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Observational Study of Solar Magnetic Active Phenomena

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Abstract. The electric current separated into two parts reflected the quantative properties of heterogeneity and chirality of magnetic field, and defined them as the shear and twist components of current. We analyze the basic configuration and evolution of superactive region NOAA 6580-6619-6659.

It is found that the contribution of the twist component of current cannot be reflected in the normal analysis of the magnetic shear and gradient of the active regions. The observational evidence of kink magnetic ropes generated from the subatmosphere cannot be found completely in some super delta active regions.

Key words. Sun: activity—flares—magnetic fields.

1. Introduction

It is believed that the newly emerging magnetic flux of opposite polarities and the shear of transverse magnetic field near the magnetic neutral line in active regions are important parameters for the non-potential magnetic field (Hagyard *et al.* 1984). The non-potentiality relates to the existence of electric current and the trigger of solar flares (Lin and Gaizauskas 1987).

2. Magnetic shear, twist and relationship with electric current

The electric current reflects the non-potentiality of magnetic field in the solar atmosphere and can be inferred from the magnetic field in the form

$$\mathbf{J} = \frac{1}{\mu_0}(\nabla \times \mathbf{B}), \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-3}\,\mathrm{GmA}^{-1}$.

The magnetic shear or twist normally reflects the existence of electric current and helicity in the active region. The electric current can be written in the form (Zhang 2001)

$$\mathbf{J} = \frac{1}{\mu_0}(\nabla B) \times \mathbf{b} + \frac{B}{\mu_0} \nabla \times \mathbf{b}, \tag{2}$$

where $\mathbf{B} = B\mathbf{b}$ and $\mathbf{b}$ is the unit vector along the direction of magnetic field and $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$. This provides that the electric current in solar active regions relates to the properties of gradient and chirality of magnetic field. The first term in equation (2) connects with the heterogeneity and orientation of magnetic field, *i.e.*, the shear of vector magnetic field. The second term in equation (2) connects with the twist of unit magnetic lines of force and the intensity of field. We can artificially define that the first term is the shear current and the second term is the twist current in equation (2). According to equation (2), the vertical current can be inferred from

$$J_z = \frac{1}{\mu_0}\left(b_y \frac{\partial B}{\partial x} - b_x \frac{\partial B}{\partial y}\right) + \frac{B}{\mu_0}\left(\frac{\partial b_y}{\partial x} - \frac{\partial b_x}{\partial y}\right). \tag{3}$$

3. Delta active region NOAA 6580-6619-6659

3.1 *Formation of large-scale non-potential magnetic field*

Figure 1 shows the sunspots and corresponding vector magnetic field in this large delta active region NOAA 6580-6619-6659 observed at Huairou Solar Observing Station of National Astronomical Observatories of China in 1991 (Ai & Hu 1986). It is found that the sunspots of opposite polarities grew with the emergence of magnetic flux from the sub-atmosphere to form a bipolar region, and became a compact delta region gradually. The twist of transverse component of photospheric magnetic field increased with the development of active region. As the shear angle of magnetic field is defined by that between the connected line of large-scale magnetic poles of opposite polarities and the transverse field near the magnetic neutral line, one can find that the shear angle of transverse field increased from about 30° on April 14 to 44° on June 9. The flux of magnetic poles of negative polarity increased faster than positive one in active region NOAA 6580-6619-6659. The total magnetic flux in active region NOAA 6580-6619-6659 increased from 2.7×10^{21} Mx to 2.2×10^{22} Mx (maximum value of this active region) during the period between April 14 and June 9, 1991. The total flux increased more than 8 times.

3.2 *The relationship between the magnetic shear, gradient and current*

The magnetic shear is an important parameter to measure the non-potentiality of magnetic field in solar active regions (Wang *et al.* 1994), while the non-potential field can also be measured from the strong magnetic gradient of active regions, which is strongly correlated with active region CME productivity (Falconer 2001).

