The Horizontal and Vertical Electric Currents in Three Solar Active Regions and Their Relations With Flares† *

JI Hai-sheng 1,2 SONG Mu-tao 1 ZHANG Yan-an 1 SONG Shu-min 3
1Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008
2National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012
3Xinjiang-Urumchi Astronomical Station, National Astronomical Observatories, Chinese Academy of Sciences, Urumchi 830011

Abstract In this work, systematic calculations are carried out for the distributions of electric currents in three super-active regions (large δ-type spot groups) NOAA 5395, 6659 and 6891. A method of computation published by us is for the first time applied to reveal the distribution of horizontal currents in active regions. The relation between currents and flare kernels may be divided into two kinds, i.e. close correlation and quasi-close correlation. Our statistical results are as follows: (1) For the vertical and horizontal currents, the rates of close correlation are, respectively, 29% and 10%, and those of quasi-correlation are 50% and 30%. (2) Some flare kernels are correlated with both kinds of current, but most flare kernels are correlated with only one kind. (3) There is a small percentage (about 6%) of flare kernels that are not correlated with either kind of current. (4) The two kinds of current supplement each other, and this may be noted in flare forecast. Our analysis also reveals that the places with strong shearing of magnetic field correspond to intense vertical currents and the places with large gradients of magnetic field in the vicinity of magnetic neutral line correspond to intense horizontal currents.

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

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1. INTRODUCTION

As early as 1960s, Severny\[1\] used vector magnetograms to predict flares. His results showed that flares often occur in places where the orientation of the transverse magnetic field changes rather chaotically (case 1) or where the gradient of the longitudinal magnetic field is large (case 2). According to Ampere’s law, case 1 corresponds to strong vertical currents, and case 2, to strong horizontal currents. In the 1980s, with the advent of modern magnetographs as well as the in-depth development of the CCD and computer techniques, increasingly more papers on vertical currents in solar active features were published, and among them there were a series on the relationship between the vertical currents and flare kernels\[2–11\]. On the other hand, up to the present, it is still not possible to investigate the relation between flare kernels and horizontal currents by means of observations\[12\].

Wang et al. discovered that horizontal currents can play an important role in solar active regions. As pointed out in their research, when the gradient of longitudinal magnetic field in the vicinity of the neutral line increases, the shearing motion of gas intensifies and vertical currents also become stronger. It was also pointed out that most flare kernels do not coincide with the peak positions of the vertical currents, rather they are located on their boundaries. Under the hypothesis of force-free field, we\[13\] proposed a method for estimating the horizontal currents. In this paper we shall apply this method to analyze three active regions, namely, NOAA 5395, 6659 and 6891, compute the distributions of the two kinds of currents in them, and compare their positions with the positions of the flare kernels. We shall then present our statistical results.

2. SELECTION AND REDUCTION OF MATERIAL

First we must comment on the system of coordinates used. As pointed out by Hagyard\[5\], when the planar coordinates perpendicular to the line of sight are transformed to spherical coordinates on the solar surface, the transverse magnetic field may get mixed up with the longitudinal magnetic field, and the distribution of electric currents can thereby be altered. Because the transverse and longitudinal fields come from different components of polarization (i.e., \(\sigma^\pm\) and \(\pi\)) and are measured with different accuracies, we prefer to have the plane of the viewing field as the datum plane \(Z = 0\) of the rectangular coordinate system. Therefore, the \(Z\)-direction corresponds to the direction of the line of sight (i.e., the longitudinal direction), while the \(X\)- and \(Y\)-directions, to the horizontal (transverse) directions.

