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Differential coronal rotation and solar activity

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Abstract. We investigated the latitudinal variation in the coronal rotation by using observations taken with Nobeyama Radioheliograph (*NoRH*) at 17 GHz. The time series bins are formed on different latitude regions of the solar full disc (SFD) radio image, which extend up to ±60° in both the hemispheres. The sidereal rotation rate as a function of latitude for each year during 1999-2005 are obtained. The analysis reveals that the equatorial rotation rate of the corona is comparable to the photosphere and the chromosphere. However, at higher latitudes, the corona rotates less differently than the photosphere and the chromosphere. The differential rotation obtained at the height of these emissions is quite variable throughout the period of study. The equatorial rotation period and latitude dependent differential rate seem to vary almost systematically with sunspot numbers. This indicates its dependence on the phases of the solar activity cycle.

Keywords : Sun: corona – Sun: radio radiation – Sun: rotation

1. Introduction

The coronal rotation has been studied using different methods and various tracers (Chandra & Vats 2011). But the estimate of latitudinal profiles of coronal rotation and its dependence on the phases of the solar cycle is found to vary significantly. In the last couple of decades, the coronal rotation has also been investigated using radio emissions at different frequencies (Vats et al. 1998a,b; Kane, Vats & Sawant 2001; Mouradian, Bocchia & Boston 2002; Chandra & Vats 2011). The differential rotation as a function of altitude (Vats et al. 2001) and latitude (Chandra, Vats & Iyer 2009, 2010) and its correlation with the phases of the solar cycle (Mehta 2005) have been

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determined using radio flux data. The present study with Nobeyama Radioheliograph (*NoRH*) at 17 GHz, for the period 1999-2005, gives very interesting information about the differential rotation of the solar corona at the height of these emissions (Chandra, Vats & Iyer 2009)).

2. Data analysis

The radio images obtained from the Nobeyama Radioheliograph (*NoRH*) at 17 GHz during the years 1999-2005 were analyzed in the present work. Each radio image had a pixel size of 512 by 512 pixels, on which thin latitude bins were superposed on the solar full disc (SFD) at an interval of 10° along the heliocentric latitude. The average flux of all the pixels in a particular bin (say, at equator) changes with next radio image. If we take one radio image per day for the whole year then, an annual time series of the average intensity variation in radio flux is generated for each latitude bin. In this way a total of 17 time series could be obtained. Using the flux modulation method, autocorrelation coefficient was calculated for each time series (up to the lag of 150 days) and plotted for each latitude bin. The radio images of the period 1999 to 2005 was found to be most suitable for the estimation of autocorrelation coefficient. The autocorrelation curve obtained for these years showed clear rotational modulation up to the latitudes of 60° in both the hemispheres.

The synodic rotation period can be obtained by locating the position of autocorrelation coefficient's peak on the time lag axis of the curve. If curve shows smoothness and cyclic nature then farthest peak's position can be chosen to attain the maximum possible accuracy. Choosing first peak will introduce an error of one day. The error will decrease to 1/2, 1/3, 1/4 or 1/5 of a day, respectively, when second, third, forth or fifth peak position is chosen. The synodic period is then converted to the sidereal rotation period at each latitude (Chandra, Vats & Iyer 2010). In Figure 1, the sidereal periods are plotted with respect to the latitude for each year. The error bar associated with any value of sidereal rotation period depends on the selection of the peak and therefore vary between ± 0.2 to ± 1 day.

To compare the sidereal rotation rate $\Omega(\psi)$, a curve based on least square method can be fitted in to each year's rotation profile using the standard polynomial expansion, $\Omega(\psi) = A + B\sin^2\psi + C\sin^4\psi$, where ψ is the heliographic latitude. The term A represents the equatorial rotation rate. The B and C represents the differential rotation rate at lower and higher latitudes, respectively. Since we have not used the data beyond the ±60° latitude and using third term would require accurate data for higher latitudes also. Hence, it is sufficient to use only the first two terms of the standard polynomial expansion (Beck 2000; Badalyan 2010). Therefore, we use the traditional representation of the sidereal rotation rate $\Omega(\psi)$ given in two terms only, *i.e.*, $\Omega(\psi) = A + B\sin^2\psi$. The rotation rate $\Omega(\psi)$ is related to the rotation period $T(\psi)$ as, $T(\psi) = 360°/\Omega(\psi)$, where $T(\psi)$ is in day and $\Omega(\psi)$ in degree/day.

