AN INVESTIGATION OF CYCLE-RELATED CHANGES OF THE SOLAR ROTATION BY TRACING MICROWAVE LOW BRIGHTNESS TEMPERATURE REGIONS

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Abstract. Indications of possible changes of the solar rotation rate during several phases of the solar activity cycle (the years analyzed were 1979, 1980, 1981, 1982, 1987, 1988, 1989, 1990 and 1991) were found. The solar rotation rates were determined by tracing microwave Low brightness Temperature Regions in the latitude range ±55°. These changes of the rotation rate, although of low statistical significance, indicate that the Sun has nearly equal rotation rates during successive cycle maxima, which are different from the measured rotation rates in the periods between the maxima.

1. Introduction

From the observational point of view, there are some indications that the shapes of the differential rotation curve change during the solar activity cycle (Howard and LaBonte, 1983; Stix, 1989; Pecker, 1994, and references therein), although the reported results are not always mutually consistent. The solar differential rotation is usually represented by the following expression:
\[ \omega(b) = A + B \sin^2 b + C \sin^4 b \]  

where \( \omega \) represents the rotation rate expressed in deg/day (°/d), \( b \) is the heliographic latitude, and \( A, B, C \) are the solar rotation parameters. We regard a change of the solar rotation rate as statistically significant if the change is larger than the sum of the threefold error of the rotation rate in one period (e.g. cycle maximum) and the threefold error of the rotation rate in another period (e.g. cycle minimum). This is a very strict criterium, which, in the case of rotation rates, requires:

\[ \Delta \omega \equiv \omega_1 - \omega_2 > 3M(\omega_1) + 3M(\omega_2) \]  

where \( M \) represents the standard error. Although the results on the possible changes of the solar rotation are not always presented in a form that the criterium given by Equation (2) can be applied, we can say that most of the results reported in the literature are either statistically insignificant or only marginally significant. However, there are published measurements which do have the required statistical significance according to Equation (2), e.g. papers by Gilman and Howard (1984), Balthasar, Vázquez and Wöhl (1986), Japaridze and Gigolashvili (1992), Solonsky and Makarova (1992).

2. Data and Reduction Procedures

The data set and the reduction procedures are described in detail in the papers by Brajša et al. (1992a) and by Brajša et al. (1995). The Low brightness Temperature Regions (LTRs) were identified on full-disk solar microwave maps obtained by a 14 m dish diameter radio telescope at the Metsähovi Radio Research Station, Helsinki University of Technology (Urpo, Pohjolainen and Teräsranta, 1992). The Cassegrain telescope system can be used at the frequencies 10-100 GHz (wavelengths 3 cm - 3 mm) and a part of the telescope observing time has been used for solar research since 1976. Annually the telescope has been reserved for solar measurements for 4-10 weeks, typically during summer months. In this paper we used maps of the whole Sun at 37 GHz; at this frequency the telescope beam size amounts to 2.4 arc min. The
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sensitivity of the receivers is good enough for 0.1 sfu resolution. In the temperature scale the resolution is better than 100 K and it is limited by short term changes in the atmospheric attenuation. Solar maps are measured by scanning the solar disk in right ascension and by changing the declination in small steps between the subsequent scans.

The LTRs were used as tracers, and their central meridian distances were fitted by the linear least square method, giving one sidereal rotation rate for each identified LTR. Sidereal rotation rates lying outside the interval of 11.00°/d and 15.99°/d were excluded from the analysis. The northern and the southern solar hemisphere were treated together (a separate analysis of the two solar hemispheres in relation to the solar rotation can be found in Brajša et al., 1995), and in total 489 individual rotation rates were determined. Then subsequent years were combined, and the number of individual evaluated rotation rates in various time periods was as follows: 70 in 1979/80, 59 in 1981/82, 41 in 1987/88 and 319 in 1989/90/91. The intensity of solar activity in these periods, as defined by the relative Wolf number, was taken into account, and only years when the solar activity was similar were combined.

