Magnetic Configuration Associated with Two-Ribbon Solar Flares

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ABSTRACT

The magnetic configuration of flare-bearing active regions (ARs) is one key aspect for understanding the initiation of solar flares. In this paper, we perform a comparative analysis between the magnetic configurations of two X-class two-ribbon flares happening in AR 10930 and AR 11158, whose photospheric magnetic fields were observed by the Hinode and SDO satellites, respectively. The corresponding coronal magnetic fields were calculated based on the nonlinear force-free field model. The analysis shows that both the flares were initiated in local areas with extremely strong current density, and the magnetic chirality (indicated by the sign of force-free factor $\alpha$) along the main polarity inversion line (PIL) is opposite for the two ARs, that is, left-handed ($\alpha < 0$) for AR 10930 and right-handed ($\alpha > 0$) for AR 11158. Our previous study (He et al. 2014) showed that, for the flare of AR 10930, prominent magnetic connectivity (indicated by concentrated $\alpha$ and current distributions) was formed above the main PIL before the flare and was totally broken after the flare eruption. The two branches of broken magnetic connectivity, combined with the isolated electric current at the magnetic connectivity breaking site, compose a Z-shaped configuration. In this work, we find similar results for the flare of AR 11158 except that its magnetic configuration is inverse Z-shaped, which corresponds to the right-handed chirality of AR 11158 in contrast to the left-handed chirality of AR 10930. We speculate that two-ribbon flares can be generally classified to these two magnetic configurations by chirality ($\alpha$ sign) of ARs.

Keywords: Sun: activity — Sun: corona — Sun: flares — Sun: magnetic fields — Sun: photosphere — solar-terrestrial relations

1. INTRODUCTION

Solar flares are a significant eruptive phenomenon observed in the solar atmosphere, which manifest as sudden enhancements across a broad band of electromagnetic wave spectrum (e.g., optical emission in photosphere and chromosphere, and soft X-ray emission in corona). They are believed to be the result of magnetic energy release in the corona (Priest & Forbes 2002; Shibata & Magara 2011; Benz 2017). A typical major solar flare event is usually accompanied with coronal mass ejection (CME) (Forbes 2000; Zhang et al. 2001; Zhang & Low 2005; Chen 2011; Webb & Howard 2012). Beneath the erupting plasmas is the flaring arcade. At the footpoints of the flaring arcade, two bright flare ribbons can be seen in chromosphere images observed via chromospheric spectral lines such as Hα, Ca II H, etc. This kind of typical solar flare events are also called two-ribbon flares. Big flares and associated CMEs may cause drastic disturbances to the solar-terrestrial space weather and impact the safety of spacecraft as well as the human life on the Earth (Schwenn 2006; Pullkinen 2007; Koskinen et al. 2017; Lanzerrorti 2017). Flare activity was also discovered on the solar-type stars other than the Sun (Schaefer et al. 2000; Benz & Gudel 2010; Shibata & Magara 2011; Maehara et al. 2012; Notsu et al. 2013; Shibayama et al. 2013; Balona 2015; Davenport 2016).

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Solar flares commonly come from solar active regions (ARs), and the magnetic configuration of flare-bearing ARs is one key aspect for understanding the initiation and evolution of solar flares (e.g., Chen et al. 2012; Sun et al. 2015; Jiang et al. 2016, 2018; Liu et al. 2016; Cheng et al. 2017; Guo et al. 2017; Hao et al. 2017; Inoue et al. 2018) and other related eruptive phenomena in the solar atmosphere (e.g., Zhang et al. 2012; Ouyang et al. 2017; Wang et al. 2017; Liu et al. 2018). The non-potential property of the magnetic fields with electric current permeating inside is believed to be the critical aspect related to the activity level of ARs (e.g., Wang et al. 1996; Leka & Barnes 2003; Schrijver 2016). All these kinds of analyses request full three-dimensional (3-D) distribution data of vector magnetic field in the solar atmosphere. However, currently only the vector magnetic fields at the photosphere of ARs can be measured with high precision and resolution, especially by the space-based facilities such as the Hinode satellite (Kosugi et al. 2007) and the Solar Dynamics Observatory (SDO) satellite (Pesnell et al. 2012). For the coronal magnetic field above the photosphere, one has to rely on physical modeling and numerical calculation to obtain the vector magnetic field distribution in the 3-D space, where the observed photospheric vector magnetic field is employed as the constraint condition at the bottom boundary (e.g., Sakurai 1989). The nonlinear force-free field (NLFFF) model (Wiegelmann & Sakurai 2012; Régnier 2013) is the most commonly used model for calculating the 3-D distribution of the coronal magnetic field, which well represents the physical condition of the steady corona (e.g., Aschwanden 2005). In the NLFFF model, magnetic force overwhelms other forces. As a result, the magnetic field vector $B$ satisfies $\nabla \times B = \alpha B$ and $\nabla \alpha \cdot B = 0$, where the parameter $\alpha$ is a scalar function of spatial position and is called force-free factor. The equation $\nabla \times B = \alpha B$ means that the direction of the electric current density

