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The causality between the rapid rotation of a sunspot and an X3.4 flare *

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Abstract Using multi-wavelength data of Hinode, the rapid rotation of a sunspot in active region NOAA 10930 is studied in detail. We found extraordinary counterclockwise rotation of the sunspot with positive polarity before an X3.4 flare. From a series of vector magnetograms, it is found that magnetic force lines are highly sheared along the neutral line accompanying the sunspot rotation. Furthermore, it is also found that sheared loops and an inverse S-shaped magnetic loop in the corona formed gradually after the sunspot rotation. The X3.4 flare can be reasonably regarded as a result of this movement. A detailed analysis provides evidence that sunspot rotation leads to magnetic field lines twisting in the photosphere. The twist is then transported into the corona and triggers flares.

Key words: Sun: sunspots — Sun: flares — Sun: magnetic fields

1 INTRODUCTION

It is now widely accepted that flares derive their power from free energy stored in stressed or non-potential magnetic fields in active regions (Zirin et al. 1973; Hagyard et al. 1984). However, details of the process of rapid transformation of magnetic energy into kinetic energy of particles, radiation, plasma flows and heat have not been very clear. How the magnetic energy is stored and released still needs more observational evidence. Thus, it remains a very important issue in solar physics.

There are several characteristics of active regions which favor causing flares. If active regions have strong magnetic gradients (Wang et al. 1994, 2006), highly sheared transverse magnetic fields (Rausaria et al. 1993; Chen et al. 1994; Wang et al. 1996), emerging fluxes (Schmieder et al. 1997; Chen & Shibata 2000; Liu & Zhang 2001; Zhang 2006), and flux cancellation (Wang & Shi 1993; Zhang & Wang 2001; Zhang et al. 2001), flares are triggered more often. Besides the observations mentioned above, sunspot rotation (Evershed 1910; Nightingale et al. 2001, 2002; Brown et al. 2003; Yan et al. 2008) may be involved with energy buildup and the energy is released later via flares (Stenflo 1969; Régnier et al. 2006; Yan et al. 2007, 2008). Rotation of a sunspot in the photosphere may cause an injection of twist into the corona (Tian et al. 2006), which was proven by TRACE EUV images, and also by the S-shaped or inverse S-shaped structures in the soft X-ray images of Yohkoh/SXT (Canfield et al. 1999; Pevtsov 2002).

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In this paper, we describe the rapid rotation of the sunspot and the relationship between the sunspot rotation and the X3.4 flare. An emphasis on the possible causality of flare eruption is made by tracing the evolution of this active region from the photosphere to the corona. This may add significant and reliable evidence to an argument that rotation triggers the flare.

2 OBSERVATIONAL DATA

Data used in this paper contain those detailed as follows: 1. Continuum intensity images and vector magnetograms from the Spectropolarimeter (SP) of the Solar Optical Telescope (SOT, Tsuneta et al. 2008), and X-ray images from the X-Ray Telescope (XRT, Golub et al. 2007) aboard Hinode (Kosugi et al. 2007); 2. Soft X-ray flux of GOES 12.

In this paper, we used the Fast Map of SP data. The reduction of spectropolarimetric data from Hinode is carried out by the radiative transfer equation derived by Unno (1956) and improved by Landolfi et al. (1982), and a Milne-Eddington atmosphere is assumed. The 180 degree ambiguity is resolved by comparing vector magnetograms with potential fields (Metcalf et al. 2006).

3 PROCESS OF AN X3.4 FLARE

NOAA 10930 is a bipolar active region, which was composed of a big sunspot with negative polarity and another small sunspot with positive polarity (see Fig. 1). There were many B class flares, C class flares, and two X class flares occurring in this active region recorded from 2006 December 9 to 14. Here, we only analyze the prominent X3.4 flare in detail.

According to soft X-ray emission from GOES 12 (see Fig. 2), there was an X3.4 flare in this active region. It occurred at 02:14 UT and reached its peak at 02:40 UT.

