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A relationship between the solar rotation and activity in the period 1998 - 2006 analyzed by tracing small bright coronal structures in SOHO-EIT images

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ABSTRACT

Context. We analyze precise measurements of the solar differential rotation determined by tracing small bright coronal structures (SBSC) in SOHO-EIT images and compare the derived solar rotation parameters with the status of solar activity in the period 1998-2006.
Aims. The study aims to find a relationship between the rotation of the SBCS described by the solar rotation parameters and indices of solar activity on monthly and yearly temporal scales.
Methods. Full-disc solar images obtained with the Extreme Ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO) were used to analyse solar differential rotation determined by tracing SBSC. An automatic method to identify and track the SBSC in EIT full-disk images of 6 hours cadence is applied. We performed a statistical analysis of the monthly and yearly values of solar sidereal rotation velocity parameters A and B (corresponding to the equatorial rotation velocity and the gradient of the solar differential rotation, respectively) as a function of various solar activity indices.
Results. The dependence of the solar rotation on the phase of the solar cycle was found. It is clearly visible for the solar rotation parameter A, while the results are not conclusive for the parameter B. The relationship between the solar rotation and activity, expressed by the monthly relative sunspot number, the smoothed monthly relative sunspot number, the yearly relative sunspot number and the interdiurnal variability (IDV) index was investigated. The statistically significant correlation was found for the solar rotation parameter A, while a very low and insignificant correlation was obtained for the rotation parameter B.
Conclusions. During the maximum of the solar cycle 23 and just after it, the equatorial solar rotation velocity was lower than in other phases of the cycle, when there was less activity.This is consistent with other observational findings, obtained by different tracers and methods.

Key words. Sun: rotation – Sun: corona – Sun: activity

1. Introduction

Measurements of the solar differential rotation provide precisely determined observational constraint on theoretical models of the solar convection zone and the solar MHD dynamo. The conservation of angular momentum, its transport to maintain the differential rotation profile and an interplay with magnetic field are very important for understanding physical properties of the Sun and solar-type stars. Many indications of cycle-related variations of the solar rotation have been reported using different tracers and methods (e.g., Howard 1984; Schröter 1985; Snodgrass 1992; Stix 2002). Most often, sunspots and sunspot groups were used as tracers mainly due to the long term data sets available from various observatories. For the investigation of possible variations of the solar rotation, the Greenwich data set was used by Balthasar & Wöhl (1980), Arévalo et al. (1982) and Balthasar et al. (1986), the Kanzelhöhe data set by Lustig (1983), the Mt. Wilson data set by Gilman & Howard (1984) and by Hathaway & Wilson (1990), the Mitaka data set by Kambry & Nishikawa (1990), the Suzuka data set by Suzuki (1998), the extended Greenwich data set by Pulkkinen & Tuominen (1998), Javaraiah (2003), Zuccarello & Zappalá (2003), Javaraiah et al. (2005), Javaraiah & Ulrich (2006), and Brajša et al. (2006, 2007), the Kodaikanal data set by Gupta et al. (1999) and the Abastumani data set by Khutsishvili et al. (2002). Also, temporal variations of the solar rotation were studied using other features, e.g., magnetic fields (Sheeley et al. 1987; Brajša et al. 1992; Sheeley et al. 1992), coronal holes (Nash et al. 1988), observations of the corona in the green line (Rybák 1994; Altrock

2003), Hα filaments (Japaridze & Gigolashvili 1992; Brajša et al. 1997; Gigolashvili et al. 2003), microwave low-brightness-temperature regions (Brajša et al. 1997, 1999, 2000), and faculae (Meunier et al. 1997). Changes of the solar rotation were investigated also by the helioseismological method using the GONG and SOHO-MDI data at the base of the convective zone (Howe et al. 2000a,b, 2001) and at high latitudes (Antia & Basu 2001). Recently, the time-series analysis was applied to investigate temporal changes of the solar rotation, especially using the radio data (Heristchi & Mouradian 2009; Chandra et al. 2009). **Various frequencies correspond to various altitudes in the solar corona and different methods have been used (e.g., the Sun analysed as a star with no latitudinal dependence, autocorrelation analysis with a time lag, etc.). However, it seems that up to now either a very weak or no correlation between the coronal rotational period and the sunspot activity can be verified (Vats et al. 2010; Chandra & Vats 2011). This result refers to the height of about 60 000 km and the observing frequency of 2.8 GHz.**

If we adopt the working hypothesis of the corrrelation between the solar rotation and activity, then the strongest effect should have been observed during the Maunder minimum (1645-1715). In spite of many investigations (e.g., Eddy et al. 1976; Abarbanell & Wöhl 1981; Ribes & Nesme-Ribes 1993; Mendoza 1999; Vaquero et al. 2002; Casas et al. 2006), the results are still not conclusive, due to the general uncertainty of measurements in those times and the different time subintervals when particular observations were performed (just before or at the very beginning of the Maunder minimum, during the Maunder minimum, during the deep Maunder minimum and just after the regular cycles started again). In addition, new discoveries and reductions of the observations from that time have often been reported. However, there is a strong evidence that sunspots rotated faster at low latitudes with a more pronounced differential profile during the Maunder minimum (Eddy et al. 1976).

