A precise measurement of the solar differential rotation by tracing small bright coronal structures in SOHO-EIT images

Results and comparisons for the period 1998–2006^{*}

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ABSTRACT

Aims. We precisely determine the solar rotation velocity during most of the 23rd solar cycle, in the years 1998–2006. We measure the solar differential rotation by tracing small bright coronal structures (SBCS) in SOHO-EIT images.

Methods. The 28.4 nm EIT channel was used and positions of more than 55 000 structures were measured applying an interactive and improved automatic method of data reduction.

Results. We achieve the closest representation of the observational data when all three solar differential rotation parameters are used and obtain the formula $\omega(b) = 14.499(\pm 0.006) - 2.54(\pm 0.06) \sin^2 b - 0.77(\pm 0.09) \sin^4 b$. This result represents the sidereal rotation velocity in deg day^{-1} and is produced by the automatic method applied in 1998–2006. A north-south rotational asymmetry and a rigid component of the solar rotation at high latitudes were found.

Conclusions. A more differential rotation profile of SBCS than of sunspots and sunspot groups was found. The rotation velocity of SBCS is very similar to those obtained by small photospheric magnetic features. The north-south rotational asymmetry of SBCS was interpreted with a model of the relationship between solar rotation and activity. The rigid component of the solar rotation at high latitudes, identifiable only from the results of the automatic method, was related to larger structures mostly identified by that method, in contrast to the interactive method, which detected smaller structures.

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

1. Introduction

Solar rotation is one of the fundamental properties of the Sun as a star and an investigation of the relationship between the solar rotation and activity is an important observational task. Measurements of the solar differential rotation provide an observational constraint on theoretical models of the rotating convection zone and the solar MHD dynamo, which appears to play a decisive role in generating and maintaining a solar magnetic field and the whole activity of the Sun (Stix 2002; Ossendrijver 2003; Rüdiger & Hollerbach 2004; Rozelot & Neiner 2009). Understanding the solar activity cycle, which is driven by a MHD dynamo, remains a key unsolved problem in solar physics, along with, e.g., the heating of the solar corona and solar flares.

In resolving these problems, sunspots have been most often used as tracers, mainly because of the long-term data sets available from various observatories, e.g., Greenwich and Mt. Wilson

(Newton & Nunn 1951; Gilman & Howard 1984; Howard et al. 1984; Balthasar et al. 1986; Howard & Gilman 1986; Zappala & Zuccarello 1991; Pulkkinen & Tuominen 1998; Brajša et al. 2002a; Ruždjak et al. 2004, 2005, in prep.). However, apart from the advantage of long time coverage, sunspots and sunspot groups have serious disadvantages, such as their well-known complex and variable structure, a very pronounced butterfly diagram, and the enormous difference in the number of tracers present on the Sun at maximum and minimum activity.

In the present analysis, we use small bright coronal structures (SBCS) as tracers of the solar rotation determination and in this way some of the above mentioned disadvantages can be avoided. SBCS are localized tracers covering solar latitudes more uniformly than the sunspots, their latitudinal range varies during the cycle much less than for sunspots, and the difference in the number of tracers between activity maximum and minimum is much lower (e.g., Brajša et al. 2005, and references therein). Owing to the absence of ordinary active regions, the discernibility of SBCS during the periods of the activity minimum is even better than at maximum. The SBCS are highly correlated with the coronal bright points discernible in the EUV and soft X-ray spectral

^{*} Tables 3–11 and Figs. 4, 5 are only available in electronic form at <http://www.aanda.org>

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regions. Their most important physical characteristics were summarized by Brajša et al. (2004, 2008b, and references therein).

Positions of SBCS identified and traced in full-disc SOHO-EIT images, acquired during 6 months in the 1998–1999 period, were reduced and analysed for determination of solar rotation and related topics in a series of papers (Brajša et al. 2001b, 2002b, 2004, 2008b; Vršnak et al. 2003). For data reduction, two methods are used: an interactive one and an automatic one. In the present paper, we extend the analysis with the interactive method to two additional months in the year 1999 and apply an improved automatic method to the extensive data set obtained in the years 1998–2006 (data from a total of 93 months). A subset of this data was previously used to compare the sidereal angular rotation velocity of the SBCS and sub-photospheric layers during the declining phase of the solar cycle 23 (Zaatri et al. 2009).

2. The SOHO-EIT data set

The data set consists of several thousand full-disc full-resolution solar filtergrams recorded in the Fe XV line at the wavelength of 28.4 nm with the EIT instrument (Delaboudiniere et al. 1995) onboard the SOHO spacecraft. Images were usually taken every 6 h, i.e., with a regular cadence of 4 images per day, although sometimes there were gaps of 12 h or more between the successive images. All images were preprocessed by correcting defects (e.g., grid, CCD flat field) and the CCD offset. Additional information about the images used and their prereduction were given by Brajša et al. (2001b).

Among the four EIT channels, we chose to use data from the 28.4 nm one since it corresponds to the highest temperature and appears to provide the sharpest image contrast, which is suitable for identifying SBCS. The contamination by the transition region emission (Mg VII, Si VII) is not a serious problem, since the magnetic field lines are anchored to the photosphere.

Measurements were performed in the period 1998–2006 covering most of the 23rd solar cycle. In the years 1998–1999, data from all calendar months were not suitable for the analysis (data from only 9 months were considered), while in the period 2000–2006 data from all calendar months were analysed. In Tables 3–11, the time periods are listed according to the year of observation.

3. The interactive and automatic methods of data reduction

The interactive method of data reduction is based on a visual identification of a particular SBCS that can be used as a tracer. The data reduction programs were written in IDL. All full disc solar images were visually inspected and the SBCS identified in a sequence of images. The main criterion for identifying a SBCS was checking its persistence in consecutive images at approximately the same latitude but shifted in the central meridian distance (*CMD*) according to the elapsed time. The *CMD* values of the identified features were then measured in selected consecutive images and fitted as a function of time (*t*). The correlation coefficient of the function *CMD(t)* was generally very high, implying that the tracers had been correctly identified.

More details about the interactive method, such as distinguishing between different tracer subtypes, tracing times and lifetimes of the features, as well as the intensity and area evolution were described in the papers of Brajša et al. (2001a,b, 2008b) and of Mulec et al. (2007). The interactive method has many advantages that allow detailed studies of SBCS (e.g.,

Vršnak et al. 2003; Mulec et al. 2007; Brajša et al. 2008b), but also some important disadvantages. The main disadvantages are that the method is extremely time consuming and the difficulty in various observers applying the method in exactly the same way.