Figure 2 shows the distribution of magnetic shear in the active region 6659 on June 9, 1991. The shear is defined from the shear angle weighted by transverse magnetic field

$$\theta_T = B_T \cdot \cos^{-1} \frac{\mathbf{B}_T \cdot \mathbf{B}_{pT}}{B_T B_{pT}}, \tag{4}$$

where B_T and B_{pT} are observed transverse field and calculated one from the magnetic charges in the photosphere. The amplitude of the shear angle relates to that of the transverse field and the angle difference between the observed transverse field and

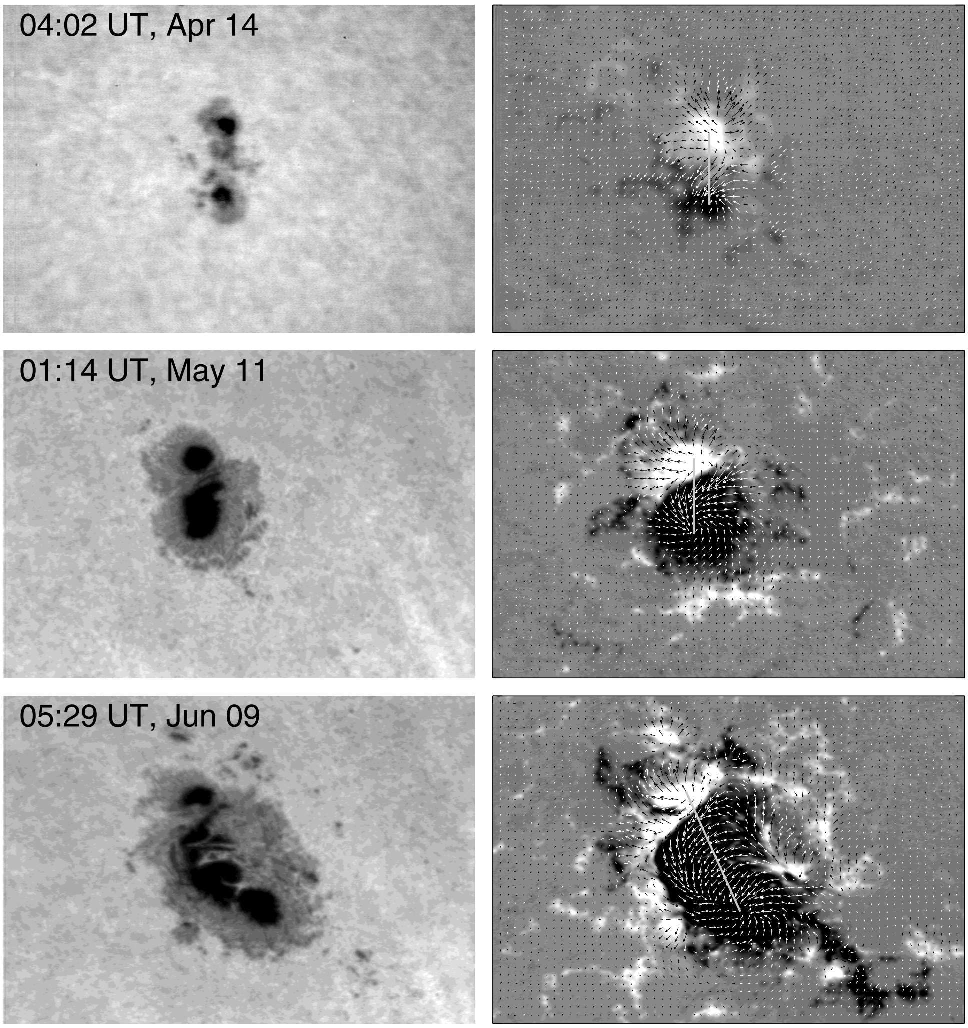

Figure 1. The white light images (left) and vector magnetograms (right) in active region NOAA 6580-6619-6659 in 1991. The white (black) areas indicate positive (negative) polarity. The horizontal arrows mark the transverse component of magnetic field. The straight lines connect the magnetic main poles of opposite polarities. North is at the top, west is at the right. The size of images is $5.23' \times 3.63'$.

inferred potential one. It is noticed that the definition of the shear angle of the transverse field in equation (4) is slightly different from the first term of equation (2), but the physical means are almost the same.

