TEMPORAL VARIATIONS OF THE SOLAR MERIDIONAL FLOWS FROM RING DIAGRAM ANALYSIS

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ABSTRACT

We use MDI data obtained over the past six years to determine changes in solar meridional flows with time. We have used ring diagram analysis to study the flows. We also study the North-South antisymmetric component of solar rotation. We find distinct solar activity related changes in the meridional flows, in particular, the anti-symmetric component of the meridional flow shows a decrease in speed with time.

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

1. INTRODUCTION

Global mode analyses have shown that the solar rotation rate, varies with time in the outer 10% of the solar radius (Howe et al. 2000; Antia & Basu 2000), however, global modes are only sensitive to the north-south symmetric part of rotation rate. With ring diagram analysis, we can look at the north-south antisymmetric component of solar rotation also. Furthermore, global modes do not give any information about meridional flows either, which can be studied using local analysis techniques, such as ring diagrams are needed.

In this work we use a ring diagram analysis (Hill 1988; Patrón et al. 1997) to study the temporal variation of the meridional flows and the north-south antisymmetric component of solar rotation.

2. DATA AND TECHNIQUE

The data used consist of three dimensional power spectra obtained from full disc Dopplergrams. The Dopplergrams were taken at a cadence of 1 minute. The area being studied was tracked at the surface rotation rate. To minimize the effect of foreshortening we have only used data when the region was passing through the central meridian. Each power spectrum was obtained from a time series of 1664 images covering 15° in longitude and latitude. Successive spectra are separated by 15° in heliographic longitude of the central meridian. For each longitude, we have used 15 spectra centered at latitudes ranging from 52.5°N to 52.5°S with a spacing of 7.5° in latitude.

We use seven sets of data. Each set consists of the average of the power spectrum for a fixed latitude. The characteristics of the different sets are listed in Table. 1. This table also lists the mean 10.7 cm radio flux during the period covered by the data. This should give an index of solar activity during each set.

Table 1. Regions studied

No.	Carr. Rot.	No. of spectra	Lon.	Time	10.7cm Flux
1	1911	12	285-120	1996.07	70.5 ± 0.5
2	1921	8	120-015	1997.04	71.4 ± 0.5
3	1932	9	360-240	1998.02	84.8 ± 1.3
4	1948	24	360-015	1999.04	120.4 ± 2.5
5	1964	24	360-015	2000.06	188.9 ± 3.8
6	1975+76	24	120-135	2001.4-5	154.1 ± 3.2
7	1985	15	300-075	2002.01	224.0 ± 3.4

To extract the flow velocities and other mode parameters from the three dimensional power spectra we fit a model with asymmetric peak profiles specified by Basu & Antia (1999), i.e.,

$$P(k_x, k_y, \nu) = \frac{e^{B_1}}{k^3} + \frac{e^{B_2}}{k^4} + \frac{\exp(A_0 + (k-k_0)A_1 + A_2(\frac{k_x}{k})^2 + A_3\frac{k_x k_y}{k^2})S_x}{x^2+1} \quad (1)$$

