Relationship between rotating sunspots and flare productivity

X.-L. Yan,1,2⋆ Z.-Q. Qu1 and D.-F. Kong3

1National Astronomical Observatories/Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming, Yunnan 650011, China
2Graduate School of Chinese Academy of Sciences, Zhongguancun, Beijing, China
3Jiaxing University, Jiaxing, Zhejiang, China

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ABSTRACT
To understand both the effects of dynamo and the nature of flaring activity, we identified rotating sunspots and then classified them into six types by using the data of Transition Region and Coronal Explorer and Solar and Heliospheric Observatory/Michelson Doppler Imager in Solar Cycle 23. The classification is made by their rotating directions and relative positions (leading or following sunspots), while the corresponding samples are given. The statistics of flares relevant to these sunspots are presented to show the relationship between different types of rotating sunspots and their flare productivity. It is found that some types of rotating sunspots are in favour of producing flares, and, outstandingly those active regions with sunspots of rotating direction opposite to the differential rotation have much higher strong (X-class) flare productivity. Furthermore, we found that the ratio of the number of flares defined in this paper is inconsistent to the number evolution of the six types of rotating sunspots. The maximum ratios of the six types except type VI appear after the maximum year. Additionally, there are total 60 possible patterns of rotating sunspots belonging to the six types, among which 35 patterns are found but 25 patterns remain to be discovered in other solar cycles. These results not only place further constraints on the dynamo theory but also reveal that the rotation motions of sunspots can be greatly helpful to the energy buildup of solar flares.

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

1 INTRODUCTION
Rotating sunspots have already been observed for several decades (Evershed 1910; Maltby 1964; Gopasyuk 1965). With the high spatial and temporal resolution of recent satellite-borne telescopes, more and more rotating sunspots are becoming easier to be identified (Nightingale et al. 2000, 2002; Brown et al. 2003).

Sunspot’s rotation can shear and twist magnetic field lines, which is believed to be a source of non-potentiality. It is generally accepted that energies released by flares are provided by the non-potential parts of the magnetic fields. That is to say, the flare process is the release of the free magnetic energy in solar active region (Régnier & Priest 2007a). Wang et al. (1996) reported that the characteristics of the non-potentiality can be deduced from shear angle and vertical currents. They found flare occurrence associated with sheared magnetic fields and great enhancement of vertical currents. As is known, the non-potential magnetic configuration is most likely to be responsible for the eruptive phenomenon. Régnier & Amari (2004) and Régnier & Priest (2007b) found that the twisted and sheared flux bundles in the corona have strong currents, which are sufficient to trigger flares. But how to accumulate and store the non-potential energy still remains a problem in solar physics. Much earlier, Stenflo (1969) suggested that sunspot rotation may be involved with the buildup of energy, which later releases by a flare. Régnier & Canfield (2006) found that the slow rotation of the sunspot in NOAA 8210 enables the storage of magnetic energy and allows for the release of magnetic energy as C-class flares. The rapid rotation of the sunspots may be a mechanism of injecting twist into corona, which can cause sigmoids/Ω loop that can erupt as flares and coronal mass ejections (Canfield et al. 1999; Brown et al. 2002; Pevtsov 2002; Yan & Qu 2007).

Recently, more and more observations provided the evidence that the rotating sunspot is involved in the large flare activity. Zhang, Li & Song (2007) reported that a flare is caused by an interaction between a fast rotating sunspot and ephemeral regions. In addition, Schrijver et al. (2008) used non-linear force-free modelling to show the evolution of the coronal field associated with a rotating sunspot, and suggested that the flare energy comes from an emerging twisted flux rope.

Yan, Qu & Xu (2008) reported the detailed information about the polarities, rotation directions and helicities of rotating sunspots. Following this investigation, we classify rotating sunspots and then give detailed flare productions of different rotating sunspots in this paper.
2 OBSERVATIONS

The main observations used in this paper are as follows.

1. The Transition Region and Coronal Explorer (TRACE) white light images with a cadence of about 1 min (Handy et al. 1999).
2. Full-disc 96-minute line-of-sight magnetograms and full-disc white light images taken by the Michelson Doppler Imager (MDI; Scherrer et al. 1995) aboard the Solar and Heliospheric Observatory (SOHO; Domingo, Fleck & Poland 1995).

The requirement for these observations with white light images and magnetograms of the active regions is that they should cover at least two days, passing through the region of ±40° in latitude and longitude on solar disc.