$$j = \frac{1}{4\pi} \nabla \times B$$

(in electromagnetic cgs units)

is parallel ($\alpha > 0$) or anti-parallel ($\alpha < 0$) to the direction of the magnetic field $B$, and hence the corona system is in equilibrium since the Lorentz force in this situation is zero. The equation $\nabla \alpha \cdot B = 0$ means that the value of $\alpha$ is invariant along one individual field line (Wiegelmann & Sakurai 2012; Régnier 2013).

In our previous work, He et al. (2014) calculated the time-series of coronal magnetic fields based on the NLFFF model for a notable active region, AR 10930, before and after the X3.4-class two-ribbon flare event on 2006 December 13, and investigated the magnetic configuration associated with the flare by analyzing the spatial distribution variations of the electric current density $j$ and the force-free factor $\alpha$ before and after the flare. The photospheric vector magnetic field of AR 10930 was observed by the Spectro-Polarimeter (SP) instrument (Lites et al. 2013) aboard Hinode (Kosugi et al. 2007). Their results showed that, for the X3.4 flare of AR 10930, prominent magnetic connectivity (indicated by concentrated $\alpha$ and current distributions) was formed above the main polarity inversion line (PIL) before the flare and was totally broken after the flare, and the two branches of the broken magnetic connectivity, combined with the isolated electric current at the magnetic connectivity breaking site, compose a Z-shaped structure. In this work, we perform a comparative analysis for the magnetic configuration of the X2.2-class two-ribbon flare event happening on 2011 February 15 in another notable active region, AR 11158, whose photospheric vector magnetic field was observed by the Helioseismic and Magnetic Imager (HMI) instrument (Scherrer et al. 2012) aboard SDO (Pesnell et al. 2012). We are interested in the comparison between the magnetic configurations of the two ARs. In Section 3, we display the coronal magnetic fields of the two ARs, which were calculated based on the NLFFF model for the preflare and postflare magnetograms. Then the magnetic nonpotentiality of the two ARs are discussed on the basis of the derived coronal magnetic fields. In Section 4, we explore the chiral characteristics of the magnetic fields of the two ARs. In Section 5, we analyze and compare the magnetic configurations associated with the two flare events. More discussions on the magnetic configurations of the two-ribbon solar flares are given in Sections 6. Section 7 is the conclusion.

2. TWO MAJOR SOLAR FLARE EVENTS IN AR 10930 AND AR 11158

As introduced in Section 1, both the X3.4 flare of AR 10930 (e.g., Kubo et al. 2007; Zhang et al. 2007; Schrijver et al. 2008; Inoue et al. 2012; He et al. 2014) and the X2.2 flare of AR 11158 (e.g., Schrijver et al. 2011; Sun et al.
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2012; Wang et al. 2012; Liu et al. 2012) are notable and representative two-ribbon flares happening on the Sun. The two flare events, together with their accompanied CMEs, caused prominent disturbances to the solar-terrestrial space weather conditions (e.g., Carrano et al. 2009; Malandraki et al. 2009; Raghav et al. 2018). Table 1 summarizes the basic information (source active region, flare class, date, start time, peak time, and location) of the two major solar flare events. The soft X-ray light curves of the two flares (1.0–8.0 Å band) are shown in Figure 1 (the top row). The data of the solar soft X-ray fluxes were acquired by the Geostationary Operational Environmental Satellites (GOES) and were provided by the National Centers for Environmental Information (NCEI; formerly the National Geophysical Data Center, https://www.ngdc.noaa.gov/stp/satellite/goes/index.html) of the National Oceanic and Atmospheric Administration (NOAA). The bottom row of Figure 1 displays the flare-ribbon images of the two flares in the chromosphere, which were observed by the Solar Optical Telescope (SOT) of Hinode (Tsuneta et al. 2008) through the Ca ii H spectral line (3968.5 Å).

