Postprint: Calculation of Line-of-Sight Current Density Associated with an X2.2-Class Flare in Active Region AR11158

Authors: Yang Liping, Liang Hongfei, Liu Jihong, Wang Nan, Sun Xia, Li Zihan

Date: 2020-11-19T00:00:00+00:00

Abstract

High-energy solar activity eruptions are closely related to the current structures within active regions, and Ampere' s law j__z= 〖1/ _0 (×B)〗 _z is the theoretical basis for measuring the line-of-sight current density in active regions. Since random noise inevitably exists in measured vector magnetic fields, current densities calculated using different forms of Ampere' s law exhibit significant differences. To compare the differences in results calculated by different forms and explore a practical method for current calculation, based on the vector magnetogram of active region AR11158 measured by the Solar Dynamic Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) on February 15, 2011, the line-of-sight current density distributions in the active region were calculated using both the differential algorithm and integral algorithm of Ampere' s law. The results show that the line-of-sight current density j__z distribution obtained by the differential algorithm is far more affected by random noise than that obtained by the integral algorithm, and the current structures in the distribution map are less clear than those obtained by the integral algorithm. Additionally, when the radius of the integration loop is increased, the noise signal in the calculated current distribution map decreases rapidly, thereby making the current structures in the calculated line-of-sight current distribution map clearer. However, when the radius of the integration loop is further increased, while obtaining a clearer current distribution map, some fine structures in the current distribution map are also distorted. This study demonstrates that appropriately expanding the integration loop for calculating line-of-sight current distribution maps can reduce the influence of random noise on the calculation results, thereby obtaining clear and realistic line-of-sight current distribution maps, but an excessively large radius of the integration path will, while eliminating noise effects, cause loss of some fine structures in the current distribution. Therefore, in practical current calculations, high-resolution vector magnetograms should be used, and

an appropriate integration path should be selected to calculate the line-of-sight current in active regions using the integral algorithm of Ampere's law, thus helping us explore the relationship between flare eruptions and current structures within active regions.

Full Text

Vertical Electric Current Density Associated with an X2.2 Flare in Active Region AR11158

Yang Liping[1,2], **Liang Hongfei**[1,2], **Liu Jihong**[3,4], **Wang Nan**[1,2], **Sun Xia**[1,2], **Li Zihan**[1,2]

[1]School of Physics and Electronic Information, Yunnan Normal University, Kunming, Yunnan 650500, China
[2]Key Laboratory of High Energy Astrophysics of Yunnan Province, Kunming, Yunnan 650500, China
[3]Yunnan Observatories, Chinese Academy of Sciences, Kunming, Yunnan 650216, China
[4]School of Mechanical and Electrical Engineering, Shijiazhuang University, Shijiazhuang, Hebei 050039, China

Abstract: Solar energetic eruptions are closely related to current structures within active regions, with Ampere's law serving as the theoretical foundation for measuring vertical current density. However, random noise inevitably present in measured vector magnetic fields leads to significant differences in current density calculations depending on the form of Ampere's law employed. To compare these different computational approaches and identify a practical method for current calculation, we analyzed vector magnetograms of active region AR11158 measured by the Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) on February 15, 2011. Using both differential and integral algorithms of Ampere' s law, we computed the distribution of vertical current density within the active region. The results demonstrate that the vertical current density distribution obtained through the differential algorithm is far more susceptible to random noise than that from the integral algorithm, with current structures appearing less clearly defined. Furthermore, when the integration loop radius is expanded, the noise signal in the calculated current distribution decreases rapidly, yielding clearer current structures. However, continued expansion of the integration loop radius, while producing clearer current distribution maps, simultaneously distorts some fine-scale structures. This study confirms that appropriately expanding the integration loop can reduce the impact of random noise on calculations and produce clear, reliable vertical current distribution maps, though excessively large integration radii eliminate noise at the cost of losing fine structural details. Therefore, in practical current calculations, high-resolution vector magnetograms should be used with Ampere' s law in integral form, selecting an appropriate integration path to calculate vertical currents in active regions, thereby helping us explore the relationship between flare eruptions and current structures.

