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ROLE OF SUNSPOT AND SUNSPOT-GROUP ROTATION IN DRIVING SIGMOIDAL ACTIVE REGION ERUPTIONS

LIRONG TIAN and DAVID ALEXANDER
Department of Physics and Astronomy, Rice University, Houston, TX 77251-1892, U.S.A.
(e-mail: alicetlr@rice.edu)

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Abstract. We study active region NOAA 9684 (N06L285) which produced an X1.0/3B flare on November 4, 2001 associated with a fast CME (1810 km s^{-1}) and the largest proton event (31 700 pfu) in cycle 23. SOHO/MDI continuum image data show that a large leading sunspot rotated counter-clockwise around its umbral center for at least 4 days prior to the flare. Moreover, it is found from SOHO/MDI 96 m line-of-sight magnetograms that the systematic tilt angle of the bipolar active region, a proxy for writhe of magnetic fluxtubes, changed from a positive value to a negative one. This signifies a counter-clockwise rotation of the spot-group as a whole. Using vector magnetograms from Huairou Solar Observing Station (HSOS), we find that the twist of the active region magnetic fields is dominantly left handed ($\alpha_{\text{best}} = -0.03$), and that the vertical current and current helicity are predominantly negative, and mostly distributed within the positive rotating sunspot. The active region exhibits a narrow inverse S-shaped H_α filament and soft X-ray sigmoid distributed along the magnetic neutral line. The portion of the filament which is most closely associated with the rotating sunspot disappeared on November 4, and the corresponding portion of the sigmoid was observed to erupt, producing the flare and initiating the fast CME and proton event. These results imply that the sunspot rotation is a primary driver of helicity production and injection into the corona. We suggest that the observed active region dynamics and subsequent filament and sigmoid eruption are driven by a kink instability which occurred due to a large amount of the helicity injection.

1. Introduction

Coronal mass ejections (CMEs) are thought to be the predominant form of solar activity affecting our space environment. Consequently, it is very important to investigate the causes leading to the eruption of CMEs from the solar corona. Recent studies have suggested that CMEs occur as a response to an over-accumulation of magnetic helicity and an ejection of that helicity from the Sun into interplanetary space (Rust, 1994; Low, 1996). Thus, understanding the buildup processes of magnetic helicity is a central issue in understanding the initiation of CMEs. Helicity injection possibly relates to two kinds of rotational motion observed in active regions. The first is the rotation of active region sunspots where the whole sunspot is observed to rotate around the axis of its umbral center (e.g. Brown *et al.*, 2003). The other relates to the systematic rotation of the whole sunspot-group, that the center of one magnetic polarity relatively rotates around the center of another polarity (e.g. Tian *et al.*, 2005a).

The earliest reports of vortical magnetic patterns around sunspots (Hale, 1927; Richardson, 1941) displayed a preferred rotation direction in each hemisphere: about 80% of sunspot vortices showed a counter-clockwise (clockwise) rotation in the northern (southern) hemisphere. Knoska (1975), however, found no evidence for such a hemispheric dependence on the direction of the sunspot rotation. McIntosh (1981) observed that penumbral filaments and chromospheric fibrils in the vicinity of 300 sunspots showed a hemispheric-dependent predominant sense of curvature, regardless of spot polarity and phase of the activity cycle. The sunspots studied exhibit a dominance of left-handed (right-handed) spiral structures in the northern (southern) hemisphere. Ding, Hong, and Wang (1987) further confirmed this result. Most recently, Brown *et al.* (2003) found pronounced sunspot rotation in active regions using white light movies from TRACE.

Anti-clockwise (clockwise) rotation of the spots in the northern (southern) hemisphere may generate vortical structures, if observed fine structures are aligned with the magnetic fields. Seehafer (1990) suggested that the sunspot rotation could provide a possible photospheric generation mechanism for atmospheric currents. The current generation due to the rotation of the spots leads to the result that current helicity is predominantly negative in the northern hemisphere and positive in the southern hemisphere. More recently, observations of the twist parameter α_{best} (Pevtsov, Canfield, and Metcalf, 1995), chromospheric filaments (Martin, Bilimoria, and Tracadas, 1994), and coronal sigmoid structures (Rust and Kumar, 1996) also display such a hemispheric tendency: left-handedness in the northern hemisphere and right-handedness in the southern hemisphere. Therefore, in the northern (southern) hemisphere, left (right)-handed spiral fibril patterns would be produced by counter-clockwise (clockwise) rotation of the spots, resulting in negative (positive) current helicity, i.e., left (right)-handed twist of magnetic fields. These can be visualized by the diagram in Figure 1.