| Source Active Region | Flare Class | Date           | Start Time | Peak Time | Location | Attribute       |
|----------------------|-------------|----------------|------------|-----------|----------|----------------|
| AR 10930             | X3.4        | 2006 December 13 | 02:14 UT   | 02:40 UT  | S06W22   | two-ribbon; CME |
| AR 11158             | X2.2        | 2011 February 15 | 01:44 UT   | 01:56 UT  | S20W12   | two-ribbon; CME |

a The serial numbers of the solar active regions were assigned and issued by the Space Weather Prediction Center (SWPC) of NOAA (https://www.swpc.noaa.gov/products/solar-region-summary).

b The classes, start times, and peak times of the solar flares were compiled and issued by the SWPC of NOAA (https://www.swpc.noaa.gov/products/solar-and-geophysical-event-reports), which are based on the 1-minute averaged 1.0–8.0 Å solar soft X-ray flux data (see Figures 1a and 1b) acquired by the GOES series of satellites.

c The flare locations are expressed in degrees (heliographic coordinate system). ‘S’ means south from the solar equator and ‘W’ means west from the central meridian. The coordinate values for the X3.4 flare of AR 10930 were derived from the solar 195 Å full-disk image data observed at 2006-12-13 02:36:09 UT by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudini`ere et al. 1995) aboard the Solar and Heliospheric Observatory (SOHO) spacecraft (Domingo et al. 1995); the coordinate values for the X2.2 flare of AR 11158 were derived from the solar 94 Å full-disk image data observed at 2011-02-15 01:56:02 UT by the Atmospheric Imaging Assembly (AIA) instrument (Lemen et al. 2012) aboard SDO (Pesnell et al. 2012).

3. CORONAL MAGNETIC FIELD AND NONPOTENTIALITY OF THE TWO ACTIVE REGIONS

To analyze the variations of magnetic field configuration through the flare eruptions, for each flare event in AR 10930 and AR 11158 (see Table 1), we selected one photospheric vector magnetogram before the flare and one magnetogram after the flare, and calculated the coronal magnetic field distribution for each magnetogram based on the NLFFF model. The algorithm for the NLFFF numerical modeling was developed and described in detail in our previous papers (He & Wang 2008; He et al. 2011), which is an improvement from the direct boundary integral equation (DBIE) approach suggested by Yan & Li (2006). (Note that DBIE is an advancement of the original BIE method proposed by Yan & Sakurai 2000, see also Wang et al. 2000, 2001; He & Wang 2006; He et al. 2011.) This method has been utilized to analyze the coronal magnetic structures for a variety of solar ARs (He & Wang 2008; He et al. 2011, 2012, 2014; Liu et al. 2013; Wang et al. 2013; Yang et al. 2014; Wang et al. 2015).

Figure 2 displays the employed photospheric vector magnetograms before and after the two flare events. The left column of Figure 2 is for AR 10930 and the right column is for AR 11158. The top row of Figure 2 is for the magnetograms before the flare eruptions and the bottom row is for the magnetograms after the flare eruptions. The vertical components ($B_z$) of the vector magnetograms are visualized by gray scale images (white color for positive polarity and black color for negative polarity), and the transverse components ($\vec{B}_t$) of the magnetograms are visualized by the small arrows overlying the $B_z$ images. The magnetogram data of AR 10930 and AR 11158 were acquired by the SP instrument of Hinode (Lites et al. 2013) and the HMI instrument of SDO (Scherrer et al. 2012), respectively. The data reduction procedure for the Hinode-SP magnetic field data of AR 10930 can be found in our previous paper (He et al. 2014); for AR 11158, we adopted the hmi.sharp_cea_720s data product of the SDO-HMI vector magnetic
Figure 1. GOES X-ray flux curves (1.0–8.0 Å band, 1-minute averaged data; top row) and Hinode-SOT flare-ribbon images (Ca ii H 3968.5 Å filtergram; bottom row) of the two major solar flare events in AR 10930 and AR 11158. Left column is for the X3.4-class flare of AR 10930 and right column is for the X2.2-class flare of AR 11158. The X-ray flux data of the two flares were obtained by GOES-12 and GOES-15 satellites, respectively. The vertical dashed lines in the top panels illustrate the observation times of the two flare-ribbon images in the context of the flare X-ray flux profiles.

field pipeline (Bobra et al. 2014; Centeno et al. 2014; Hoeksema et al. 2014). The field of view of the magnetograms is about 224′′ × 159′′ for both ARs, and the projection effect in the original magnetic field data has been corrected.

