Antia et al. (1998).

2. RESULTS

Fig. 1 shows the time-averaged rotation rate in the solar interior obtained using 2D RLS inversion for GONG and MDI data. The outer shear layer — where the rotation rate increases with depth — is seen at all latitudes in the GONG inversion results. In the MDI results, however, the shear layer appears to reverse sign close to the surface at high latitudes. Below this there is again another shear layer where rotation rate increases with depth. The sharp peak around latitude of 75° 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 shear layer at these latitudes.

The magnitude of the increase in the rotation rate in the outermost shear layer, $\delta\Omega$, for a few selected latitudes is shown in Fig. 2. There does not appear to be any significant systematic temporal variation in any of these panels. Only $\delta\Omega$ at latitudes around 60° obtained by 1.5D inversions of GONG data appears to show a mild increase with

Proc. SOHO 10/GONG 2000 Workshop, 'Helio- and Asteroseismology at the Dawn of the Millennium', Santa Cruz de Tenerife, Tenerife, Spain, 2-6 October 2000 (ESA SP-464, January 2001)

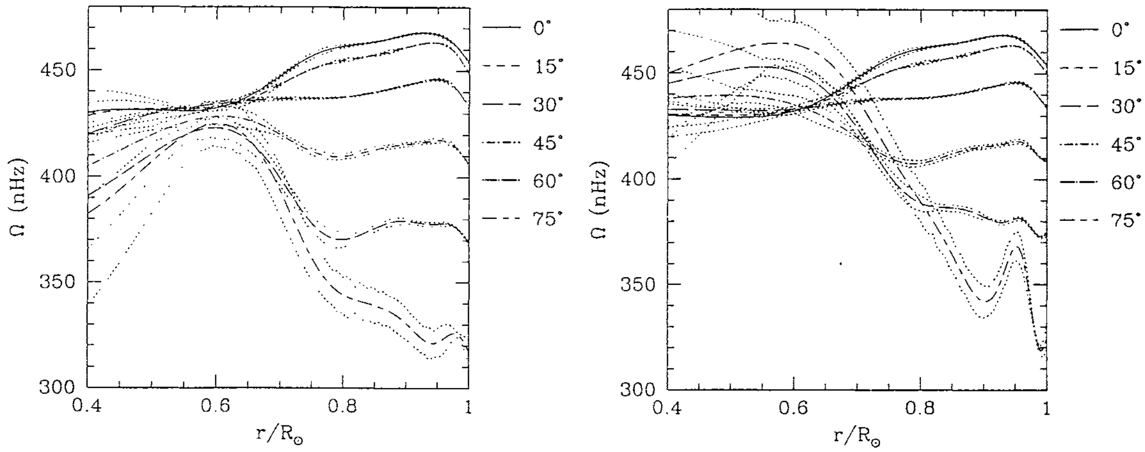

Figure 1. Temporal average of rotation rate in the solar interior obtained using 2D RLS inversion of GONG (left panel) and MDI (right panel) data. Various curves show the rotation rate at different latitudes as a function of radial distance, with dotted lines showing the error estimates.

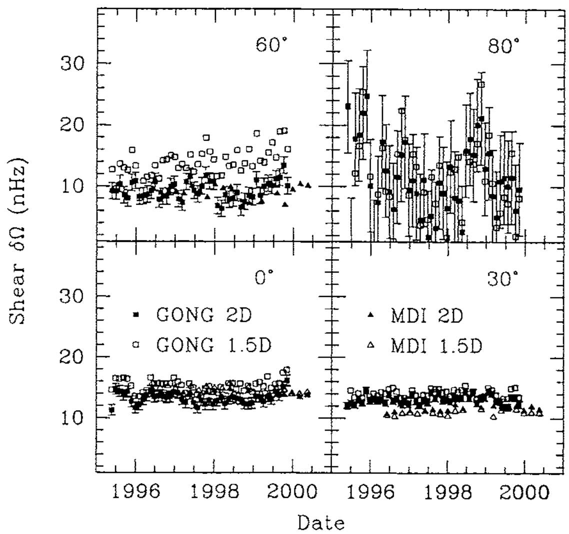

Figure 2. The increase in the rotation rate in the outermost shear layer as a function of time at a few selected latitudes. The results were obtained using different data sets and inversion techniques. Since MDI results show a reversal of the gradient in the outer shear layer at high latitudes, the results are not shown in the corresponding panels.

time. This is not seen in other results. We do not see any temporal variation in the depth of the shear layer either.

We also try to find latitudinal variation in the properties of this shear layer. For this purpose we take temporal averages of $\delta\Omega$ and of the depth of the shear layer at each latitude. The results are shown in Fig. 3. There is considerable variation between different results for $\delta\Omega$, but all of them show a decrease in $\delta\Omega$ with latitude. The agreement between different results is much better for depth and all show a decrease in the thickness of the shear layer with latitude.