Howard, Sivaraman, and Gupta (2000) studied the sunspot-group rotation of a large sample of active regions and found that the magnetic axes of growing (presumably younger) sunspot-groups rotate more rapidly than do decaying (presumably older) groups. López Fuentes *et al.* (2003) studied 22 long-lived (several solar rotations) active regions, and found that 10/14 (5/8) active regions rotated counter-clockwise (clockwise) in the northern (southern) hemisphere. Zhou and Zheng (1998) studied five active regions all of which produced large proton events. Three active regions, located in the northern hemisphere, showed a similar pattern of a counter-clockwise rotation of the axis of the sunspot-group prior to the events, followed by a rotation in the opposite direction after the events. The other two active regions, located in the southern hemisphere, also exhibited a transition in their rotation direction after a event. However, one rotated counter-clockwise, another clockwise before the events. Ishii *et al.* (2003) studied several major flare-producing active regions in cycle 23, for which the magnetic neutral lines rotated

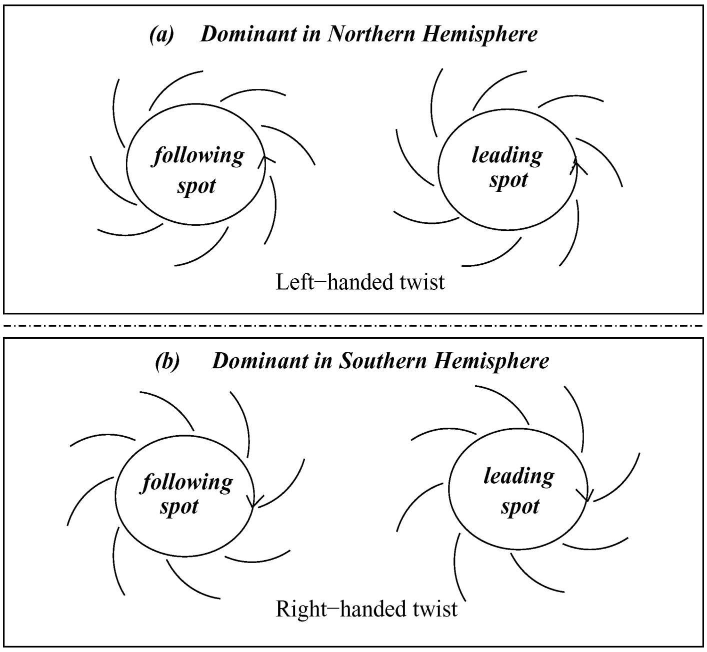

Figure 1. A diagram to describe (a) left-handed spiral spot, counter-clockwise rotating sunspot and left-handed twist ($\alpha_{\rm best} < 0$) in the northern hemisphere; (b) right-handed spiral spot, clockwise rotating sunspot and right-handed twist ($\alpha_{\rm best} > 0$) in the southern hemisphere.

clockwise (counter-clockwise) in the northern (southern) hemisphere. This study, in fact, also reflects sunspot-group rotation. All of the aforementioned studies imply that the systematic rotation of active regions is closely related to major solar activity.

Sunspot and spot-group rotation have been studied separately for many years, but only recently has the attention been focused on the two kinds of rotation at the same time. Démoulin *et al.* (2002) and Mandrini *et al.* (2004) have suggested that magnetic helicity can be generated not only by rotation of each polarity of sunspot (twist), but also by the relative rotation of positive and negative polarities, i.e., sunspot-group rotation (writhe). Because both terms have a given sign and are monotonic functions of time, helicity injection and accumulation in the corona becomes possible when both have the same sign. Thus, the rotation of individual sunspots and the sunspot-group as a whole likely relate to the production of coronal current (energy) and helicity injection, which are closely related to flare eruption and the onset of CMEs.

The present study is motivated by a number of questions associated with sunspot and sunspot-group rotation in active regions, and the transfer of helicity between twist and writhe:

- What is the primary mechanism which causes the observed sunspot and sunspot-group rotation?
- What is the relationship between the two kinds of rotation and helicity for an active region?
- Is there a special relationship signifying helicity injection and accumulation in the corona which closely relate with solar eruption?

To answer these questions, we study in detail an active region which produced a major flare with fast CME and the largest proton event in cycle 23, and which has pronounced sunspot and spot-group rotation. Our observations are introduced in Section 2. We describe our results in Section 3, and summary and discussion are given in Section 4.