The gradient of photospheric longitudinal magnetic field in the active region can be inferred from

$$|\bigtriangledown(B_z)| = \sqrt{\left(\frac{\partial B_z}{\partial x}\right)^2 + \left(\frac{\partial B_z}{\partial y}\right)^2}. \tag{5}$$

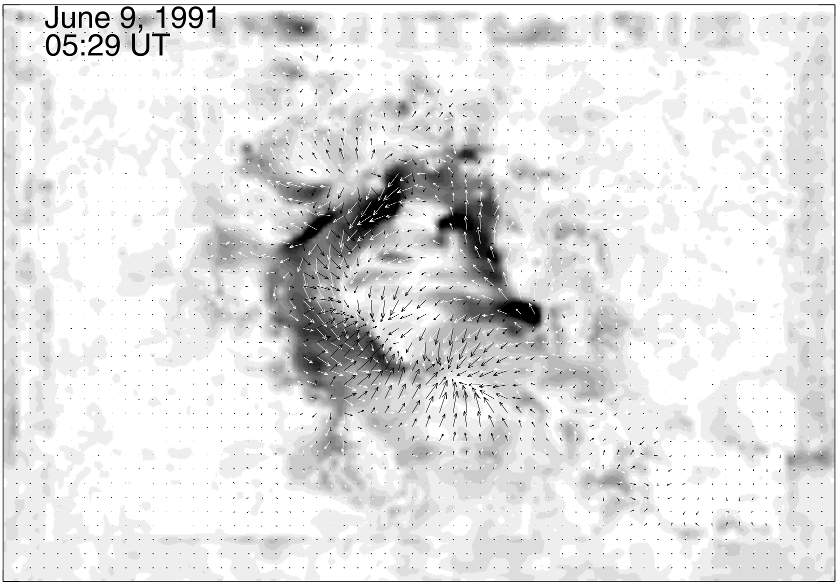

Figure 2. The distribution of magnetic shear in active region NOAA 6659 on June 9, 1991. The white arrows mark the observed transverse field and the black arrows show the transverse components inferred from the calculation of magnetic charges.

The distribution of the magnetic shear and corresponding magnetic gradient in active region NOAA 6580-6619-6659 inferred from photospheric vector magnetograms is shown in Fig. 3. The main contribution of magnetic shear in the active region comes from the deviation of the transverse field from the potential field inferred by magnetic charges in the photosphere, while the magnetic gradient comes from the non-uniformity of the longitudinal field.

By comparing equations (4–5) with equation (2), it is found that the basic information on the magnetic shear and gradient are contained in the shear term of the current. The definition of the angle of observed magnetic shear in equation (4) relative to the direction of transverse field inferred from the potential field is slightly different from the orientation of transverse field relative to $\bigtriangledown B$, but it reflects the difference of the reference systems in analyzing the non-potentiality of magnetic field only. This means that the shear component of the current actually provides both magnetic shear and gradient of field in active regions. The directions of magnetic shear and gradient are lost in equations (4–5). Moreover, it is also noticed that the contribution of twist component of the current is not contained in the analysis of the magnetic shear of transverse field and the gradient of longitudinal field in the active regions. This means that the electric current is a relative complete quantity than the magnetic shear and gradient in the study of the non-potential field. The magnetic shear and gradient are not enough to describe the magnetic non-potentiality completely.

3.3 *Comparison between twist and shear components in the current*

Figure 4 shows the distribution of shear and twist components in the electric currents in active region NOAA 6580-6619-6659 inferred from photospheric vector