The identification of a rotating sunspot is done by either of the two criteria: (1) a sunspot rotates around its umbral centre and (2) a sunspot rotates around another sunspot within the same active region. Additionally, the projection effect is eliminated according to the methods of Brown et al. (2003).

3 CLASSIFICATION OF ROTATING SUNSPOTS

By the criteria described above, we identified 186 rotating sunspots in 153 active regions. In this paper, we added the other four rotating sunspots, which were missed in Yan et al. (2008) from the same samples. The distribution and evolution of rotating sunspots on the solar disc from 1996 December to 2007 December can be seen from fig. 1 of Yan et al. (2008). Rotating sunspots are divided into six types (see Fig. 1) and each type is further divided into subtypes according to their rotating directions and its relative locations (leading or following sunspots) within one active region. As the polarities of the leading and the following sunspots of active regions in two hemispheres are opposite, some subtypes are sorted into two patterns. Note that the black circles and the white ones in Fig. 1 indicate negative and positive polarities, respectively. The vertical lines denote the rotation axes through the umbral centres, while the curving arrows encircling the axes and other sunspots indicate rotation directions. In order to describe the different types, one example was given to each of the six types by using white light images and magnetograms. The detailed classification of rotating sunspots is described as follows.

Type I: one sunspot rotates around its umbral centre, i.e. it spins. This type can be divided further into four patterns (see type I in Fig. 1). Type Ia comprises 9 per cent, type Ib 9 per cent, type Ic 37 per cent and type Id 45 per cent of this type. The rotating sunspots of this type are mainly the leading ones. This type has eight sub-patterns associated with polarity. Considering the main following sunspot spins while the leading sunspot does not rotate obviously, we take NOAA 10486 as an example (see Fig. 2). The following sunspot had two umbrae. During the evolution of four days, the two umbrae rotated anticlockwise about 180°. One can see the umbrae F1 and F2 changing their locations in the active region clearly from SOHO/MDI white light images and magnetograms. This active region was responsible for the largest flare of this Solar Cycle (e.g. Del Zanna et al. 2006; Liu et al. 2006; Mandrini et al. 2006; Schrijver et al. 2006; Liu et al. 2007). Among the samples obtained, there are 42 per cent of the total rotating sunspots belonging to this type.

Type II: one sunspot rotates around the other without detectable spin within one active region. This type can be classified into four

Figure 1. Cartoon showing the six types of rotating sunspots. The arrows indicate the rotational directions of rotating sunspots. The vertical lines denote the rotation axes of rotating sunspots penetrating the umbral centres. The left sunspot indicates the following one in the active region, while the right sunspot indicates the leading one. The black and the open circles indicate the negative and positive polarity.

Figure 2. Type Ia. Left-hand panel denotes the SOHO/MDI white light images of NOAA 10486, while the right-hand panel denotes the SOHO/MDI magnetograms obtained at the same time. The two umbrae of the rotating sunspot are signed by F1 and F2. The levels of the magnetograms are 100, 200, 500, 1000G. Note that the other magnetograms use the same levels.

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Figure 3. Type Ila. Left-hand panel denotes the TRACE white-light images of NOAA 10484, while the right-hand panel denotes the SOHO/MDI magnetograms. The black boxes in the white light images and the white boxes in the magnetograms denote the same location of the rotating sunspot.

patterns (see type II in Fig. 1). Type Ila comprises 20 per cent, type IIb 12 per cent, type IIc 27 per cent and type IId 41 per cent of this type. This type also has eight subpatterns associated with polarity. NOAA 10484 can be shown as an example. In three days, the following sunspot with negative polarity rotated anticlockwise by dozens of degrees (see Fig. 3), while the positive polarity sunspot showed no apparent rotation. NOAA 10484 was also a highly flare-productive region (Li, Berlicki & Schmieder 2005; Guo et al. 2006). This type occupied 22 per cent of the total rotating sunspots.

Type III: both leading sunspot and following sunspot spin within one active region. This type can also be sorted into four patterns (see type III in Fig. 1). The former two types account for 30 per cent and the latter two types for 20 per cent. There are eight subpatterns associated with polarity. NOAA 8574 can be used as an example (see Fig. 4). One can clearly see that both the leading and the following sunspots spun. We found 22 per cent among 186 samples belonging to this type.