To avoid these disadvantages and to accelerate the data reduction, an automatic method was developed (Brajša et al. 2001b, 2002b; Wöhl et al. 2001). It relies on the IDL procedure, “Regions Of Interest (ROI) segmentation”, which was initially developed to detect and identify stars and galaxies in deep sky images of galaxy clusters. The ROI parameters that can be preset are the sharpness of the subimages (*s*), their circumference range (*c*), and the intensity range of their brightness (*i*). The following ROI parameters were used: *s* was limited to between 30 and 255 relative units, *c* was in the range from 30 to 80 EIT pixels (80 to 210 arcsec), and *i* was limited between 100 and 600 relative intensity units (Brajša et al. 2002b). The centres of the selected subimages were automatically traced in triplets of consecutive full-disc solar images taken every 6 h and the last image in a triplet was the first one in the next triplet.

In the first phase of the application of the automatic method (Brajša et al. 2002b), the numerically allowed latitudinal variation in the traced feature was 1 deg from one image to the next and all synodic rotation velocities outside the range 7–17 deg day^{−1} were excluded from further analysis. However, it was found that these criteria were not conservative enough, especially for images taken during the high solar activity phases (Brajša et al. 2008c). The automatic method was therefore improved: the allowed change in latitude from one image to the next, to identify the same structure, was reduced from 1 to 0.8 deg, the synodic rotation velocity filter was reduced to 9.5–16.5 deg day^{−1}, and the differential rotation gradient of $-3.0 \times \sin^2 b$, where *b* is solar latitude, was in addition imposed.

In the present work, all data were reduced using the improved automatic method. The data from the first 6 months of the entire observational period (1998–1999; Brajša et al. 2002b) were therefore re-reduced.

4. Results

The measured synodic rotational velocities were transformed into the sidereal ones with the time-dependent procedure taking into account the variable velocity of the Earth and SOHO in their orbits around the Sun (e.g., Roša et al. 1995).

We used the most common representation of the solar differential rotation

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

where ω represents the angular rotation velocity expressed in deg day^{−1}, *b* the heliographic latitude, and *A*, *B*, and *C* the solar rotation parameters. Three different approaches to the fitting procedure were used (e.g., Brajša et al. 1997): in the first one, the parameter *C* = 0; in the second one, all three parameters were used, but generally with *C* ≠ 0; and in the third one, all three parameters were taken into account, but setting *B* = *C*. The third procedure was introduced by Scherrer et al. (1980) to avoid the possibility of crosstalk between the parameters *B* and *C*. In this case, Eq. (1) was transformed to $\omega(b) = y(x) = A + B(x + x^2)$ by performing the substitution $x = \sin^2 b$. We now take $x + x^2 = x'$ leading to $y(x') = A + Bx'$, which is now fitted with the linear least squares method, as usual (e.g., Brajša et al. 1997).

Extreme rotation velocity values, which are regarded as erroneous, were excluded in two steps called filters. In applying the first filter all sidereal rotation velocity values lower than

Fig. 1. Sidereal rotation velocities determined by tracing coronal bright points with the interactive method for 8 selected months during 1998–1999 (see Table 1). The data points excluded by the second filter, as described in text, are shown by crosses. The fitted differential rotation curve using all data points presented here and the error ranges of 2 deg day^{−1} are denoted by dotted lines. The full line indicates the differential rotation curve of the filtered data (stars). It is defined by the differential rotation parameters given in the third line of Table 2.

8 deg day^{−1} and higher than 18 deg day^{−1} were excluded regardless of the tracer’s latitude. The rotation velocity parameters from Eq. (1) were then found for all remaining data points (1st step). To apply the second filter all velocity values differing by $\delta = 2.0$ deg day^{−1} or more from the mean curve were excluded from the data and new parameters were recalculated (2nd step). An example of the application of this two-step velocity filter is presented in Fig. 1 and Table 2. This filtering was applied when data from certain periods (months, years or longer intervals) were combined together. Thus the sum of all used tracers differs slightly when adding monthly numbers and comparing them with final annual sums. A similar result holds when the yearly results are combined to form longer periods.

4.1. The interactive method: 1998–1999

For the case $C = 0$, the differential rotation parameters, obtained by applying the interactive method for 8 months during 1998–1999 are given in Table 1. From these results, a combined data set was composed for the whole interval and the interactive method was applied. The solar differential rotation results for this combined data set are presented in Figs. 1 and 2 and Table 2. In Fig. 2 and Table 2, the differential rotation curves and the solar rotation parameters for all three fitting cases (described earlier) are presented.

The application of the interactive method is extremely time consuming and the results presented here are a combination of efforts of many observers. Most often the data from the same months were analysed by more than just one observer and the selection of individual results, combined and used in the present paper, is based on the monthly values published by Brajša et al. (2001a, 2008a). In the Acknowledgements, the names of all observers who contributed to this effort are listed.

Table 1. Differential rotation parameters A and B from Eq. (1) and their standard errors M in deg day^{−1} for the interactive method.

Year	Month	N	$A \pm M_A$	$B \pm M_B$	Source
1998	6	89	14.62 ± 0.09	-3.05 ± 0.40	1
1998	11	48	14.60 ± 0.13	-3.61 ± 0.47	1
1998	12	175	14.46 ± 0.08	-3.13 ± 0.22	1
1999	3	161	14.70 ± 0.09	-3.47 ± 0.29	1
1999	4	199	14.55 ± 0.07	-2.78 ± 0.36	1
1999	5	250	14.68 ± 0.07	-3.68 ± 0.24	1
1999	10	149	14.67 ± 0.08	-3.08 ± 0.24	2
1999	11	184	14.66 ± 0.09	-3.56 ± 0.23	2

Notes. 1. Brajša et al. (2001a). 2. Brajša et al. (2008a). N – the number of traced structures in each month after applying the two-step velocity filter.

Table 2. Similar to Table 1 for the combined interactive data set from 8 months, 1998–1999.

N	$A \pm M_A$	$B \pm M_B$	$C \pm M_C$	Remark
1333	14.63 ± 0.04	-3.19 ± 0.13	0	1
1325	14.64 ± 0.04	-3.34 ± 0.11	0	2
1253	14.62 ± 0.03	-3.36 ± 0.09	0	3
1253	14.54 ± 0.04	-2.31 ± 0.30	-1.53 ± 0.41	4
1253	14.52 ± 0.03	-1.98 ± 0.05	-1.98 ± 0.05	5

Notes. 1. Unfiltered, $C = 0$. 2. 1st filter, $C = 0$. 3. 2nd filter, $C = 0$. 4. 2nd filter, $C \neq 0$. 5. 2nd filter, $B = C$.