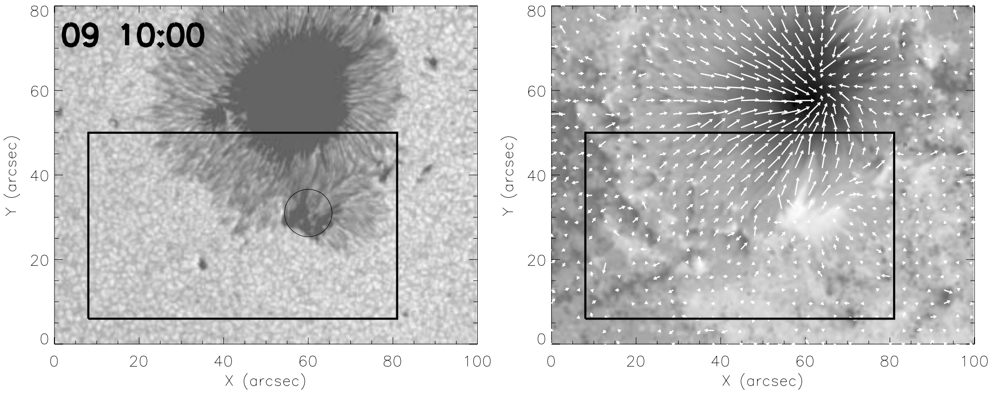

Fig. 1 Continuum intensity image (left panel) and vector magnetogram (right panel) with high resolution processed from Spectropolarimeter of SOT on 2006 December 9 respectively. Black (white) patches in the right panel indicate the negative (positive) polarity. The circle is placed at the rotating sunspot and the box outlines the field of view of Fig. 3.

By observing evolution of this active region, we noted that the small sunspot presented an extraordinary counterclockwise rotation. Figure 3 shows high resolution continuum intensity images (left panels) and vector magnetograms (right panels) with transverse components overlying longitudinal ones obtained from SP of SOT. From the evolution of continuum intensity images, one can see that the small sunspot with positive polarity not only moved from the southwest of the big sunspot to the southeast but also rotated rapidly around its umbral center. Referring to light fibrils connecting the umbra of the small sunspot in the continuum images, one can trace its rotation process. The center of the circle which

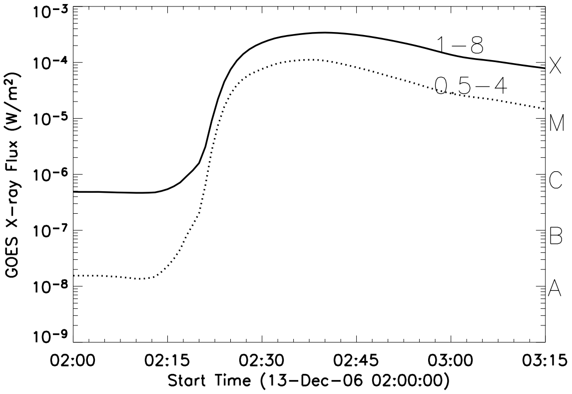

Fig. 2 Evolution of soft X-ray emission (Solid line: 1–8 Å. Dotted line: 0.5–4 Å) for the flare on 2006 December 13 from GOES 12.