Type IV: one sunspot rotates around another spinning sunspot within one active region. This type can be again divided into four patterns shown in Fig. 1. Type IVa comprises 29 per cent, type IVb 43 per cent, type IVc 14 per cent and type IVd 14 per cent of this type. There are 16 subpatterns associated with polarities, but we only found five cases in our samples. NOAA 8210 is the optimum sample, illustrated in Fig. 5. The sunspot with positive polarity rotated anticlockwise around the spinning sunspot with negative polarity. This region was also a well-studied active region (Welsch et al. 2004; Georgoulis & Labonte 2008; Régnier & Canfield 2006). Only seven pairs of rotating sunspots were found in our statistics.

Type V: one sunspot not only spins but also goes around another sunspot without detectable rotation motion within the same active region. It is classified into two patterns (see type V in Fig. 1). Type Va accounts for 33 per cent and the other for 67 per cent. The rotating sunspots of this type are mainly the following ones. This type also should have 16 subpatterns associated with polarity, but only three cases were found in our samples. NOAA 10930 is now accepted as the example (see Fig. 6). The small sunspot with positive polarity spun and rotated around the other sunspot with negative polarity. This region was also a well-studied active region (Kubo et al. 2007; Zhang et al. 2007; Schrijver et al. 2008). This type is very rare. We found only three rotating sunspots of this type.

Figure 4. Type IId. Left-hand panel denotes the TRACE white light images of NOAA 8574, while the right-hand panel denotes the SOHO/MDI magnetograms. The black/white boxes denote the rotating sunspot with positive/negative polarity.

Figure 5. Type IVb. Left-hand panel denotes the TRACE white light images of NOAA 8210, while the right-hand panel denotes the SOHO/MDI magnetograms. The black/white boxes denote the same meaning as Fig. 4.
Type Vb: Rapid rotation of sunspots clearly seen in the sequence of data. The left-hand panels showing TRACE white light images of NOAA 10930, while the right-hand panels denote the SOHO/MDI magnetograms. The boxes indicate the rotating sunspots.

Type VI: one leading sunspot and following one rotate around each other. Two patterns (see type VI in Fig. 1) are sorted into this type. Type VIb accounts for three-quarters of this type. It should have four subpatterns, but only three were observed. As a typical example, the behaviour of NOAA 10826 containing this type of rotating sunspots is analysed in Fig. 7. The number of this type was very small. Only four pairs in 186 rotating sunspots were found.

Table 1 lists the number of active regions corresponding to six types rotating sunspots in Solar Cycle 23, while Fig. 8(a) illustrates the number evolution of these active regions relevant to the six types of rotating sunspots. Types I, II and III occupy 90.8 per cent of the total number. The number of each type increased at the beginning of Solar Cycle 23 and reached the maximum in 2000, except the type V with very rare samples. These rotation configurations reflect the interior plasma motions and the interactions between the plasma and magnetic fields. Such motions and interactions tend to form the types I, II and III, but types IV, V and VI of rotating sunspots seem to be found accidently. This result implies that the interior motion of the Sun at maximum can be different from that in other periods. This may be very important for solar dynamo.

4 RELATIONSHIP BETWEEN THE TYPES AND FLARE PRODUCTIVITY

Based on the classification of rotating sunspots during Solar Cycle 23, we can investigate the relationship between the flare productions and the types (see Table 2). According to Geostationary Operational Environmental Satellite (GOES) flare records (http://www.lmsal.com/SXT/homepage.html), one can obtain the occurring time of flares, flare class (e.g. C, M, X classes) and their locations (e.g. active region). We obtained all the flares associated with active regions having rotating sunspots. The selection threshold for flares is at least C1.0. In these active regions, the high production efficiency of C-class flares is evidenced in Table 2. The productivity is defined as the ratio of the number of flares divided by the number of the active regions containing one defined-type rotating sunspots. The number in parentheses indicates the number of corresponding flare’s productivity in Table 2. This parameter for C-class flare of the types IIa, IIc, IIIa, IIIb, IVd, Va and Vb is found above 10. The types IIc, IIIb and Vb also have high productivity of M- and X-class flares.

Importantly, there are 53 active regions with rotating sunspot (e.g. types Ia, Ic, Id, Ila, Ib, IIc, IId, IIIa, IIIb, IIIc, IVd, Vb and VIb) which produced M-class flares, the rotation direction of 25 in 53 were opposite to the differential rotation. More notably, we found that there are 20 active regions with rotating sunspots, which produced X-class flares; the rotation directions of rotating sunspot in 14 active regions (e.g. types Ib, Id, Ila, IIc, IIIa, IIIc, Vb and VIb) among 20 were opposite to the differential rotation. This statistic implies that the active regions with sunspots of rotation direction opposite to the differential rotation are in favour of producing M- and X-class flares. In addition, we defined the ratio of the number of flares (e.g. C, M and X class) divided by the total number of associated active regions per year. From Fig. 8(b), one can find that the ratio of the number of flares is not in agreement with the evolution of the number of each type (see Fig. 8a). The maximum ratios of the six types except type VI appear after the maximum year.
The relationship between the types of rotating sunspots and flare productivity. Note that the threshold in flare selection is at least C1.0. The numbers of flares are based on GOES flare records. The numbers in parentheses indicate the number of corresponding flare productivity. The definition of flare productivity is given in Section 4.

