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Variations in the Solar Coronal Rotation with Altitude – Revisited

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Abstract Here we report an in-depth reanalysis of an article by Vats *et al.* (*Astrophys. J.* **548**, L87, 2001) that was based on measurements of differential rotation with altitude as a function of observing frequencies (as lower and higher frequencies indicate higher and lower heights, respectively) in the solar corona. The radial differential rotation of the solar corona is estimated from daily measurements of the disc-integrated solar radio flux at 11 frequencies: 275, 405, 670, 810, 925, 1080, 1215, 1350, 1620, 1755, and 2800 MHz. We use the same data as were used in Vats *et al.* (2001), but instead of the twelfth maxima of autocorrelograms used there, we use the first secondary maximum to derive the synodic rotation period. We estimate synodic rotation by Gaussian fit of the first secondary maximum. Vats *et al.* (2001) reported that the sidereal rotation period increases with increasing frequency. The variation found by them was from 23.6 to 24.15 days in this frequency range, with a difference of only 0.55 days. The present study finds that the sidereal rotation period increases with decreasing frequency. The variation range is from 24.4 to 22.5 days, and the difference is about three times larger (1.9 days). However, both studies give a similar rotation period at 925 MHz. In Vats *et al.* (2001) the Pearson's factor with trend line was 0.86, whereas present analysis obtained a ∼0.97 Pearson's factor with the trend line. Our study shows that the solar corona rotates more slowly at higher altitudes, which contradicts the findings reported in Vats *et al.* (2001).

Keywords Solar radio flux · Flux modulation method · Gaussian fit · Sidereal rotation period

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1. Introduction

The solar rotation is an important phenomenon and has caught the attention of many scientific research groups. The solar rotation, both in the interior of the Sun and in its atmosphere, has been extensively studied during the past four decades. In the early days of solar research, the corona could only be observed during total solar eclipses. At present, there are various ground-based (*e.g.* MAST, GONG, Cracow Astronomical Observatory Radiotelescope) and space-based (*e.g. Hinode*/XRT, SDO, SOHO/EIT, and LASCO) continuous observations of the Sun at different wavelengths, which correspond to different altitudes. These data are used to study various dynamical characteristics of the Sun as well as solar rotation in different regions of the Sun. There are mainly three methods for determining the rotation of the Sun: (i) by monitoring the motion of tracers such as sunspots, faculae, plages, convection cells, oscillation wave patterns, and low-level magnetic features, (ii) by the Doppler shift of photospheric spectral lines, and (iii) by studying the emitted flux modulations.

Dupree and Henze (1972) used tracers from spectroheliograms and analysed the Lyman continuum and extreme ultraviolet (EUV) lines to determine the rotation rate of the solar chromosphere, transition region, and corona. Nash, Sheeley, and Wang (1988) proposed that the rotation of coronal holes can be understood in terms of a current-free model of the coronal magnetic field in which holes are the footpoint locations of open field lines. Coronal X-ray bright points in soft X-ray filtergrams were used to estimate the solar rotation by Golub *et al.* (1974). Furthermore, Golub *et al.* (1974) compared the rotation obtained from X-ray bright points with KPNO magnetograms from 1970 – 1978. Rybak (1994) used Fe XIV 5303 Å green line images taken from the worldwide coronographic network to obtain the solar rotation period for the area of ± 30 deg. Brajša *et al.* (1999) determined the solar rotation with respect to altitude (differential rotation with altitude) by using daily full-disc solar maps obtained at 37 GHz and Hα images. They found angular velocity differences between two classes of microwave low-brightness-temperature regions were attributed to differences in height of these structures and traced for various phases of the solar cycle. Brajša *et al.* (2000) determined the solar rotational behaviour as well as the north–south asymmetry from the radio emission at 37 GHz. Altrock (2003) determined the rotational behaviour of the corona by using synoptic photoelectric observations of Fe XIV and Fe X. He suggested that at a latitude of $\geq 60^{\circ}$, the rotation is almost rigid in the rising phase of the solar activity, while during low solar activity, the rotation has a pronounced differential component. Low and high brightness-temperature regions (LTRs and HTRs) in the chromosphere at 37 GHz were traced by Brajša *et al.* (2009) to determine the solar rotation period using full-disc 8-mm radio maps. They simultaneously determined the height of the tracers. In order to determine the solar rotation period, Hara (2009) analysed X-ray bright points (XBPs) and also determined the differential rotation rate by using a tracer method. The coronal bright points of the green images are analysed by a tracer method (segmentation algorithm). Small bright coronal structures in SOHO/EIT images for the time period of almost an entire solar cycle were traced by Wöhl *et al.* (2010), who deduced the sidereal differential rotation profile. Sudar *et al.* (2016) used six months of SDO/AIA data for the 19.3 nm band to determine the rotation of coronal bright points. They determined their height as about 6500 km.

