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Solar activity and differential rotation

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Abstract. The coronal sidereal rotation rate as a function of latitude for each year, extending from 1992 to 2001 for soft X-ray images and from 1998 - 2005 for radio images are obtained. The present analysis reveals that the equatorial rotation rate of the corona is comparable to the photosphere and the chromosphere, However, at the higher latitudes, the corona rotation quite differently than the photosphere and chromosphere. The latitude differential obtained by both radio and X-ray images is quite variable throughout the period of the study. The equatorial rotation period seems to vary almost systematically with sunspot numbers which indicates its dependence on the phases of the solar activity cycle.

Keywords. Sun: corona – Sun: rotation – Sun: radio radiation – Sun: X-rays, gamma rays

1. Introduction

The Sun rotates on its axis approximately once every 27 days as seen from the Earth. The rotation is not uniform, being substantially slower near the poles than at the equator. This superficial aspect of the solar differential rotation was well known from sunspot observations as early as the 17th century. However the details of its variability are known in this century only. It is only within the last 30 years that it has become possible to observe the rotation profile in the solar interior. The subtle temporal variations have become quite evident with the help of helioseismology. Heliosesmology is the study of the waves that propagate within the Sun. The inferences from the properties of these waves reveal the solar interior structure and dynamics. This is the most important tool we have to measure this internal rotation. Basu & Antia (2000) found that during the high activity period in 1998 the equatorial region was rotating slower than the smoothed average rotation rate. It was rotating faster at other times. On the other hand, Antia & Basu (2001) estimated using MDI data that the polar rotation rate decreases between 1995 and 1999 after which it has started increasing. Howe (2009) reviewed in detail the solar interior rotation and its variation.

The rotation of the solar atmosphere, the photosphere and the chromosphere has been investigated in quite some details; especially there are extensive reviews of these measurements and their temporal and latitudinal variations (Howard 1996 and Beck 2000) There are many references in these review papers. The rotation has been measured by three methods, namely, (1) Tracers: using quasi permanent features on the solar surface *e.g.* sunspots, filaments etc. (2) Spectroscopy: wherein one measures Doppler shift of emission lines and (3) Flux Modulation: this is the method that we have used extensively (Vats *et al.* 1998a and Vats *et al.* 1998b). The disk integrated radio flux at multi-frequency (11) radio emissions over 26 months. This showed that there is a systematic change in rotation period as a function of altitude in the solar corona (Vats *et al.* 2001). The disk

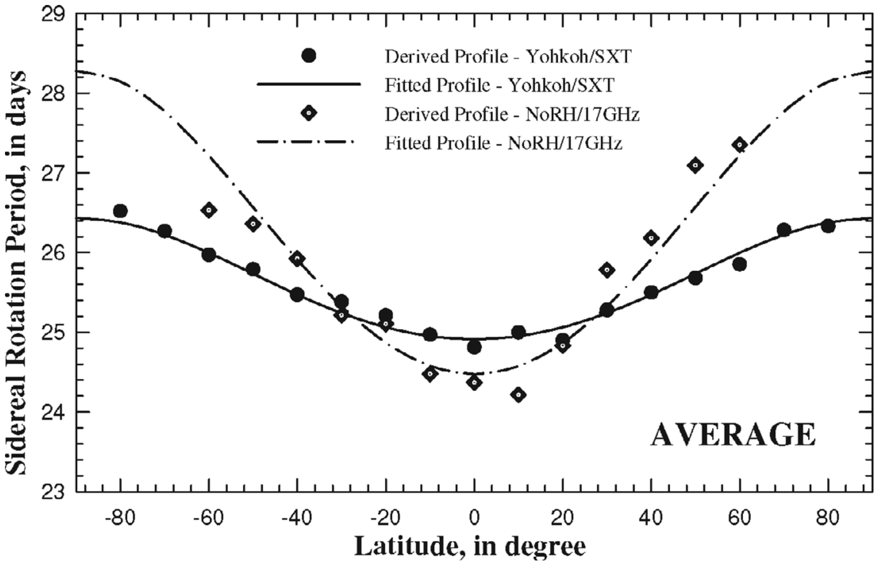

Figure 1. Average rotation profiles obtained by flux modulation method.