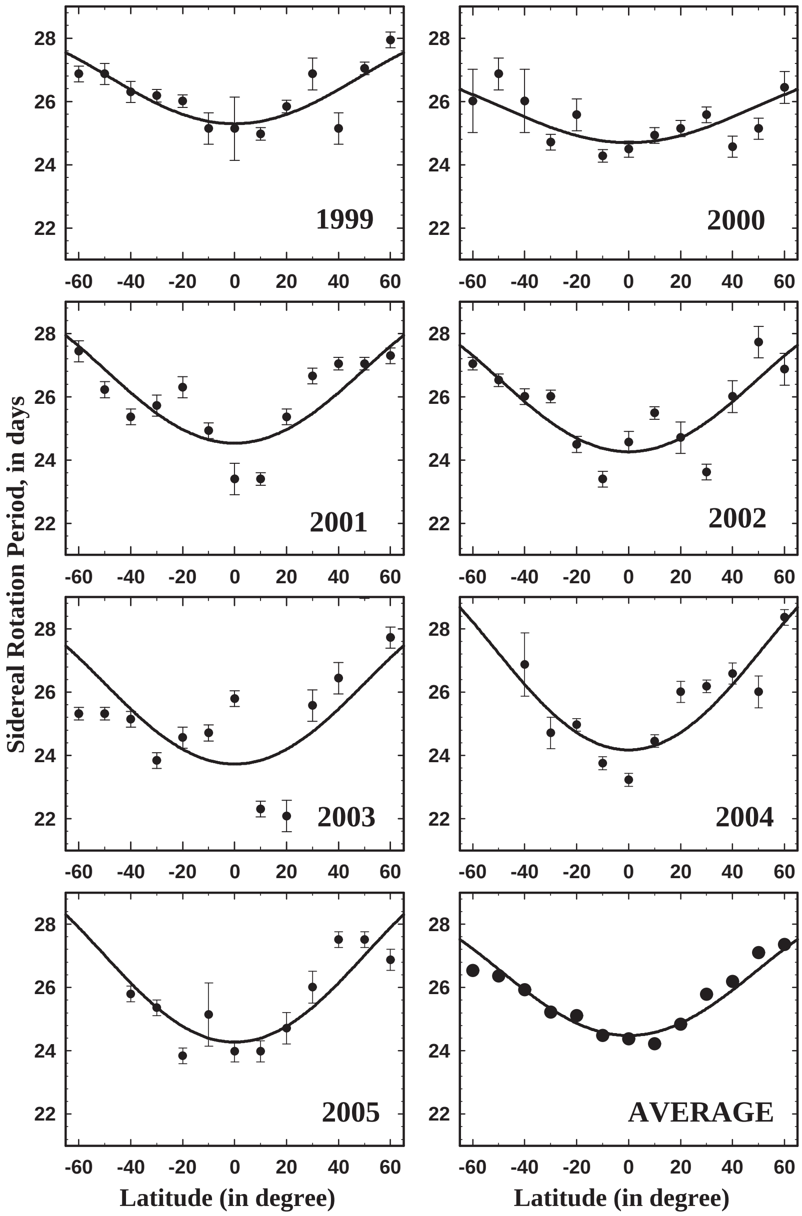

Figure 1. Sidereal rotation periods as a function of latitude. These are obtained from the radio images at 17 GHz of the years 1999-2005. The size of error bars depends on the selection of the peak in determination of the rotation period. The least square curves fitted in the rotation profiles of the sidereal period are also shown. The average rotation profile as a function of latitude is also plotted separately (last plate).

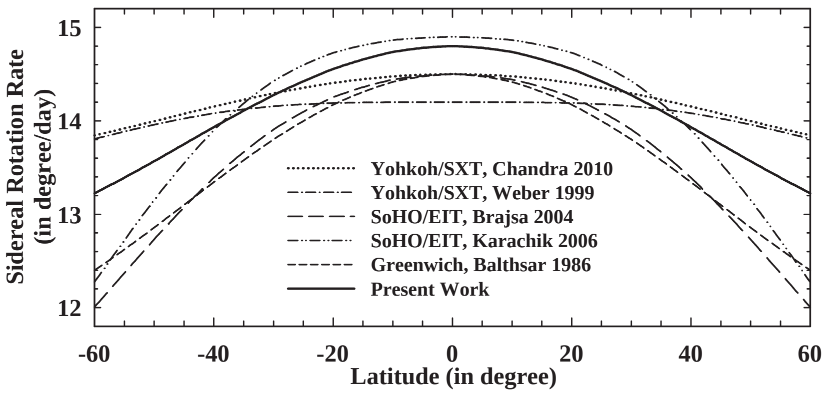

Figure 2. Comparison of sidereal rotation rate profiles obtained by various methods and solar features.

3. Discussion

The mean rotation rate at the equator (derived through the coefficient A) matches well, in the error limit, with most of the observations shown in Fig. 2. Interestingly, the mean equatorial rotation rate (14.8 deg/day) is found to be almost the same, when compared with the extreme ultraviolet (EUV) chromospheric results of Brajša, Wöhl & Vršnak (2004); Karachik, Pevtsov & Sattarov (2006) and photospheric sunspot results of Balthasar, Vázquez & Wöhl (1986) (14.7, 14.9 and 14.6 deg/day, respectively). The mean rotation rate suggests that near the equator the radio corona rotates almost at a speed close to the speed of the photosphere and the chromosphere.