Fig. 2. Mean values of sidereal rotation velocities obtained using the interactive method (the same data set as in Fig. 1). The averaging is performed in 5 deg latitude bins and the error bars indicate the standard errors of the means in each bin. The three lines represent least squares fits to all filtered data as indicated in the legend (see also Table 2).

4.2. The automatic method: 1998–2006

The solar rotation parameters found by the automatic method are presented in Tables 3–11, for the nine years of observations, 1998–2006. We note that in the first two years, 1998 and 1999, not all months were covered, because of either a lack of observations or inadequate data. Later, in the period 2000–2006, in each year all 12 months were covered with observations suitable for further reduction. The results for data from a total of 93 months are therefore presented.

In these tables, the number of structures found per month, the number of triplets used per month, and the average number

Table 12. Similar to Tables 3–11 for the annual data sets, $N_{\text{all}} = 50\,589$.

Year	$N_{\text{s/y}}$	$A \pm M_A$	$B \pm M_B$
1998	874	14.54 ± 0.04	-3.28 ± 0.15
1999	3020	14.52 ± 0.02	-2.84 ± 0.09
2000	7274	14.48 ± 0.01	-3.11 ± 0.05
2001	6872	14.47 ± 0.02	-2.97 ± 0.06
2002	7111	14.46 ± 0.02	-3.02 ± 0.06
2003	9447	14.45 ± 0.01	-2.77 ± 0.05
2004	7586	14.55 ± 0.01	-2.85 ± 0.06
2005	5177	14.64 ± 0.01	-3.11 ± 0.07
2006	3228	14.65 ± 0.02	-2.70 ± 0.11

Table 13. Similar to Table 2 for the combined automatic data set from 93 months, 1998–2006.

N	$A \pm M_A$	$B \pm M_B$	$C \pm M_C$	Remark
54455	14.467 ± 0.006	-3.01 ± 0.03	0	1
50595	14.529 ± 0.005	-3.03 ± 0.02	0	2
50595	14.499 ± 0.006	-2.54 ± 0.06	-0.77 ± 0.09	3
50595	14.451 ± 0.005	-1.84 ± 0.01	-1.84 ± 0.01	4

Notes. 1. 1st filter, $C = 0$. 2. 2nd filter, $C = 0$. 3. 2nd filter, $C \neq 0$. 4. 2nd filter, $B = C$.

of structures per triplet are also given. For each month, two sets of the results were calculated: one for all tracers according to the criteria described above and another for the subsets of selected stable structures.

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 *CMD*. In general, fewer than half of the structures were found to be stable. The difference between the equatorial rotation velocity of all structures and that of the selected stable structures was found to be statistically significant at the 3σ level. The mean of the monthly differences for those two cases is -0.030 ± 0.009 deg day $^{-1}$.

Thus the stable structures exhibit a slightly higher equatorial rotation compared to all structures. This finding is similar to a result published by Hara (2009, Fig. 4) from X-ray bright points observed with Yohkoh/SXT in the years 1994 until 1997. However, in that paper a mean increase in the equatorial rotation velocity by 0.005 deg day $^{-1}$ for an increase of the lifetime by one hour was found, about a factor of 2 larger than our result.

Finally, the results for the nine years under consideration and for all time periods taken together (93 months in those nine years) are given in Tables 12 and 13, respectively. In Table 13, the solar differential rotation parameters are presented after applying the 1st and the 2nd filter, and for the three different fitting procedures.

In Fig. 3, the mean values of sidereal rotation velocities obtained using the automatic method are given for the 5 deg latitude bins. The corresponding error bars indicate the standard errors in the means for each bin. For the three fitting procedures, the solar differential rotation curves are also given. The least squares fits were performed for all filtered data (not only for the mean values).

The error bars are very small, because of the high precision of the measurements and the huge numbers of data points in each 5-deg bin. Therefore, we present separately the 5-deg bin averages and solar differential rotation curves enlarged for the low (0–40 deg) and high (40–90 deg) latitude parts in Figs. 4 and 5, respectively. It is interesting that the application of the fitting

Fig. 3. Similar to Fig. 2 for the automatic method, all data 1998–2006 (see Table 13).**Table 14.** The north-south asymmetry of the solar rotation for the results of the interactive (1998–1999) and the automatic (1998–2006) method. N – the number of traced structures.

N	$A \pm M_A$	$B \pm M_B$	Method
600	14.63 ± 0.04	-3.58 ± 0.14	interactive, north
653	14.62 ± 0.04	-3.18 ± 0.13	interactive, south
25357	14.518 ± 0.007	-3.09 ± 0.03	automatic, north
25242	14.540 ± 0.007	-2.96 ± 0.03	automatic, south

procedure with all three parameters, A – C , allowing $B \neq C$, represents the observational data in the optimal way (Figs. 3–5), due to the excellent latitudinal coverage of the tracers used.

4.3. The north-south asymmetry of the solar rotation

The solar rotation parameters are given separately for the northern and southern solar hemispheres in Table 14. The results for both reduction methods, the interactive and the automatic one, are presented. For the interactive method, the difference in the equatorial rotation velocity between hemispheres (the parameter A) is very small and statistically insignificant. On the other hand, the gradient in the solar rotation (the parameter B) differs between the two solar hemispheres, the difference being statistically significant at the 1σ level. For the automatic method, the difference in the solar rotation parameter A is statistically significant at the 1σ level and the difference in the solar rotation parameter B is statistically significant at the 2σ level. A smaller difference in the equatorial rotation velocity is consistent with the continuity requirement of the rotation velocity. For both methods, the southern solar hemisphere rotates more rapidly, which can also be clearly seen in Figs. 6 and 7, where the results of the interactive and automatic methods are presented, respectively.

5. Discussion

5.1. Comparing results of interactive and automatic methods for data of 1998–1999

A comparison of the results obtained by the interactive and automatic methods was possible for 8 months in the period

Fig. 6. The north-south asymmetry for the interactive method.

Fig. 8. A comparison of the results obtained by the interactive and the automatic method for the 8 selected months during 1998–1999, see also Table 15.

Fig. 7. The north-south asymmetry for the automatic method.

Table 15. A comparison of the results obtained by the interactive and the automatic method (upper and lower parts of the table, respectively) for the 8 selected months during 1998–1999, see also Tables 1 and 2.