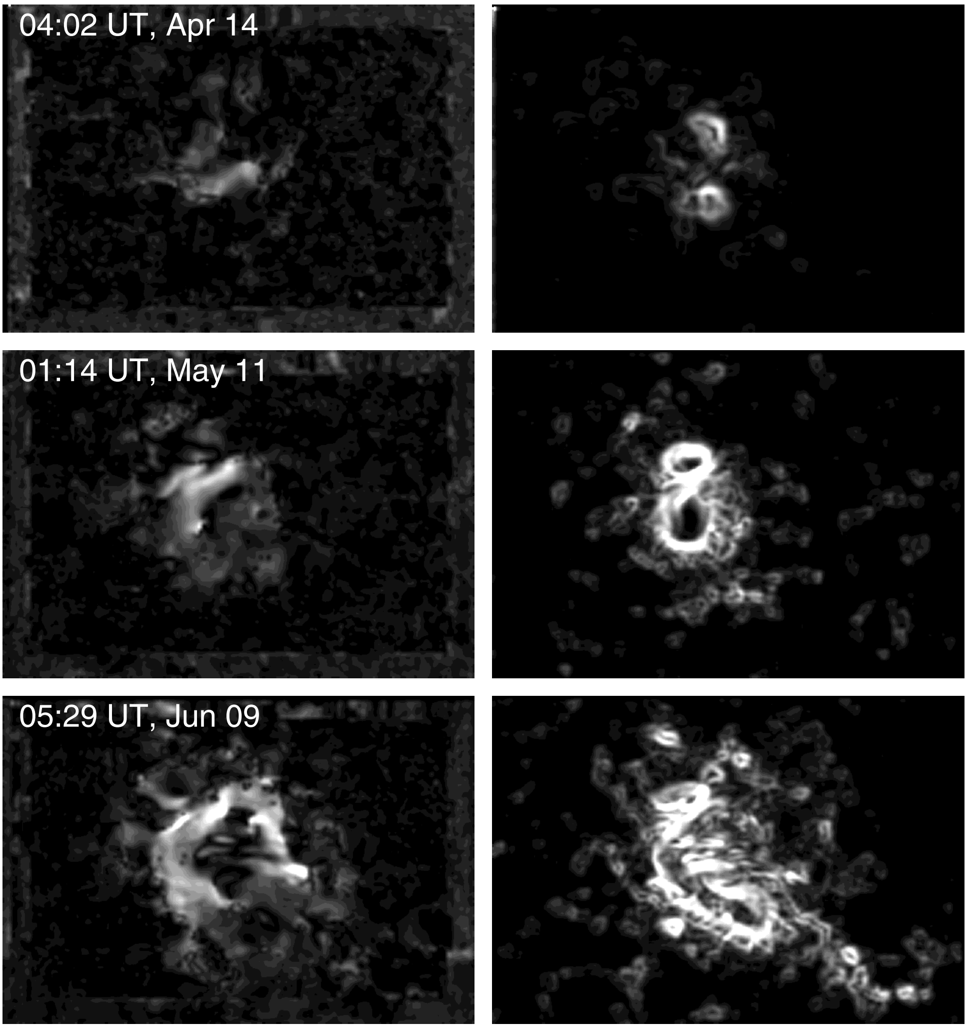

Figure 3. The magnetic shear (left) and gradient (right) in active region NOAA 6580-6619-6659 in 1991 inferred from photospheric vector magnetograms in Fig. 1.

magnetograms. The shear and twist components of the current contain more information on the intrinsic property of non-potentiality of magnetic field in the active regions than the total current. We can find that the topological distribution of both components of the current and their basic relationship relates with the development of active regions, *i.e.*, the topology of electric current in the photosphere obviously connects to the amount of magnetic flux in the active region. The shear current probably consists of an observational evidence of that current flows near the interface of the magnetic poles of opposite polarity and the reason why the inversion line of the vertical electric current obviously crosses the magnetic inversion line in some active regions (Zhang 1997). The mean ratio of statistical standard errors between the shear and twist current in NOAA 6580-6619-6659 on April 14–16 is 0.80, on May 9–13 is 0.54 and on June 8–9 is 0.5. This means that the increment of shear component of the current with