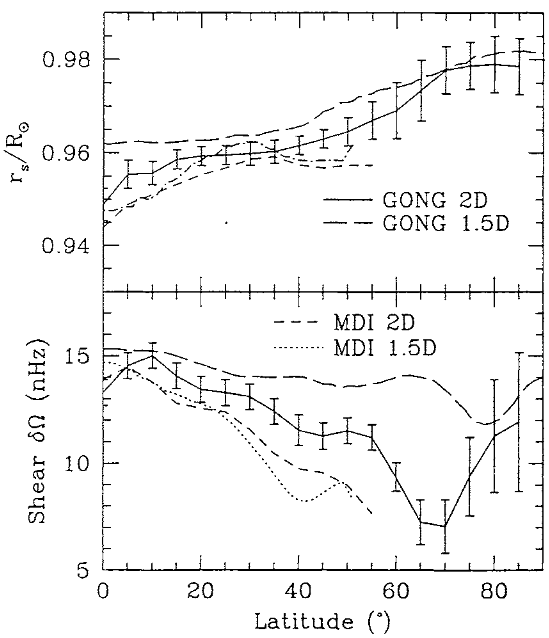

Figure 3. The increase in the rotation rate in the outermost shear layer as a function of latitude is shown in the lower panel. The upper panel shows the position of the base of the outermost shear layer as a function of latitude. The results were obtained using different data sets and inversion techniques. Since MDI data show a reversal of the rotation-rate gradient in the outer shear layer at high latitudes, the corresponding lines have been truncated.

The rotation rate in the outer layers of the Sun shows temporal variations with a well known pattern similar to the torsional oscillations at the surface. To study the temporal variations in the rotation rate we look at the residuals

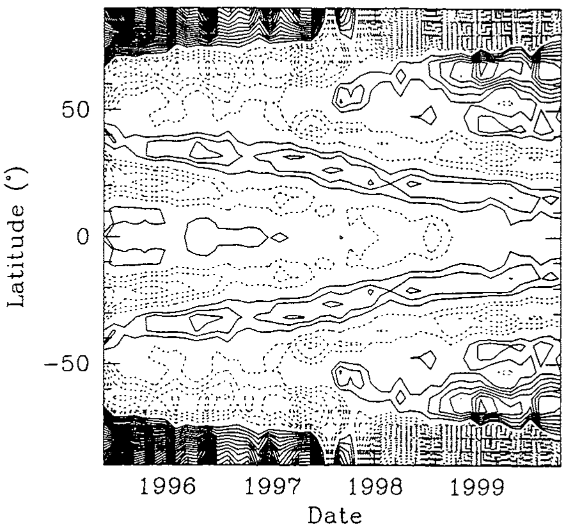

Figure 4. A contour diagram of the rotation-rate residuals at $r = 0.98R_\odot$ obtained using 2D RLS inversion of GONG data. The continuous contours are for positive $\delta\Omega$, while dotted contours denote negative values. The contours are drawn at interval of 0.4 nHz.

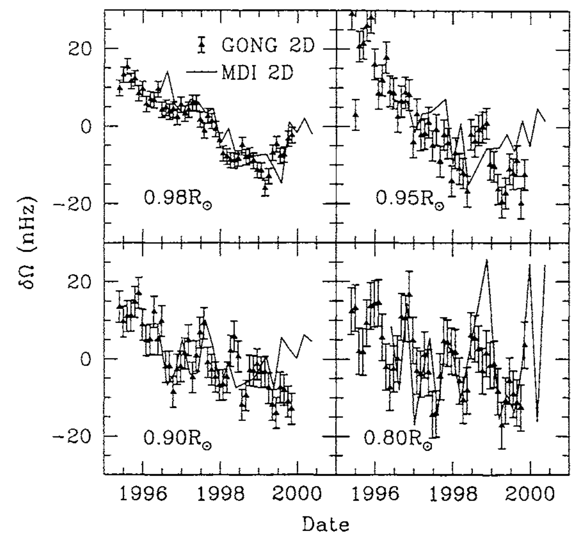

Figure 5. The rotation-rate residuals at the latitude of 85^0 plotted as a function of time at a few selected radii as marked in each panel. The results were obtained using 2d RLS inversion of GONG and MDI data. The error bars for the MDI results are not shown for clarity, but these are comparable to those in GONG.

in the rotation rate obtained by subtracting the temporal mean of 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. 4. Apart from the well known bands of torsional oscillations we can also see that the rotation rate in the polar region has been decreasing with time during the period 1995–2000. At low latitudes the bands move towards the equator. At high latitudes the bands seem to move towards the poles.

In Fig. 5 we show the rotation-rate 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 decrease in the rotation rate with time and these variations persist up to a depth of $0.1R_\odot$. This decrease is significantly larger than the error estimates. Below a depth of $0.1R_\odot$, the errors are too large and it is not clear if the pattern persists. The GONG results at 0.8 $R_\odot$ seem to show periodic behaviour with a period of 1 year. To check for periodicity we take the Fourier transform of these data. The corresponding peak in power spectrum is not found to be statistically significant.