Keywords: active region; flare; vector magnetic field; electric current density; Ampere’ s law

---

Solar flares are high-energy explosive phenomena in the solar atmosphere, often accompanied by coronal mass ejections (CMEs) that release large quantities of high-energy particle streams and magnetic clouds into interplanetary space, becoming a primary cause of hazardous space weather. Therefore, studying flare eruption mechanisms is crucial for effective prevention of catastrophic space weather. Research indicates that magnetic flux emergence and cancellation, sunspot rotation, and shear motion are three primary mechanisms triggering major flares. A study of multiple flares in active region AR12673 (including an X9.3-class flare) proposed a new trigger mechanism where eruption is induced by blockage from pre-existing magnetic fields. During September 4-10, 2017, AR12673 produced 88 flares, including 4 X-class, 27 M-class, and 57 C-class events, with the two most intense flares occurring on September 6 (X9.3) and September 10 (X8.2). The X9.3 flare was the strongest of Solar Cycle 24, producing significant geophysical effects. Consequently, this active region has been extensively studied, with results showing that shear motion and sunspot rotation played important roles in triggering the two successive X-class flares and CMEs. Flare energy release occurred in low-shear magnetic loops above the neutral line, with photospheric enhancements caused by high-energy particles from the flare bombarding the photosphere. Magnetic reconnection is considered an effective mechanism for rapid energy release during flares, typically occurring in highly sheared magnetic field regions. During reconnection, magnetic topology changes, converting magnetic energy into thermal energy for plasma heating and kinetic energy for particle acceleration. The initial energy release is generally believed to occur primarily in the corona, with flares driven by free magnetic energy released through reconnection. Free magnetic energy refers to the difference between total magnetic energy and potential field energy —the greater the deviation of an active region’ s magnetic configuration from a potential field, the larger the difference between total and potential field energy, the stronger the non-potentiality, the more free magnetic energy stored, and the greater the probability of flare production. Shear and twist of magnetic field lines in and below the photosphere, as well as emerging magnetic flux, all contribute to the non-potential nature of active region magnetic fields. Since magnetic field gradients are large at neutral lines with no significant variation in the longitudinal component but highly sheared horizontal fields, substantial free magnetic energy is generated under magnetic pressure, causing most flares to occur near magnetic neutral lines. Studies of five X-class flares found that magnetic shear along neutral lines significantly increased after the flares. Recent high-resolution vector magnetogram studies indicate that active regions with strong shear along their main neutral lines contain substantial net currents. Research on current distributions in active regions shows that flare- and

CME-productive active regions are inherently endowed with large net currents, consistent with recent observational results. Furthermore, flare ribbon positions and morphology are closely related to strong photospheric current ribbons, with morphological changes in flare ribbons during evolution potentially associated with current ribbons. Regions of high current density in solar active regions coincide with Hα flare kernels and areas of extreme magnetic shear, supporting the theory that flares are triggered by plasma instabilities caused by strong currents. These studies confirm that currents may exist before flare eruptions and play important roles in them, with close relationships between current ribbons and flare ribbons in active regions. Therefore, calculating current distributions in strong magnetic fields on either side of active region neutral lines is significant for predicting flare eruption locations and morphology.