The enhanced electron density model suggested by Aschwanden & Benz (1995) was used to estimate the average height of origin of the radio emissions. The height adopted from Vats et al. (2001) suggests that the radio emissions at 17 GHz originate approximately at the height of $\sim 1.2 \times 10^4$ km above the solar surface. It means that such emissions originate almost at the interface of the chromosphere and the corona. Hence the equatorial rotation rate matches more with the photospheric or the chromospheric results.

The latitudinal rotation profiles obtained through the coefficient B seem to indicate the fact that the corona displays a variety from almost rigid (Lewis et al. 1999) to reasonably differential rotation. The coefficient B shows that the corona does rotate differentially as in the photosphere and the chromosphere (Balthasar, Vázquez & Wöhl 1986; Brajša et al. 2004); but the latitude gradient of rotation rate is much lower (-3.1 and -2.8 deg/day, respectively). The value of coefficient B due to Weber et al. (1999) (-0.0 deg/day) and Chandra, Vats & Iyer (2010) (-0.8 deg/day) is found to be the closest to the present study (-2.1 deg/day), at the middle latitudes.

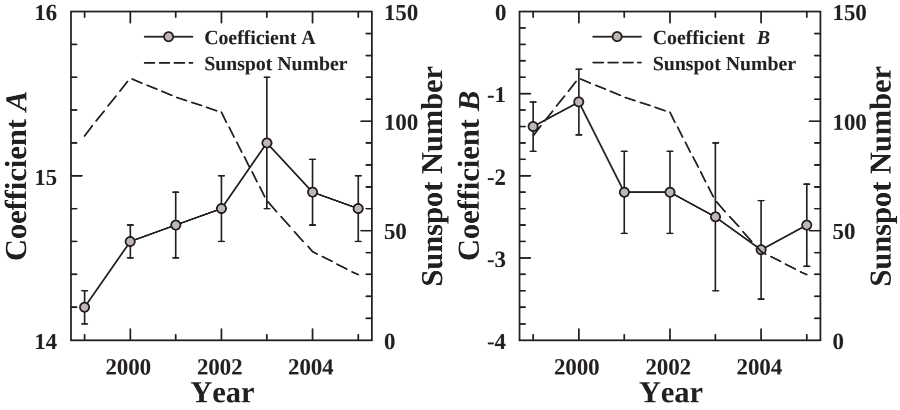

Figure 3. Temporal variation of the coefficients *A* and *B*. For comparison annual sunspot numbers are also plotted.

The coefficients *A* and *B* are compared with the annual sunspot numbers (see Fig. 3). This gives evidence of the dependence of the coronal rotation on the phases of the solar cycle. Fig. 3 (left panel) shows that the coefficient *A* (continuous line with error bars), which represents the coronal equatorial rotation rate, is neither in phase nor anti-phase with the annual sunspot number (dashed line), but there seems to be a time lag of $\sim$ 3 years between them. The error of *A* varies from $\pm$ 0.1 to $\pm$ 0.4. The temporal variation of *A* is apparent. It means that the equatorial rotation of the corona at this emission waxes and wanes in step with the Sun's activity but it changes course only after three years of the sunspot numbers.

The latitude dependent of differential gradient is found to be in phase with the annual sunspot numbers. The coefficient *B* represents the coronal differential rotation and this also seems to depend on the phases of the solar cycle. The error of *B* varies from $\pm$ 0.3 to $\pm$ 0.9. Fig. 3 (right panel) shows that the temporal variation of coefficient *B* (continuous line with error bars) derived from the present work seems to be in phase with the annual mean sunspot number (dashed line) through out the period of study, except in the year 2005. There are some data gaps at higher latitudes in the years 2004 and 2005 (as shown in Fig. 1). Therefore, there will be a comparatively higher uncertainty in the determination of coefficient *B* in these years.

4. Conclusions

The equatorial rotation rate is found to be nearly the same, when compared with the extreme ultraviolet chromospheric results (Brajša et al. 2004; Karachik et al. 2006) and Greenwich results (Balthasar, Vázquez & Wöhl 1986). So we conclude that at the equator the radio corona rotates almost at a speed close to the speed of its lower atmospheric layers. The differential rotation rate with respect to the latitude shows that the corona rotates differentially as in the case of the photosphere and the chromosphere (Balthasar, Vázquez & Wöhl 1986; Brajša et al. 2004); but the gradient of differential rotation is much lower. The differential rotation gradient due to Weber et al. (1999) and Chandra, Vats & Iyer (2010) are more close to the results at the middle latitudes. When coefficients *A* and *B* (representing equatorial rotation rate and differential rotation rate, respectively) are compared with the annual sunspot numbers. Both are found to be in phase with the solar activity cycle, but with some lag.

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