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. 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. 7 shows the results for the 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

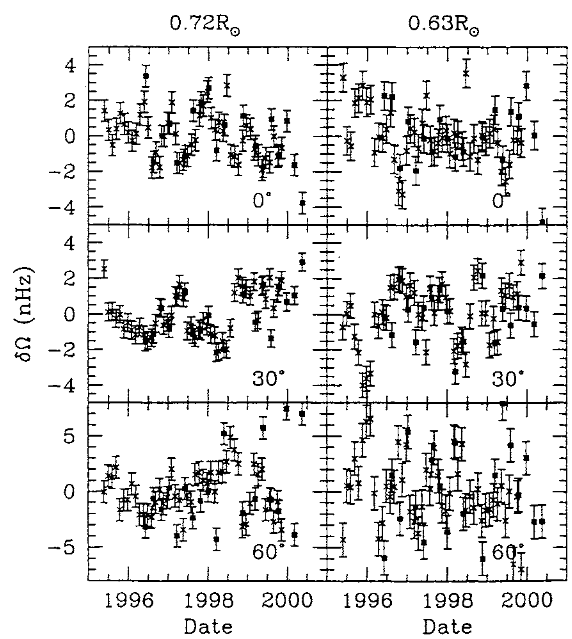

Figure 6. The rotation-rate residuals as a function of time at a few selected radii and latitudes. The radii are marked at the top of the figure, while latitudes are marked in each panel. The crosses show the results obtained using GONG data, while filled squares show the results from MDI data using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

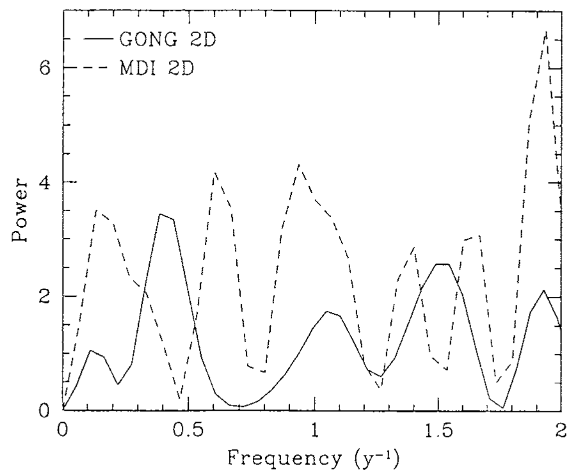

Figure 7. Power spectra obtained from various results for the residual rotation rate in the equatorial region at $r = 0.72R_\odot$.

due to data gap are treated as zeros.

From Fig. 7 it is clear that we do not see any significant peak in the power spectra. All the peaks in Fig. 7 are less than 1σ error estimates. With the same normalization, the peak in power spectrum of Howe et al. (2000b) is about 4 times higher than the peaks in Fig. 7. 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. It may be noted that the spacing of 72 days between MDI data sets is adequate to detect 1.3 year periodicity. In fact, the Nyquist frequency for this spacing would be about 2.5 yr^{-1} which is about three times larger than the frequency at which Howe et al. find periodicity.

3. CONCLUSIONS

Rotation rate obtained from inversion of GONG data show that the outer shear layer persists at all latitudes. The MDI results however, appear to show a reversal of the rotation-rate gradient in the outer shear layer at high latitudes (beyond 50–60°). This difference could be due to the high latitude jet like feature seen in inversions of MDI data. There is no significant temporal variation in either the depth of the shear layer, or the magnitude of increase in rotation rate with depth in this layer. The magnitude of the increase in the rotation rate in the shear layer decreases with latitude. However, there are significant systematic variations between different results. The depth of the outer shear layer decreases with increasing latitude and there is reasonable agreement between different results.

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 bands of faster and slower rotation moving towards the equator with time. At high latitudes it appears that the bands move towards the pole. This is quite similar to what is seen in theoretical results of Covas et al. (2000). The rotation rate in the polar regions in the outer layers decreased with time during 1995-2000. 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. It would be interesting to check how long the decrease in polar rotation rate would continue in future.

We do not find any evidence for the 1.3 year periodicity at the equatorial region at $r = 0.72R_\odot$, reported by Howe et al. (2000b). Because of the steep variation in the rotation rate at the tachocline, inversion results are not expected to be reliable in the region where the periodicity is reported. A more detailed study of rotation rate in this region using forward modelling technique is reported in another paper in this meeting.

ACKNOWLEDGMENTS

This work utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofisico de Canarias, and Cerro Tololo Inter-American Observatory. This work also utilizes data from the Solar Oscillations Investigation / Michelson Doppler Imager (SOI/MDI) on the Solar and Heliospheric Observatory (SOHO). SOHO is a project of international cooperation between ESA and NASA.

REFERENCES

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

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

Basu S., Antia H. M., 2000, Solar Phys., 192, 449

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

Howe R., Antia H. M., Basu S., Christensen-Dalsgaard J., Korzennik S. G., Schou J., Thompson M. J., 1998, in Proc. SOHO 6/GONG 98 Workshop on Structure and Dynamics of the Interior of the Sun and Sun-like Stars, ESA SP-418 eds. S. G. Korzennik and A. Wilson, (Noordwijk:ESA), p. 803.

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, Sci, 287, 2456

Schou J., 1999, ApJ, 523, L181

Schou J., et al. 1998, ApJ, 505, 390

Thompson M. J., et al. 1996, Science, 272, 1300