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Letter to the Editor

Solar surface rotation: N-S asymmetry and recent speed-up

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ABSTRACT

Context. The relation between solar surface rotation and sunspot activity is still not fully resolved. The sunspot activity has been significantly reduced in solar cycle 24, and several solar activity indices and flux measurements experienced unprecedentedly low levels during the last solar minimum.
Aims. We aim to reveal the momentary variation of solar surface rotation, especially during the recent years of reduced solar activity.
Methods. We used a dynamic, differentially rotating reference system to determine the best-fit annual values of the differential rotation parameters of active longitudes of solar X-ray flares and sunspots in 1977–2012.
Results. The evolution of the rotation of solar active longitudes obtained from observing X-ray flares and sunspots is very similar. Both hemispheres have increased their rotation rate since the late 1990s, with the southern hemisphere rotating slightly faster than the north. In the 1980s, rotation in the northern hemisphere was considerably faster, but it experienced a major decrease in the early 1990s. On the other hand, little change was found in the rotation of the southern hemisphere during these decades. This led to a positive asymmetry in the north-south rotation rate in the early part of the time interval studied.
Conclusions. The rotation of both hemispheres has been speeding up at roughly the same rate since the late 1990s, with the southern hemisphere rotating slightly faster than the northern hemisphere. This period coincides with the start of a significant weakening of the solar activity, as observed in sunspots and several other solar, interplanetary, and geomagnetic parameters.

Key words. Sun: activity – Sun: flares – Sun: rotation – sunspots – Sun: evolution

1. Introduction

During the last solar minimum, which was exceptionally long, several solar activity indices and flux measurements reached unusually low values. The activity level in the current cycle 24 is significantly lower than in the past few solar cycles. The remarkably long and deep solar minimum and the weak cycle 24 have caused intensive attention in the solar and space physics community (Jian et al. 2011; Clette & Lefèvre 2012; Wang et al. 2009; Solomon et al. 2010, 2011; Cliver & Ling 2011).

Here we study the changes in solar surface rotation during the past few decades, including the period of activity weakening, by analyzing the rotation of solar active longitudes. Sunspots and other forms of solar magnetic activity are not uniformly distributed in solar longitude, but are centered around certain longitude bands, which are called active longitudes (ALs). Active longitudes have been observed in several studies using different data bases (Temmer et al. 2006; Chen et al. 2011; Li 2011; Muraközy & Ludmány 2012).

A few recent studies (Berdyugina & Usoskin 2003; Usoskin et al. 2005; Zhang et al. 2011) that used a dynamic, differentially rotating coordinate system have been able to show convincingly that the ALs are persistent structures that are sustained for several tens of years, and possibly even longer. A large part of various forms of solar activity are produced by regions that are themselves rotating differentially. The persistence of ALs is clearly demonstrated in this reference frame, and the level of longitudinal asymmetry increases significantly more than in any rigidly rotating system. Moreover, the stronger forms of solar activity are more asymmetrically distributed than the weaker, more diffusive forms (Zhang et al. 2011).

Solar surface rotation has been studied for a long time using various forms of solar activity (Balthasar & Wöhl 1980; Pulkkinen & Tuominen 1998; Wang et al. 1988; Brajša et al. 2000). The secular deceleration of solar rotation was suggested by Brajša et al. (2006) and Li et al. (2014), while a secular acceleration trend was found by Heristchi & Mouradian (2009). A north-south (N-S) asymmetry in solar rotation was reported by many authors, for instance, by Brajša et al. (2000, 2002), who separately traced low-temperature regions and coronal bright points, and by Javaraiah & Komm (1999), who used sunspot groups as tracers.

It was found very recently by studying the rotation of ALs of sunspots for the past twelve solar cycles that the long-term evolution of the solar surface rotation has a quasi-periodicity of about 80–90 years (Zhang et al. 2013, Paper I). The rotation was found to be N-S asymmetric during most of this time period, as also confirmed by Suzuki (2014). The level of non-axisymmetry was found to increase when using shorter fit lengths in Paper I. However, very short interval fits of a few solar rotations lead to losing the continuous evolution of the rotational phase and thereby cause a larger uncertainty when determining the rotation parameters. A three-year fit interval has been found to be the best-fit length for a satisfactory representation and continuous evolution.