In the present paper Small Bright Coronal Structures (SBCS) are used as tracers for the solar rotation determination and for a comparison of the deduced solar rotation parameters with indices of solar activity on monthly and yearly temporal scales. The main physical characteristics of SBCS were summarized by Brajša et al. (2004, 2008a, and references therein), while their good latitudinal coverage on the Sun was described by, e.g. Brajša et al. (2005, and references therein). Solar rotation determined tracing SBCS and its comparison with the sidereal angular rotation velocity of subphotospheric layers were recently analyzed by Zaatri et al. (2009) and by Wöhl et al. (2010, hereafter denoted as Paper I). In this work we use the same data set and the same automatic method of data reduction for the determination of the monthly and yearly solar rotation parameters, as in Paper I. Besides the automatic method of data reduction applied in the present work, in Paper I also the interactive method was used, the results of the two methods were compared, the north-south asymmetry of the solar rotation and the rigid rotational component at high solar latitudes were investigated. Also, a detailed comparison of the measured solar rotation of SBCS with the results of other tracers and methods was presented in Paper I. In the present paper we extend that analysis by studying the temporal evolution of the solar rotation determined tracing SBCS and a relationship between the solar rotation and activity during most of the 23rd solar cycle (1998 - 2006). As proxies for the solar activity we use the relative sunspot number (monthly, monthly smoothed and yearly values) and the strength of the interplanetary magnetic field represented by the interdiurnal variability (IDV) index (Svalgaard & Cliver 2005).

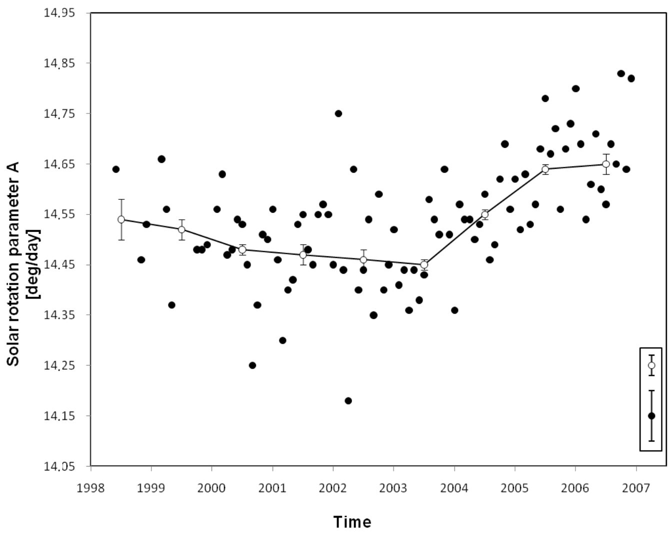

Fig. 1. Solar sidereal rotation parameter A as function of time; monthly (black dots) and yearly values (open circles) with corresponding error bars for yearly values and typical mean value uncertainties given in the right corner of the figure.

2. The SOHO-EIT data set and the automatic method of data reduction

Several thousand full-disc full resolution solar filtergrams recorded in the Fe XV line at the wavelength of 28.4 nm taken with the Extreme Ultraviolet Imaging Telescope (EIT) in the years 1998 - 2006 were analysed. In these images SBCS were identified and used as tracers for the solar rotation determination. The detailed description of the data set and the automatic method of data reduction are presented in Paper I (and references therein). The total amount of reduced data exceeds 50 000 triplets of SBCS (Paper I), which is of the same order of magnitude as the number of pairs of daily position measurements of sunspot groups analyzed in the Greenwich Photoheliographic Results by Balthasar et al. (1986). In the present work we use the monthly and yearly parameters of the solar differential rotation published in Paper I and compare them with various solar activity proxies.