With continuously improving temporal and spatial resolution of observational instruments, our understanding of solar eruption mechanisms has deepened, with accurate vector magnetic field measurements being crucial for studying trigger mechanisms. Solar vector magnetic field measurements are based on the Zeeman effect. Since polarization signals from the corona and transition region are extremely weak, vector magnetic fields in these regions are currently difficult to obtain, leaving the photosphere as the only region where magnetic fields can be accurately measured. Using measured photospheric magnetic field structures as boundary conditions, the nonlinear force-free field (NLFFF) model can be applied to extrapolate possible three-dimensional spatial vector magnetic field structures. However, since coronal vector magnetic fields cannot be accurately measured, calculating current distributions in the corona is nearly impossible. Based on accurately measured photospheric vector magnetograms, we can apply Ampere' s law to calculate vertical current density distributions in the photosphere. Since observational instruments are inevitably affected by systematic and random errors during vector magnetic field measurements—systematic errors primarily originate from assumptions and simplifications about solar atmospheric parameters, instrument scattering and abnormal reflection, and system coherence, while random errors mainly arise from atmospheric seeing and instrument electrical noise—systematic errors can be somewhat eliminated from raw data or reduced through methods like dark-field and flat-field processing. The remaining systematic errors are continuously differentiable functions across the field of view, affecting currents in predictable ways. Random errors, however, vary randomly across spatial pixels, cannot be eliminated from raw data, and typically follow normal distributions, posing significant obstacles to calculating vertical current density using the differential algorithm of Ampere' s law. By introducing random noise into vector magnetic fields, previous research studied the relationship between noise effects and spatial resolution, analyzing results from differential, small-loop integral, and large-loop integral methods, finding that the integral form of Ampere' s law along a large loop yielded the best results when high-order terms were neglected. To further verify these results and examine the correspondence between flare ribbons and current ribbons, we used vector magnetic field observations of AR11158 from SDO/HMI on February 15, 2011, applying four forms of Ampere' s law (differential form, small-loop integral, medium-loop integral, and large-loop integral) to calculate the vertical current distribution in this active region, comparing results with appropriately expanded integration loops. We also examined the relationship between current density extrema and flare ribbon positions and morphology to test the validity and rationality of the current density calculation method.

1.1 Data Sources

The Solar Dynamics Observatory (SDO) carries three instruments: the Helioseismic and Magnetic Imager (HMI), the Atmospheric Imaging Assembly (AIA), and the Extreme Ultraviolet Variability Experiment (EVE). SDO/HMI provides data on photospheric vector magnetic fields, intensity, and Doppler velocities. On February 15, 2011, active region AR11158 located at S20W12 exhibited a complex $\beta\gamma$ magnetic configuration and produced an X2.2-class flare between 01:44 UT and 02:06 UT lasting approximately 22 minutes. References [28-29] provide detailed studies of this active region. In this work, we use magnetic field data from SDO/HMI during the flare eruption, with a spatial resolution of 0.5 arcseconds per pixel and temporal resolution of 45 seconds per frame. Vector magnetic field measurements are obtained through polarization radiative transfer equations based on the Zeeman effect, with specific processing details described in [30]. SDO/HMI employs the Very Fast Inversion of the Stokes Vector (VFISV) technique [31] to derive vector magnetograms with a temporal resolution of 12 minutes per frame. The 180° azimuth ambiguity inherent in solving vector magnetic fields from polarization radiative transfer equations poses significant challenges. Various methods have been developed to address this, including potential field calibration, force-free field approximation, minimum energy method, magnetic charge method, and continuity method. The SDO team preprocesses vector magnetic field data using the minimum energy method [35] to resolve the 180° ambiguity, enabling successful solar magnetic field research.

SDO/AIA observes different layers of the solar atmosphere, simultaneously providing information in 10 different wavelength bands: 7 extreme ultraviolet (EUV) bands (30.4 nm, 17.1 nm, 19.3 nm, 21.1 nm, 33.5 nm, 9.4 nm, 13.1 nm), 2 ultraviolet (UV) bands (170 nm and 160 nm), and 1 visible light band (continuum at 450 nm). Reference [38] details the corresponding spectral lines and observation regions for each band. AIA images have a spatial resolution of 0.6 arcseconds per pixel and temporal resolutions of 12 seconds per frame (EUV bands) and 24 seconds per frame (UV bands). This study uses SDO/AIA data from the 170 nm and 30.4 nm bands, where 170 nm observes the temperature minimum region and photosphere, while 30.4 nm observes the chromosphere and transition region.