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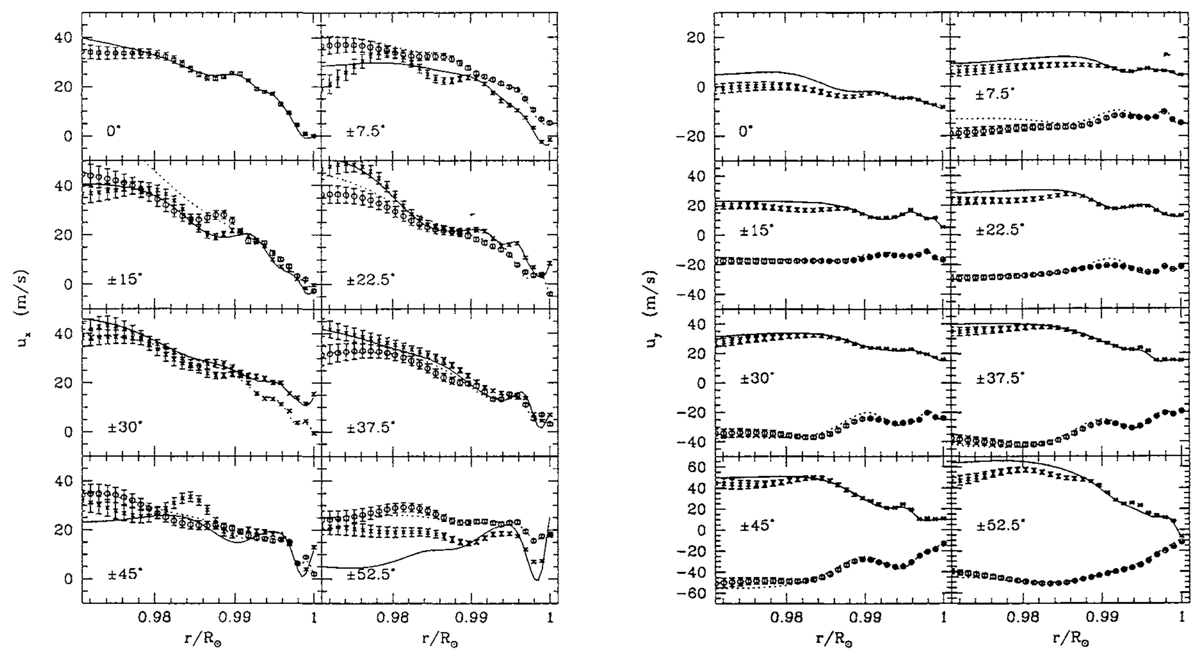

Figure 1. The components u_x and u_y obtained for the CR1911 data plotted as a function of radius for different latitudes. The points are OLA inversion results. The lines are RLS results. Crosses and continuous lines are Northern hemisphere results, while circles and dotted lines are Southern hemisphere results.

where

$$x = \frac{\nu - ck^p - U_x k_x - U_y k_y}{w_0 + w_1(k - k_0)}, \quad (2)$$

$$S_x = S^2 + (1 + Sx)^2, \quad (3)$$

and the 13 parameters $A_0, A_1, A_2, A_3, c, p, U_x, U_y, w_0, w_1, S, B_1$ and B_2 are determined by fitting the spectra using a maximum likelihood approach (Anderson, Duvall & Jefferies 1990). The parameter S measures the asymmetry in the peak profile. The form of asymmetry is the same as that used by Nigam & Kosovichev (1998). While all of these parameters may be varying with time, in this work we have only considered the variation in flow velocities determined by U_x and U_y.

The fitted U_x and U_y for each mode represents an average of the velocities in the x and y directions over the entire region in horizontal extent and over the vertical region where the mode is trapped. We can invert the fitted U_x (or U_y) for a set of modes to infer the variation in horizontal flow velocity u_x (or u_y) with depth. We have used two different techniques to invert the velocities, (a) the regularized least squares (RLS) method, and (b) the method of optimally localized averages (OLA).

The velocity component u_x contains information about the solar rotation rate, modulo the rate at which the region was tracked. The component u_y is the meridional flow velocity.

3. RESULTS

Figure 1 shows the inverted horizontal velocities as a function of radius for the CR1911 data. The velocity component u_x is nothing but the rotation velocity (including the zonal flows) after subtraction of the rate at which the regions were tracked. The near-surface shear layer is seen very clearly in Fig. 1. There is some indication that the gradient in this outer shear layer is reversing at the highest latitude of 52.5° considered here. This is similar to what has been seen in global mode analysis of MDI data (Schou et al. 1998). Fig. 1, also shows the meridional flows, it is clear that we do not see the returning flow from the high latitudes to the equator up to the depth of $0.03R_\odot$ resolved by the mode set considered. There is a southward flow at the Equator just below the surface, but this could be a result of pointing errors of the instrument. This southward flow was also seen by Giles et al. (1997) and Basu et al. (1999). It can be seen that the two independent inversion results obtained using RLS and OLA technique are in reasonably good agreement.