N	$A \pm M_A$	$B \pm M_B$	$C \pm M_C$	Remark
1253	14.62 ± 0.03	-3.36 ± 0.09	0	1
1253	14.54 ± 0.04	-2.31 ± 0.30	-1.53 ± 0.41	2
1253	14.52 ± 0.03	-1.98 ± 0.05	-1.98 ± 0.05	3
3473	14.53 ± 0.02	-2.98 ± 0.08	0	4
3473	14.49 ± 0.03	-2.53 ± 0.22	-0.73 ± 0.33	5
3473	14.43 ± 0.02	-1.81 ± 0.05	-1.81 ± 0.05	6

Notes. 1. 2nd filter, $C = 0$, interactive method. 2. 2nd filter, $C \neq 0$, interactive method. 3. 2nd filter, $B = C$, interactive method. 4. 2nd filter, $C = 0$, automatic method. 5. 2nd filter, $C \neq 0$, automatic method. 6. 2nd filter, $B = C$, automatic method.

1998–1999, when both methods were applied. Using the three fitting procedures, the solar differential rotation parameters calculated after the 2nd filter are presented for this case in Table 15. The mean velocity values for 5-deg latitude bins and corresponding differential rotation curves for the interactive and automatic

methods are given in Fig. 8. For the interactive method, the equatorial rotation velocity and the gradient in the differential rotation are slightly larger, in comparison to the automatic method. This finding agrees with the more rigid solar rotation component found by the automatic method, which was obtained in a preliminary form by Brajša et al. (2002b) for a smaller data set and an earlier version of the automatic method.

5.2. A comparison with other data

We present a comparison of the differential rotation parameters calculated by tracing SBCS in the present work with the results obtained by other methods and tracers in Table 16. Apart from the coronal bright points and similar tracers identified in the EUV and X-ray parts of the spectrum, the results obtained by tracing sunspots, $H\alpha$ filaments, and different radio sources observed at mm wavelengths are compared with the cross-correlation of magnetic structures and measurements of Doppler shifts.

An unusual disagreement is found in Table 16, in addition to the well-known observational findings that structures consisting of concentrated magnetic fields, such as sunspots, have a more rapid rotation velocity than the surrounding plasma measured by Doppler shifts and that large-scale coronal tracers have a rigid component in their rotation. Kariyappa (2008) and Hara (2009) both measured the rotation velocity of coronal bright points in Yohkoh/SXT images during mostly overlapping time periods. However, the rotation results, especially at the solar equator, differ significantly (lines 3 and 4 in Table 16).

It is interesting that the equatorial rotation velocity of coronal bright points taken from the literature (the rotation parameter A , lines 1–8 in Table 16) vary across a wide range from $14.19 \text{ deg day}^{-1}$ to $17.6 \text{ deg day}^{-1}$. The same parameter for the SBCS, which partly corresponds to the coronal bright points, were found to be in a much narrower range between $14.499 \text{ deg day}^{-1}$ and $14.62 \text{ deg day}^{-1}$ (lines 9–17 in Table 16). At present, we have no explanation for this discrepancy, besides that in this work we used a large, homogeneous data set, leading to more common rotation values at the solar equator.

Table 16. A comparison of differential rotation parameters A – C from Eq. (1) for SBCS (Tables 13 and 15) with other results. R – remark.

Tracer/method	Time	$A \pm M_A$	$B \pm M_B$	$C \pm M_C$	Source	R
Coronal bright points	1967	14.65 ± 0.2			Dupree & Henze (1972)	1
Coronal bright points	1973	14.6 ± 0.3			Golub et al. (1974)	2
Coronal bright points	1992–2001	17.6 ± 0.4	-4.5 ± 1.1		Kariyappa (2008)	3
Coronal bright points	1994–1997	14.39 ± 0.01	-1.91 ± 0.10	-2.45 ± 0.17	Hara (2009)	4
Coronal bright points	1996	14.34 ± 0.03	-1.3 ± 0.3	-2.3 ± 0.5	Karachik et al. (2006)	5
Coronal bright points	1998–1999	14.454 ± 0.027	-2.22 ± 0.07	-2.22 ± 0.07	Brajša et al. (2004)	6
Coronal bright points	2005	16.0 ± 0.1	-0.7 ± 1.3	-4.9 ± 1.9	Karachik et al. (2006)	7
Coronal bright points	2007	14.19 ± 0.17	-4.2 ± 0.8		Kariyappa (2008)	8
SBCS	1998–1999	14.62 ± 0.03	-3.36 ± 0.09		present work, Table 15, interactive method	9
SBCS	1998–1999	14.54 ± 0.04	-2.31 ± 0.30	-1.53 ± 0.41	present work, Table 15, interactive method	10
SBCS	1998–1999	14.52 ± 0.03	-1.98 ± 0.05	-1.98 ± 0.05	present work, Table 15, interactive method	11
SBCS	1998–1999	14.53 ± 0.02	-2.98 ± 0.08		present work, Table 15, automatic method	12
SBCS	1998–1999	14.49 ± 0.03	-2.53 ± 0.22	-0.73 ± 0.33	present work, Table 15, automatic method	13
SBCS	1998–1999	14.43 ± 0.02	-1.81 ± 0.05	-1.81 ± 0.05	present work, Table 15, automatic method	14
SBCS	1998–2006	14.529 ± 0.005	-3.03 ± 0.02		present work, Table 13, automatic method	15
SBCS	1998–2006	14.499 ± 0.006	-2.54 ± 0.06	-0.77 ± 0.09	present work, Table 13, automatic method	16
SBCS	1998–2006	14.451 ± 0.005	-1.84 ± 0.01	-1.84 ± 0.01	present work, Table 13, automatic method	17
Sunspots	1853–1996	14.531 ± 0.003	-2.75 ± 0.05		Pulkkinen & Tuominen (1998)	18
Sunspots	1874–1976	14.551 ± 0.006	-2.87 ± 0.06		Balthasar et al. (1986)	19
Sunspots	1874–1976	14.528 ± 0.006	-2.77 ± 0.05		Ruždjak et al. (in prep.)	20
Sunspots	1874–2008	14.500 ± 0.005	-2.71 ± 0.05		Ruždjak et al. (in prep.)	21
Sunspots	1880–1976	14.37 ± 0.01	-2.59 ± 0.16		Brajša et al. (2002a)	22
Sunspots	1921–1982	14.522 ± 0.004	-2.84 ± 0.04		Howard et al. (1984)	23
Sunspots	1921–1982	14.393 ± 0.010	-2.95 ± 0.09		Howard et al. (1984)	24
Sunspots	1977–2008	14.43 ± 0.01	-2.51 ± 0.09		Ruždjak et al. (in prep.)	25
H α filaments	1919–1929	14.48	-2.16		d’Azambuja & d’Azambuja (1948)	26
H α filaments	1972–1973	14.45	-1.43		Adams & Tang (1977)	27
H α filaments	1972–1987	14.45 ± 0.15	-0.11 ± 0.90	-3.69 ± 0.90	Brajša et al. (1991)	28
HTRs	1979–1991	14.91 ± 0.10	-2.56 ± 0.84		Brajša et al. (2009)	29
LTRs	1979–1991	14.44 ± 0.06	-1.91 ± 0.26		Brajša et al. (2009)	30
LTRs	1979–1991	13.92 ± 0.06	-4.09 ± 0.34		Brajša et al. (2009)	31
Magnetic	1967–1980	14.307 ± 0.005	-1.98 ± 0.06	-2.15 ± 0.11	Snodgrass (1983)	32
Magnetic	1975–1991	14.42 ± 0.02	-2.00 ± 0.13	-2.09 ± 0.15	Komm et al. (1993)	33
Magnetic	1996–1997	14.50 ± 0.03	-1.72 ± 0.22	-2.31 ± 0.30	Pevtsov & Latushko (2000)	34
Magnetic	1997	14.00 ± 0.54	-2.24 ± 1.22	-1.78 ± 0.79	Deng et al. (1999)	35
Doppler	1966–1968	13.76	-1.74	-2.19	Howard & Harvey (1970)	36
Doppler	1967–1984	14.05	-1.49	-2.61	Snodgrass (1984)	37
Doppler	1978	13.96 ± 0.10			Perez Garde et al. (1981)	38
Doppler	1981–1982	13.99 ± 0.06			Küveler & Wöhl (1983)	39
Doppler	1983–1986	13.92 ± 0.12			Lustig & Wöhl (1989)	40