3. Results

3.1. Temporal evolution

As usually, the solar differential rotation is represented by:

$$\omega(\psi) = A + B\sin^2\psi + C\sin^4\psi, \quad (1)$$

where ω represents the angular rotation velocity expressed in deg/day, ψ the heliographic latitude, and A, B, and C the solar rotation parameters. In the present work we put $C = 0$ to make the comparison with the indices of solar activity easier and to use the monthly and yearly differential rotation parameters from the Paper I.

The time dependence of the solar sidereal differential rotation velocity parameters A and B for the time interval 1998-2006 was analysed and represented graphically. **Monthly and annual dependences of the solar rotation parameters A and B are displayed in Figs. 1 and 2, respectively. Errors for the data concerning monthly values are given in Paper I.**

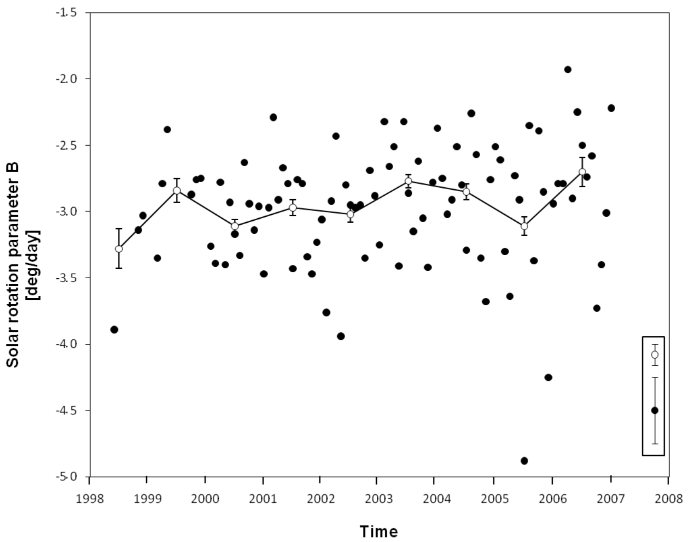

Fig. 2. Solar sidereal rotation parameter B as function of time; monthly (black dots) and yearly values (open circles) with corresponding error bars for yearly values and typical uncertainties given in the right corner of the figure.

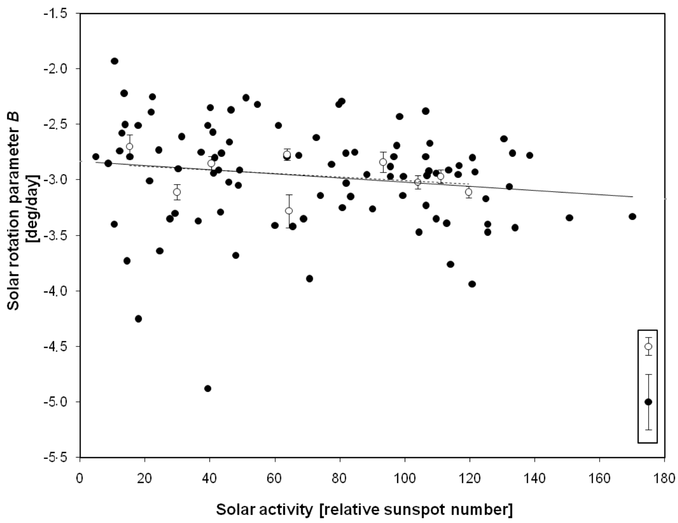

Fig. 4. Solar sidereal rotation parameter B as function of the relative sunspot number (*SN*); monthly (black dots, full line) and yearly values (open circles, dotted line). Typical uncertainties are given in the right corner of the figure.

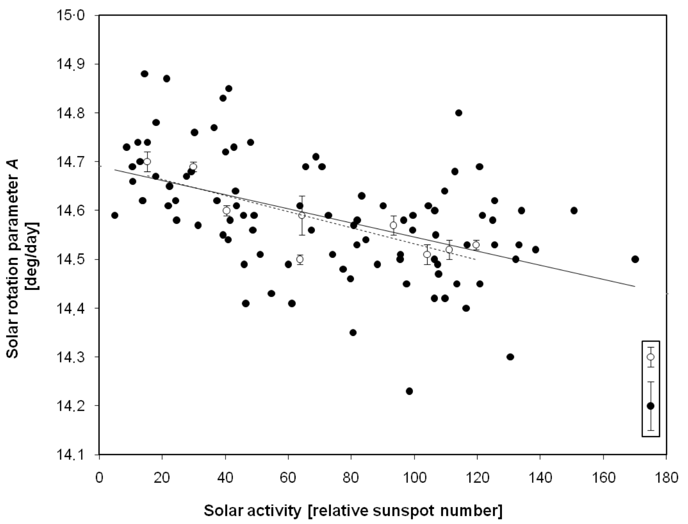

Fig. 3. Solar sidereal rotation parameter A as function of the relative sunspot number (*SN*); monthly (black dots, full line) and yearly values (open circles, dotted line). Typical uncertainties are given in the right corner of the figure.