2. Observations of the NOAA 9684 Active Region

Activity reports of BBSO and Online Weekly Report of Solar Geophysical Data have described AR 9684 observation in detail at *http://www.bbso.njit.edu/* and *http://www.sec.noaa.gov/weekly/*. The active region was a β region at N05E68 on October 28, 2001. By October 30 it had developed into a $\beta\gamma$ magnetic classification. The region decayed slightly from October 31 to November 1, mostly in the trailing sunspots. A very nice filament and inverse-S sigmoid structure were observed to lie along the magnetic neutral line. The magnetic complexity grew very slightly over November 2–3. New opposite polarity flux emerged along the edge of the large leading sunspot, creating a $\beta\gamma\delta$ region on November 4. A portion of the filament and the sigmoid erupted producing a X1.0/3B event at 16:30 UT on November 4 at N05W18, with a very fast full halo CME ($1810\,\mathrm{km\,s^{-1}}$) and the largest proton event (31 700 pfu) in this cycle. This activity was reflected in the observations of a severe geo-magnetic storm with $K_P = 8$. On November 5, the active region also produced an M2.1 flare. However, after producing the X1.0/3B event, it was observed to be in a decayed phase until rotating beyond the west limb. Table I summarizes the observed properties for the AR 9684.

3. Active Region Rotation

In this paper, we use SOHO/MDI continuum images and 96 m line-of-sight magnetograms, BBSO H_α images, and Yohkoh/SXT soft X-ray images, which represent the structures in the photosphere ($T \sim 6000$ K), the chromosphere ($T \sim 10\,000$ K), and corona ($T > 3$ MK), respectively. The vector magnetograms from HSOS are used to calculate the best-fit force-free parameter (α_{best}), vertical current and current helicity.

TABLE I
Location and magnetic class of the active region (from Online Weekly Report).

Date	Latitude CMD	Spot area	Magnetic classification
October 30	N05E41	470	β
October 31	N06E25	470	$\beta\gamma$
November 1	N06E14	440	β
November 2	N06E00	430	$\beta\gamma$
November 3	N06W15	440	$\beta\gamma$
November 4	N05W28	550	$\beta\gamma\delta$
November 5	N07W40	490	$\beta\gamma\delta$

3.1. Rotating sunspot and sunspot-group

Figure 2 shows the continuum images for AR 9684 obtained from SOHO/MDI. From the figure, we notice that the active region is mainly composed of a large leading sunspot (denoted by the top-right arrow) and some smaller following

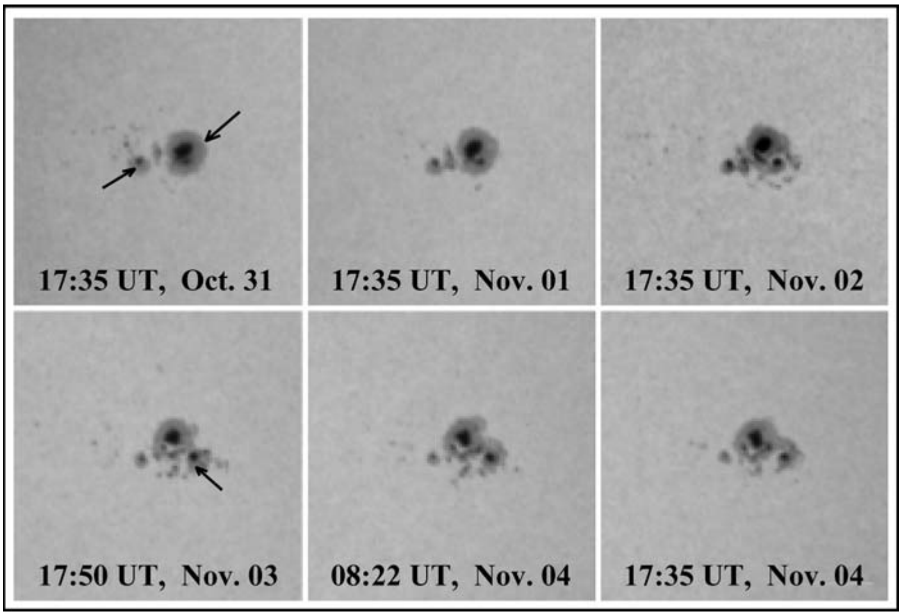

Figure 2. Continuum images obtained from SOHO/MDI. *Top-right arrow* denotes the positive leading sunspot rotating counter-clockwise. *Bottom-left arrow* denotes the major negative following sunspot. *Bottom-right arrow* denotes the spot detaching from the major spot.