To keep the compatibility between the Hinode-SP data and the SDO-HMI data, we rebinned the SP magnetograms to a similar spatial resolution of the HMI data (about 0.5′′/pixel), as displayed in Figure 2. All the magnetograms were further rebinned to 1′′/pixel resolution (to reduce the burden of computing) as the input data for NLFFF modeling. The azimuth ambiguity in the vector magnetograms were resolved with the nonpotential magnetic field calculation (NPFC) technique (Georgoulis 2005) for the SP data (see He et al. 2014), and with the Minimum Energy (ME0) approach (Metcalf 1994; Leka et al. 2009) for the HMI data as adopted by the HMI team (Hoeksema et al. 2014). In this work, our analysis is focused on the main PIL zones (see description below) of the magnetograms, where the photospheric magnetic field is relatively strong and the noise level is relatively low, thus the impacts of the different instruments and the azimuth disambiguation methods on the analysis results are minimized (see e.g., Sainz Dalda 2017 for comprehensive studies on this issue).

From the magnetograms of AR 10930 and AR 11158 shown in Figure 2, it can be seen that the main PILs between the dominant positive polarity and negative polarity of \( B_z \) are well developed for both ARs. These main PIL zones are indicated by the black boxes in Figure 2. Along the main PILs, the direction of \( \mathbf{B}_t \) is nearly parallel to the orientation of PIL, which represents strong magnetic shear. The strong magnetic shear implies strong magnetic nonpotentiality of the two ARs (Wang et al. 1996; Leka & Barnes 2003).

The distributions of the calculated coronal magnetic fields (through the NLFFF model) corresponding to the four magnetograms are displayed in Figure 3. It can be seen from Figure 3 that the field lines of both ARs show strong shear and even twist above the main PILs before flare, which relaxed to some extent after flare. These sheared and twisted field lines also indicate strong magnetic nonpotentiality of the two ARs (Schrijver 2016).

To demonstrate the nonpotential characteristics of the two ARs more directly. We derived the values of electric current density \( j \) from the coronal magnetic field data of the two ARs by using Equation (1). The spatial distributions
of the current density in corona corresponding to the four magnetograms in Figure 2 are illustrated in Figure 4. It can be seen from Figure 4 that the electric current of the two ARs is mainly distributed in the areas around the main PILs (indicated by the white boxes in Figure 4), which generally correspond to the highly twisted or sheared field lines (see Figure 3) and hence are indicative of high nonpotentiality. Especially, in each active region there exists an area possessing the highest current density values (indicated by the white arrows and labeled with ‘Core Area’ in Figure 4). By comparing the current density images with the flare-ribbon images in Figure 1, it can be seen that the core areas in the two ARs coincide with the zones of flare initiation enclosed by the flare ribbons. This result indicates that the major flares of the two ARs happen in the local areas with extremely strong current density, which represent the most active zones in the two ARs.

4. CHIRALITY OF THE MAGNETIC FIELDS IN THE TWO ACTIVE REGIONS

The magnetograms of AR 10930 and AR 11158 in Figure 2 exhibit that, for both ARs, the positive polarity of $B_z$ is roughly below the main PILs and the negative polarity is above the main PILs (see the main PIL zones indicated by the black boxes in Figure 2). Yet the direction of $\vec{B}_t$ (illustrated by the small arrows in Figure 2) along the main PILs is opposite for the two ARs, that is, the transverse magnetic field vector is rightward for AR 10930 and leftward for AR 11158. This property is called the chirality of the magnetic fields of ARs. Specifically, the left-handed or right-handed chirality is defined by the morphological relation between the direction of $\vec{B}_t$ and the polarity orientation of $B_z$ following the left-hand or right-hand rule, in which the thumb points in the direction of $\vec{B}_t$ and the other four fingers point from the positive polarity to the negative polarity of $B_z$ with the palm facing the PIL. Thus, the magnetic chirality is left-handed for AR 10930 and right-handed for AR 11158. (Note that this definition of chirality for vector magnetic field in solar ARs is consistent with the chirality definition in literature for solar chromospheric filaments, see e.g., Ouyang et al. 2017.)
Figure 3. Field line diagrams illustrating the coronal magnetic fields corresponding to the four photospheric magnetograms in Figure 2. The coronal magnetic field data were calculated based on the NLFFF model, in which the photospheric vector magnetogram data (rebinned to about 1″/pixel) were employed as the bottom boundary condition. The $B_z$ component of the photospheric magnetogram is displayed as contour plot in each panel. The field lines were traced up to 21 Mm (about 29″) high. Closed field lines are in white and open field lines are in black.