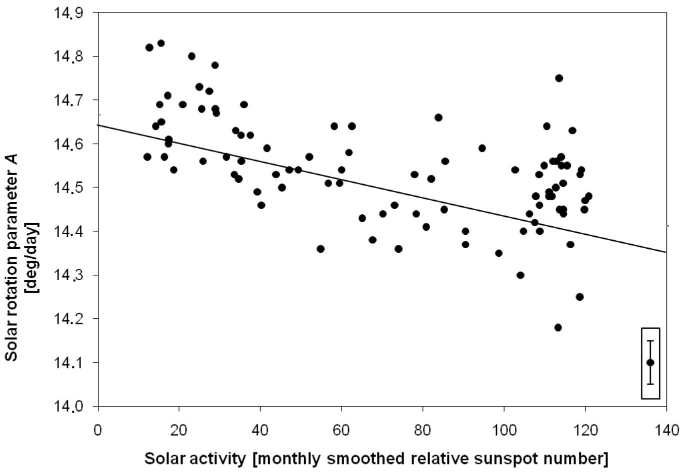

Fig. 5. Monthly values of the solar sidereal rotation parameter A as a function of the monthly smoothed relative sunspot number (*SSN*). Typical uncertainty is given in the right corner of the figure.

On the time scale of months the parameter A shows a slight increase after the activity maximum and the parameter B shows no evidence of a statistically significant time dependence (Figs. 1 and 2). On the annual time scale the variation of the parameter A represented in Fig. 1 is more pronounced as those of the parameter B given in Fig. 2. Solar sidereal equatorial rotation velocity, represented by the parameter A, decreases up to the year 2003 and then the A values increases (Fig. 1).

3.2. A relationship between the solar rotation and activity

In order to examine correlation between the solar rotation and activity we performed a statistical analysis of the monthly and yearly values of solar sidereal rotation velocity parameters A and B as a function of different solar activity indices. Solar activity was represented by the monthly relative sunspot number (SN), also called the Wolf number and monthly smoothed relative sunspot number (SSN). This data series are provided by the Solar influences data analysis center (SIDC) of the Royal Observatory of Belgium (SIDC-team 1998-2006). **The solar cycle dependence of solar sidereal rotation parameters A_{st} and B_{st}, obtained from selected stable structures, was also examined.** The identification of stable structures was performed by searching for pairs of triplets with a difference in latitude of less than 0.5 deg and continuing values in longitude, i.e., in the central meridian distance (CMD). In general, less than half of the structures were found to be stable (Paper I).

The statistical analysis for the annual values of the solar sidereal rotation parameters A and B have been determined as a function of the solar activity (represented with SN and SSN) and also as a function of the interplanetary magnetic field strength,

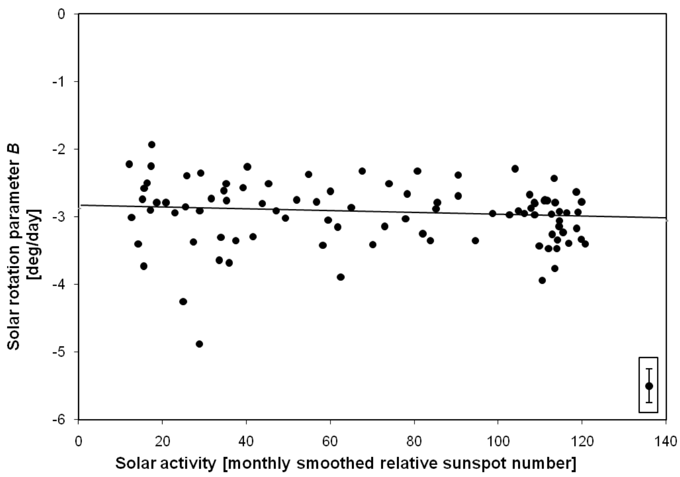

Fig. 6. Monthly values of the solar sidereal rotation parameter ***B*** **as a function of the monthly smoothed relative sunspot number (*****SSN*****). Typical uncertainty is given in the right corner of the figure.**