Notes. 1. OSO-4, Mg X spectroheliograms; 2. Skylab, soft X-rays; 3. Yohkoh/SXT; 4. Yohkoh/SXT; 5. SOHO-EIT, 19.5 nm; 6. interactive method, with height correction, 6 months; 7. SOHO-EIT, 19.5 nm; 8. Hinode/XRT; 9. 8 months, $C = 0$; 10. 8 months, $C \neq 0$; 11. 8 months, $B = C$; 12. 8 months, $C = 0$; 13. 8 months, $C \neq 0$; 14. 8 months, $B = C$; 15. 93 months, $C = 0$; 16. 93 months, $C \neq 0$; 17. 93 months, $B = C$; 18. Extended Greenwich, sunspots & sunspot groups; 19. Greenwich, sunspot groups; 20. Greenwich, $CMD < 58$ deg, ($8 < \omega < 19$) deg day $^{-1}$; 21. Greenwich & SOON/USAF/NOAA, $CMD < 58$ deg, ($8 < \omega < 19$) deg day $^{-1}$; 22. Greenwich, only stable recurrent sunspot groups; 23. Mt. Wilson, sunspots; 24. Mt. Wilson, sunspot groups; 25. SOON/USAF/NOAA, $CMD < 58$ deg, ($8 < \omega < 19$) deg day $^{-1}$; 26. Meudon; 27. Big Bear, with height correction; 28. Big Bear & Kanzelhöhe, with height correction; 29. High brightness temperature regions (HTRs), 8 mm, Metsähovi, without height correction; 30. Low brightness temperature regions (LTRs), 8 mm, Metsähovi, without height correction; 31. Low brightness temperature regions (LTRs), 8 mm, Metsähovi, with height correction; 32. Mt. Wilson, photospheric magnetic fields; 33. Kitt Peak, photospheric magnetic fields; 34. SOHO-MDI, large-scale photospheric magnetic field; 35. Huairou/Beijing, photospheric high-latitude magnetic fields; 36. Mt. Wilson, photosphere, spectroscopic; 37. Mt. Wilson, photosphere, spectroscopic; 38. Locarno, photosphere, spectroscopic; 39. Locarno, photosphere, spectroscopic; 40. Capri, photosphere, spectroscopic.

When only the first two parameters from Eq. (1) are taken into account, the SBCS parameters analysed in this work are similar to (the parameter A) or larger than (the parameter B) the corresponding values for sunspots and sunspot groups. For the parameter B , the absolute values are considered, implying that SBCS have a more differential rotation profile than sunspots. On the other hand, when all three parameters from Eq. (1) are considered, there is general agreement with the results of the photospheric magnetic fields. This is a consequence of the magnetic nature of SBCS, and the disagreement with sunspots might be

caused by the superior latitudinal coverage of SBCS compared to sunspots.

5.3. The north-south asymmetry of the solar rotation compared with the solar activity status

A more rapid yet weaker differential solar rotation profile was found for the southern solar hemisphere during the subinterval (1998–1999) when the interactive method was applied and

during the whole observing interval (1998–2006) when the data were reduced with the automatic method. For the automatic method, the north-south rotational asymmetry is statistically significant at the 2σ level (Sect. 4.3., Table 14, Figs. 6 and 7). The first time interval (1998–1999) coincides with the ascending phase of the solar cycle No. 23, while the whole time period (1998–2006) embraces most of the activity maximum of the same solar cycle.

The observed north-south rotational asymmetry can be interpreted in the framework of a model of interdependence of solar rotation and activity, taking into account the balance between Reynolds and Maxwell stresses (Brun 2004; Brun et al. 2004; Brajša et al. 2006, 2007). During most of the 23rd solar cycle, the southern solar hemisphere was more active (Temmer et al. 2006, their Fig. 6 and Table 2). This is also true for the first part of the ascending phase (1998–1999) of that solar cycle. Stronger magnetic activity in the southern solar hemisphere therefore on average suppresses, to some extent, the differential rotation. Maxwell stresses, related to the magnetic field, oppose the usual Reynolds stresses, which are the main cause of the differential character of the solar rotation.

5.4. On the rigid component of the solar rotation at high latitudes

The rotation results obtained with the automatic method of data reduction detect a rigid rotational component at high solar latitudes, roughly between 60 and 80 deg. This can be clearly seen in Figs. 3, 5, and 7. It is interesting that this rigid component is even more pronounced in the more active, southern solar hemisphere (Fig. 7). On the other hand, nothing like that was found in the results of the interactive method (Figs. 2, 6, and 8), apart from a small more rapidly rotational component at heliographic latitudes between 50 and 60 deg, but only in the southern solar hemisphere (Fig. 6). This rigid component of the solar rotation found for the automatic method is consistent with the difference between the gradients of the solar rotation, i.e., the parameter B , for the two methods. The difference is statistically significant at the 2σ level, the rotation determined by the automatic method being more rigid (a lower absolute value of the rotation parameter B) as can be seen in Table 15.