contains all the umbral features of the small sunspot is labeled as "O1" to illustrate the reference frame. Light fibrils also rotated around the center of the sunspot umbrae, so one can evaluate their motions and easily obtain rotation angle and speed. Arrows labeled by numbers indicated different penumbral fibrils which are used for tracing the change of the rotation. In this figure, dashed lines in the small sunspot indicate the radius of the circle. The rotation angle increased during the evolution of four days and reached 259 degrees (see Fig. 4a). Two peaks appeared in the curve which recorded the rotation speeds on Dec. 11 and 12 (see Fig. 4b). Because time resolution is not so high, we only get a relatively rough average of the rotation speed. Following sunspot rotation, corresponding magnetic force lines between the two sunspots around the magnetic inversion line became sheared (see the right panels of Fig. 3). The transverse magnetic fields assumed a spiral pattern around the center of the umbrae of the rotating sunspot. The average strength of transverse magnetic fields in the box in Figure 1 increased rapidly before December 12 (see Fig. 4c). Simultaneously, the expansion of the magnetic field-covered area (the box labeled region in Fig. 1) related to the rotating sunspot can be seen. The negative magnetic fluxes increased from December 11 to 13. However, positive magnetic fluxes first increased and then rapidly decreased (see Fig. 4d). After we checked the magnetograms, we found that there are two reasons accounting for this phenomenon. On one hand, there are many small positive magnetic fluxes around the main positive sunspot which diffused out of the region following the main positive sunspot emergence. On the other hand, some of the longitudinal magnetic fields may be transformed into the transverse ones while the sunspot rotates. During the five days' rotation of the sunspot, the X3.4 flare erupted as mentioned above.

As is well-known, rapid evolution of magnetic loops generally induces evolution of the corresponding coronal magnetic fields. A sequence of XRT images in Figure 5 shows evolution of coronal loops with high temperature during sunspot rotation. One can see the formation process of the sheared loops' structure from December 10 to December 11. Three dashed lines in Figure 5b denote the three shearing loops. An inverse S-shaped structure appeared on December 12 accompanying the sunspot rotation (see Fig. 5c). The inverse S-shaped loop and another loop are denoted by 1 and 2 respectively in Figure 5c. Before the X3.4 flare, the two loops almost merged into one sheared loop denoted by dashed curves in Figure 5d. During the X3.4 flare, the loops became more sheared at 02:20:18 UT and the width of the loop became narrow as shown by a white arrow in Figure 5e. After the flare, the sheared loops disappeared and became potential post-flare loops denoted by dashed lines in Figure 5f. The sheared and inverse S-shaped structures favor the occurrence of magnetic reconnection according to common sense (Ji et al. 2007; Pevtsov 2002). Foot points of these loops can be seen rooted in the magnetic condensed region. Therefore, the corresponding rotation can shear these loops, and then trigger the eruption.