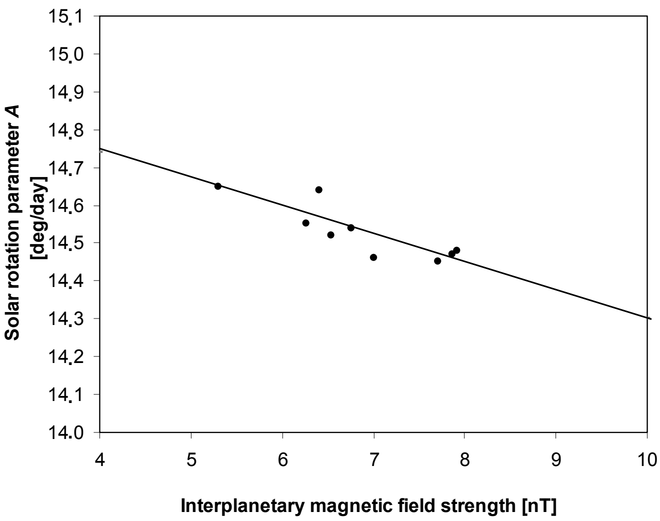

Fig. 7. Yearly values of the solar sidereal rotation parameter *A* as a function of the interplanetary magnetic field strength derived from the interdiurnal variability (IDV) index.

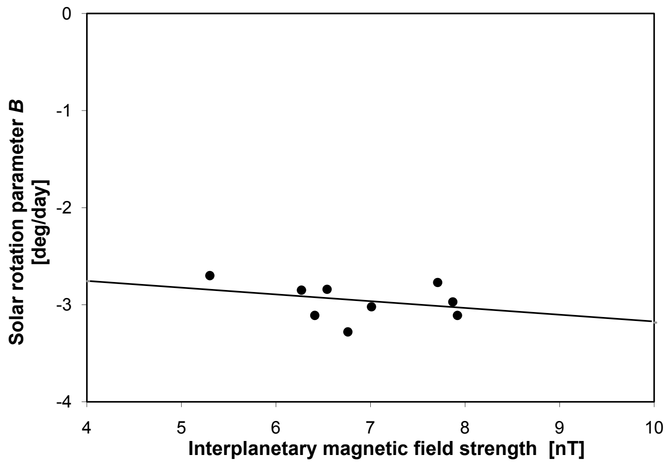

Fig. 8. Yearly values of the solar sidereal rotation parameter *B* as a function of interplanetary magnetic field strength derived from the interdiurnal variability (IDV) index.

Monthly	ρ	b	M_b	Fig.	t
$A = f$(SN)	-0.49	-0.0015	0.0003	**3**	**−5.36**
$B = f$(SN)	-0.16	-0.0019	0.0012	**4**	**−1.57**
$A = f$(SSN)	-0.57	-0.0018	0.0003	**5**	**−6.57**
$B = f$(SSN)	-0.11	-0.0013	0.0013	**6**	**−1.01**
$A_{st} = f$(SN)	-0.34	-0.0012	0.0003		**−3.46**
$B_{st} = f$(SN)	-0.17	-0.0030	0.0018		**−1.68**
$A_{st} = f$(SSN)	-0.40	-0.0015	0.0004		**−4.22**
$B_{st} = f$(SSN)	-0.15	-0.0028	0.0020		**−1.43**
Yearly	ρ	b	M_b		
$A = f$(SN)	-0.83	-0.0016	0.0004	**3**	**−3.94**
$B = f$(SN)	-0.32	-0.0016	0.0018	**4**	**−0.88**
$A = f$(BIDV)	-0.85	-0.0732	0.0172	**7**	**−4.26**
$B = f$(BIDV)	-0.33	-0.0712	0.0774	**8**	**−0.92**

Table 1. Statistical results for monthly and yearly solar sidereal rotation velocity parameters *A* and *B* as functions of solar activity represented by the monthly relative sunspot number (*SN*), the monthly smoothed relative sunspot number (*SSN*), and the interplanetary magnetic field strength represented by the IDV index. A_{st} and B_{st} denote solar sidereal rotation parameters obtained from selected stable structures. ρ is the **(Spearman) rank-order** correlation coefficient, b the slope of the straight lines fitted through the set of data points under consideration, M_b is the standard error, **and** t **is the test parameter for statistical significance of** ρ**.**

derived from the IDV index (Svalgaard & Cliver 2005). The following values were calculated in the statistical analysis: the correlation coefficient ρ, the slope of the straight lines fitted through the statistical set of data points b and the corresponding standard error M_b. The values are given in Table 1 and represented in Figs. 3–8. **Typical uncertainties are also given in these figures. In Figs. 7-8 the error bars are not repeated, as they are the same as in previous cases for the yearly values.**

According to results given in Table 1 and displayed in Figures 3–8 we obtained the highest correlation between the solar sidereal rotation parameter *A* and the **yearly activity proxies.** Generaly, solar sidereal rotation parameters obtained from selected stable structures A_{st} and B_{st} have lower correlations with solar activity than the parameters *A* and *B*. However, the parameter B_{st} shows slightly higher correlation with solar activity in comparison with the parameter *B*. Concerning yearly data, the correlation of the parameter *A* with the relative sunspot number (SN), and the interplanetary magnetic field strength derived from the IDV index is very high, and in all cases correlation coefficient ρ exceeds 0.80.