For the transverse magnetic field, there exists the so-called problem of the 180° ambiguity. We adopt a widely used method to resolve this, namely, the observed transverse field and the potential transverse field should form a small angle (i.e., \(B \cdot B_{\text{potential}} > 0\)), then the methods of Krall et al.\[2\] and Gary et al.\[14\] are used to check. In order to eliminate the small-scale turbulent fluctuations and other errors, we smoothed the \(B_x\), \(B_y\) and \(B_z\) data. We used the method of integration of Green’s function, i.e., with a kind of \(\delta\)-function as kernel, we integrated or summed the \(u_{ij}\)'s over the whole range to obtain the smoothed data. For instance, for a data set of size \(N \times M\), the smoothed data are given by the following expression:
\[ \bar{u}_{ij} = b \sum_{I,J=0}^{M,N} u_{IJ} \frac{z}{[(x_I - x_i)^2 + (y_J - y_j)^2 + z^2]^{3/2}}, \quad u \equiv (B_x, B_y, B_z). \]

Here the parameter \( z = \min(\frac{\Delta x}{2}, \frac{\Delta y}{2}) \), and the \( \delta \)-function is the Green’s function of linear force-free field given by Chiu [15]. This method of smoothing can extremely effectively eliminate small-scale turbulent fluctuations in observational data and other errors. The distribution of vertical electric currents calculated on the basis of the smoothed data is almost the same as that given by the other authors [10]. The most important feature is that the iteration with the smoothed data converge extremely well [13].

Next, the smoothed values of \( B_x, B_y \) and \( B_z \) are taken to be the boundary conditions on the plane \( z = 0 \). By using the method of iteration proposed by us, \( \frac{\partial B_z}{\partial z} \) and \( \frac{\partial B_y}{\partial z} \) were computed. Thus on the plane \( z = 0 \) the values of \( J_x, J_y \) and \( J_z \) are simultaneously obtained. In practice, we took only the distribution of \( J_\perp = \sqrt{J_x^2 + J_y^2} \) to be the distribution of horizontal currents.

We selected three super-active regions (all of them are large \( \delta \)-type spot groups), i.e. NOAA 5395, 6659 and 6891, and studied the distribution of electric currents in them. The magnetic field data were provided by Huairou Observing Station. In order to avoid serious effect of projection, we only used data taken within 3-4 days from the center of the solar disc. The magnetic field data generally possess a spatial resolution of 1.5 arcsec and a temporal resolution of 40 seconds. The accuracies of the transverse and longitudinal magnetic fields are, respectively, about 150 G and 20 G. Using sunspot profiles as reference, the \( H_\alpha/H_\beta \) flares were superposed on the magnetograms. The following magnetic field material (one magnetogram per day) was used: NOAA 5395 (33 N 260 L) on March 8-15, 1989; NOAA 6659 (33 N 250 L) on June 6, 8, 9, 12, 14, 1991; NOAA 6891 (12 S 188 L) on October 25, 27, 30, 31, 1991.

The flare material consists of full-disc or partial monochromatic solar images in \( H_\alpha \) and \( H_\beta \) taken at the Ganyu Observing Station of Purple Mountain Observatory, at the Huairou Observing Station of Beijing Observatory and at the Xingjiang-Urumchi Astronomical Station. The flare and magnetic data were kept to be simultaneous as far as possible, so as to ensure physical significance. The flare data can also be found in the publication S.G.D. For NOAA 5395, 338 flares were listed in S.G.D., but in the \( H_\alpha/H_\beta \) flare material chosen by us, only 36 flares were recorded. Of these, 4 are of class X, 22 of class M, and 7 of importance classes \( \geq 2 B \). For NOAA 6659, S.G.D. listed 94 flares and we studied only 24 (comprising 3 of class X, 4 of class M, and 4 of importance classes \( \geq 2 B \)). For NOAA 6891, S.G.D. listed 91 flares among which we studied only 19 (3 of class X, 4 of class M, and 3 of importance classes \( \geq 2 B \)).

To find out the relation between the electric currents and flares, we carefully determined, for each flare, the place of its initial brightening, superposed it on the magnetogram and made comparison with the electric current contours (see Fig.1). Our method of superposition is similar to that of Lin et al. [8]. As proposed by Wang et al. [11], one may distinguish the two cases of coincidence with the region of maximum current” or with the edge of the region of maximum current. So we distinguish between a “close correlation” and a “quasi-
correlation", the former is when the flare kernel is partially or completely superposed within the 90% maximum isopleth (or the main peak), the latter is when the flare kernel is partially or completely superposed within the 80% maximum isopleth (or the secondary peak).