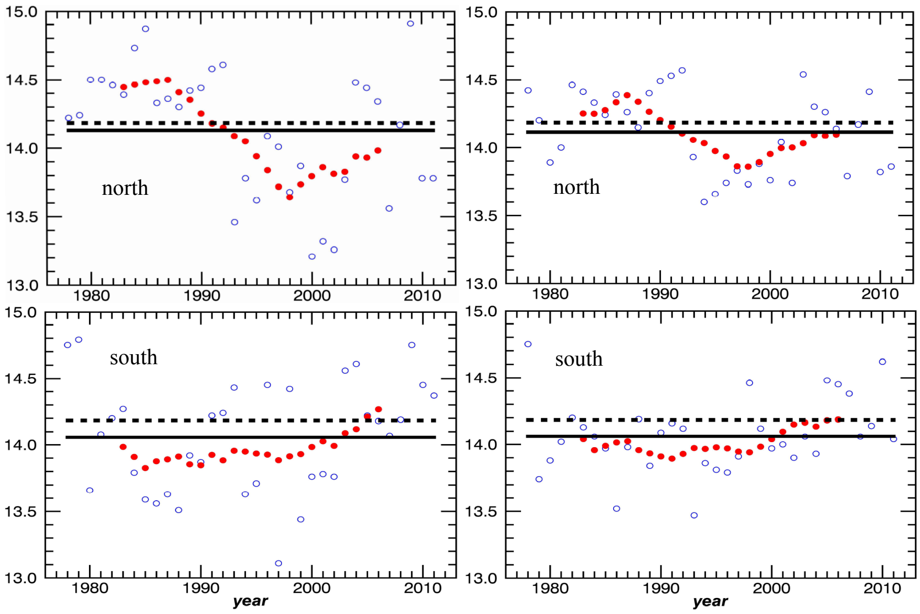

Fig. 1. *Left-hand panels*: yearly values of Ω_{17} in units of deg/day in the north (*top*) and south (*bottom*) for X-ray flares. Open circles stand for the yearly best-fit values, filled circles demonstrate the 11-point running mean values. The solid horizontal line denotes the average Ω_{17} over the entire study period, the dashed line the sidereal Carrington rotation rate. *Right-hand panels*: the same as in the *left-hand panels*, but for sunspots.

Here we use solar X-ray flares as tracers to study the rotation parameters of the sun for 1977–2012. To compare the results of flares with those of sunspots, we also extended the analysis of sunspots to the recent years. We present the yearly rotation rates at the average latitude of flares and of sunspots.

2. Data and analysis method

We studied solar X-ray flares of class-B and higher observed by the NOAA GOES satellites during the period of 1977–2012. Most GOES X-ray flares were identified by simultaneous optical flare observations or by solar X-ray images before 2007. Many X-ray flares since 2008 have no accompanying optical flare, however. Fortunately, the flare location can be identified during the whole time period using the NOAA/USAF sunspot region number. To keep the treatment consistent throughout the entire study period, we used the location of the sunspot region where the flare occurred as the location of the flare. GOES X-ray flare data[1] provides the NOAA/USAF sunspot group number where the flare is observed, but no location information for the sunspot groups. The location information of sunspot groups can be retrieved from NOAA/USAF sunspot data[2]. For sunspots we study the NOAA/USAF sunspot groups for the common period of solar flares.

The analysis method can be found in earlier studies (Usoskin et al. 2005; Zhang et al. 2011; Paper I), and is briefly described here. Differential rotation of the solar surface is commonly described as

$$\Omega_\phi = \Omega_0 - B\sin^2\phi, \qquad (1)$$

where Ω_ϕ stands for the sidereal (all rotation rates are taken to be sidereal here) angular velocity at latitude ϕ, Ω_0 (deg/day) denotes the equatorial angular velocity, and B (deg/day) describes the differential rotation rate. The active longitudes are also assumed to follow the same form as the differential rotation at their own specific values for the parameters Ω_0 and B.