4. Discussion, interpretation and conclusion

In this paper we have found a dependence of the solar rotation on the phase of the solar cycle (Figs. 1–2). This is clearly visible for the solar rotation parameter *A*, corresponding to the equatorial rotation velocity (Fig. 1), while the results are not conclusive for the gradient of the solar differential rotation, expressed by the parameter *B* (Fig. 2). As expected, these results are visible more clearly when the yearly values (open **circles** Figs. 1–2) are considered instead of the monthly values (black **dots** Figs. 1–2), where the noise is much larger.

We note that Gissot (2009) developed an automatic procedure for identification and tracking structures in sequences of full-disc solar images. This procedure is based on a tracking algorithm of solar features derived from wavelet transformation of the images. Among various subtopics, that procedure was applied to the determination of the solar rotation using the archive of EIT He II 30.4 nm images that now covers more than the 23^{rd} solar cycle. Similar as in the present paper, larger noise was found in the temporal evolution of the rotation parameter B, than of the rotation parameter A. In spite of some similarities, the dependence of the solar rotation parameter A on the time are not the same for the two investigations (present work and Gissot 2009).

Further, a relationship between the solar rotation and activity, expressed by different proxies (the monthly relative sunspot number, the smoothed monthly relative sunspot number, the yearly relative sunspot number and the IDV index), was also investigated. These results are presented in Table 1 and in Figs. 3–8. Again, the statistically significant correlation was found for the solar rotation parameter A, while a very low and insignificant correlation was obtained for the rotation parameter B. As can be seen in Table 1, the slope of the linear least-square fitting is statistically significant on the 3σ level for all cases when the parameter A is considered. For those cases the correlation coefficient is in the range from 0.34 to 0.57 for the monthly values and in the range from 0.83 to 0.85 for the yearly values (Table 1), clearly indicating a higher correlation when the yearly values are considered. **Statistical significance of correlations was determined testing null hypothesis ($\rho = 0$,"no correlation exist") at the level of 0.05. For monthly values degree of freedom is 91. As seen from Table 1 calculated test parameter t is for all "A-correlations" greater than Student's distribution value of t at chosen level of significance e.g. $t(0.05, 91) = 1.64$. Therefore null hypotesis is rejected. On the other side, all calculated values of t for "B-correlations" except for $B_{st} = f(SN)$ dependence given in Table 1 are lower than the value $t(0.05, 91) = 1.64$. Therefore for B values null hypotesis is accepted in all cases except for $B_{st} = f(SN)$. For yearly values, where degree of freedom is 7 and $t(0.05, 7) = 1.89$ the null hypotesis is rejected for both A correlations and accepted for both B correlations (Press et al. 1989).**

Our most important result is that during the maximum of the solar cycle 23 and just after it, the equatorial solar rotation velocity, expressed by the rotation parameter A, was lower than in other phases of the cycle, when there was less activity. This is in agreement with the high correlation between the rotation parameter A and various indices of solar activity. This result is consistent with many other observational findings, obtained by different tracers and methods. So, a higher average rotation velocity in activity minima was found by many authors who analyzed the solar rotation using various sunspot data series by different methods (Lustig 1983; Gilman & Howard 1984; Balthasar et al. 1986; Hathaway & Wilson 1990; Gupta et al. 1999; Khutsishvili et al. 2002; Zuccarello & Zappalá 2003; Brajša et al. 2006). **Moreover, Chandra et al. (2010) measured differential rotation of the soft X-ray solar corona and investigated it's variation with the solar activity. They have found that the equatorial rotation velocity correlates well with the corresponding solar cycle phase, while the parameters B and C do not show any systematic variations. Our results obtained in the present paper are in agreement with the results of Chandra et al. (2010).**

A further implication of the correlation between the solar rotation and activity is a higher solar rotation which should have been observed during the Maunder minimum. Some modern analyses of the data from the period of Maunder minimum suggest exactly this type of behavior, although there is no general agreement on this topic, as we have seen in Sect. 1. Since the floor of the interplanetary magnetic field is about 4 nT, **this is an expected value for the Maunder minimum** (Svalgaard & Cliver 2007, 2010), we can find a corresponding value for the solar rotation parameter A, describing the equatorial rotation velocity, from **Fig. 7**. It is for about 0.2 deg/day larger than average value for sunspots in usual solar activity conditions and in a good agreement with the value reported by Eddy et al. (1976) for the Maunder minimum.