The left four panels show the distributions of longitudinal magnetic field and vertical current. The solid contours indicate positive values, the dashed contours, negative ones. The right four panels show the distributions of longitudinal magnetic field and horizontal current. The solid contours are the isopleths of the current.

3. MAGNETOGRAMS AND ANALYSIS OF CURRENT CHARACTERISTICS

NOAA 5395 was the strongest active region in the 22nd maximum year. Its spot was of the characteristic $\delta$-type. The spot did not dissolve during the 10 days it was seen (March 8-15, 1989) and only got elongated along the direction of the equator. This active region possessed a U-shaped neutral line. Moreover, in its center there was persistent rotational motion of gas\cite{11}. Unfortunately, all the major events happened at night time in China, but this did not matter for our correlation analysis.

In Fig.1, the flare kernels and vertical/horizontal currents are superposed on the magnetograms. Conspicuous contrasts can be seen in Fig.1, (a1) and (a2), (b1) and (b2). On March 10, the flare kernels coincided well with the vertical currents, and had almost no connection at all with the horizontal currents. However, on March 11, the situation was just the opposite, and this can be interpreted as follows. The flare of March 10 was produced in the region of strong magnetic field of the main spot, and violent rotational motion increased the vertical currents. But on March 11, the flares occurred in the vicinity of the magnetic neutral line and in regions of hybrid magnetic polarities, where horizontal currents were comparatively intense. However, if we relax the criterion for correlation, then between the flare kernel of March 11 and the secondary peak of the vertical current there was a correlation, and this can be known from the data given in Tables 1-3. The first four columns of the tables give, in turn, the date, the U.T. of the beginning, maximum and end of the flare, the 5th and 6th columns are the optical and X-ray importance classes, the 7th column, the total number of flare kernels, the 8th and 9th columns, the numbers of flare kernels which are respectively correlated with the vertical and horizontal currents, the 10th column, the number of flare kernels not correlated with the currents and the 11th column lists the labels of the correlated flare kernels used in Fig.1. On March 13, the active region was evidently elongated along the direction of the equator. Almost all the flare kernels were located in the regions of maximum horizontal currents. But on this day the flare kernels were also correlated with the secondary maxima of the vertical currents. From this we may learn that vertical and horizontal currents play their roles either alternately or jointly.

The active region NOAA 6659 (June 5-17, 1991) produced about 100 flares, about half the number produced by NOAA 5395. Nonetheless, NOAA 6659 is also a typical $\delta$-type spot. It did not fall apart during its whole existence on the solar surface, and it was merely elongated along the direction of the equator. On June 6 and 11, we observed two large events of importance classes 4B/X12.0 and 3B/12.0. As may be seen in Fig.1(b), the flare kernel of June 6 was closely correlated with the horizontal current, while that of June 11,
Fig. 1  Flare kernels (shaded areas) superposed on magnetograms and current density maps
with the vertical current. On June 9, the principal maxima of the vertical and horizontal currents nearly coincided, so the flare kernel was closely correlated with both. As for its cause, we have found that the region of strong shearing was just located in the vicinity of the U-shaped neutral line. Moreover, in the penumbra of the main spot there was a small patch with opposite polarity (indicated by an arrowhead in Fig.1(c)). In this region, the horizontal current should be very intense. However, due to strong shearing the vertical current in this place was also very intense[10].

### Table 1 NOAA 5395 (March 3, 1989)

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In comparison with the two foregoing active regions, NOAA 6891 (Oct.23 – Nov.3, 1991) produced rather fewer flares. In the early stage, this active region displayed the characteristics of an isolated δ-type spot. After Oct.29, it began to disperse and elongate along the equator. Moreover, this active region was close to NOAA 6892, so it was not quite
isolated. In consequence of this, some flares were produced by the interaction of these two active regions. It is worthwhile pointing out that a section of the U-shaped neutral line in NOAA 6891 was located in the vicinity of quadrupoles. A helical filament was suspended above it, and most of the flares were produced in this region. The other sections were close to dipoles, and they yielded almost no flares\cite{16}. On October 27, in the region of hybrid polarities (i.e., near the quadrupoles), there were produced two X-class flares and eruptions. In this region, both vertical and horizontal currents were strong. Therefore, flares were closely correlated with both kinds of current. The X-class flare, which occurred on October 27, was closely correlated only with the horizontal current, and quasi-correlated with the vertical current. This can be interpreted as follows. When the active region became elongated and dissolved, the U-shaped neutral line got elongated and twisted, and the horizontal current was concentrated in the vicinity of the U-shaped neutral line. This led to the X-class flare produced on this day being closely connected only with the horizontal current.