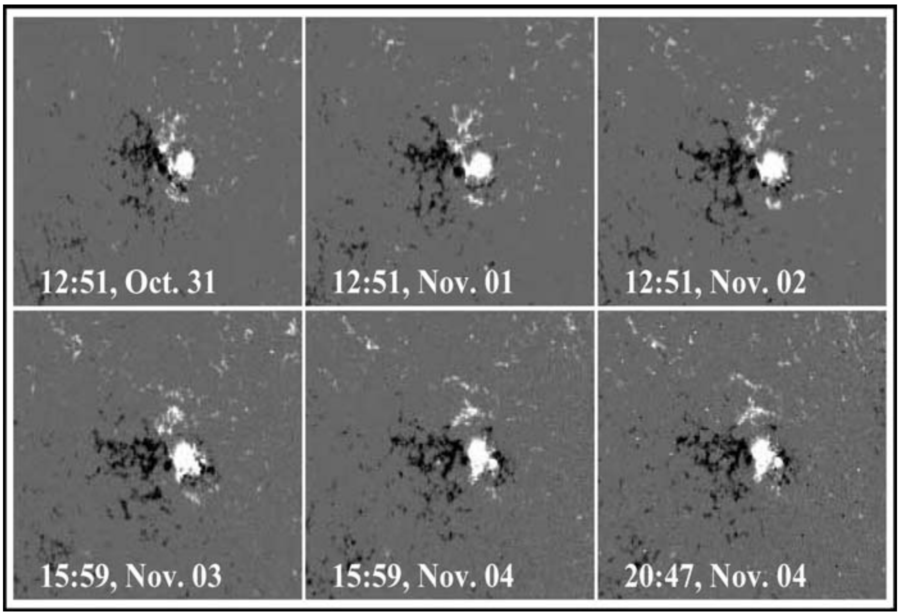

Figure 3. SOHO/MDI 96 m line-of-sight magnetograms. *White patches* denote positive magnetic fields; *black patches* denote negative magnetic fields.

sunspots (bottom-left arrow). The biggest sunspot has a positive polarity (see Figure 3). As the spot evolves, a small spot is observed to detach from the large positive sunspot (denoted by bottom-right arrow), disrupting the penumbra of the leading spot sometime on November 3. This shows up clearly in a movie of the white light images from October 29 to November 4 (see the movie at *http://spacibm.rice.edu/∼alicetlr/9684*). The most significant feature seen in the movie is that the large leading spot rotates counter-clockwise. During the first 4 days, the rotation is faster, then slows down from November 2. At the same time, the spot-group also rotated counter-clockwise around the active region axis, the line joining the center of the large leading spot to the small following one. It has been found previously (Howard, Sivaraman, and Gupta, 2000; Brown *et al.*, 2003) that the younger the active region, the faster the sunspot-group and sunspots rotate. AR 9684 shows evidence of being a younger active region when it first appears around the east limb. This point can be confirmed by the data in Figure 4, which shows evolution of the polarity separation and tilt angle.

3.2. Line-of-sight Magnetograms and Systematic Tilt Angle of the Active Region

Figure 3 shows SOHO/MDI 96 m line-of-sight magnetograms. From this figure, it can be seen that AR 9684 (N06) is approximately a normal Hale-region (Hale

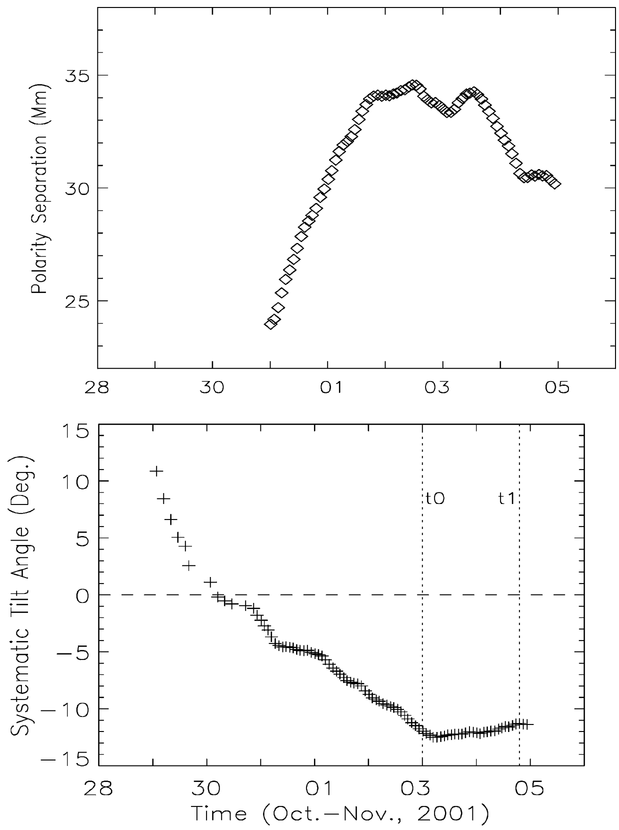

Figure 4. Evolution of the polarity separation and systematic tilt angle. t_0 and t_1 denote the times when the active region crossed the meridian line and when a major flare X1.0/3B erupted.