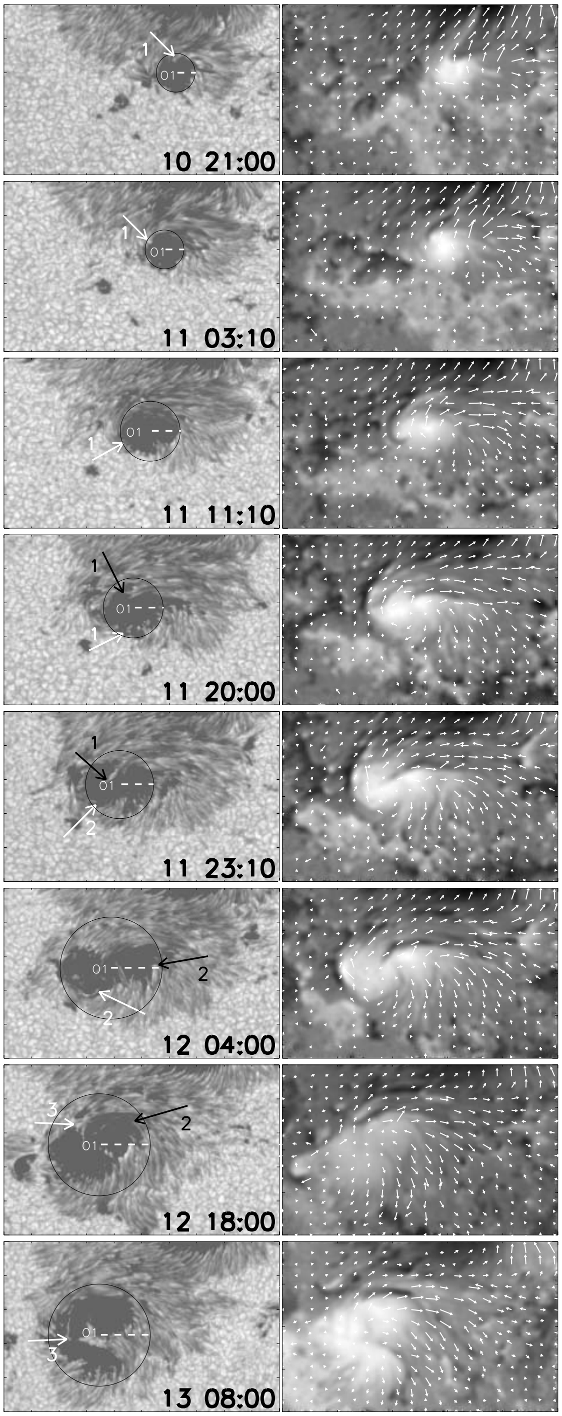

Fig. 3 Rapid rotation of sunspots seen in the sequence of continuum intensity images and vector magnetograms from Spectropolarimeter of SOT. The circle includes the umbra of the rotating sunspot. The arrows in the left panels are specified in detail in the text. The field of view is $75'' \times 45''$.

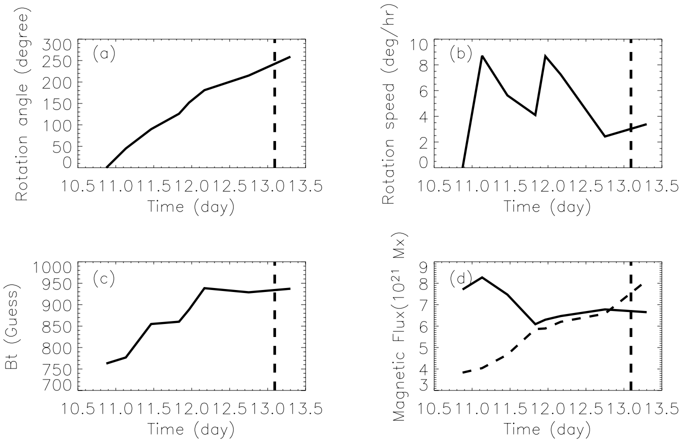

Fig. 4 Plots showing the evolution of the rotation angle (a), rotation speed (b), the average strength of transverse magnetic fields (c), and the positive (solid line)/negative (dashed line) magnetic fluxes (d). The vertical dashed lines denote the beginning time of the X3.4 flare.

From the above descriptions, one easily thinks of this: the sunspot rotation caused movement of loop footpoints and shearing of magnetic field lines. The lower magnetic field lines of loops were twisted in the photosphere and then the twist was transported into the corona. It is worth pointing out that Gibson et al. (2002, 2004) observed magnetic flux ropes in the corona and simulated the rotation of the sunspot. They found that sunspot rotation can form an S-shaped structure in the corona. In this paper, we identified the result again from observations.

4 SUMMARY AND DISCUSSION

In the above sections, we investigated the active region NOAA 10930 from 2006 December 10 to 13 in detail. From the evolution of this active region, we have found rapid rotation of the small sunspot. Furthermore, the rapid rotations took place before the X3.4 flare. By viewing vector magnetograms of this active region, we found magnetic force lines which were highly sheared along the neutral line following the sunspot rotation. From X-ray images above this region, sheared loops and the inverse S-shaped loop in the corona were identified. Comparing with the work of Zhang et al. (2007), we analyzed this active region by using high spatial resolution continuum intensity images, vector magnetograms, and XRT images. Our purpose is to reveal the possible causality between the rotating sunspot and the flare.

