Contrasting the solar rotation rate of cycles 23 and 24

H. M. Antia¹ and Sarbani Basu²
¹ Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
² Department of Astronomy, Yale University, P. O. Box 20801, New Haven CT 06520-8101, U. S. A.
E-mail: antia@tifr.res.in, sarbani.basu@yale.edu

Abstract. The minimum between solar cycles 23 and 24 was quite unusual compared with other minima for which detailed data are available and this pointed to the possibility that cycle 24 will be unusual. Cycle 24 is almost at its maximum now and we take this opportunity to compare and contrast the solar rotation rate and zonal flows between the two cycles. We find that the rotation rate during cycle 24 is slightly lower than that during cycle 23. Additionally we find that the poleward branch of the zonal flow that is believed to be the harbinger of the next solar cycle is very week in cycle 24.

1. Introduction

The period of solar activity minimum before the onset of cycle 24 was unusual in its duration and depth. The cycle 24 minimum was longer that of cycle 23; it was quieter as measured by the 10.7 cm flux; the polar fields were weaker (Lo et al. 2010) and the solar winds were slower (Manoharan 2012). The differences were present inside the Sun too, particularly with regards to solar zonal flows (Howe et al 2009; Antia & Basu 2010) as well as meridional flows (Basu & Antia 2010).

The Global Oscillation Network Group (GONG) and the MDI instrument on board SOHO have been collecting helioseismic data since the minimum preceding solar cycle 23. The data sets span cycle 23 in its entirety as well as the ascending part of cycle 24. These data sets provide the means of determining the rotation rate in the solar interior, and we use these data to compare and contrast the solar rotation rate during cycles 23 and the ascending part of cycle 24. We use odd order splitting coefficients from GONG data (Hill et al. 1996) and MDI data (Schou 1999) for inferring the rotation rate in the solar interior.

In this work we use 170 data sets obtained by GONG. Each set covers a period of 108 days with a spacing of 36 days between consecutive data sets; the sets thus overlap in time. The data cover a period from May 1995 to April 2012. Additionally we use 73 sets from MDI. Each MDI set covers a period of 72 days and the sets do not overlap. The MDI data sets cover a period from May 1996 to April 2011, with a gap around 1998 when contact with the SOHO satellite was lost. We use the 2D Regularized Least Squares (2D RLS) technique as described by Antia et al. (1998) for determining the rotation rate.
2. Results

In Fig. 1 we show the change in the latitude-independent part of the solar rotation rate at three different depths. The latitude-independent part of the rotation rate was obtained by inverting the splitting coefficient $a_1$. The changes were obtained by subtracting the average rotation rate from the rotation rate at each epoch. Note that there appears to be a solar-cycle related change, with the fastest rotation at the cycle 23 solar maximum and the slowest during the two minima. Also note that the rotation rate is slower during cycle 24 than it was in cycle 23, in particular the solar rotation rate as shown by the latest data point which is close to the cycle 24 maximum is lower than the rate at cycle 23 maximum, at least in the outer layers in the Sun. The data are too noisy in deeper layers to determine whether or not the rotation rate in the deeper layers changed too. The results with GONG data show some large variations at the cycle 23 maximum which the MDI data do not, that could be due to some systematic differences introduced during the upgrade of GONG instruments. Although, $\delta \Omega$ is comparable to errorbars at individual points, if we take average over neighbouring points the value will be significant. Further, the changes in the latitude-independent part of the solar rotation rate correlate well with the 10.7 cm flux, which is a proxy for solar activity. This can be seen in Fig. 2.

The pattern of the solar zonal flows is also different between the two cycles. We define the zonal flow rate as

$$\delta \Omega(r, \theta, t) = \Omega(r, \theta, t) - \langle \Omega(r, \theta, t) \rangle,$$  \hspace{1cm} (1)

where $\Omega$ is the rotation rate, $r$, the radius, $\theta$ the latitude and $t$ time. $\langle \Omega(r, \theta, t) \rangle$ is the time average of the rotation rate. From the zonal flow rate we can define the zonal flow velocity as

$$\delta v_{\phi} = \delta \Omega r \cos \theta.$$  \hspace{1cm} (2)

Thus the zonal flow is simply the residual of the rotation when the average rotation is removed.