Figure 4. The projected current density distributions in corona corresponding to the four magnetograms displayed in Figure 2. The intensity values were obtained by vertically averaging $|j|$ in a 21 Mm (about 29″) high modeling volume. The local area with highest current density values in each panel is indicated by a white arrow and labeled with ‘Core Area’. The white box in each panel indicates the main PIL zone of the corresponding magnetogram (same as in Figure 2).
The chiral characteristics of ARs can be quantitatively indicated by the signs of force-free factor $\alpha$ of the coronal magnetic field. The values of $\alpha$ in corona can be computed from the coronal magnetic field data based on the equation (He et al. 2011, 2014):

$$\alpha = \frac{(\nabla \times B) \cdot B}{B^2}. \tag{2}$$

Figure 5 shows the distributions of force-free factor $\alpha$ at the height of about 2.5″, where the four panels correspond to the four magnetograms of the two ARs in Figure 2. It can be seen from Figure 5 that along the main PILs of the two ARs (indicated by the black boxes in Figure 5), $\alpha < 0$ (rendered in red color) for AR 10930, which means that the directions of the electric current and the magnetic field are opposite, while for AR 11158 $\alpha > 0$ (rendered in blue color), which means that the electric current and the magnetic field have the same direction. According to Ampere’s rule in electromagnetism, the direction of electric current along the main PILs should be leftward for both ARs to be compatible with the polarity distribution of $B_z$ shown in Figure 2. Thus, for AR 10930 with rightward $\vec{B}_t$ (left-handed chirality) along the main PIL, $\alpha < 0$; and for AR 11158 with leftward $\vec{B}_t$ (right-handed chirality) along the main PIL, $\alpha > 0$.

The chirality discrepancy of the two ARs can also be reflected by the orientations of coronal magnetic field lines (see Figure 3) as well as the orientations of flare ribbon distributions (see bottom row of Figure 1), which are all consistent with the directions of $\vec{B}_t$ (see Figure 2). Table 2 summarizes the corresponding relationship between various features representing magnetic field chirality, including the direction of transverse magnetic field in photosphere, sign of force-free factor $\alpha$, orientation of coronal magnetic field lines, and orientation of flare ribbon distribution (see Figures 1, 2, 3, and 5). All these features show that the chiral characteristic is coherent throughout the main PILs of the two ARs.

5. MAGNETIC CONFIGURATIONS ASSOCIATED WITH THE TWO FLARE EVENTS

The spatial distribution of force-free factor $\alpha$ not only exhibits chiral characteristics of ARs by its sign, but also reveals the magnetic connectivity properties in the coronal magnetic fields of ARs. Note that in the force-free magnetic field, $\alpha$ is a constant along each field line (see the description in Section 1). He et al. (2014) studied the variations of $\alpha$ and current density distributions in AR 10930 before and after the X3.4 flare eruption (see the left columns of Figures 4 and 5). They found that a prominent magnetic connectivity (manifesting as a strip of concentrated $\alpha$ distribution

![Figure 5. Diagrams illustrating the $\alpha$ spatial distributions (at height about 2.5″) corresponding to the four magnetograms displayed in Figure 2. The negative and positive $\alpha$ values are rendered in red and blue colors, respectively. The black box in each panel indicates the main PIL zone of the corresponding magnetogram (same as in Figure 2).](image-url)
Table 2. Correspondence Between Various Features Representing Magnetic Field Chirality

| Feature Concerning Chirality Along the Main PIL | Magnetic Field Chirality |
|-----------------------------------------------|--------------------------|
|                                              | Left-Handed\(^a\) | Right-Handed\(^a\) |
| Direction of \(\vec{B}_t\) in Figure 2\(^a\)  | rightward (→) | leftward (←) |
| Sign of force-free factor \(\alpha\) (see Figure 5)\(^b\) | negative (\(\alpha < 0\)) | positive (\(\alpha > 0\)) |
| Orientation of coronal magnetic field lines in Figure 3\(^c\) | right-leaning (⧸) | left-leaning (⧹) |
| Orientation of flare-ribbon distribution in Figure 1\(^d\) | right-leaning (⧸) | left-leaning (⧹) |

\(^a\)The left-handed or right-handed chirality is defined by the morphological relation between the direction of \(\vec{B}_t\) (the thumb pointing in) and the polarity orientation of \(B_z\) (pointing from the positive polarity to the negative polarity by the other four fingers with the palm facing the PIL) in photospheric vector magnetograms.