Assuming that the two ALs are at Carrington longitude Λ_0 and $\Lambda_0 \pm 180°$ and follow the differential rotation of solar surface, one can measure the distance between the longitude of a flare or sunspot group and the nearest AL. The merit function can be defined as the mean square of these distances either without any weighting on flares or sunspots (Zhang et al. 2011), or by weighting the flares with their normalized peak intensity and the sunspots with their normalized area. The merit function $\epsilon(\Lambda_{01}, \Omega_0, B)$ depends on the three parameters Λ_0, Ω_0, and B of the active longitudes. We used the least-square method to search for the best-fit parameters. The three-year running fit interval was used here, yielding the rotation parameters for the middle year.

We studied both the weighting and the no-weight method. The results obtained with the two methods are very similar. Therefore we only present the results of the no-weight method here.

3. Results

3.1. N-S asymmetry and recent speed-up of solar rotation

We separately calculated the yearly rotation rates Ω_{17} of ALs defined by formula (1) at the reference latitude 17° for X-ray flares and sunspots. The values of Ω_{17} are presented in Fig. 1 (left-hand panels for X-ray flares and right-hand panels for sunspots; top panels for the northern and bottom panels for the southern hemisphere). Open circles depict the yearly values of Ω_{17} for the central year of each three-year fit interval. The 1σ error for each Ω_{17} value is within ±0.015 deg/day, which is too small to be shown in the figure. To demonstrate the long-term variation pattern more clearly, the 11-point running mean values are shown in the figure as filled circles.

The rotation rates of Ω_{17} in the two hemispheres obtained with X-ray flares depict little correlation from 1977 until before 2000. In the 1980s the north rotates faster than the south, but slows down in the 1990s even below the southern rate. During this time, the southern rotation rate remains rather constant. The rotation rate has been speeding up in both hemispheres since before 2000, with the southern hemisphere rotating faster than the north. The rotation evolution obtained for sunspots depicts a

[1] ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/
[2] http://solarscience.msfc.nasa.gov/greenwch.shtml

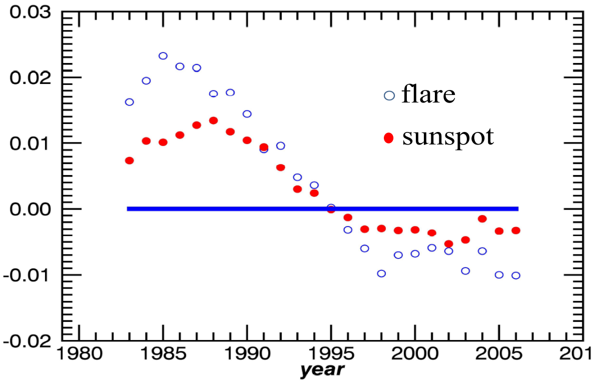

Fig. 2. Yearly values of the N-S asymmetry ((N–S)/(N+S)) of the solar rotation at latitude 17° obtained from Fig. 1 for X-ray flares (open circles) and for sunspots (filled circles).

pattern that is notably similar to that of flares. However, the recent rotation of the northern hemisphere according to sunspots is somewhat faster than that of to flares. Therefore, the hemispheric asymmetry in the rotation rate is weaker for sunspots. This is probably caused by a few large and flare-productive active regions that rotate rather slowly in the northern hemisphere. Figure 2 depicts the N–S asymmetry ((N–S)/(N + S)) of the solar rotation at a latitude of 17° obtained for X-ray flares (open circles) and sunspots (filled circles). The evolution of the hemispheric asymmetry of solar rotation is quite similarly depicted by flares and sunspots: while the asymmetry was fairly constant and negative since the late 1990s, it was strongly positive in the 1980s and decreased rapidly from the mid-1980s to the mid-1990s.

That the southern hemisphere rotates faster than the north can also be seen in the migration of ALs in the two hemispheres. Figure 3 demonstrates the migration of ALs in the Carrington reference frame in the northern (top) and southern (bottom) hemispheres in 2004. Black dots denote B-flares, triangles C-flares, red dots M-flares, and stars X-flares. The two solid lines in each panel depict the migration of the two ALs from the beginning to the end of 2004. The dotted lines on either side of the two solid AL lines denote the 90° (±45°) regions around the two ALs.