et al., 1919; Zirin, 1988) in the beginning, with a positive leading polarity at a lower latitude and a diffuse negative following polarity at a higher latitude. However, the following negative polarity displays a drift toward the solar equator. To qualify this we calculate the systematic tilt angle of the active region and determine its evolution. First, the flux-weighted centers for positive and negative polarities are calculated.

We define the center positions of each polarity via

$$x_c = \frac{\sum x(i,\ j)B_z(i,\ j)\mathrm{d}s}{\sum B_z(i,\ j)\mathrm{d}s} \quad \text{and} \quad y_c = \frac{\sum y(i,\ j)B_z(i,\ j)\mathrm{d}s}{\sum B_z(i,\ j)\mathrm{d}s},$$

where $\mathrm{d}s = \mathrm{d}x\mathrm{d}y$ is the area of each pixel. Thus, the tilt angle is defined as the angle that the line joining the two centers makes with the solar equator. The systematic tilt angle of an active region is obtained based on the Cartesian coordinate differences between the two polarities in the heliographic plane:

$$\tan(\varphi) = \frac{y_2 - y_1}{x_2 - x_1}.$$

We set the coordinates such that positive (negative) tilts correspond to active regions tilted clockwise (counter-clockwise) to the equator. Thus, the positive (negative) tilt angle can be used as a proxy for the right (left)-handed writhe of a fluxtube rising through the photosphere from the solar interior.

The separation distance of the two polarities can be calculated by the coordinate differences between them. Figure 4 shows evolution of the polarity separation and systematic tilt angle of AR 9684 over several days near the meridian line. It is found that the polarity separation grew prior to November 2, signifying that the associated fluxtube was emerging as the sunspot rotated. The tilt angle is positive before October 30, and negative after it. Using the previous sign definition for the tilt angle, the positive value corresponds to a right-handed writhe of the fluxtube, while the negative value corresponds to a left-handed writhe. Thus, the change of the writhe for AR 9684 from October 29 to November 3 is negative, that is $\Delta W_r < 0$. This implies that the whole active region and its corresponding fluxtube rotates counter-clockwise.

3.3. Vector Magnetogram, Vertical Current, and Vertical Current Helicity Building Up

The description for the Solar Magnetic Field Telescope of HSOS and the calibration of the vector magnetograms can be found in many papers (Wang *et al.*, 1996; Tian *et al.*, 2001, and references therein). The 180° ambiguity is removed by a linear force-free field method (Wang and Abramenko, 2000). Thus, we can obtain the vector distribution of the magnetic fields of an active region, B_x, B_y, and B_z. Then we can calculate the vertical electric current density via

$$J_z = \frac{1}{\mu}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right),$$

and partial current helicity which can be determined via,

$$h_z = (\nabla \times B)_z \cdot B_z = \mu J_z B_z.$$

Since the HSOS vector magnetogram generally has a noise level in the transverse fields lower than 100 G on a day with a good seeing, we calculate the current density and current helicity density at pixels where the transverse magnetic field ($B_\perp = \sqrt{B_x^2 + B_y^2}$) is larger than 300 G.

A vector magnetogram of the rotating spot of AR 9684 at 02:36 UT on November 3, 2001 is shown in the top of Figure 5, where the short transverse lines denote the transverse field, $B_\perp$, while black and white patches denotes line-of-sight magnetic