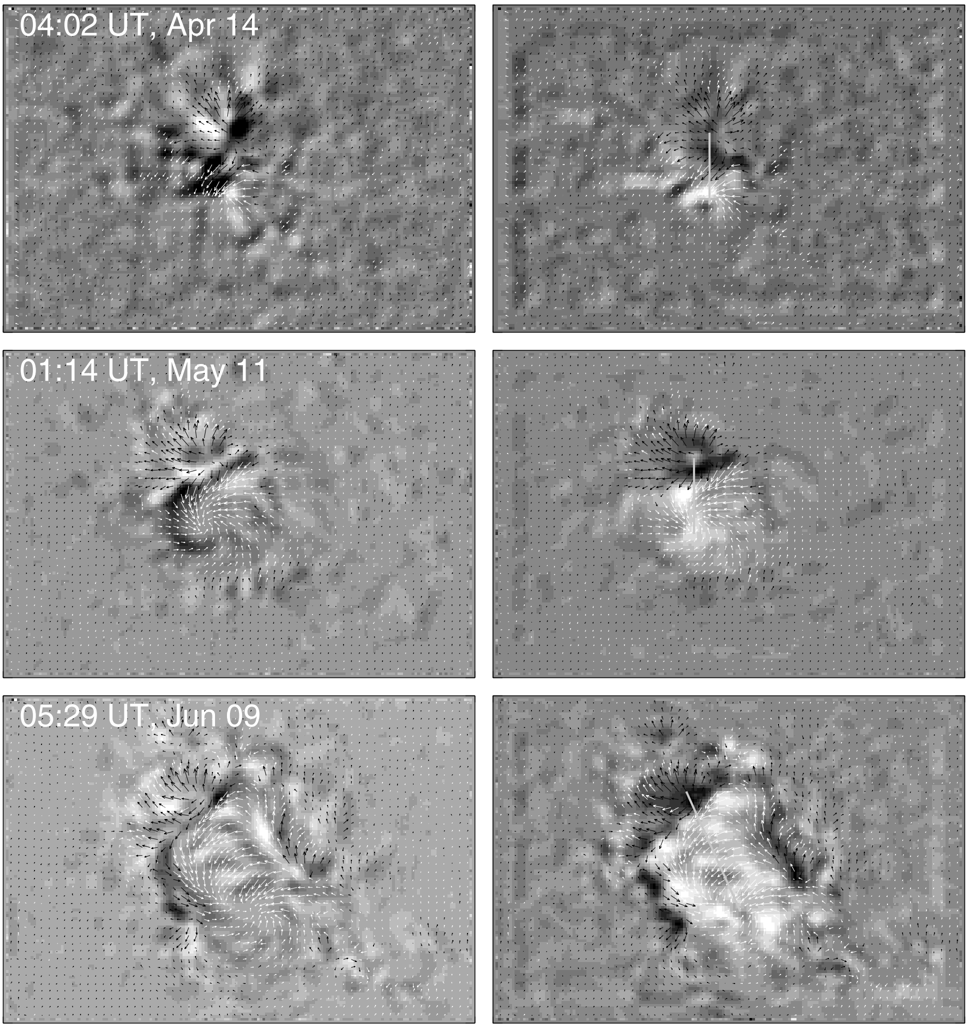

Figure 4. The vertical components of shear (left) and twist (right) component of current in active region NOAA 6580-6619-6659 inferred from the corresponding vector magnetograms of Fig. 1. The white (black) indicates the up (down) flow. The horizontal arrows indicate the transverse components of magnetic field. The straight lines connect the magnetic main poles of opposite polarities.

the development of active region NOAA 6580-6619-6659 is slower than twist one. The twist component of the current shows a dominant tendency of anti-correlation with longitudinal magnetic field, while shear component of the current does not. We can find a basic conclusion that the twist component of the current is the dominant one for the total current in the active region. A similar case has been demonstrated by Leka and Barnes (2003a, b) also. The significant contribution of the shear component of the current near the magnetic neutral line in the early stage of the active region probably reflects that the portion of non-force free field is more notable than the late stage (Georgoulis & Labonte 2004), as one believes that the shear and twist component of the vertical currents provides the different basic information of the total current (Zhang 2001; Leka & Barnes 2003a, b) and the shear component of the current is not cancelled by the twist one completely.