A similar spin-up of the solar rotation, i.e., a rigid rotational component at high solar latitudes, determined by magnetic field patterns was reported by Sheeley et al. (1987) and Stenflo (1989a,b). In both cases, the solar magnetic field patterns were autocorrelated with the time lag of one solar rotation. However, this rigid component in the solar rotation was not present when the magnetic field patterns were cross-correlated in daily magnetograms separated by a couple of days (Snodgrass 1983) and in that case a typical, continuously decreasing rotation velocity profile with latitude was found.

To interpret this curious behaviour of solar magnetic field patterns, two models were proposed. Sheeley et al. (1987) proposed magnetic flux-transport models, in which supergranular diffusion and meridional motions distribute magnetic elements across the solar surface. On the other hand, Stenflo (1989a) proposed a continual replacement of evanescent surface magnetic flux by sources deep inside the convection zone. However, as pointed out by Snodgrass (1992), in both models the long-lived and the short-lived magnetic structures have different rotation properties because of different correlation procedures applied. Snodgrass (1992) claims that this difference is not due to the difference in the time lag, but is a result of a selection effect, in particular of spatial resolution. Snodgrass (1992) concludes

that the autocorrelation method identifies large-scale structures, while the cross-correlation on short timescales finds small-scale features.

Finally, we can apply this line of reasoning to our results. It is well known that SBCS correspond to magnetic regions of different length scales. The rotational behaviour of SBCS is also consistent with this finding (e.g., Sect. 5.2. in the present paper). In one of our earlier works (Brajša et al. 2002b), we reported that the automatic method chooses mostly small active regions and parts of larger, ordinary active regions, while the interactive method identifies predominantly point-like structures and small loops, i.e., coronal bright points on a smaller spatial scale. We can therefore interpret the observed spin-up of the solar rotation, found by the automatic method at high latitudes, with this selection effect. Applying the automatic method, larger objects are identified and traced, which each have a rigid rotation component.

6. Summary and conclusions

We have precisely determined the solar differential rotation by tracing small bright coronal structures (SBCS) in SOHO-EIT images during the period 1998–2006. The 28.4 nm EIT channel was used and positions of more than 55 000 structures have been measured. Both interactive and the automatic methods of data reduction were applied and their results were compared for similar time periods. The closest representation of the observational data has been obtained by using all three solar differential rotation parameters from Eq. (1) and allowing $B \neq C$. This has been possible because of the very comprehensive latitudinal coverage of the tracers used.

The results imply a more differential rotation profile of SBCS than of sunspots and sunspot groups. The rotation velocity of SBCS is very similar to those obtained for small photospheric magnetic features. This is unsurprising, since SBCS correspond mostly to small bipolar magnetic structures.

A north-south rotational asymmetry of SBCS was found and interpreted in terms of a model of the relationship between solar rotation and activity. Finally, a rigid component of the solar rotation of SBCS discovered at high latitudes by applying the automatic method, can be interpreted as the result of a selection effect. The automatic method has a greater tendency to identify larger structures, while the interactive method identifies mostly smaller features and the two types of SBCS have different rotational properties at high latitudes.

In a continuation of the present work (Jurdana-Šepić et al., in prep.), we will investigate the relationship between the parameters of the solar rotation and the solar activity using the monthly and yearly values of the solar rotation parameters presented in this work. In this way, we would like to complement some earlier studies of the coronal rotation variation (e.g., Nash et al. 1988; Rybák 1994, 2000; Altrock 2003; Brajša et al. 2007; Gissot 2009, and references therein) and to compare those results for coronal structures with those obtained using other tracers and methods in different time periods (Table 16 in the present paper).

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Table 3. Differential rotation parameters A and B from Eq. (1) and their standard errors M in deg day^{-1} obtained applying the automatic method to monthly data sets for the year 1998.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
6	290	38	7.6	14.64 ± 0.07	-3.89 ± 0.30
6st	143			14.78 ± 0.10	-4.44 ± 0.43
11	211	28	7.5	14.46 ± 0.08	-3.14 ± 0.35
11st	90			14.25 ± 0.12	-2.77 ± 0.73
12	372	58	6.4	14.53 ± 0.06	-3.03 ± 0.20
12st	202			14.60 ± 0.07	-2.99 ± 0.28

Notes. $N_{s/m}$ = the number of structures found per month; $N_{t/m}$ = the number of triplets used per month; $N_{s/t}$ = the average number of structures per triplet.

The results after applying the two-step velocity filter are given. The number of structures found in this year, $N_{s/y} = 873$. The index “st” after the calendar month indicates the subset of selected stable structures.

Table 4. Similar to Table 3 for the year 1999, $N_{s/y} = 3014$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
3	442	71	6.2	14.66 ± 0.05	-3.35 ± 0.22
3st	219			14.62 ± 0.08	-3.26 ± 0.32
4	714	109	6.6	14.56 ± 0.04	-2.79 ± 0.20
4st	436			14.56 ± 0.05	-2.70 ± 0.27
5	433	72	6.0	14.37 ± 0.06	-2.38 ± 0.24
5st	244			14.26 ± 0.08	-1.52 ± 0.34
10	594	89	6.7	14.48 ± 0.05	-2.87 ± 0.20
10st	288			14.45 ± 0.07	-2.97 ± 0.28
11	414	79	5.2	14.48 ± 0.06	-2.76 ± 0.22
11st	205			14.49 ± 0.09	-2.88 ± 0.31
12	417	82	5.1	14.49 ± 0.06	-2.75 ± 0.20
12st	204			14.45 ± 0.09	-2.55 ± 0.27