The longitudinal location of one AL increases gradually from 120° to 180°–190° in the Carrington reference frame in 2004 in the northern hemisphere, yielding a total increase of 60–70° in one year, while in the southern hemisphere the total increase in this year is about 160°–170°. This indicates that both hemispheres rotate consistently faster than the Carrington reference frame (as shown in Fig. 1), and the southern hemisphere rotates significantly faster than the north (as depicted by the negative values in Fig. 2).

3.2. Non-axisymmetry of ALs

We define the measure of non-axisymmetry Γ as

$$\Gamma = \frac{N_1 - N_2}{N_1 + N_2}, \tag{2}$$

where N_1 and N_2 denote the number of solar flares that appeared within (N_1) or outside (N_2) the two AL regions, which are taken here as the two 90°-longitude bands, depicted in Fig. 3.

The averaged yearly values of Γ for sunspots and for each flare class are listed in Table 1. The asymmetries for the different flare classes were calculated using the same rotation parameters as for the (common) ALs. The corresponding fractions of flares in the ALs are also listed in Table 1. The non-axisymmetry of flares in the southern hemisphere systematically increases with flare class from 0.42 (71%) for B-flares to 0.68 (84%) for X-flares. In the northern hemisphere, the increase of non-axisymmetry with flare class is less dramatic and less systematic. The non-axisymmetry 0.49 (74%) of X-flares is slightly lower than the non-axisymmetry 0.51 (75%) of M-flares. This indicates that the rotation rates of the active regions in the northern hemisphere that produce X-class flares and those that produce other flares of other classes have somewhat larger differences than in the southern hemisphere.

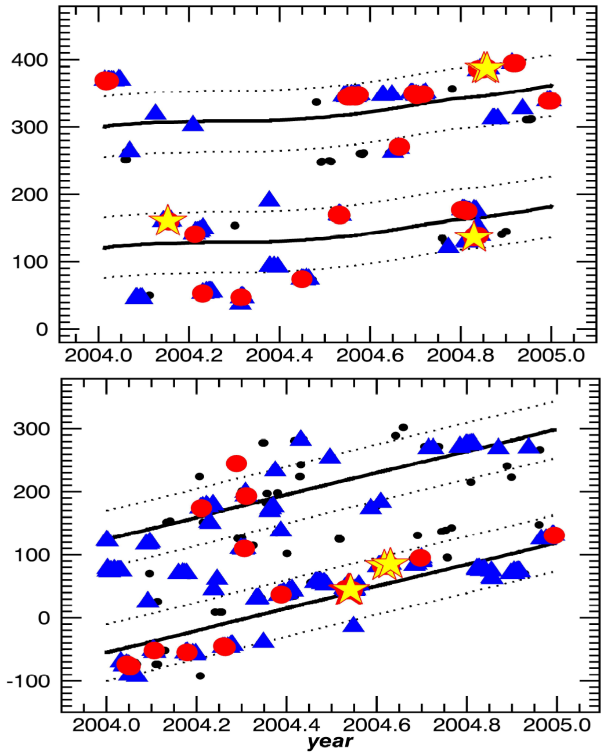

Fig. 3. Migration of ALs in units of degrees in the Carrington reference frame in the north (*top*) and south (*bottom*) in 2004. Black dots stand for B-flares, triangles for C-flares, red dots for M-flares, and stars for X-flares. The two solid lines depict the migration of the two ALs from the beginning to the end of 2004 with 45° extensions on each side denoted by dotted lines.

Table 1. Average non-axisymmetries of sunspots and the different flare classes obtained with the best-fit parameters of ALs.

	North	South
	Γ	Γ
sunspots	0.31 (66%)	0.33 (67%)
B-flares	0.42 (71%)	0.42 (71%)
C-flares	0.47 (74%)	0.43 (71%)
M-flares	0.51 (75%)	0.57 (79%)
X-flares	0.49 (74%)	0.68 (84%)

Notes. Percentage of flares and sunspots within the two ALs, $N_1/(N_1 + N_2)$, are given in parenthesis.