1.2 Calculation Methods

Figure 1 Figure 1: see original paper shows the longitudinal magnetogram of AR11158 at 02:00:00 UT on February 15, with white representing positive polarity and black representing negative polarity. The area enclosed by the black box contains a pair of opposite magnetic polarities, with the red arrow indicating the magnetic neutral line (polarity inversion line) separating positive and negative fields, shown as yellow dashed lines in (a) and (b). An oval negative polarity region lies above the neutral line, while a crescent-shaped positive polarity region lies below, with extremely large magnetic field gradients near the neutral line. Figure 1(b) presents the vector magnetogram observed by SDO/HMI at the same time, with longitudinal magnetic field as the background and small arrows representing transverse magnetic field components. Blue arrows cover positive polarity regions, red arrows cover negative polarity regions, arrow length indicates transverse field magnitude, and arrow direction shows transverse field orientation. The grayscale background matches Figure 1(a), representing longitudinal field strength. The vortex-like structure evident in the transverse field arrows suggests strong currents may exist in the active region. We use these vector magnetograms to calculate current density distributions using different forms of Ampere' s law, comparing results to identify the optimal calculation method. In addition to vector magnetograms, the Solar Dynamics Observatory also acquired monochromatic images in various wavelength bands. Figures 1(c) and (d) show monochromatic images of the X2.2 flare in AR11158 on February 15, 2011, observed by SDO/AIA at 170 nm (01:58:08 UT) and 30.4 nm (01:58:12 UT). The flare ribbons appear primarily within the black box region, with some structures along its upper right edge. Comparing Figures 1(a), (c), and (d) reveals that the flare occurred mainly near the magnetic neutral line.

Research indicates that solar active regions may contain sheet-like current structures with relatively small spatial scales but high material densities. While abundant observational data for these structures have been obtained, particularly during flare eruptions, accurately measuring current intensities and specific current density distributions within them remains challenging. We calculate the vertical current density J_z on the photospheric surface using photospheric vector data from HMI. Given the discrete nature of vector magnetogram data, the differential form of Ampere' s law $J_z = \frac{1}{\mu_0}(\nabla \times \mathbf{B})_z$ is typically used, where μ_0 is the vacuum permeability. As shown in Figure 2 [Figure 2: see original paper], calculations use values of B_x and B_y at midpoints A(x+Δx,y), B(x,y+Δy), C(x-Δx,y), and D(x,y-Δy) on the four sides of the innermost small square, with the difference formula:

$$J_{z0}(x,y) = \frac{1}{\mu_0}\left[\frac{B_y(x+\Delta x,y) - B_y(x-\Delta x,y)}{2\Delta x} - \frac{B_x(x,y+\Delta y) - B_x(x,y-\Delta y)}{2\Delta y}\right]$$

where J_{z0} is the vertical current density calculated using the differential method. This equation shows that higher spatial resolution (smaller Δx and Δy) yields finer current density structures. However, measured magnetic fields $\mathbf{B}$ are often affected by random noise, introducing error vectors $\mathbf{n}$. Representing the true magnetic field value plus systematic errors as $\mathbf{B}_t$, the measured field can be expressed as $\mathbf{B} = \mathbf{B}_t + \mathbf{n}$. The calculated vertical current density J_{z0} then becomes the sum of the true vertical current density $J_{z,true}$ and error current density $J_{z,noise}$ generated by random noise:

$$J_{z0} = J_{z,true} + \frac{1}{\mu_0}\left(\frac{n_y(x+\Delta x, y) - n_y(x-\Delta x, y)}{2\Delta x} - \frac{n_x(x, y+\Delta y) - n_x(x, y-\Delta y)}{2\Delta y}\right)$$

Equation (3) demonstrates that when random noise components n_x and n_y remain constant, decreasing Δx and Δy with increasing spatial resolution ultimately amplifies the vertical current density, drowning out the true current signal. Therefore, the integral form of Ampere' s law is typically employed:

$$J_z = \frac{1}{\mu_0}\frac{\oint \mathbf{B}_t \cdot d\mathbf{l}}{ds}$$

where $\mathbf{B}_t$ is the measured transverse magnetic field, $\mathbf{B}_t = B_{tx}\hat{\mathbf{i}} + B_{ty}\hat{\mathbf{j}}$, with $\hat{\mathbf{i}}$, $\hat{\mathbf{j}}$ being unit vectors in the x and y directions and B_{tx}, B_{ty} the measured transverse field components; ds is the area enclosed by the integration path, typically a square with side length $n\Delta x$, where n is the number of spatial grid points, so $s = n\Delta x \times n\Delta y$. Equation (4) shows that Δx varies with vector magnetic field spatial resolution—higher resolution requires larger loops, lower resolution requires smaller loops. Selecting an appropriately sized integration loop based on resolution can rapidly reduce random noise effects. Small, medium, and large loops are typically defined based on resolution.

