QUASI-STATIC THREE-DIMENSIONAL MAGNETIC FIELD EVOLUTION IN SOLAR ACTIVE REGION NOAA 11166 ASSOCIATED WITH AN X1.5 FLARE

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ABSTRACT

We study the quasi-static evolution of coronal magnetic fields constructed from the non-linear force-free field (NLFFF) approximation aiming to understand the relation between the magnetic field topology and ribbon emission during an X1.5 flare in active region (AR) NOAA 11166. The flare with a quasi-elliptical and two remote ribbons occurred on 2011 March 9 at 23:13 UT over a positive flux region surrounded by negative flux at the center of the bipolar AR. Our analysis of the coronal magnetic structure with potential and NLFFF solutions unveiled the existence of a single magnetic null point associated with a fan–spine topology and is co-spatial with the hard X-ray source. The footpoints of the fan separatrix surface agree with the inner edge of the quasi-elliptical ribbon and the outer spine is linked to one of the remote ribbons. During the evolution, the slow footpoint motions stressed the field lines along the polarity inversion line and caused electric current layers in the corona around the fan separatrix surface. These current layers trigger magnetic reconnection as a consequence of dissipating currents, which are visible as cusp-shaped structures at lower heights. The reconnection process reorganized the magnetic field topology whose signatures are observed at the separatrices/quasi-separatrix layer structure in both the photosphere and the corona during the pre-to-post flare evolution. In agreement with previous numerical studies, our results suggest that the line-tied footpoint motions perturb the fan-spine system and cause null point reconnection, which eventually causes the flare emission at the footpoints of the field lines.

Key words: Sun: corona – Sun: evolution – Sun: flares – Sun: magnetic fields – Sun: photosphere

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1. INTRODUCTION

Solar flares are caused by energy release in the corona due to magnetic reconnection. Flares emit electromagnetic radiation in a wide range of wavelengths and are frequently associated with coronal mass ejections (CMEs) and they expel solar energetic particles. Consequently they influence and drive space weather events (e.g., see Schrijver et al. 2011; Vemareddy et al. 2012c). Bright ribbons are commonly observed in Hz and in extreme-ultraviolet (EUV) during both eruptive and non-eruptive flares. According to the standard two-dimensional (2D) flare models (CSHKP; Carmichael 1964; Studier 1966; Hirayama 1974; Kopp & Pneuman 1976), these phenomena are caused by magnetic reconnection in current sheets. During these processes, the charged coronal particles become energized and accelerated. Some particles gyrate around the field lines and propagate toward their footpoints, precipitating at different layers of the solar atmosphere. They appear as ribbons in a wide range of wavelengths. Therefore, ribbons are nothing but the footpoints of coronal loops providing information about the linkage and field line topology in flaring active regions (ARs). Such a proposed 2D picture of the field line connectivity is difficult to imagine and leads often to elusive interpretations.

Reconnection corresponds to the change in the magnetic connectivity by breaking and reconnecting field lines in resistive regions where ideal magnetohydrodynamics (MHD) are violated and the plasma is not frozen in the magnetic field. By tracing the temporal evolution of three-dimensional (3D) magnetic structures, it is possible to gain insights into the conditions leading to an eruption. Previous topological analysis of magnetic structures constructed from analytic configurations or potential and linear force-free extrapolations revealed preferred sites for current sheet formation and associated features like null points, separatrices surfaces, and separator lines (Priest & Forbes 1989; Demoulin et al. 1993, 1997). Magnetic null points (Lau & Finn 1990; Parnell et al. 1996) generate separatrices of two flux systems of individual connectivity. Across the separatrix surfaces, the connectivity is discontinuous and contains an infinite magnetic field gradient. Since not all reconnecting configurations contain null points (Demoulin et al. 1997), the concept of separatrices was generalized to quasi-separatrix layers (QSLs; Priest & Forbes 1992; Priest & Demoulin 1995). Unlike separatrices, QSLs are locations with continuous connectivity, but still with large connectivity gradients. These are also favorable sites for the formation and build-up of current layers, similar to separatrices in the presence of footpoint motions.

Subsequently, it was important to search for the locations of such topological features in observational data and several reports gave evidence for the presence of magnetic null points as well as QSLs in flaring ARs (Mandrini et al. 1997; Aulanier et al. 2000; Fletcher et al. 2001; Manoharan & Kundu 2003; Sun et al. 2012; Savcheva et al. 2012). The role of these topological features in reconnection is explored in several theoretical (Demoulin et al. 1993, 1996, 1997; Priest & Forbes 2000; Longcope 2005) and numerical (Moreno-Insertis et al. 2008; Parari et al. 2009; Masson et al. 2009) studies.