We note that the equatorial rotation velocity of SBCS, averaged over the whole observing period 1998 - 2006, is very similar to the equatorial rotation velocity of sunspots and sunspot groups (solar rotation parameter A, Table 16 in Paper I). So, the solar rotation parameter A determined tracing SBCS is a very good proxy for the solar equatorial rotation determined by sunspots and sunspot groups.

The most probable theoretical interpretation of the observed phenomena is based on the interaction between the solar differential rotation and magnetic field, as discussed in detail in the papers by Brajša et al. (2006, 2007, and references therein). A higher rotation velocity at low latitudes is consistent with a lower magnetic activity on the Sun. This is the result of numerical simulations performed by Brun (2004), and by Brun et al. (2004), in agreement with an analytical approach to solve the angular momentum equation (Lanza 2006, 2007).

Finally, we can raise the question why in our analysis no significant dependence of the differential rotation parameter B, on time and/or on the activity level, was found. During the periods of high magnetic activity on the Sun, a more rigid (i.e., a less differential) rotational component should be observed, yielding a smaller absolute B value (Brun 2004; Lanza 2007). The most probable explanation for our lack to find this is the fact that for the determination of the solar rotation parameters we used data from all latitudes, even in polar regions, i.e., above 80 deg of latitude (Paper I). At those high latitudes the noise and various sources of systematic errors are much larger than at the low latitudes. So, these effects smear the variations of the parameter B, while having barely an influence on the parameter A. Also, the effect of the height of the tracers on the measured rotation velocity increases with the latitude and has the largest influence in polar regions (e.g., Roša et al. 1998). Moreover, the north-south rotational asymmetry in our data set is much larger at medium and high latitudes than at the lower ones (Paper I). So, as a suggestion for a future work, we will repeat the analysis imposing different cut-offs in the latitude (especially excluding the polar regions) and performing the data reduction separately for the two solar hemispheres.

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References

Abarbanell, C. & Wöhl, H. 1981, Sol. Phys., 70, 197
Altrock, R. C. 2003, Sol. Phys., 213, 23
Antia, H. M. & Basu, S. 2001, ApJ, 559, L67