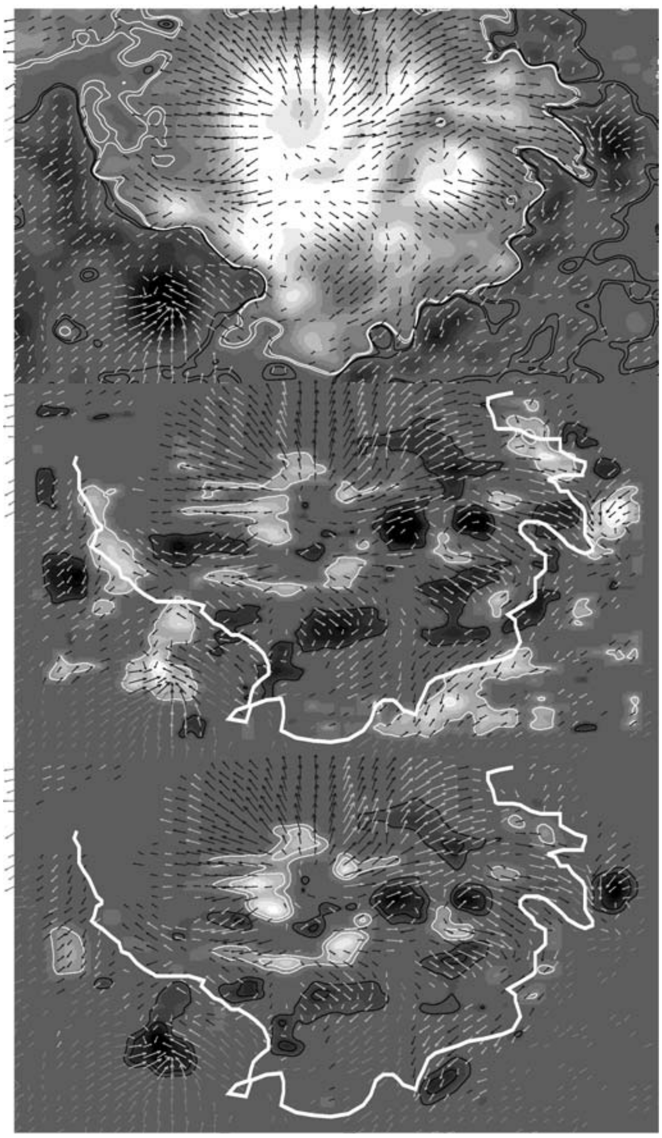

Figure 5. A HSOS vector magnetogram (*top*) of the rotating spot of AR 9684 at 02:36 UT on November 3, and corresponding vertical current (J_z) and vertical current helicity (h_z) overlaid with the transverse magnets fields (*middle* and *bottom*). The *black* (*white*) denotes negative (positive) values. The thick white lines denote the magnetic neutral line. The size of each image is $160'' \times 110''$.

fields, B_z. The middle of the figure shows the distribution of the vertical current density overlaid with the transverse magnetic fields. The thick white long curve denote the magnetic neutral line, which separates positive and negative polarities. We note that the dominant negative current is distributed within the positive polarity sunspot which rotated counter-clockwise. The bottom of the figure shows the partial current helicity density, h_z, overlaid with the transverse magnetic fields. The h_z patterns are also dominantly negative in the whole region, which is consistent with the result that the sunspot rotates counter-clockwise, and follows the hemispheric helicity rule in the northern hemisphere (Pevtsov, Canfield, and Metcalf, 1995). Comparing the curve of transverse filed lines and the sign of h_z, we note the consistency between them, see Figure 1.

3.4. Magnetic field twist, sigmoidal filament, and corona structure

On the basis of the current density J_z calculated previously, we can determine the force-free field parameter,

$$\alpha = \frac{(\nabla \times B)_z}{B_z} = \mu \frac{J_z}{B_z},$$

for the magnetogram. In this way, we can obtain the best-fit single value for the active region as a whole, α_{best}, which is used to denote a measure of the overall twist of the active region magnetic fields. During its traversal of the solar disk, the active region exhibited a negative mean twist with a value,

$$\alpha_{\text{best}} = -0.029 \pm 0.005.$$

From Figure 6, one clearly sees a dark H_α filament running exactly along the magnetic inversion line; the shape of the soft X-ray coronal structure, an inverse-*S* shaped sigmoid, is almost the same as that of the filament. The filament and sigmoid also displayed a counter-clockwise rotation which can be seen by comparing the axis of the sigmoid and filament in Figure 6a and c. This agrees with counter-clockwise rotation of the whole magnetic system shown in Figures 3 and 4. A movie of SXT images (*http://spacibm/~alicetlr/9684*) suggest that the sunspot rotation contributes to the formation and development of the sigmoid. During the major flare which occurred at 16:30 UT on November 4, the sigmoid erupted to a cusp geometry with a strong brightening in its southern (and western) portion, closest to the rotating sunspot. This sigmoid to cusp transition is thought to signify a sigmoid eruption (Sterling and Hudson, 1997).