More important is that we must combine these findings and trace the causality chain from the sunspot rotation to the flare eruption by using those high spatial resolution images. Therefore, we can conclude that the rotation produces and transports the twist of the loops through their legs to the tops where the twist is evidenced by XRT observations. Thus, one can derive the result that sunspot rotation serves as a driver for both twisted magnetic loop formation and the associated non-potential eruption. Thus, the chain of causality for the X3.4 flare eruptions can be traced as follows: the rapid rotation of the sunspot, the evolution of their transverse magnetic fields, and the corresponding evolution of the configuration of magnetic loops in the corona, and then the eruption. All of these provide reliable evidence that photospheric motion makes magnetic loops twist from the photosphere through the chromosphere into the corona, which subsequently causes flares.

As is also well known, the Coriolis force can make sunspots rotate in a clockwise (counterclockwise) direction in the northern (southern) hemisphere while differential rotation gives rise to the reverse motion. Bao et al. (2002) analyzed several origins of the twist in magnetic flux tubes. Besides the Coriolis force and differential rotation, they have also analyzed the α-effect, surface flow, and magnetic

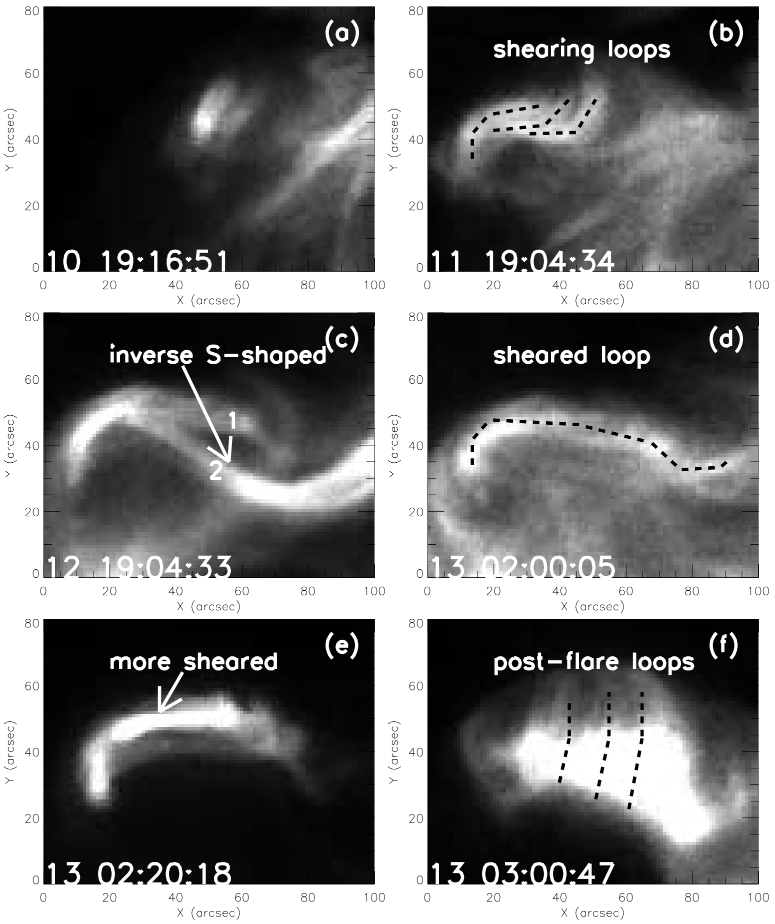

Fig. 5 A series of X-ray images observed with Be-thin filter by XRT of Hinode from 2006 December 10 to December 13. The dashed lines and arrows are described in the text.

reconnection. However, many different viewpoints exist in the literature. For example, Brown et al. (2003) thought that differential rotation does not play a major role in producing sunspot rotation. They suggested that photospheric flow and flux-tube emergence may be responsible for sunspot rotation. Su et al. (2008) proposed that Lorentz force may be a possible driving force for sunspot rotation. Following the development of technology and theory, mechanisms of sunspot rotation are expected to be solved in the future.

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