In Fig. 3 we plot the solar zonal flows at 0.98 $R_\odot$ as a function of time. We show two versions of the flow velocity. The results in the top panel were obtained using Eqs. 1 and 2 with $\langle \Omega(r, \theta, t) \rangle$ defined as the average over cycle 23, the lower panel shows results with $\langle \Omega(r, \theta, t) \rangle$ defined as the average over cycle 24. The higher rotation rate of cycle 23 washes out some of the weaker

**Figure 1.** The change in the latitudinally independent component of the solar rotation rate plotted as a function of time obtained with GONG (left) and MDI (right) data.
features of the zonal flow during cycle 24, in particular we cannot see the high-latitude poleward branch of the zonal flow during cycle 24, this had earlier led to speculation that this might mean that cycle 25 may be delayed (Hill et al. 2011). The weak polar branch is seen more clearly in the lower panel of Fig. 3. As is clear, the flow is much weaker than the corresponding flow during cycle 23. It should be noted that we have data for only a part of cycle 24 and hence the average rotation rate during this period is heavily biased by the values during the deep and extended minimum. This will also affect the pattern in lower panel of Fig. 3.

Plots of the zonal flow seen at different latitudes plotted as a function of radius and time show other differences between the flows during cycles 23 and 24, as can be seen in Fig. 4. Basu & Antia (2003) found that during cycle 23, the low latitude flows appears to rise from the deeper layers to the surface at a speed of about 0.05\(R_\odot\) per year. The signature of this rise is different in cycle 24, in particular, at 10° latitude, the flow stalled between 0.8 and 0.9\(R_\odot\) before beginning.
**Figure 4.** The zonal flow velocity plotted as a function of radius and time for a few latitudes. Only GONG results are shown.

**Figure 5.** The zonal flow velocity at 0.98$R_\odot$ plotted as a function of time for different latitudes. The blue points are MDI results, the red are GONG results and the black line is the fit to the GONG data using the function shown in Eq. 3. Note that while the low and high latitude flows fit well to the function over both cycle 23 and 24, at mid latitudes, we cannot fit cycles 23 and 24 simultaneously.
its rise.

We can examine differences in the zonal flows between the two cycles in more detail by fitting the zonal flow (i.e. rotation rate residuals) with a periodic function and examining if the same form fits both cycles. Antia & Basu (2010) had found that the cycle 23 zonal flows could be fitted to a form given by

\[
\delta v(r, \theta, t) = \sum_{k=1}^{3} A_k \sin(k \omega_0 t + \phi_k),
\]

with \( \omega_0 = 11.7 \) years. In the above expression \( A_k \) is the amplitude of the \( k \)th component and \( \phi_k \) a phase. We show the same fit to the zonal flows in Fig. 5. We can see that while the same value of \( \omega_0 \) fits the low and high latitude flows in both cycles 23 and 24, at intermediate latitudes there are deviations from this form during cycle 24 and the two cycles cannot be fitted simultaneously. Further, in the intermediate latitude range (50°–65°) the rotation rate during cycle 24 is lower than that during the same phase of cycle 23.

3. Summary
We have used available rotational splitting data from the GONG and MDI projects to compare the solar rotation rate and zonal flows during solar cycle 24 with that of solar cycle 23. We find that latitude-independent part of the solar rotation rate of cycle 24 is lower than that of cycle 23, at least in the outer layers of the Sun. This component of the rotation rate shows a correlation with the 10.7 cm flux, which is a solar activity indicator. While examining the zonal flows we find that the poleward, prograde flow that is the precursor of cycle 25 is very weak compared with the corresponding flow that was the precursor of the current cycle. While the zonal flows at all latitudes in cycle 23 can be fitted with three harmonics of an 11.7 year period, we cannot simultaneously fit the mid-latitudes of cycle 24. However, the low and high latitudes of cycle 23 and 24 can be fitted simultaneously.

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