integrated measurements give no information on the latitude variation. Radio images at 17 GHz for the period 1999 - 2005 give very interesting information about the differential rotation of the solar corona at the height of this emission. The differential profile is shallower than those for photosphere and chromospheres. A comparison of radio and X-ray measurements is shown in Figure 1. This figure based on the recent work for estimating differential rotation in corona by flux modulation method using radio and X-ray images. The radio images are from Nobeyama Radioheliograph for the years 1999 - 2001 (Chandra, Vats & Iyer 2009). The X-ray images of Yohkoh SXT for the years 1991 - 2001 are used by Chandra, Vats & Iyer (2010). The aim of this paper is to discuss the temporal variation of the rotation as a function solar activity during the years 1998 - 2001 for radio observations and for the years 1991 - 2001 for X-ray measurements.

2. Results

Using radio images at 17 GHz of Nobeyama Radioheliograph and Yohkoh soft X-ray images (Chandra, Vats & Iyer 2009 and Chandra, Vats & Iyer 2010) have provided value of the coefficients A and B of the equation of differential rotation rate $\Omega(\psi) = A + B\sin^2\psi$. Here ψ is solar latitude. The mean rotation profiles of these extensive measurements in X-ray and at Radio wavelength are shown in Figure 1 by a dash-dot-dash and a continuous curve, respectively. The mean profiles show an interesting behaviour. The equatorial region radio measurements indicate a faster rotation rate, whereas at high latitude X-ray measurements indicate a faster rotation rate. Vats *et al.* (2001) used the coronal electron density model (Aschwanden & Benz 1995) and estimated that the radio emission at 17 GHz would be originating from a height $\sim 1.2 \times 10^4$ km above the photosphere. There is also as an assumption in this calculation that emission occurs at frequencies $\sim$ second harmonic of local plasma frequency in the corona. The Yohkoh images are known to represent an average X-ray emission over a height of ~ 0.5 solar radii above the photosphere.

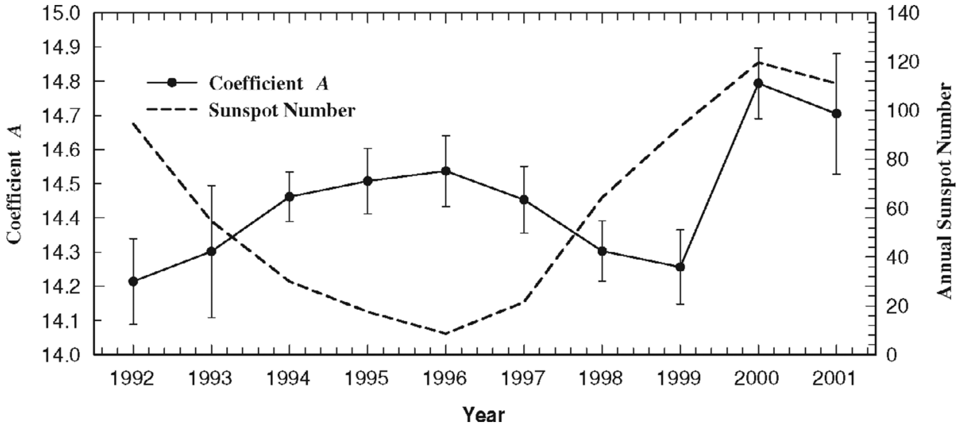

Figure 2. Temporal variation of A (equatorial rotation rate) and sunspots number.

Thus these profiles represent slightly different parts of the solar atmosphere. However, the difference in these is an interesting aspect and both these profiles show differential rotation. Review of many observations of surface rotation of the Sun (Beck 2000) show that the equatorial rotation period is $\sim$ 25 days and that near poles is $\sim$ 36 days. The profiles shown in Figure 1 are quite shallower than those in the photosphere and chromosphere. Thus the corona does have a differential rotation but it is shallower than in the lower parts of solar atmosphere. It is now believed that the sunspots and solar activity cycle are connected to the differential rotation of the Sun through a complex manner.