As shown in Figure 2, the loop integral method uses transverse magnetic field $\mathbf{B}_t$ values along the integration path to calculate the average current density within the enclosed area, yielding the current density at the loop center O(x,y). The result represents the average current density over the integration region. Integration proceeds counterclockwise, with loops centered at O(x,y) expanding from small to large (or inner to outer), designated as small loop (square with 2Δx side length, integration path C_1), medium loop (square with 4Δx side length, integration path C_2), and large loop (square with 6Δx side length, integration path C_3). The small loop integration path follows the square edges through points (x+Δx, y+Δy), (x-Δx, y+Δy), (x-Δx, y-Δy), and (x+Δx, y-Δy), with corresponding vertical current density J_{z1}. From Equation (3), the small loop formula is:

$$J_{z1}(x,y) = \frac{1}{\mu_0}\frac{\oint_{C_1} \mathbf{B}_t \cdot d\mathbf{l}}{ds} = \frac{1}{\mu_0}\frac{\sum_{C_1} \mathbf{B}_t \cdot \Delta\mathbf{l}}{(2\Delta x)(2\Delta y)}$$

where $ds = 2\Delta x \times 2\Delta y$.

The medium loop integration path follows the square edges through points (x+2Δx, y+2Δy), (x-2Δx, y+2Δy), (x-2Δx, y-2Δy), and (x+2Δx, y-2Δy), with corresponding vertical current density J_{z2}:

$$J_{z2}(x,y) = \frac{1}{\mu_0}\frac{\oint_{C_2}\mathbf{B}_t \cdot d\mathbf{l}}{ds} = \frac{1}{\mu_0}\frac{\sum_{C_2}\mathbf{B}_t \cdot \Delta\mathbf{l}}{(4\Delta x)(4\Delta y)}$$

where $ds = 4\Delta x \times 4\Delta y$.

The large loop integration path follows the square edges through points (x+3Δx, y+3Δy), (x-3Δx, y+3Δy), (x-3Δx, y-3Δy), and (x+3Δx, y-3Δy), with corresponding vertical current density J_{z3}:

$$J_{z3}(x,y) = \frac{1}{\mu_0}\frac{\oint_{C_3}\mathbf{B}_t \cdot d\mathbf{l}}{ds} = \frac{1}{\mu_0}\frac{\sum_{C_3}\mathbf{B}_t \cdot \Delta\mathbf{l}}{(6\Delta x)(6\Delta y)}$$

where $ds = 6\Delta x \times 6\Delta y$.

Figure 3 [Figure 3: see original paper] shows vertical current density distributions calculated using both differential and loop integral methods of Ampere' s law during the flare eruption (02:00:00 UT). "Dif" denotes the differential method, "Int" the integral method, "1C" small loop, "2C" medium loop, and "3C" large loop. White and black represent positive and negative current density distributions, respectively, with corresponding vertical current density values of +0.05 $\mathrm{A \cdot m^{-2}}$ and -0.05 $\mathrm{A \cdot m^{-2}}$. For comparison and analysis, we apply identical vertical current density thresholds of \$$\pm 0.05 A \cdot m$\^{}{-2}\$ for both differential and integral methods. Figures 3(a) and (b) show distributions calculated using the differential method and integral method (small loop), respectively. Figures 3(c) and (d) show results with expanded integration loops: (c) medium loop and (d) large loop. Due to random noise in measured transverse magnetic fields, the current density distribution from the differential method (Figure 3(a)) shows greater noise influence compared to the small-loop integral method (Figure 3(b)). When expanding the integration loop to two loops (medium loop, Figure 3(c)), the resulting current density distribution exhibits even less noise than the small-loop method. With three loops (large loop, Figure 3(d)), although noise is further reduced, some fine structures in the current density distribution become noticeably distorted. Therefore, considering random noise, the optimal approach is to expand the integration loop to two loops, i.e., using the medium-loop integral method to calculate vertical current density.