The aforementioned results imply that the inverse-S shaped filament and sigmoid are associated with an active region with an overall negative twist. The filament and the sigmoid also acquire a negative writhe, signified by their counter-clockwise rotation similar to that of the active region magnetic structure as a whole. This result is consistent with that obtained by Martin, Bilimoria, and Tracadas (1994) and Rust and Kumar (1994, 1996) for inverse-S shaped filaments and sigmoids, with a negative twist and having same sign of twist and writhe (Rust and LaBonte, 2005).

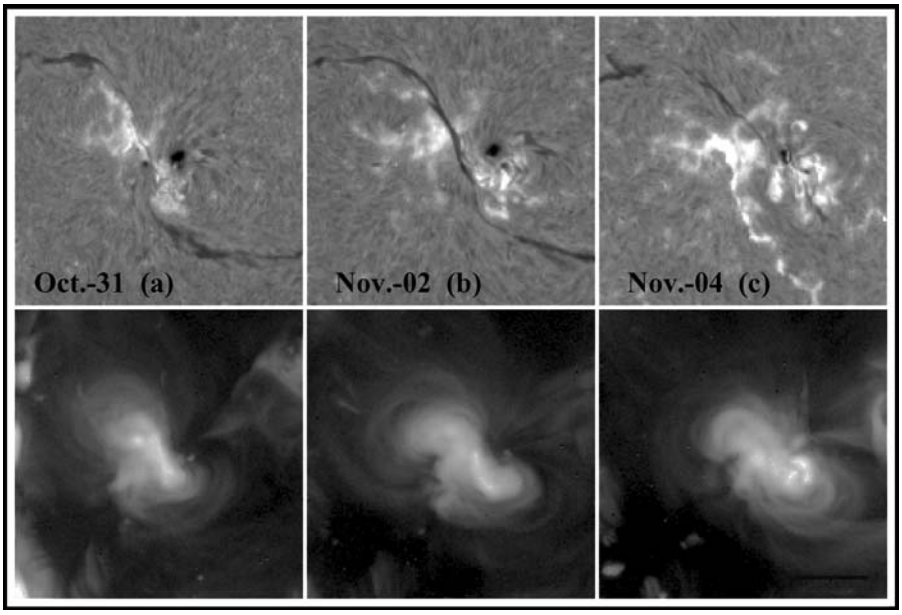

Figure 6. The filament in H_α images (10^4 K) obtained in BBSO, and inverse-S shaped sigmoid in corona (3 MK) obtained by SXT/Yohkoh. The size of images are $375'' \times 375''$.

4. Summary and Discussion

In this paper, we study active region NOAA 9684 in the northern hemisphere, which has a large positive leading spot exhibiting significant counter-clockwise rotation. We calculate the systematic tilt angle of the active region, using SOHO/MDI 96 m line-of-sight magnetograms, and find that the active region changed its magnetic axis from a positive value to a negative one during its transit across the solar disk, signifying a counter-clockwise rotation of the sunspot-group as a whole. Using vector magnetograms obtained from HSOS, we find that the active region magnetic fields show predominantly left-handed twist ($\alpha_{\rm best} \simeq -0.03$), possibly produced by the counter-clockwise rotating sunspot. Negative vertical current and vertical current helicity are distributed mostly within the positive polarity leading spot. After several days of counter-clockwise rotation of both the sunspot and sunspot-group, a $\beta\gamma\delta$ magnetic structure formed, with a inverse-S-shaped narrow H_α filament and soft X-ray sigmoid. On November 4, the sigmoid erupted, and a portion of the filament closely associated with the rotating spot disappeared, in conjunction with a X1.0/3B flare, a very fast CME (1810 km s^{-1}) and the biggest proton event (31 700 pfu) in this cycle. All of the aforementioned results imply that the sunspot rotation played an important role in the large flare eruption and the onset of the fast CME.

For an active region, magnetic fields in the photosphere connect not only to magnetic tubes (or loops) above the photosphere but also to magnetic fluxtubes under the solar surface. For such an isolated magnetic system, a rising Ω-shaped fluxtube obtains some initial helicity H_0 from the dynamo action in the deep interior (Rädler and Seehafer, 1990; Seehafer, 1996; Gilman and Charbonneau, 1999). During its rise through the convection zone into the photosphere and corona, the fluxtube exhibits two complimentary forms of helicity: twist of the magnetic field lines (T_w) and writhe of the fluxtube axis (W_r). Since magnetic helicity is approximately conserved not only in ideal MHD, but also in resistive MHD (Berger, 1984), $T_w + W_r = H_0$ or $\Delta T_w = -\Delta W_r$. The observed decrease of the systematic tilt angle ($\Delta_\varphi < 0$) for AR 9684, signifying the counter-clockwise rotation of the sunspot-group, implies an accumulation of left-handed writhe or a decrease of the total writhe ($\Delta W_r < 0$). Thus, helicity conservation requires an increase of the twist helicity i.e. $\Delta T_w > 0$, implying that additional positive twist should be added into the magnetic system. Such a positive twist would show up as a clockwise rotation of the sunspot. This is opposite, however, to the observed counter-clockwise rotation of the large positive sunspot in AR 9684. The continued negative (left-handed) twist must therefore be produced by some as yet unspecified mechanism in solar interior (Fisher *et al.*, 2000, and references therein), which is consistent with the observed counter-clockwise rotation of the sunspot. We envisage a scenario similar to the following.