\(^b\)Note that according to Ampere’s rule in electromagnetism, the direction of electric current along the main PILs should be leftward for both ARs to be compatible with the polarity distribution of \(B_z\) shown in Figure 2. Thus, for AR 10930 (left-handed chirality), \(\vec{B}_t\) and current along the main PIL is in the opposite direction, and hence \(\alpha < 0\); while for AR 11158 (right-handed chirality), \(\vec{B}_t\) and current along the main PIL is in the same direction, and hence \(\alpha > 0\).

\(^c\)Note that the orientation of the coronal magnetic field lines is consistent with the direction of \(\vec{B}_t\).

\(^d\)The orientation of the flare-ribbon distribution means the pointing direction from one ribbon to another ribbon (and not the azimuth of the ribbon itself), which is consistent with the direction of \(\vec{B}_t\).

associated with a strong current) was formed above the main PIL before the flare, and this magnetic connectivity was totally broken after the flare eruption (manifesting as two separate patches of \(\alpha\) distribution around the main PIL), as demonstrated in the left part of Figure 6a. Besides, the two branches of the broken magnetic connectivity, combined with the isolated electric current at the magnetic connectivity breaking site (left over from the strong current associated with the prominent magnetic connectivity before the flare), compose a Z-shaped configuration, which is sketched in the right part of Figure 6a.

We are interested in the magnetic configuration associated with the X2.2 flare of AR 11158, for its chiral characteristic is opposite to that of AR 10930 (note that AR 10930 is left-handed with \(\alpha < 0\) and AR 11158 is right-handed with \(\alpha > 0\); see Table 2). The \(\alpha\) and current density distributions in the main PIL zone of AR 11158 (see the right columns of Figures 4 and 5) also show that a prominent magnetic connectivity was formed along the main PIL before the X2.2 flare and the magnetic connectivity was totally broken after the flare eruption (see the illustrative diagrams in the left part of Figure 6b). This result is just the same as AR 10930, except that the relative position of the two branches of broken magnetic connectivity of AR 11158 (upper-left vs. lower-right) is different from that of AR 10930 (lower-left vs. upper-right). The magnetic configuration diagram (i.e., the two branches of the broken magnetic connectivity combined with the isolated electric current at the magnetic connectivity breaking site) for the X2.2 flare of AR 11158 is sketched in the right part of Figure 6b. From Figure 6b, it can be seen that the magnetic configuration of this flare event is inverse Z-shaped, which corresponds to the right-handed chirality (positive \(\alpha\)) of AR 11158 in contrast to the left-handed chirality (negative \(\alpha\)) and the Z-shaped configuration of AR 10930.