3.4 *Twist and writhe of magnetic ropes*

The magnetic twist and writhe are two basic quantities reflecting the properties of solar helical magnetic loops, which probably generated in the solar sub-atmosphere. Linton *et al.* (1999) proposed that a concentrated kink would first emerge highly tilted, rotate during its subsequent emergence while remaining compact and develop strong shear along its magnetic neutral line. The main characteristic of the kink instability is that the flux loop axis is distorted having the same handedness as the twist. This mechanism necessarily implies that the sign of twist and writhe should be the same (Linton *et al.* 1999; Lopez Fuentes *et al.* 2003). While, it is found that the mean twist and writhe (relates to the tilt angle of active regions) of magnetic field in most bipolar active regions show opposite signs (Tian *et al.* 2001), the opposite statistical result is obtained by Holder *et al.* (2004).

In the northern hemisphere, the right-handed writhe of magnetic loops caused by Coriolis force probably implies that the magnetic field in the photosphere should twist clockwise (contrary-clockwise) in the positive (negative) poles due to the conservation of magnetic helicity. The magnetic field in active region NOAA 6580-6619-6659 twisted in left-handedness in the magnetograms is shown in Fig. 1. The shearing motion of magnetic weighting center of positive (negative) polarity towards east (west) direction in Fig. 1 implies that the writhe of magnetic loops is right-handedness (Lopez Fuentes *et al.* 2003). By comparing the mean sign of the handedness of twist magnetic field (magnetic helicity) and the evolution of active region (the relative moving direction of the magnetic main poles), one can find that active region NOAA 6580-6619-6659 belongs to the regular one, i.e., it is the opposite signs between twist and writhe of magnetic field.

As one analyzes the evolution of active region NOAA 6580-6619-6659 by the Daily Activity Solar Maps in Solar-Geophysical Data, it is found that the tilt angle of the active region was about 68° on April 14, 52° on May 11 and 46° on June 9, while the corresponding force free factor $\alpha_{\rm best}$ was -3.3, -4.2 and -4.5 (unit is 10^{-8} m^{-1}) for the areas that the transverse field is larger than 200G in vector magnetograms and corresponding mean current helicity density $\overline{h_{cz}}$ was -0.22, -4.8 and -5.2 (unit is 10^{-4} G^{2}m^{-1}). The similar tendency of tilt angles of the active region can also be found in the Kitt Peak synoptic magnetic maps. It is found that the reference tilt angles were about 86°, 54°, 50°, 22°, 28° and 14° in 1841, 1842, ... , 1846 Carrington rotation respectively, even if in 1844, 1845 and 1846 Carrington rotation the active region became the enhanced magnetic networks. The tilt angle of the active region decreased and the twisted magnetic field increased during the development of active region. This means that the mean writhe magnetic field does not relax with the twist one synchronously.

4. The formation of non-potentiality of the magnetic field

Figure 5 shows an example of Hβ flares in the active region on May 10, 1991. The Hβ flare ribbons occurred in both sides of the magnetic neutral line. A ribbon consisted