The rotation of the solar corona is relatively less precisely determined, mainly because of the following three reasons: (1) the features are less distinct, such as coronal holes, (2) the corona cannot be observed easily because it is more tenuous (very low density) than the other solar regions, and (3) it is very difficult to measure the magnetic field directly there (Zwaan, 1987; Vats *et al.*, 2001; Chandra, 2010).

In the past, different solar observational datasets have been reported by various investigators for the solar coronal rotation variations at various heights. Gawronska and Borkowski

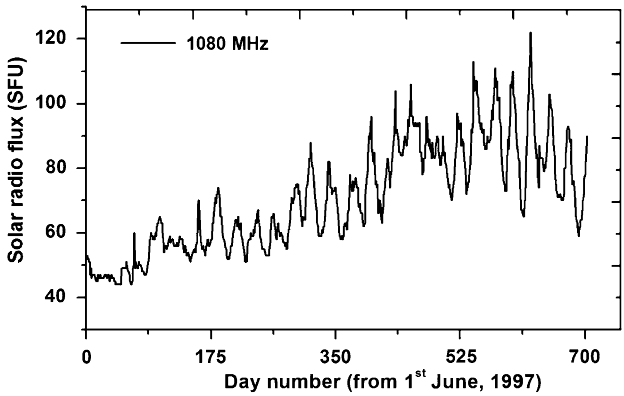

Figure 1 Solar radio flux at 1080 MHz (solar flux unit) from 1 June 1997 to 31 July 1999 (703 days).

(1995) used 125 MHz daily solar radio flux data, Vats *et al.* (1998) and Vats *et al.* (2001) and Chandra (2010) used 2800 MHz daily solar radio flux data, Chandra, Vats, and Iyer (2010) used SXT images, Chandra and Vats (2011) used NoRH images, Karachik, Pevtsov, and Sattarov (2006) used coronal bright points from SOHO/EIT 19.1 nm images, Brajša *et al.* (2004) used 28.4 nm SOHO/EIT images of coronal bright points, and Weber *et al.* (1999) and Kariyappa (2008) used SXT images to obtain the sidereal rotation period of the corona.

The differential rotation as a function of height in the solar corona was reported for the first time by Vats *et al.* (2001). For radio emissions the height increases with decreasing frequency. Therefore, the observations at different frequencies give information at different altitudes in the solar corona. The authors found that the sidereal rotation period at 2800 MHz from the lower corona is ∼24.1 days. There are two methods to estimate the solar coronal rotation using radio emission: (1) the autocorrelation function method used by Vats *et al.* (2001), Chandra, Vats, and Iyer (2009), Chandra (2010), and Chandra and Vats (2011); (2) and the wavelet analysis method used by Temmer *et al.* (2006) and by Xie, Shi, and Xu (2012). In the present study, we also used the autocorrelation function method.

2. Observations

The continuous daily observations of disc-integrated solar radio flux measurements at 275, 405, 670, 810, 925, 1080, 1215, 1350, 1620, and 1755 MHz were taken from the Cracow Astronomical Observatory in Poland,[1] and the measurements at 2800 MHz are from the Algonquin Radio Observatory in Canada.[2] The data sets for a period of 26 months (01 June 1997 – 31 July 1999) were used in the current study to revisit the analysis of the same data sets as were used by Vats *et al.* (2001). A typical example of the daily solar radio flux is plotted *versus* time and shown in Figure 1. The sample plot shown in the figure is for the 1080 MHz solar radio flux. Figure 1 clearly shows the modulation due to solar rotation, but it is rather difficult to obtain an accurate rotation period from this plot. We therefore further analysed the solar flux using the autocorrelation analysis method.

[1] http://www.oa.uj.edu.pl/sol/index.html.

[2] http://www.ngdc.noaa.gov.

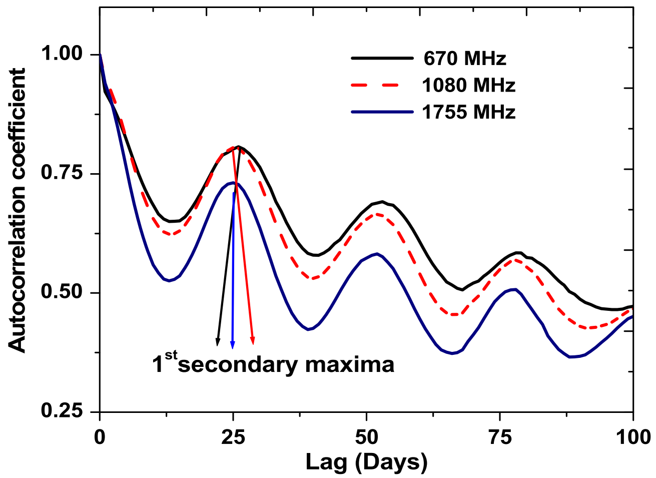

Figure 2 Autocorrelograms for three different radio frequency fluxes as a function of lag (days) for up to 100 day lags at 670 MHz (solid black line), 1080 MHz (dashed red line), and 1755 MHz (blue line).