Comparing Figure 3(c) with Figure 1(a) reveals that strong currents primarily originate in strong magnetic field regions near the neutral line, showing good correspondence with strong fields. Figures 1(a), (c), and (d) indicate that flare ribbons appear in regions near the neutral line, suggesting a positional correspondence between current ribbons and flare ribbons. As shown in Figure 4

[Figure 4: see original paper], we align the vertical current density distribution calculated using the medium-loop integral method (Figure 3(c)) with monochromatic images at 170 nm and 30.4 nm from the same flare moment (Figures 1(c) and (d)) after projection correction. Green and blue contour lines represent positive and negative current ribbons, respectively, with corresponding vertical current densities of +0.02 $\mathrm{A \cdot m^{-2}}$ and -0.02 $\mathrm{A \cdot m^{-2}}$. The results show that flare ribbons appear roughly in locations with stronger currents where more free magnetic energy is stored and released, and that flare ribbons and current ribbons exhibit similar morphologies.

3 Discussion and Conclusion

Determining where solar flares will erupt and what morphology they will assume has long been a frontier topic in solar physics. Flare eruptions are closely related to active region currents, which manifest primarily as vertical currents generated by variations in the transverse magnetic field from vector magnetograms. Therefore, selecting an effective method for calculating vertical currents in active regions is particularly important. Without considering random noise, both differential and integral forms of Ampere’ s law produce similar vertical current density results as spatial resolution increases. However, when random noise is considered, the differential form, though computationally efficient, yields increasing current density dispersion and uncertainty as spatial resolution improves (grid spacing Δx and Δy decrease). Even smoothing the vertical current density distribution eliminates not only noise signals but also underlying current signals. The integral form, while more computationally intensive, reduces measurement dispersion and minimizes random error effects. Expanding the integration loop effectively reduces vector magnetic field spatial resolution (increasing grid spacing Δx and Δy), rapidly decreasing measurement dispersion and improving accuracy. The variance of vertical current density calculated using Ampere’ s law in integral form is smaller than that from the differential form. When the integration path exceeds the linear size of the smallest spatial resolution structures in the vector magnetogram, fine structures in the resulting current density distribution become distorted. Using high-resolution vector magnetograms to find an appropriate integration path for calculating vertical current density can remove noise signals while preserving original current signals, yielding more accurate results.

Based on this theory, we compared several methods for calculating vertical current density: the differential algorithm, small-loop integral method, medium-loop integral method, and large-loop integral method (Figure 3). We conclude that when random noise is considered, the integral algorithm of Ampere’ s law with the integration loop expanded to the second loop produces the clearest vertical current density distribution without distorting fine current structures. Figure 4 shows that flare ribbons and current ribbons exhibit remarkably similar eruption positions and morphology, demonstrating that calculated vertical current density distributions are crucial for accurately predicting flare eruption locations and morphology. To theoretically analyze whether an integration path is appropriate, simulations could set a true current density value in the vector magnetic field. However, since our data are observational with spatial sampling affected by random noise, true current density values cannot be determined. Therefore, this work validates the accuracy of the simulation method from [24] using actual observational data, showing that expanding the integration loop (to the medium loop in this study) yields the best current density distribution. This approach allows us to predict possible flare eruption locations and morphology using calculated vertical current density distributions, validating the effectiveness and reliability of our current calculation method. Future work will utilize AIA data from other wavelength bands to study flare ribbons and current ribbons in multiple active regions, testing the rationality and universality of this method.

References:

[1] Gosling J T, Mccomas D J, Phillips J L, et al. Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections[J]. Journal of Geophysical Research Space Physics, 1991, 96(A5).

[2] Zirin, H, Wang. Narrow lanes of transverse magnetic field in sunspots[J]. Nature, 1993.

[3] Yan X L, Qu Z Q. Rapid rotation of a sunspot associated with flares[J]. Astronomy & Astrophysics, 2007, 468(3):1083-1088.