Arévalo, M. J., Gomez, R., Vázquez, M., Balthasar, H., & Wöhl, H. 1982, A&A, 111, 266
Balthasar, H., Vázquez, M., & Wöhl, H. 1986, A&A, 155, 87
Balthasar, H. & Wöhl, H. 1980, A&A, 92, 111
Brajša, R., Ruždjak, D., & Wöhl, H. 2006, Sol. Phys., 237, 365
Brajša, R., Ruždjak, V., Vršnak, B., et al. 1997, Sol. Phys., 171, 1
Brajša, R., Ruždjak, V., Vršnak, B., et al. 1999, Sol. Phys., 184, 281
Brajša, R., Ruždjak, V., Vršnak, B., et al. 2000, Sol. Phys., 196, 279
Brajša, R., Vršnak, B., Ruždjak, V., et al. 1992, Hvar Obs. Bull., 16, 13
Brajša, R., Wöhl, H., Ruždjak, D., et al. 2007, Astron. Nachr., 328, 1013
Brajša, R., Wöhl, H., Vršnak, B., et al. 2004, A&A, 414, 707
Brajša, R., Wöhl, H., Vršnak, B., et al. 2008a, CEAB, 32, 165
Brajša, R., Wöhl, H., Vršnak, B., et al. 2005, Sol. Phys., 231, 29
Brun, A. S. 2004, Sol. Phys., 220, 333
Brun, A. S., Miesch, M. S., & Toomre, J. 2004, ApJ, 614, 1073
Casas, R., Vaquero, J. M., & Vázquez, M. 2006, Sol. Phys., 234, 379
Chandra, S. & Vats, H. O. 2011, MNRAS, 603C
Chandra, S., Vats, H. O., & Iyer, K. N. 2009, MNRAS, 400, L34
Chandra, S., Vats, H. O., & Iyer, K. N. 2010, MNRAS, 407, 1108C
Eddy, J. A., Gilman, P. A., & Trotter, D. E. 1976, Sol. Phys., 46, 3
Gigolashvili, M. S., Mdzinarishvili, T. G., Japaridze, D. R., & Chargeishvili, B. B. 2003, New Astronomy, 8, 529
Gilman, P. & Howard, R. 1984, ApJ, 283, 385
Gissot, S. 2009, PhD thesis, Universite Catholique de Louvain, ch. 5, p. 79
Gupta, S. S., Sivaraman, K. R., & Howard, R. F. 1999, Sol. Phys., 188, 225
Hathaway, D. H. & Wilson, R. M. 1990, ApJ, 357, 271
Heristchi, D. & Mouradian, Z. 2009, A&A, 497, 835
Howard, R. 1984, ARA&A, 22, 131
Howe, R., Christensen-Dalsgaard, J., Hill, F., et al. 2000a, Sci, 287, 2456
Howe, R., Christensen-Dalsgaard, J., Hill, F., et al. 2000b, ApJ, 533, L163
Howe, R., Hill, F., Komm, R. W., et al. 2001, in Recent insights into the physics of the Sun and heliosphere: Highlights from SOHO and other space missions, ed. P. Brekke, B. Fleck, & J. Gurman (Astron. Soc. Pac, San Francisco), p. 40
Japaridze, D. R. & Gigolashvili, M. S. 1992, Sol. Phys., 141, 267
Javaraiah, J. 2003, Sol. Phys., 212, 23
Javaraiah, J., Bertello, L., & Ulrich, R. K. 2005, Sol. Phys., 232, 25
Javaraiah, J. & Ulrich, R. K. 2006, Sol. Phys., 237, 245
Kambry, M. A. & Nishikawa, J. 1990, Sol. Phys., 126, 89
Khutsishvili, E. V., Gigolashvili, M. S., & Kvernadze, T. M. 2002, Sol. Phys., 206, 219
Lanza, A. F. 2006, MNRAS, 373, 819
Lanza, A. F. 2007, A&A, 471, 1011
Lustig, G. 1983, A&A, 125, 355
Mendoza, B. 1999, Sol. Phys., 188, 237
Meunier, N., Nesme-Ribes, E., & Grosso, N. 1997, A&A, 319, 673
Nash, A. G., Sheeley, N. R. J., & Wang, Y.-M. 1988, Sol. Phys., 117, 359
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1989, Numerical Recipes in Pascal (Cambridge University Press), p.498
Pulkkinen, P. & Tuominen, I. 1998, A&A, 332, 755
Ribes, J. C. & Nesme-Ribes, E. 1993, A&A, 276, 549
Roša, D., Vršnak, B., Božić, H., et al. 1998, Sol. Phys., 179, 237
Rybák, J. 1994, Sol. Phys., 152, 161
Schröter, E.-H. 1985, Sol. Phys., 100, 141
Sheeley, N. R. J., Nash, A. G., & Wang, Y.-M. 1987, ApJ, 319, 481
Sheeley, N. R. J., Wang, Y.-M., & Nash, A. G. 1992, ApJ, 401, 378
SIDC-team. 1998-2006, World Data Center for the Sunspot Index, Monthly Report on the International Sunspot Number, Online catalogue of the sunspot index, Royal Observatory of Belgium, http://www.sidc.be/sunspot-data
Snodgrass, H. 1992, in The Solar Cycle, ed. K. Harvey (ASP Conf. Ser. 27, ASP, San Francisco), p. 205
Stix, M. 2002, The Sun (Berlin: Springer-Verlag, 2nd Ed.), 277
Suzuki, M. 1998, Sol. Phys., 178, 259
Svalgaard, L. & Cliver, E. 2005, J. Geophys. Res., 110, A12103
Svalgaard, L. & Cliver, E. 2007, ApJ, 661, L203
Svalgaard, L. & Cliver, E. 2010, J. Geophys. Res., 115, A09111
Vaquero, J. M., Sánchez-Bajo, F., & Gallego, M. C. 2002, Sol. Phys., 207, 219
Vats, H. O., Chandra, S., & Iyer, K. N. 2010, in Magnetic Coupling between the Interior and Atmosphere of the Sun, ed. S. S. Hasan & R. J. Rutten (Springer Berlin Heidelberg), p. 526-528
Wöhl, H., Brajša, R., Hanslmeier, A., & Gissot, S. 2010, A&A, 520, A29
Zaatri, A., Wöhl, H., Roth, M., Corbard, T., & Brajša, R. 2009, A&A, 504, 589
Zuccarello, F. & Zappalá, R. 2003, Astron. Nachr., 324, 464