3. Analysis and Results

The autocorrelation is defined by Equation 1 given below.

$$P_x(l) = P_x(-l) = \frac{\sum_{k=0}^{n-1}(x_k - \overline{x})(x_{k-1} - \overline{x})}{\sum_{k=0}^{n-1}(x_k - \overline{x})^2}, \tag{1}$$

where l is the lag, n is the number of observations, and $k = 0, 1, 2, 3, 4, \ldots,$ $P_x(l)$ is the autocorrelation at lag l.

The data of all the 11 frequencies (given in the observations section) were analysed using this equation. The autocorrelograms obtained at three different frequencies are shown in Figure 2. They are nearly same as those obtained by Vats *et al.* (2001) (Figure 1c of Vats *et al.*, 2001) and show several maxima corresponding to the synodic rotation period. For higher accuracy ($\leq$0.1 day), the twelfth maximum was used by Vats *et al.* (2001). To estimate the solar coronal rotation, we used the first secondary maximum, which was also used by Chandra and Vats (2011), Xie, Shi, and Xu (2012), and by other researchers. The first secondary maxima were fitted with a cosine function by Chandra and Vats (2011) to obtain a good estimation of the rotation period. We used a Gaussian fit to the first secondary maximum because we assume that the time corresponding to the peak of the fit provides a better estimate of the rotation period.

In Figure 3 the Gaussian fit of the first secondary maximum is plotted for the 1080 MHz observations, and the centre of the Gaussian fit gives the synodic rotation period. The Gaussian fit is determined by

$$y = \frac{A}{w\sqrt{\frac{\pi}{2}}} \mathrm{e}^{\frac{-2(x-x_0)^2}{w^2}} + y_0, \tag{2}$$

where x_0 is the centre of the maximum and w is twice the standard deviation of the Gaussian ($2 * \sigma$), or approximately 0.849 times the width of the peak at half the peak value. A is the area below the curve and y_0 is the baseline offset.

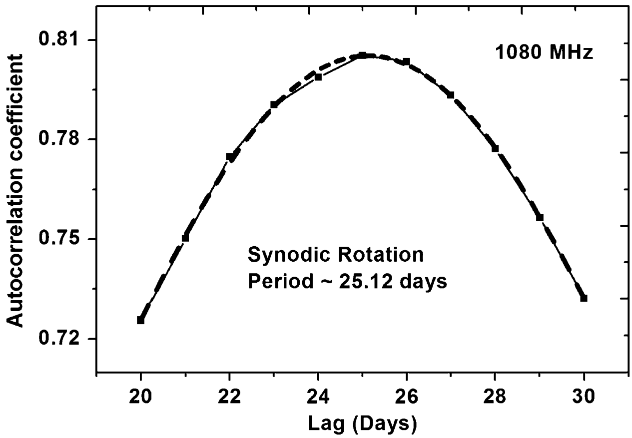

Figure 3 Sample example of a Gaussian fit over the first secondary maximum of the autocorrelogram at 1080 MHz (the dashed line represents the Gaussian fit and the solid line represents the first secondary maximum of the autocorrelograms).

The synodic rotation period is the apparent rotation period of the Sun as seen from the Earth, which is orbiting around the Sun. Thus the sidereal rotation (actual) period can be determined using the following relation

$$T_{\mathrm{sid}} = \frac{T_{\mathrm{syn}} \times 365.26}{T_{\mathrm{syn}} + 365.26}, \tag{3}$$

where T_{sid} is the sidereal period and T_{syn} is the synodic period.

The value of 365.26 is the number of days in an Earth sidereal year. The solar sidereal rotation period is estimated for only nine radio frequencies, as the autocorrelation curves at two lower frequencies (275 and 405 MHz) are noisy. A plot of the sidereal rotation period as a function of solar radio frequencies of our study and the study by Vats *et al.* (2001) is shown in Figure 4. The trend line is a polynomial fit and is fitted for our study and for the results of Vats *et al.* (2001). The polynomial fit is evaluated by a polynomial function as defined by

$$p(x) = \sum_{k=1}^{j} a_k x^k, \tag{4}$$

where j is the number of observations, k is $1, 2, 3, \dots, j$ $(k \neq 0)$ and a is a constant.