The coefficients A and B represent equatorial rotation rate and the mid-latitude differential rate, respectively. The variation of A from Yohkoh SXT measurements is shown in Figure 2. There are two curves in this figure as a function of time (for the entire period of Yohkoh observations for the years 1992 - 2001); the dashed curve is for the sunspot number and the continuous curve for coefficient A. The sunspot number (which is a measure of solar activity) decreases from 1992 to 1996, whereas the value of the coefficient A increases steadily during this period. The increasing in A is about 3%. After 1996, the behaviour of both (the sunspots and A) is almost opposite, except in the year 2000 when the value of coronal rotation rate is rather high. The coefficient A obtained from the observations of Nobeyama Radio Heliograph is shown in Figure 3. The curves of Figure 3 are for a slightly different epoch (1999 to 2005). Here, the variation of A and the sunspots are not opposite to each other. However, the peak of solar activity is in 2000, whereas peak of A is in 2003, so there is lag of 3 years. However, the change in the value of A is > 6 %. The change in the equatorial rotation rate as a function of time or the solar activity by X-ray measurements is only half of radio measurements.

The difference in the behavior of coefficient A obtained by Radio and X-ray could be either due to difference in the two epochs or could be due to a difference in the region of their emission in the solar atmosphere.

3. Summary and discussions

The presented study shows that corona has differential rotation. The equatorial part of the corona rotates slightly faster than that of the photosphere and chromospheres. The region of higher latitudes in the corona rotates much faster than the corresponding region of the lower solar atmosphere. Casas, Vaquero & Vazquez (2006) used sunspot

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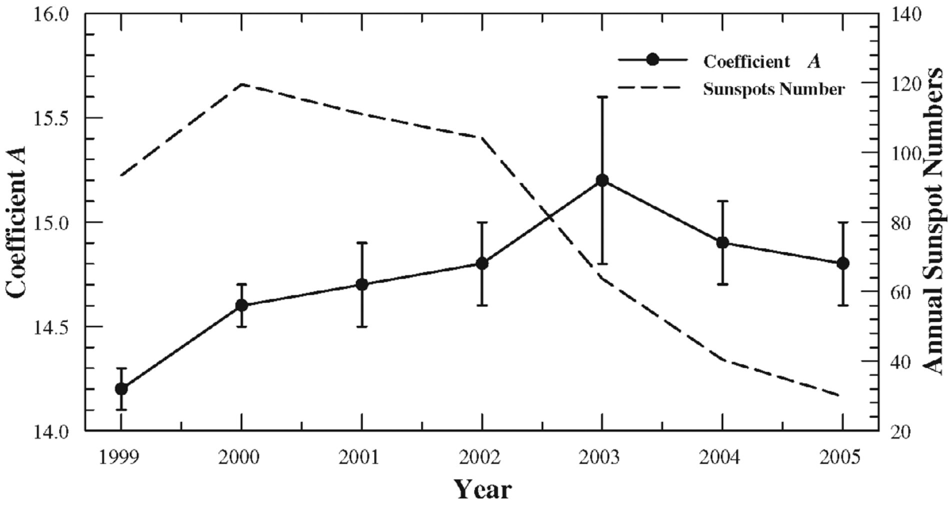

Figure 3. same as in Figure 2, this is for Radio measurements.

drawings to investigate the behavior of solar rotation during the episode of reduced solar activity, known as the Maunder Minimum (MM). This confirmed the conclusion of Ribes & Nesme-Ribes (1993), that during the MM the solar surface rotates slowly at the equator and it shows a higher level of differential rotation with latitude. Balthasar, Vázquez & Wöhl (1986) reported a similar, but smaller decrease in the equatorial rotation rate between cycles 13 and 14 ($\sim$ 1901), accompanied by a change in the decay rate of sunspots. This epoch did coincide with the minimum of the 80-year activity cycle. Present work using X-ray images suggest that the equatorial rotation rate is anti-correlated with the sunspot activity, except in the year 2000. The radio images at 17 GHz show that the equatorial rotation rate (A) and the sunspot number have a lag of 3 years. The B coefficient representing the differential part is almost in phase with the sunspot number. More studies are needed to ascertain the temporal and spatial variability of the rotation rate.

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