Table 5. Similar to Table 3 for the year 2000, $N_{s/y} = 7254$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	621	116	5.4	14.56 ± 0.05	-3.26 ± 0.21
1st	284			14.48 ± 0.08	-2.96 ± 0.33
2	508	101	5.0	14.63 ± 0.06	-3.39 ± 0.24
2st	225			14.65 ± 0.09	-2.85 ± 0.37
3	464	105	4.4	14.47 ± 0.06	-2.78 ± 0.21
3st	212			14.39 ± 0.08	-2.41 ± 0.34
4	613	117	5.2	14.48 ± 0.05	-3.40 ± 0.18
4st	276			14.50 ± 0.07	-3.37 ± 0.26
5	757	118	6.4	14.54 ± 0.04	-2.93 ± 0.17
5st	333			14.57 ± 0.06	-2.84 ± 0.25
6	614	95	6.5	14.53 ± 0.05	-3.17 ± 0.17
6st	281			14.59 ± 0.08	-3.16 ± 0.23
7	414	108	3.8	14.45 ± 0.06	-3.33 ± 0.23
7st	166			14.52 ± 0.10	-3.03 ± 0.34
8	821	121	6.8	14.25 ± 0.04	-2.63 ± 0.15
8st	402			14.25 ± 0.06	-2.52 ± 0.20
9	545	102	5.3	14.37 ± 0.06	-2.94 ± 0.19
9st	246			14.37 ± 0.08	-2.43 ± 0.30
10	566	116	4.9	14.51 ± 0.05	-3.14 ± 0.17
10st	227			14.70 ± 0.08	-3.50 ± 0.25
11	557	99	5.6	14.50 ± 0.05	-2.96 ± 0.19
11st	232			14.56 ± 0.08	-3.28 ± 0.32
12	774	116	6.7	14.56 ± 0.05	-3.47 ± 0.17
12st	363			14.68 ± 0.07	-3.87 ± 0.25

Table 6. Similar to Table 3 for the year 2001, $N_{s/y} = 6882$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	813	108	7.5	14.46 ± 0.05	-2.97 ± 0.20
1st	340			14.49 ± 0.07	-2.89 ± 0.28
2	717	90	8.0	14.30 ± 0.05	-2.29 ± 0.21
2st	297			14.26 ± 0.08	-2.00 ± 0.31
3	823	122	6.7	14.40 ± 0.04	-2.91 ± 0.16
3st	412			14.48 ± 0.06	-3.15 ± 0.21
4	559	88	6.4	14.42 ± 0.05	-2.67 ± 0.22
4st	220			14.50 ± 0.09	-2.60 ± 0.35
5	494	67	7.4	14.53 ± 0.06	-2.79 ± 0.21
5st	245			14.48 ± 0.08	-2.40 ± 0.29
6	528	107	4.9	14.55 ± 0.05	-3.43 ± 0.19
6st	225			14.57 ± 0.08	-3.58 ± 0.31
7	779	118	6.6	14.48 ± 0.04	-2.76 ± 0.16
7st	334			14.53 ± 0.06	-2.74 ± 0.23
8	655	98	6.7	14.45 ± 0.05	-2.79 ± 0.18
8st	311			14.55 ± 0.07	-3.12 ± 0.27
9	366	88	4.2	14.55 ± 0.07	-3.34 ± 0.22
9st	164			14.78 ± 0.10	-3.85 ± 0.27
10	432	117	3.7	14.57 ± 0.06	-3.47 ± 0.19
10st	161			14.61 ± 0.10	-3.52 ± 0.28
11	275	77	3.6	14.55 ± 0.08	-3.23 ± 0.25
11st	82			14.69 ± 0.13	-3.88 ± 0.43
12	441	117	3.8	14.45 ± 0.06	-3.06 ± 0.21
12st	173			14.40 ± 0.10	-2.95 ± 0.29

Table 7. Similar to Table 3 for the year 2002, $N_{s/y} = 7123$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	311	108	2.9	14.75 ± 0.08	-3.76 ± 0.23
1st	114			14.83 ± 0.11	-3.62 ± 0.32
2	378	98	3.9	14.44 ± 0.07	-2.92 ± 0.21
2st	145			14.62 ± 0.12	-2.67 ± 0.33
3	568	110	5.2	14.18 ± 0.06	-2.43 ± 0.22
3st	209			14.25 ± 0.10	-2.66 ± 0.31
4	408	97	4.2	14.64 ± 0.07	-3.94 ± 0.24
4st	147			14.77 ± 0.14	-4.47 ± 0.47
5	614	122	5.0	14.40 ± 0.05	-2.80 ± 0.19
5st	284			14.40 ± 0.08	-2.74 ± 0.27
6	537	98	5.5	14.44 ± 0.05	-2.95 ± 0.20
6st	234			14.47 ± 0.08	-2.79 ± 0.31
7	636	114	5.6	14.54 ± 0.05	-2.97 ± 0.19
7st	288			14.59 ± 0.07	-2.90 ± 0.25
8	747	113	6.6	14.35 ± 0.05	-2.95 ± 0.19
8st	295			14.38 ± 0.08	-2.27 ± 0.35
9	627	106	5.9	14.59 ± 0.05	-3.35 ± 0.17
9st	300			14.65 ± 0.07	-3.29 ± 0.23
10	861	119	7.2	14.40 ± 0.04	-2.69 ± 0.17
10st	393			14.52 ± 0.07	-2.47 ± 0.26
11	600	101	5.9	14.45 ± 0.05	-2.88 ± 0.19
11st	255			14.40 ± 0.07	-2.76 ± 0.28
12	836	119	7.0	14.52 ± 0.04	-3.25 ± 0.17
12st	390			14.71 ± 0.06	-3.83 ± 0.26

Table 8. Similar to Table 3 for the year 2003, $N_{s/y} = 9450$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	686	112	6.1	14.41 ± 0.05	-2.32 ± 0.24
1st	356			14.39 ± 0.06	-1.82 ± 0.35
2	864	95	9.1	14.44 ± 0.04	-2.66 ± 0.18
2st	431			14.51 ± 0.06	-2.51 ± 0.26
3	1103	117	9.4	14.36 ± 0.04	-2.51 ± 0.14
3st	471			14.44 ± 0.05	-2.64 ± 0.20
4	748	97	7.7	14.44 ± 0.04	-3.41 ± 0.18
4st	325			14.47 ± 0.07	-3.16 ± 0.28
5	1040	118	8.8	14.38 ± 0.03	-2.32 ± 0.15
5st	532			14.40 ± 0.05	-2.10 ± 0.20
6	729	81	9.0	14.43 ± 0.04	-2.86 ± 0.19
6st	316			14.58 ± 0.06	-3.27 ± 0.27
7	506	72	7.0	14.58 ± 0.06	-3.15 ± 0.22
7st	263			14.56 ± 0.08	-3.07 ± 0.31
8	735	106	6.9	14.54 ± 0.04	-2.62 ± 0.19
8st	328			14.65 ± 0.06	-2.91 ± 0.28
9	677	84	8.1	14.51 ± 0.04	-3.05 ± 0.22
9st	316			14.64 ± 0.06	-2.75 ± 0.32
10	734	90	8.2	14.64 ± 0.04	-3.42 ± 0.18
10st	358			14.63 ± 0.06	-3.25 ± 0.25
11	914	107	8.5	14.51 ± 0.04	-2.78 ± 0.17
11st	428			14.61 ± 0.05	-2.91 ± 0.25
12	714	100	7.1	14.36 ± 0.04	-2.37 ± 0.18
12st	358			14.37 ± 0.06	-2.19 ± 0.27