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From the above analysis we can see that not all flare kernels are concerned with horizontal or vertical currents. This fact motivated us to make a statistical study of the relation between the currents and flares in these active regions. The results are listed in Table 4.
Table 3  NOAA 6891 (October 1991)

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Table 4  Statistical results

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<th>Numbers quasi-correlating with transverse current</th>
<th>Numbers intimately correlating with longitudinal current</th>
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From the table, we see that, on the average, 29% of flares are closely correlated with vertical currents and 20%, with horizontal currents. The percentages of quasi-correlation are, respectively, 53% and 31%. Thus, the correlation is closer between flares and vertical currents. Also, it is noteworthy that there are quite a few flares that are not correlated with the peak current of either type. Such flares amount to about 6% on average. These statistical results demonstrate that the non-potential magnetic energy of flares is expressed in the electric currents in the active regions. When analysing the relationship between flares and currents, we should not restrict ourselves to vertical currents. The energy of the flares comes from the free energy of the non-potential magnetic field. By using the observed $B_z$ component of the photosphere and Chiu’s integration formula, one may calculate the
magnetic structure of the active region's potential field. In this case, the magnetic field lines go directly from the N-pole to the S-pole, in the direction perpendicular to the magnetic inversion line (the magnetic neutral line), and there is no shearing at all. When the magnetic field lines shear a neutral line, an intense vertical current generally appears. Analogously, the magnetic configuration of a potential field does not possess a large horizontal gradient of the $B_z$ field, where the horizontal current is strong. Therefore, in every place where there is magnetic shearing and a large horizontal gradient of $B_z$, it is certain that the magnetic field must deviate greatly from a potential field. In other words, only when both vertical and horizontal currents are strong, can a region of spot activity reveal the non-potential characteristics of the magnetic field, and in this case it is easier for much stronger flare activity to take place.

4. CONCLUSIONS

As is well known, the non-potential energy of solar flares is released quite rapidly. This non-potential magnetic energy is expressed in the magnetic field configuration by electric currents. Now, currents are vectors, so mere vertical currents are not sufficient. On the basis of this idea, we re-examined the currents in the same regions, and for the first time considered the effect of horizontal currents. We classified the relation between the currents and flare kernels into two kinds, close correlation and quasi-correlation. We analyzed three active regions and got the following statistical results: (1) For vertical and horizontal currents, the fractions of close correlation are, respectively, 29% and 10%, and those of quasi-correlation are, respectively, 50% and 30%; (2) Some flare kernels are correlated with both kinds of current, but most flare kernels with only one kind; (3) A small percentage (about 6%) of flare kernels are not correlated with either kind of current; (4) Currents of both kinds are complementary to each other. All these results tell us that the general characteristic of all active regions is the existence of current systems.

However, owing to the following reasons we cannot use the concept of total current. (1) Horizontal currents and vertical currents are found in different ways. The former come from observation, whereas the latter are from computation. (2) The calculated horizontal current is much larger than the vertical current, about one or two orders of magnitudes larger. This problem is worthy of further investigation.

A property common to the three active regions is the U-shaped neutral line. Along such a neutral line, the gradient of the longitudinal field can be especially large at places, and there exists a mix of polarities. So there are intense horizontal currents. The common property of the three active regions can also be said to be strong shearing, caused by the rotational motion of the gas above the regions. Therefore, intense vertical currents always exist. As demonstrated by the results of research in several recent maximum years, flares may be readily produced in these two kinds of locations.
References