The inverted values of u_x contain information about the north-south antisymmetric component of rotation. Since the rate at which the regions were tracked was symmetric about the equator, any difference between the inverted u_x at a given latitude of the northern hemisphere and that at the same latitude in the southern hemisphere is caused by the asymmetry of the rotation rate about the equator. The north-south

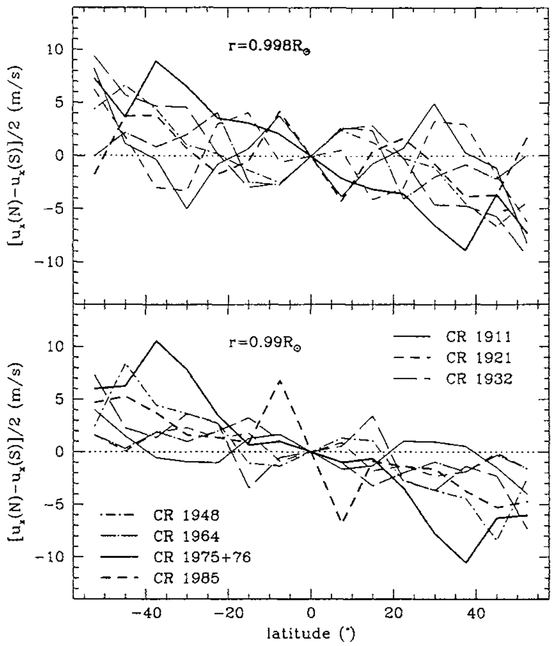

Figure 2. The North-South antisymmetric component of the solar rotation velocity as a function of latitude at two different depths. RLS results are shown here.

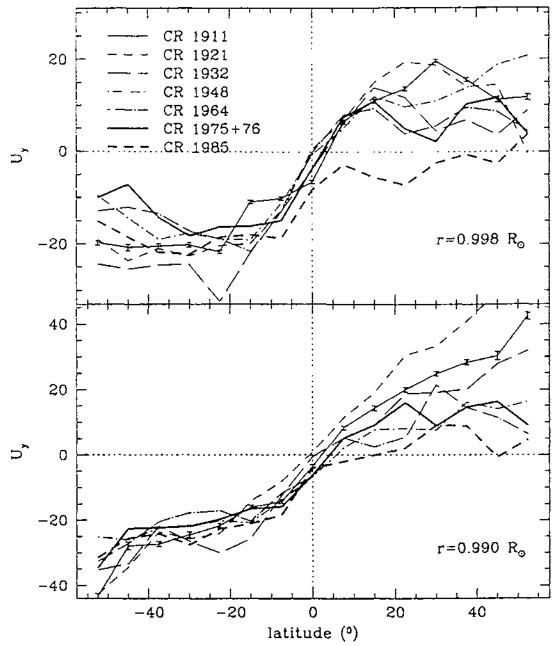

Figure 3. The meridional flow velocities obtained from the different data sets plotted as a function of latitude for two different depths. Only OLA results are shown. RLS results are very similar.

antisymmetric component of the rotation velocity at various times are shown in Fig. 2. We show only RLS results. OLA results are very similar. The component does appear to change with time, however, it is not clear if there is any systematic temporal variation. It is possible that we have to look at intermediate time-steps to discern any pattern. Alternately, it is possible that the apparent variations are due to errors in inversions. At a depth of $0.01R_\odot$ the antisymmetric component appears to be significant. An average over all data sets shows a significant slope at this depth.

The meridional flow velocity, u_y, at two different depths is shown as a function of latitude in Fig. 3. The results of all seven data sets are shown. The meridional flow shows a definite, and systematic time variation. The maximum velocity of the flow is smaller when the Sun is more active. There is a small southward flow at the equator (which was discussed in relation to Fig. 1) at all times, but that could be an artifact of pointing errors and as such the significance of the flow is difficult to ascertain. We note that the expected 'S' shape of the flow is seen only at very shallow depths. At deeper layers, the low activity data sets do not show any tendency of lowering velocity, while the high activity data do. The time variation is seen more clearly if we plot the north-south antisymmetric component of the flow, which is shown in Fig. 4. In this figure the decrease in velocity at high latitudes with time can be clearly seen.