Table 9. Similar to Table 3 for the year 2004, $N_{s/y} = 7700$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	618	97	6.4	14.57 ± 0.04	-2.75 ± 0.20
1st	335			14.54 ± 0.05	-2.05 ± 0.27
2	807	112	7.2	14.54 ± 0.04	-3.02 ± 0.17
2st	416			14.66 ± 0.05	-3.27 ± 0.21
3	620	67	9.3	14.54 ± 0.05	-2.91 ± 0.21
3st	335			14.70 ± 0.06	-2.82 ± 0.26
4	576	76	7.6	14.50 ± 0.05	-2.51 ± 0.21
4st	272			14.48 ± 0.07	-2.37 ± 0.30
5	939	120	7.8	14.53 ± 0.04	-2.80 ± 0.18
5st	491			14.52 ± 0.05	-2.29 ± 0.28
6	338	40	8.5	14.59 ± 0.06	-3.29 ± 0.28
6st	157			14.35 ± 0.10	-0.47 ± 0.73
7	737	105	7.0	14.46 ± 0.04	-2.26 ± 0.18
7st	429			14.44 ± 0.05	-2.26 ± 0.22
8	784	118	6.6	14.49 ± 0.04	-2.57 ± 0.18
8st	459			14.51 ± 0.05	-2.44 ± 0.23
9	262	39	6.7	14.62 ± 0.07	-3.35 ± 0.30
9st	125			14.52 ± 0.09	-3.25 ± 0.35
10	919	108	8.5	14.69 ± 0.04	-3.68 ± 0.16
10st	463			14.66 ± 0.05	-3.82 ± 0.20
11	798	117	6.8	14.56 ± 0.04	-2.76 ± 0.18
11st	424			14.60 ± 0.06	-2.83 ± 0.24
12	302	47	6.4	14.62 ± 0.06	-2.51 ± 0.33
12st	142			14.69 ± 0.09	-2.36 ± 0.57

Table 10. Similar to Table 3 for the year 2005, $N_{s/y} = 5162$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	666	104	6.4	14.52 ± 0.04	-2.61 ± 0.19
1st	344			14.64 ± 0.06	-2.90 ± 0.29
2	693	101	6.8	14.63 ± 0.04	-3.30 ± 0.19
2st	341			14.68 ± 0.06	-3.25 ± 0.30
3	332	40	8.3	14.53 ± 0.06	-3.64 ± 0.25
3st	134			14.51 ± 0.09	-3.21 ± 0.44
4	1007	117	8.6	14.57 ± 0.03	-2.73 ± 0.16
4st	550			14.61 ± 0.05	-2.57 ± 0.21
5	476	111	4.3	14.68 ± 0.04	-2.91 ± 0.24
5st	274			14.63 ± 0.05	-2.08 ± 0.33
6	149	44	3.4	14.78 ± 0.07	-4.88 ± 0.56
6st	65			14.69 ± 0.11	-4.16 ± 1.26
7	445	116	3.8	14.67 ± 0.05	-2.35 ± 0.38
7st	261			14.60 ± 0.07	-2.11 ± 0.70
8	448	116	3.9	14.72 ± 0.04	-3.37 ± 0.29
8st	252			14.84 ± 0.06	-3.45 ± 0.45
9	141	30	4.7	14.56 ± 0.08	-2.39 ± 0.66
9st	60			14.62 ± 0.13	-3.16 ± 0.77
10	303	110	2.8	14.68 ± 0.05	-2.85 ± 0.28
10st	183			14.63 ± 0.07	-2.37 ± 0.41
11	343	111	3.1	14.73 ± 0.05	-4.25 ± 0.42
11st	196			14.78 ± 0.07	-4.23 ± 0.81
12	159	57	2.8	14.80 ± 0.08	-2.94 ± 0.71
12st	61			14.61 ± 0.14	-0.52 ± 1.95

Table 11. Similar to Table 3 for the year 2006, $N_{s/y} = 3221$.

Month	$N_{s/m}$	$N_{t/m}$	$N_{s/t}$	$A \pm M_A$	$B \pm M_B$
1	411	104	4.0	14.69 ± 0.05	-2.79 ± 0.34
1st	229			14.67 ± 0.06	-2.44 ± 0.37
2	289	94	3.1	14.54 ± 0.05	-2.79 ± 0.31
2st	160			14.51 ± 0.07	-2.95 ± 0.39
3	128	54	2.4	14.61 ± 0.08	-1.93 ± 0.43
3st	52			14.64 ± 0.12	-1.72 ± 0.53
4	313	115	2.7	14.71 ± 0.06	-2.90 ± 0.42
4st	167			14.78 ± 0.08	-3.12 ± 0.56
5	367	96	3.8	14.60 ± 0.05	-2.25 ± 0.37
5st	205			14.65 ± 0.07	-2.71 ± 0.58
6	232	53	4.4	14.57 ± 0.06	-2.50 ± 0.47
6st	129			14.58 ± 0.08	-2.19 ± 0.67
7	374	117	3.2	14.69 ± 0.05	-2.74 ± 0.28
7st	212			14.73 ± 0.06	-2.82 ± 0.35
8	179	67	2.7	14.65 ± 0.07	-2.58 ± 0.44
8st	91			14.85 ± 0.09	-4.80 ± 0.91
9	126	43	2.9	14.83 ± 0.08	-3.73 ± 0.54
9st	52			14.79 ± 0.14	-2.08 ± 1.31
10	332	112	3.0	14.64 ± 0.05	-3.40 ± 0.35
10st	161			14.67 ± 0.07	-3.64 ± 0.52
11	257	83	3.1	14.82 ± 0.06	-3.01 ± 0.35
11st	135			14.86 ± 0.07	-3.20 ± 0.46
12	218	69	3.2	14.57 ± 0.06	-2.22 ± 0.40
12st	115			14.68 ± 0.09	-2.06 ± 0.52

Fig. 4. The low-latitude part of Fig. 3.

Fig. 5. The high-latitude part of Fig. 3.