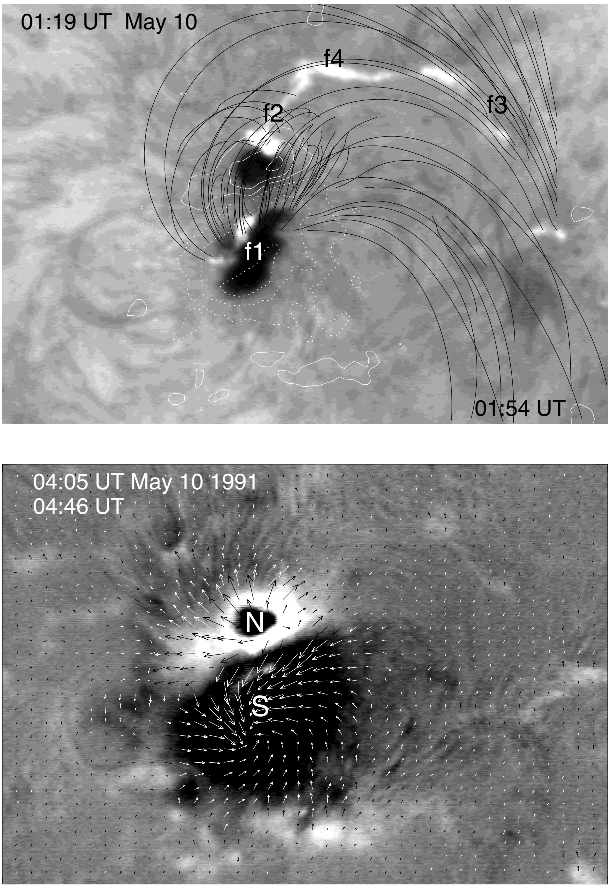

Figure 5. The Hβ flare in active region NOAA 6619 on May 10, 1991 overlapped by the exrapolated magnetic lines of force (top). The solid (dashed) contours mark the positive (negative) polarities of the photospheric magnetic field. The chromospheric longitudinal magnetic field and photospheric transverse magnetic field (bottom). The white (black) marks the positive (negative) polarity.

of two cores marked by $f1$ in the umbra of negative polarity and another one marked by $f2$, $f3$ and $f4$, where $f2$ was located in the umbra and $f3$ and $f4$ extended into the enhanced network of positive polarity. It is found that the extrapolated magnetic lines of force connect both the ribbons of opposite polarities under the approximation of linear force free field. The α factor is -4.0 (unit is $10^{-8}\mathrm{m}^{-1}$) for the extrapolated magnetic lines of force from the magnetogram on May 10, 1991. In the observational photospheric vector magnetogram, the highly sheared transverse component formed in the magnetic neutral line between the flare ribbons with opposite magnetic polarities marked by *N* and *S* in Fig. 5. Comparing the relationship between the Hβ magnetogram and photospheric transverse field, it is found that the chromospheric magnetic features around the magnetic main poles *N* and *S* show a tendency that these features are almost parallel to the direction of the photospheric transverse field. It reflects a basic evidence on the consistence between the distribution of chromospheric magnetic fibrils and direction of observational transverse field resolved 180° – ambiguity near the center of

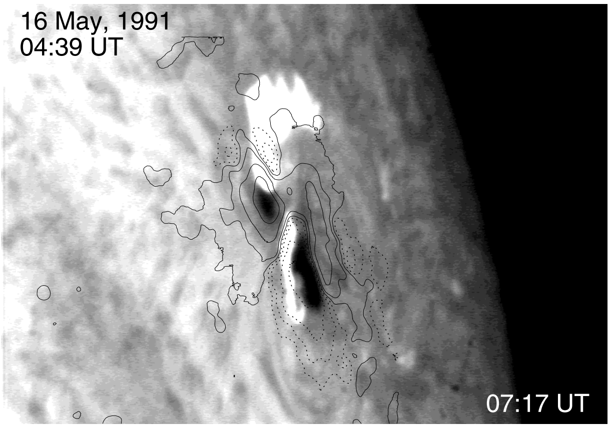

Figure 6. The Hβ flare in active region NOAA 6619 on May 16, 1991 overlapped by the photospheric longitudinal magnetic field. The solid (dashed) contours mark the positive (negative) polarities.

solar disk. The reversal structure in the umbra *N* in the chromospheric magnetograms probably is caused by the disturbance of photospheric blended lines in the wing of Hβ line (Zhang 1996). Figure 6 shows a limb Hβ flare in the active region on May 16, 1991 in which flare ribbons show the similar pattern to that of May 10, even if the projective effect of the longitudinal magnetic field influences the adjustment of the relationship between the position of flare ribbons and magnetic polarities. As the comparison with development of transverse magnetic field near magnetic neutral line in the active region in Fig. 1, it is found that the shear of magnetic field increased after flares on May 10, 16 in Figs. 5 and 6. The similar observational evidence was also demonstrated by Wang *et al.* (1994) and Zhang *et al.* (1994). It means that the increase of highly sheared magnetic field near the magnetic neutral line and the interaction with the existed field are basic processes in the development of active region NOAA 6580-6619-6659, even if a series of powerful flares occurred in it. The shear increase after powerful flares contradicts the kink model of twisted magnetic ropes. It is hard to infer that high intense kinked magnetic ropes formed after the reconnection of magnetic field related to the powerful flares.

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