[4] Yan X L, Qu Z Q, Kong D F. Relationship between rotating sunspots and flare productivity[J]. Monthly Notices of the Royal Astronomical Society, 2010, 391(4):1887-1892.

[5] Meunier N, Kosovichev A. Fast photospheric flows and magnetic fields in a flaring active region[J]. Astronomy & Astrophysics, 2003, 412(2):541-553.

[6] Yang S H, Zhang J, Zhu X S, et al. Block-induced complex structures building the flare-productive solar active region 12673[J]. The Astrophysical Journal Letters, 2017, 849: L21(7pp).

[7] Yan X L, Wang J C, Pan G M, et al. Successive X-class Flares and Coronal Mass Ejections Driven by Shearing Motion and Sunspot Rotation in Active Region NOAA 12673[J]. The Astrophysical Journal, 2018, 856(1):79.

[8] Sharykin I N, Kosovichev A G. Onset of Photospheric Impacts and Helioseismic Waves in X9.3 Solar Flare of September 6, 2017[J]. The Astrophysical Journal, 2018, 864(1).

[9] Masuda S, Kosugi T, Hara H, et al. A loop-top hard X-ray source in a compact solar flare as evidence for magnetic reconnection[J]. Nature, 1994, 371(6497):495-497.

[10] Zhou Tuanhui, Ji Haisheng, Wang Junfeng. Contraction and Shearing of Solar Flare Rings[J]. Astronomical Research and Technology, 2012(04):357-362.

[11] Lin Yuanzhang. Introduction to Solar Physics[M]. Beijing: Science Press, 2000.

[12] Sakurai T. Magnetic field structures and flares[J]. 1993, 13(9):109-117.

[13] Sun X, Hoeksema J T, Liu Y, et al. ERRATUM: "EVOLUTION OF MAGNETIC FIELD AND ENERGY IN A MAJOR ERUPTIVE ACTIVE REGION BASED ON SDO/HMI OBSERVATION" (2012, APJ, 748, 77)[J]. The Astrophysical Journal, 2016, 828(1):65.

[14] Luo Baorong, Hou Shuming. The evolution characteristics of the magnetic field velocity field of AR6659 photosphere chromosphere and its relationship with large flares[J]. Journal of the Yunnan Observatory, 1994.

[15] Wang H, Ewell, Zirin H, et al. Vector magnetic field changes associated with X-class flares[J]. Astrophysical Journal, 1994, 424(1).

[16] Ravindra B, Venkatakrishnan P, Tiwari S K, et al. Evolution of Currents of Opposite Signs in the Flare Productive Solar Active Region NOAA 10930[J]. Astrophysical Journal, 2011, 740(1):1441-1458.

[17] T. Török, J. E. Leake, V. S. Titov, et al. DISTRIBUTION OF ELECTRIC CURRENTS IN SOLAR ACTIVE REGIONS[J]. The Astrophysical Journal, 2014.

[18] Janvier M, Aulanier G, Bommier V, et al. Electric currents in flare ribbons: Observations and three-dimensional standard model[J]. Astrophysical Journal, 2014, 788(1):60.

[19] Hagyard M J. Observed nonpotential magnetic fields and the inferred flow of electric currents at a location of repeated flaring[J]. Solar Physics, 1988, 115(1):107-124.

[20] Lin Yuanzhang, Gaizauskas V. Electric current in the solar flare nuclei[J]. Science of China (Series A Mathematics Physics Astronomy Technical Science), 1987, 30(11):1184-1190.

[21] Wilkinson L K, Emslie A G, Gary G A. On neutralized currents in the solar corona[J]. The Astrophysical Journal, 1992, 392(1).

[22] Wiegelmann, Thomas, Sakurai, Takashi. Solar Force-free Magnetic Fields[J]. Living Reviews in Solar Physics, 2012, 9(1):5.

[23] Klimchuk, J.A., Canfield, R., Rhoads, J.E. The Practical Application of the Magnetic Virial Theorem[J]. The Astrophysical Journal, 1992, 385, 327.