To take a more detailed look at the meridional flow variations we decompose the flow into components (see Hathaway et al. 1996):

$$u_y(r,\phi) = -\sum_i a_i(r) P_i^1(\cos(\phi)), \qquad (4)$$

where ϕ is the colatitude, $P_i^1(x)$ are associated Legendre polynomials. The first six components are found to be significant and are shown in Fig. 5. These components also show a variation with time. For most of these components it is not clear if the temporal variation is systematic or due to errors in estimating their amplitudes. But the amplitude of dominant component, a_2, shows a systematic variation with time in the outer layers, with its magnitude reducing with time during the time period covered by MDI data. For the north-south symmetric component a_3 the low activity sets and high activity sets appear to have opposite signs in the outermost layers. It is not clear if this difference is real or due to instrumental variations during recovery of SOHO satellite.

4. CONCLUSIONS

The antisymmetric component of rotation velocity is significant in outer layers but there is no systematic temporal variation in this component. The magnitude of this component is about 5 m/s, which is much

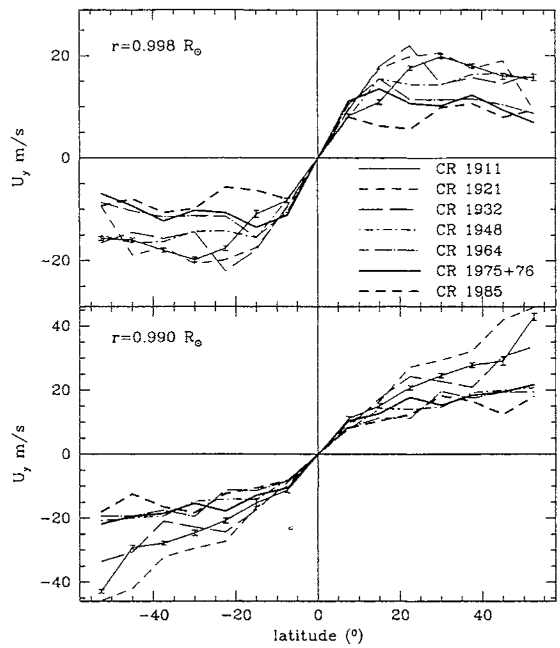

Figure 4. The North-South antisymmetric component of the meridional flow velocities shown in Fig. 3.

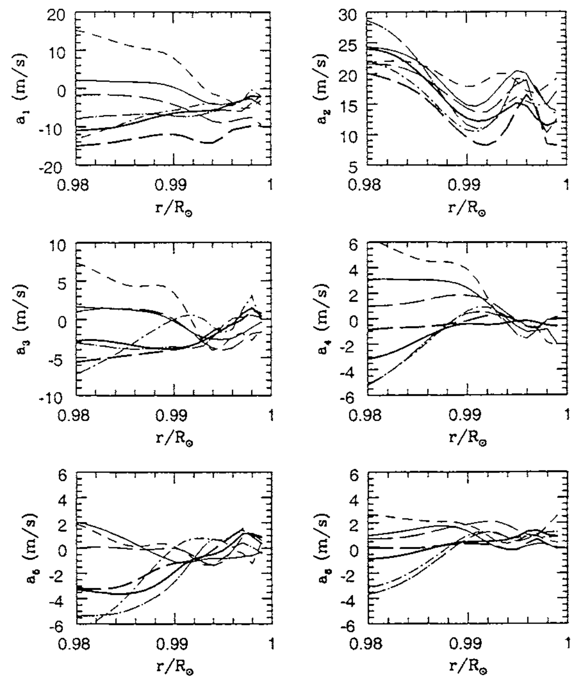

Figure 5. The amplitude of the different components of the meridional flow as defined in Eq. (3) plotted as a function of radius. The different line types represent the different data sets (see legend of Figs. 3 and 4). Only RLS results are shown, OLA results are very similar.

smaller than the symmetric component (about 2000 m/s at the equator). Though the temporal variation in the symmetric component is of similar magnitude (Howe et al. 2000; Antia & Basu 2000).

The meridional flow velocities show a clear change with time. The velocity seems to decrease with increase in solar activity. The dominant component of meridional flow velocity, i.e., $1.5a_2\sin(2\phi)$ shows systematic decrease in amplitude with time. Just below the solar surface, the value of a_2 has decreased from about 18 m/s during low activity phase to about 10 m/s during high activity. It is not clear if this variation is correlated with activity level. Data over the next 2 years after the maximum should be able to ascertain this.

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