The polynomial fit is cross correlated, and the correlation is characterized by the Pearson factor. The Pearson factor is defined as

$$R^2 = \frac{(x_1 - x_0)^2}{(y_1 - y_0)^2}, \tag{5}$$

where R is Pearson's factor, x_1 and y_1 are data points, and x_0 and y_0 are base line points.

Figure 4 fits with the trend line of our study better, and hence the estimates are more reliable. The estimates of our study show that the sidereal rotation period decreases with increasing frequency, which is in contrast to the findings of Vats *et al.* (2001). In the solar corona higher frequency radio emissions are emanating from the inner corona (lower heights), hence our study reveals that the rotation period increases with altitude, implying slower angular rotation at greater height. The variation of the rotation period ranges from

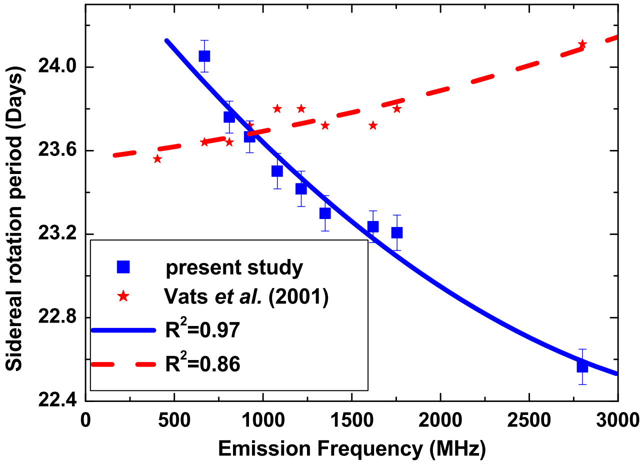

Figure 4 Comparison of the results of our study and the results by Vats *et al.* (2001). The values of Vats *et al.* (2001) are shown by the asterisk, and the dashed red line is the polynomial fit. The values of our study are shown by solid blue squares with error bars, and the solid blue line is the polynomial fit.

24.4 to 22.5 days; the difference is ∼1.9 days. The Pearson factor of the polynomial R^2 is 0.97, which is very near to an ideal one. On the other hand, the estimates of Vats *et al.* (2001) showed that the sidereal rotation period increases with increasing frequency or the rotation period decreases with increasing altitude. The variation of the sidereal rotation period ranges from 23.6 to 24.15 days; the difference is ∼0.55 days. The Pearson factor of the polynomial fit R^2 is 0.86, which is lower than that of our study. For the frequency range of 670 MHz – 2800 MHz, our study shows that the angular velocity of the disc-integrated solar corona ranges from 14.97 to 15.96 degrees per day, whereas for Vats *et al.* (2001) it varies from 15.23 to 14.92 degrees per day.

4. Discussion

We reanalysed the disc-integrated radio flux at 11 radio frequencies to estimate the solar coronal rotation period. Vats *et al.* (2001) used the same data and reported that the solar coronal rotation period decreases with increasing altitude in the solar corona. They used the twelfth maxima of the autocorrelogram to estimate solar rotation period. We fitted the first secondary maximum with a Gaussian curve, and the peak of the fit is taken as a proxy for the solar synodic rotation period. The estimates in our study and the study of Vats *et al.* (2001) are in qualitative agreement, but quantitatively, significant differences are noted. Our estimates show that the rotation period increases with increasing altitude. The variation is larger than the variation reported by Vats *et al.* (2001). The Pearson factor is found to be 0.97 in our study, but it was 0.86 for Vats *et al.* (2001). This might be because the first peak in the autocorrelation function more significant, and a Gaussian fit to the peak better estimates the rotation period. A higher Pearson factor also indicates a higher reliability of our study. It is interesting to note that at 925 MHz both studies give almost the same rotation period estimates. The reason might be the low interference at 925 MHz, which possibly increases for frequencies lower and higher than 925 MHz. The interference may be due to scattering by the plasma irregularities, which are common in the solar corona and in the upper atmosphere of Earth. The irregularities of the Earth's upper atmosphere will have a stronger effect on lower frequencies, while coronal irregularities will have a stronger effect on higher frequencies. It is likely that interference will affect higher order peaks much more than the first.

5. Conclusions

According to Vats *et al.* (2001), the coronal rotation period decreases with altitude, but our reanalysis shows that the coronal rotation period increases with altitude. However, the order of magnitude is nearly same in both studies. The reason for the opposite variation of the coronal rotation velocity (period) with altitude is currently unknown. The interference is one possibility that may have a stronger effect in the higher peaks of the autocorrelogram. The first secondary maximum we used here is therefore expected to give a more accurate estimate of the rotation period. This would make our method better than that of Vats *et al.* (2001). Moreover, an increase in rotation period with altitude appears more logical as this would mean that outer corona lags behind the inner corona. More research work is needed to further clarify this very interesting finding.

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Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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