[24] Liang H F, Ma L, Zhao H J, et al. Electric current density calculation and error analysis of solar active regions[J]. New Astronomy, 2009, 14(3):294-301.

[25] Pesnell W D, Thompson B J, Chamberlin P C. The Solar Dynamics Observatory[J]. Solar Physics, 2012, 275(1-2):3-15.

[26] Schou J, Scherrer P H, Akin D J, et al. Design and Ground Calibration of the Helioseismic and Magnetic Imager (HMI) Instrument on the Solar Dynamics Observatory (SDO)[J]. Solar Physics, 2012, 275(1-2):229-259.

[27] James R. Lemen, Alan M. Title, David J. Akin, et al. The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO)[J]. Solar Physics, 2012.

[28] C H H A B, C H W A, C Y Y A, et al. Chirality and magnetic configuration associated with two-ribbon solar flares: AR 10930 versus AR 11158[J]. Advances in Space Research, 2020, 65(12):2828-2845.

[29] Petrie G J D. A spatio-temporal description of the abrupt changes in the photospheric magnetic and Lorentz-force vectors during the 2011 February 15 X2.2 flare[J]. Solar Physics, 2013, 287(1-2):415-440.

[30] Sébastien Couvidat, Schou J, Shine R A, et al. Wavelength Dependence of the Helioseismic and Magnetic Imager (HMI) Instrument onboard the Solar Dynamics Observatory (SDO)[J]. Solar Physics, 2012, 275(1-2): p.285-325.

[31] Borrero J M, Tomczyk S, Kubo M, et al. VFISV: Very Fast Inversion of the Stokes Vector for the Helioseismic and Magnetic Imager[J]. Solar Physics, 2011, 273(1):267-293.

[32] Sakurai T, Makita M, Shibasaki K. Observation of magnetic field vector in solar active regions. MPARp, 1985, 26: 24.

[33] Krall K R, Smith Jr J B, Hagyard M J, et al. Vector magnetic field evolution energy storage and associated photospheric velocity shear within a flare-productive active region[J]. Solar Physics, 1982, 79: 59.

[34] Wang Huaning, Lin Yuanzhang. A Comprehensive Method for Determining the Azimuth of the Sun' s Transverse Magnetic Field[J]. Chinese Journal of Astrophysical Sciences, 1994, 014(002):196-196.

[35] Metcalf T R. Resolving the 180-degree ambiguity in vector magnetic field measurements: The 'minimum' energy solution[J]. 1994, 155(2):235-242.

[36] Gary G A, Moore R L, Hagyard M J, et al. Nonpotential features observed in the magnetic field of an active region[J]. APJ, 1987.

[37] Aly J J. Some properties of the solutions of a non-linear boundary value problem for a force-free field in an infinite region of space. I - Energy estimates[J]. Astronomy & Astrophysics, 1988, 203:183-188.

[38] Lemen J R, Title A M, Akin D J, et al. The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO)[J].

[39] Ciaravella A, Raymond J C, Li J, et al. Elemental Abundances and Post-Coronal Mass Ejection Current Sheet in a Very Hot Active Region[J]. Astrophysical Journal, 2002, 575(2):1116.

[40] Savage S L, Mckenzie D E, Reeves K K, et al. RECONNECTION OUTFLOWS AND CURRENT SHEET OBSERVED WITH HINODE/XRT IN THE 2008 APRIL 9 "CARTWHEEL CME" FLARE[J]. Astrophysical Journal, 2010, 722(1):329-342.

[41] Yan X L, Yang L H, Xue Z K, et al. Simultaneous Observation of a Flux Rope Eruption and Magnetic Reconnection during an X-class Solar Flare[J]. The Astrophysical Journal, 2018, 853(1): L18.

[42] K.D, LekaA, Skumanich. On the value of 'αAR' from vector magnetograph data[J]. Solar Physics, 1999.

[43] Liang Hongfei. Measurement of vector magnetic field and calculation of electric current density of the sunspot[D]. Graduate School of Chinese Academy of Sciences (Yunnan Observatory), 2006.

Note: Figure translations are in progress. See original paper for figures.