![Figure 8](https://academic.oup.com/mnras/article-abstract/391/4/1887/1747552)

**Table 1.** The number of active regions corresponding to six types rotating sunspots in Solar Cycle 23.

<table>
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<tr>
<th>Types</th>
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<th>b</th>
<th>c</th>
<th>d</th>
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</table>

5 CONCLUSIONS AND DISCUSSIONS

In this paper, we identified rotating sunspots by using the data of TRACE and SOHO/MDI, and then classified these sunspots into six types and further into 60 possible patterns according to their rotation directions and relative positions (leading or following sunspot), and finally found the relationship between these sunspots and flares.

The conclusions drawn by the statistics are outlined as follows.

1. According to the method used to classify rotating sunspots in this paper, there are 60 possible patterns in total. All the patterns of types I, II and III have been found. However, five in 16 of type IV and three in 16 of type V have been identified, respectively, in our samples and three in four patterns have been evidenced for type VI. Other undiscovered patterns are expected to be found in other solar cycles. This puts one delicate constraint on the dynamo theory.

2. We found that some types of rotating sunspots are in favour of producing flares. For instance, the average C-class flare productivity of types IIa, IIc, IIIa, IIIb, IVd, Va and Vb is above 10. Additionally, types IIa, IIIb and Vb were observed to produce M- and X-class flares, and the corresponding average productivity for M and X flares of these types is above one. Importantly, there are 53 active regions (e.g. types Ia, Ib, Ic, IIa, IIb, IIc, IIIa, IIIb, IIIc, IVb, Vb and VIb) which produced M-class flares. The rotation direction of 25 in 53 was opposite to the differential rotation. It is more notable that those active regions with sunspots (e.g. types Ib, Id, IIa, IIc, IIIa, IIIb, IIIc, IVb, Vb and VIb) of rotation directions opposite to the differential rotation have much higher strong (X-class) flare productivity. X-class flares were produced in 14 out of 20 active regions having such rotating sunspots.

3. Furthermore, we found that the ratio of the number of flares defined in this paper is inconsistent with the number evolution of the six types of rotating sunspots. The maximum ratios of the six types except type VI appear after the maximum year.

The mechanism of these rotating sunspots becomes a very difficult problem. Botha, Rucklidge & Hurlburt (2007) and Botha et al. (2008) found that the non-axisymmetric instabilities of magnetic flux tubes are driven by convection. But there are many other reasons. For example, Bao, Sakurai & Suematsu (2002) and Brown et al. (2003) discussed several mechanisms of rotating sunspots, such as differential rotation, coriolis force, \( \alpha \)-effect, surface flow, magnetic reconnection and flux tube emergence. However, there is no definite affirmation about this. It is a real challenge to the solar dynamo theory because many of these active regions do not obey the hemisphere law caused by differential rotation. Not only is the rotating direction of rotating sunspots opposite to the differential rotation, but also the rotation speed of these rotating sunspots is detected to be greater than that caused by differential rotation. The latter aspect has also been identified by Brown et al. (2003). More importantly, the two sunspots with the same rotating direction have higher flare productivity (e.g. types IIIa, IIIb) than those with opposite rotation directions (e.g. types IIc, IIIId; see Table 2). This result identified that when the two sunspots are rotating in the...
same direction, this scenario is easier to store magnetic energy and increase the helicity of the flux tube. Additionally, the number of every type increases and decreases with the same cadence of solar cycle except type V with very rare samples. These results can also put more constrain on the dynamo theory.

Because the highly twisted flux tube and sigmoid configurations have strong electric currents, they are more likely to erupt (Pevtsov 2002; Régnier & Amari 2004). Therefore, we conclude that the rotation motions of sunspots can be greatly helpful to the energy buildup of solar flares (Stenflo 1969; Régnier & Canfield 2006). This means that the kinetic rotation energy of the magnetized plasma stored in the deeper layers of solar atmosphere can be easily released via flares in the form of magnetic free energy in the upper layers.

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