6. DISCUSSION

We speculate that two-ribbon flares can be generally classified to these two magnetic configurations by chiral characteristic (\(\alpha\) sign) of ARs, that is, Z-shaped configuration for left-handed chirality (\(\alpha < 0\)) ARs (e.g., AR 10930) and inverse Z-shaped configuration for right-handed chirality (\(\alpha > 0\)) ARs (e.g., AR 11158). Then the Lorentz force acting on the isolated electric current at the magnetic connectivity breaking site is upward and hence leads to flare initial eruption (see the rightmost schematic diagrams of Figure 6 and more detailed explanation in our previous paper by He et al. 2014). The opposite combinations, i.e., a Z-shaped configuration with the right-handed chirality (\(\alpha > 0\)) or an inverse Z-shaped configuration with the left-handed chirality (\(\alpha < 0\)), are not likely for two-ribbon flares, because in these cases the Lorentz force acting on the isolated electric current at the magnetic connectivity breaking site would be
Figure 6. Diagrams illustrating (a) the Z-shaped magnetic configuration of the X3.4 flare event of AR 10930 and (b) the inverse Z-shaped magnetic configuration of the X2.2 flare event of AR 11158. The subplots on the left of the ‘=’ symbols give the $\alpha$ distribution maps in the central areas of the two ARs before and after the flare eruptions. The black boxes in the $\alpha$ diagrams indicate the main PIL zones, which are the same as in Figure 5. The bars in the preflare $\alpha$ diagrams (golden color) represent the strong electric current associated with the prominent magnetic connectivity formed before the flare; and the bars in the postflare $\alpha$ diagrams (light blue color) represent the two branches of the broken magnetic connectivity. The sketches on the right of the ‘=’ symbols illustrate the Z-shaped (for AR 10930) and the inverse Z-shaped (for AR 11158) configurations composed by the two branches of broken magnetic connectivity and the isolated electric current at the magnetic connectivity breaking site left over from the strong current formed before the flare. The rightmost schematic diagrams illustrate the upward Lorentz force $f = j \times B$ acting on the isolated electric current $j$ at the magnetic connectivity breaking site. $B_0$ (in gray color) shows the direction of the force-free magnetic field before the flare eruption, which is anti-parallel to the direction of $j$ for AR 10930 (because of $\alpha < 0$) and parallel to the direction of $j$ for AR 11158 (because of $\alpha > 0$). $B$ is the deflected background magnetic field due to the breaking of magnetic connectivity, and is roughly aligned with the two branches of broken magnetic connectivity (see detailed explanation in our previous paper by He et al. 2014). It is this magnetic field deflection from $B_0$ to $B$ that introduce the Lorentz force $f$ on the isolated electric current and cause the flare initial eruption.

downward and cannot lead to initial eruption. In Figure 7, we summarize the four situations of combination between magnetic chirality and magnetic configuration.

7. CONCLUSION

In this paper, we performed a comparative analysis of the magnetic configurations of two X-class two-ribbon flares happening in AR 10930 (on 2006 December 13) and AR 11158 (on 2011 February 15). The photospheric vector magnetograms were obtained through the direct observations by the Hinode-SP and SDO-HMI instruments, respectively. The 3-D magnetic field distribution in corona were obtained by numerical calculations based on the NLFFF model. We employed the electric current density $j$ (see Equation (1)) and the force-free factor $\alpha$ (see Equation (2)) to quantitatively describe the magnetic configurations of the two ARs before and after the flare eruptions and analyzed their variation associated with the two flare events.

The analysis by the electric current density $j$ shows that in the two ARs, the two X-class flares were initiated in the local areas with extremely strong current density. These core areas are associated with high nonpotentiality and high free magnetic energy (owing to the strong electric current), and hence indicate the initial locations of major solar eruptions.

The analysis of the force-free factor $\alpha$ shows that, although the photospheric magnetic fields of the two ARs are complex, the chirality of the photospheric and coronal magnetic fields (indicated by the sign of the force-free factor $\alpha$)
are coherent along the main PIL for each active region, that is, left-handed ($\alpha < 0$) for AR 10930 and right-handed ($\alpha > 0$) for AR 11158.

As the pre-eruption structure for major flares and accompanied CMEs, the core field is strongly sheared and/or twisted magnetic field along the main magnetic PIL (e.g., Chen 2011; Shibata & Magara 2011). Correspondingly, the $\alpha$ and electric current distributions are concentrated along the main PIL, which form the prominent magnetic connectivity before the flare. Our previous study (He et al. 2014) showed that, for the X3.4 flare of AR 10930, the prominent magnetic connectivity above the main PIL was totally broken after the flare, and the two branches of the broken magnetic connectivity, combined with the isolated electric current at the magnetic connectivity breaking site, compose a Z-shaped configuration. In this work, we find similar result for the X2.2 flare of AR 11158 except that its magnetic configuration is inverse Z-shaped, which corresponds to the right-handed chirality (positive $\alpha$) of AR 11158 in contrast to the left-handed chirality (negative $\alpha$) of AR 10930. We speculate that two-ribbon flares can be generally classified to these two magnetic configurations by chirality ($\alpha$ sign) of ARs.

The above results can be applied to the solar-terrestrial space weather studies and predictions (He et al. 2008, 2012, 2016, 2018a; Wang et al. 2009, 2018; Le et al. 2011; Yang et al. 2017). The magnetic configuration of solar flares can also provide useful implications for understanding the magnetic and flare activity properties of solar-type stars (He et al. 2015, 2018b,c,d; Yun et al. 2016, 2017; Mehrabi et al. 2017; Li et al. 2018; Mehrabi & He 2019).

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