3. Results

All individual rotation rates from the selected time periods are presented in Figure 1a-1d, and for all the time periods together in Figure 1e. The lines through these data points represent the fits obtained using Equation (1) setting the parameter C to zero. In Figure 2a-2e, such fits are compared with other fits obtained when all three parameters from Equation (1) were taken into account. Finally, in Figure 3a-3e, two-parameter fits are again compared with the three-parameter ones, but setting $B=C$ for the three-parameter fits. In all cases Equation (1) was linearized using the substitution $x = \sin^2 b$, and then a linear or polynomial least square fit was applied (Efimov, 1988; Press et al., 1989).
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Fig. 1a-1e. (a) Sidereal solar rotation rate from LTR tracings for the years 1979 and 1980. Crosses represent individual rotation rates, and the curve is the fit obtained using Equation (1) with C=0. Both solar hemispheres were taken together, and b is the absolute value of the latitude.

Fig. 1b. The same as in Fig. 1a, but for the years 1981 and 1982.
Fig. 1c. The same as in Fig. 1a, but for the years 1987 and 1988.

Fig. 1d. The same as in Fig. 1a, but for the years 1989, 1990 and 1991.
Fig. 1e. The same as in Fig. 1a, but for all years: 1979, 1980, 1981, 1982, 1987, 1988, 1989, 1990 and 1991.

Fig. 2a-2e. (a) Sidereal solar rotation rate from LTR tracings for the years 1979 and 1980. The full line represents the fit obtained using Equation (1) with $C=0$, and the dotted line the fit obtained using Equation (1) with all three parameters. Both solar hemispheres were taken together, and $b$ is the absolute value of the latitude.
Fig. 2b. The same as in Fig. 2a, but for the years 1981 and 1982.

Fig. 2c. The same as in Fig. 2a, but for the years 1987 and 1988.
Fig. 2d. The same as in Fig. 2a, but for the years 1989, 1990 and 1991.

Fig. 2e. The same as in Fig. 2a, but for all years: 1979, 1980, 1981, 1982, 1987, 1988, 1989, 1990 and 1991.
Fig. 3a-3e. (a) Sidereal solar rotation rate from LTR tracings for the years 1979 and 1980. The full line represents the fit obtained using Equation (1) with \( C=0 \), and the dotted line the fit obtained using Equation (1) with all three parameters, but setting \( B=C \). Both solar hemispheres were taken together, and \( b \) is the absolute value of the latitude.

Fig. 3b The same as in Fig. 3a, but for the years 1981 and 1982.
Fig. 3c. The same as in Fig. 3a, but for the years 1987 and 1988.

Fig. 3d. The same as in Fig. 3a, but for the years 1989, 1990 and 1991.
4. Discussion

Inspecting the errors in the determination of the fitting parameters (see the Tables in Brajša et al., 1995), none of the obtained rotation rate parameter is statistically significant in the sense of Equation (2). However, we can say that the average solar rotation rate was higher in the two successive solar activity maxima (1979/80 and 1989/90/91), and lower in the periods 1981/82 and 1987/88, as can be seen in Figures 1-3. The difference is about 3 to 4 % for medium latitudes, which is somewhat larger than the difference of 1 to 2 % which can be found in the literature (Pecker, 1994). The relationship between the solar differential rotation profile and the solar activity cycle phase obtained using LTRs as tracers is in a qualitative agreement with the results of Snodgrass (1991), who obtained higher rotation rates during the 1979/80 and 1989/90 solar activity maxima, and slower rotation rates during the time periods in between for the medium latitude ranges on both solar hemispheres. The study of Snodgrass (1991) was based on cross-correlating full-disk solar magnetograms and the results were interpreted...
in terms of torsional oscillations. Although a relationship between LTRs and the inversion lines of the longitudinal component of the photospheric magnetic field was found (Brajša et al., 1992b; Vršnak et al., 1992), a clear physical connection between LTRs and magnetic structures which were correlated by Snodgrass (1991) could not be established yet.

Further, at the qualitative level, some of our results (from the years 1979, 1980, 1981 and 1982) are consistent with the solar rotation rates determined by tracing sunspots (Gilman and Howard, 1984), who found that the rotation rate residual is larger than the average in 1979 and 1980, and smaller than the average in 1981 and 1982. These authors found, using a different data reduction procedure, a similar increase in the rotation rate for the year 1980 as we did for the 1979/80 period.

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