Over several days a significant amount of negative twist was produced and accumulated in the magnetic system, which is associated with counter-clockwise rotation of the sunspot. When the absolute value of the twist exceeds some critical value, a kink instability occurs (Hood, 1991; Rust and Kumar, 1994; Fan and Gibson, 2004). Some negative twist is traded for writhe resulting in a subsequent decrease of the writhe helicity. The decreasing writhe is evidenced by a counter-clockwise rotation of the sunspot-group and decrease of the tilt angle. Since the twist and writhe have the same sign, helicity injection and accumulation in the corona becomes possible. Thus, the corona becomes highly energetic and highly unstable and consequently capable of releasing the excess energy and helicity via major flares and fast CMEs. This scenario seems reasonable to interpret most of the observations discussed here: a negative twist associated closely with counter-clockwise rotation of the sunspot; decreasing systematic tilt angle signifying counter-clockwise rotation of the sunspot-group; the formation of a δ active region which is thought as a consequence of the kink instability (Linton *et al.*, 1999; Fan *et al.*, 1999; Tian and Liu, 2003; Tian *et al.*, 2005b); and a large flare eruption and onset of fast CMEs, thought to be a consequence of the release of over-accumulated energy and helicity.

Thus, the observed counter-clockwise sunspot rotation is regarded as a manifestation of a process in which additional magnetic helicity is being produced and transferred from the subsurface to the corona. However, a highly twisted fluxtube rising to break through the photosphere would also display some rotation of its footpoints: counter-clockwise (clockwise) for left (right) handedly twisted magnetic lines. We argue that this is not the primary cause of the sunspot rotation observed in the active region studied here, because the measured twist remained high even after the sunspot essentially stopped rotating (post November 3, 2001, see Figure 5). Moreover, because of helicity conservation, $\Delta W_r < 0$ requires $\Delta T_w > 0$. Thus, the magnetic field configuration should change to a simpler structure if the initial twist is negative and there is no other contribution to the twist. The magnetic structure of AR 9684, however, became increasingly more complex, forming a δ region on November 4 (see Table I).

Other possible origins of sunspot rotation may be excluded. For example, Cannon and Marquette (1991) and Marquette and Martin (1988) found in their studies of sunspot rotation that the origin of the rotation was neither due to the emergence of new flux, nor to the interaction with the surrounding field. Differential rotation does not play a major role in producing either sunspot rotation (see Brown *et al.*, 2003) or sunspot-group rotation (see López Fuentes *et al.*, 2003). The Coriolis force cannot be the origin of the sunspot-group rotation of AR 9684 because it produces clockwise rotation for the active regions in the northern hemisphere.

Our argument is supported by a study of Zhao and Kosovichev (2003) who found subsurface horizontal vortical flows under NOAA 9114, which displayed fast counter-clockwise rotating spots. This directly provides observational evidence that magnetic rotation also exists beneath the visible surface of the active region. Their observation shows that strong subsurface vortical flows should be taken into account as a potential source of magnetic helicity and energy buildup, which can be much stronger in the deeper layers than at the surface because mass density and the plasma β are much higher there. More recently, Rust and LaBonte (2005) displayed a rotational pattern of an untwisting flux-rope in a H_α filament on February 18, 2003, where the Ω-shaped filament was writhing counter-clockwise while each leg of the filament was rotating counter-clockwise. This observation clearly shows that the erupting filament was converting twist to writhe, evident by the rotation of one leg and the writhe of the two legs of the filament. Our study on rotating sunspots demonstrates a similar manifestation of an active region in the photosphere. Therefore, we suggest that sunspot rotation could be thought of as a result of the production and transfer of additional magnetic twist from the sub-surface to the corona, and that sunspot-group rotation in the same direction is a consequence of a fluxtube trading its twist into writhe, resulting from a kink instability caused by the large amount of twist production.

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