4. Discussion and conclusion

The relationship between solar rotation and sunspot activity is a fundamental problem. It is known that sunspot activity presents a secular increase during the twentieth century that led to the so-called modern maximum (MM; Solanki et al. 2004). Brajša et al. (2006) and Kitchatinov et al. (1999) found a secular deceleration of solar rotation, implying a negative correlation between solar rotation rate and sunspot activity. However, a secular acceleration in solar rotation has also been proposed (Heristchi & Mouradian 2009; Li et al. 2014). Moreover, Ribes & Nesme-Ribes (1993) claimed that the solar surface rotation at 20° latitude was 6% slower during the Maunder Minimum than in modern times. These latter studies suggested that the correlation between solar rotation rate and sunspot activity is positive. However, Eddy et al. (1976) suggested a faster-rotating equator during the Maunder Minimum. The results of our study are consistent with the negative relationship.

We found that the northern and southern hemispheres both have been speeding up since the late 1990s – the ending phase of the MM. The activity level in cycle 23 is significantly reduced compared with other cycles during the space era. The recent minimum between cycles 23–24 lasted rather long, and various solar activity measurements reached unusually low values. The solar wind density and the heliospheric magnetic field intensity were reduced by nearly one third, both reaching uniquely low levels since the measured time of about 50 years (Cliver & Ling 2011; Jian et al. 2011). The sunspot activity in cycle 24 is even more significantly reduced and matches the low level at the beginning of the twentieth century. This supports the negative correlation between solar rotation rate and sunspot activity.

The recent velocity increase of solar rotation was also found in our previous study of sunspots. In Paper I we studied the long-term evolution of solar rotation by analyzing the ALs of sunspots since 1870s. In addition to the recent speed-up period that started before 2000, there were several periods where one of the two hemispheres accelerated, but very few when both hemispheres were speeding up. Only two such periods were found, one during cycle 12 in the 1880s and one during cycle 14 in the early 1900s (see Fig. 1 in Paper I), but both were shorter than the period of the recent speed-up. Note that cycles 14 and 12 were the two lowest cycles at the turn of the century 100 years ago and that the minimum between cycles 14–15 lasted exceptionally long, similarly to the previous minimum. During the recent minimum, no sunspots were observed on 817 days. During the minimum between cycles 14–15 more than one thousand days were recorded as spotless (Clette & Lefèvre 2012). The recent speed-up of the sun was also found by tracing small bright coronal structures (Jurdana-Šepić et al. 2011).

The recent speed-up of solar rotation coincided with the breakdown of the mutual relationships among several solar activity and geo-activity indices. A strong divergence was observed in about 2001–2002 between the sunspot numbers and several UV/EUV flux proxies, including the F10.7 cm radio flux (Floyd et al. 2005; Lefèvre & Clette 2011; Lukianova & Mursula 2011; Kane 2003; Lean et al. 2011; Liu et al. 2011; Tapping & Valdés 2011). These changes can be understood in terms of the changes in sunspot distribution and the recent vanishing of small sunspots (Clette & Lefèvre 2012).

To summarize, we find that both solar hemispheres have increased their rotation rate since the late 1990s until recent years. Moreover, the increase rate is fairly similar in the two hemispheres, so that the hemispheric asymmetry in rotation rates has been roughly constant, with the southern rotation being slightly faster. This period of recent solar speed-up coincides with the decline of the Modern Maximum (a period of exceptionally high activity during most of the twentieth century), which is evidenced by the overall reduction of sunspot activity, vanishing of small sunspots, decreasing solar wind density and magnetic field, etc. We also note that similar albeit shorter and less significant periods of both hemispheres speeding up were only found during the two lowest solar cycles 12 and 14 at the turn of the nineteenth and twentieth century. These results strongly suggest that, at least momentarily, there can be and, in fact, there currently is a negative correlation between the solar surface rotation rate and sunspot activity. The causes of these results can be found in the interaction between the solar differential rotation and the magnetic field. Simulations (Brun 2004) have shown that low Maxwell stresses in weak magnetic fields lead to a high rotation rate at low latitudes where sunspots appear.

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