During the evolution of an AR, magnetic energy is built up (during several hours or even days) in the corona due to flux emergence and displacement (Schrijver 2009). For these slowly evolving processes, the characteristic travel time of Alfvén waves through the whole region is orders of magnitude lower than the global evolution time of the region. Consequently, dynamical and inertial effects are negligible. Moreover, the plasma pressure and gravity are negligible as well because they...
are small compared to magnetic pressure and tension, which counterbalance each other and lead to a vanishing Lorentz force. Therefore, the slow evolution of ARs can be approximated by a series of quasi-stationary, force-free equilibria in the low-plasma $\beta$ (ratio of plasma and magnetic pressures) corona. Modeling the magnetic configuration at each stage of the AR evolution in this scenario allows a detailed study of the connection between ribbons, topology, and energetics.

Nevertheless, the coronal field is force-free; the photospheric field is far away (e.g., Wiegelmann et al. 2006) from that state. Furthermore, measurement errors make it difficult to reconstruct the coronal fields. Therefore, the force-free model is a sophisticated approximation of the coronal field within the limits of current observational capabilities. Continuous photospheric field measurements from the Solar Dynamic Observatory with a cadence of 12 minutes are used as boundary conditions to model the 3D coronal magnetic field. The resulting data cubes are analyzed to reveal their topological features and related current distributions and to locate sites for energy release during explosive events like flares and CMEs. This study tries to address the possible role of magnetic topology for solar energetic events and the related flare emission.

In the present work, we analyze an X-class flare with a main quasi-elliptical ribbon and additional two elongated remote ribbons. Such elliptical geometries occur only for specific magnetic topologies and therefore have been studied rarely. To our knowledge, Masson et al. (2009) reported for the first time a C-class event with a circular ribbon accompanied by two extended remote ribbons in an emerging AR. The authors used MHD simulations in a line-tied boundary approximation to explain the formation of current sheets, the nature of reconnection, and several other observational features like ribbon brightening and Hα and EUV emission. We use a similar approach to interpret the observations in this paper, but our analysis is based on a quasi-static force-free model instead of dynamic MHD simulations.

We organize the paper as follows. In Section 2, we describe the data and in Section 3, we describe our coronal magnetic field model. We analyze the morphological flare evolution and the associated magnetic field properties in Section 4, which is followed by an analysis of the magnetic structure, topology, and coronal current distribution in Sections 5 and 6. We emphasize the relevance of our results in comparison with recent theoretical and numerical advancements in Section 7. Finally, we conclude with a summary in Section 8.

2. OBSERVATIONAL DATA

The observed flare event occurred in AR NOAA 11166 on 2011 March 9, located in the northwest (N23°W11°) part of the solar disk. The observations of the event (from 20:00 UT on 9 March to 02:00 UT on 10 March) are well covered by the Helioseismic Magnetic Imager (HMI; Schou et al. 2012) in 6173 Å, providing photospheric vector magnetic field information at 0.5 arcsec pixel$^{-1}$ resolution, and the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) in 10 wavelengths, providing solar atmospheric imaging information at 0.6 arcsec pixel$^{-1}$ resolution.

The AIA images are processed using standard procedures in SolarSoft and reduced to one minute cadence by integrating over five successive images in order to remove noise. The HMI stokes parameters are derived from filtergrams averaged over a 12 minute interval, and then they are inverted with the help of a Milne–Eddington atmospheric model, using the Very Fast Inversion of Stokes Vector (Borrero et al. 2011) algorithm to yield all three components of the photospheric magnetic field vector. The inherent 180° azimuth ambiguity in the transverse field is removed using an improved version of the “minimum energy” algorithm (Metcalf 1994; Metcalf et al. 2006; Leka et al. 2009). After correcting for projection effects (Venkatakrishnan & Gary 1989; Gary & Hagyard 1990) the data were re-mapped and transformed to heliographic coordinates from spherical coordinates using Lambert cylindrical equal-area projection (Calabretta & Greisen 2002). After all these procedures, the mean value of the estimated errors ranges up to 25, 50 G in the line-of-sight and transverse components, respectively. Therefore, we consider only pixels with values above the threshold ($|B_t| > 150$ G and $|B_\perp| > 50$ G). Detailed information about retrieving the final vector field products from level zero filtergrams are available in Hoeksema et al. (2014).

Complementary chromospheric Hα observations from the GONG site at Big Bear Solar Observatory and hard X-ray (HXR) information from RHESSI (Lin et al. 2002), are also used in this study. All maps are aligned with the magnetograms and projected onto the disk center.

3. CORONAL MAGNETIC FIELD EXTRAPOLATION AND QSL CALCULATION

In order to study the 3D magnetic field evolution above the AR in association with the flare, the photospheric vector magnetic fields are extrapolated with the help of a non-linear force-free field algorithm (NLFFF; Wiegelmann & Inhester 2010; Wiegelmann et al. 2012). The algorithm minimizes the functional

$$L = \int_V \left( w \frac{|(\nabla \times B) \times B|^2}{B^2} + w |\nabla \cdot B|^2 \right) dV + \nu \int_S (B - B_{\text{obs}}) \cdot W \cdot B - B_{\text{obs}} \cdot dS. \tag{1}$$

The first integral contains quadratic forms of the force-free and solenoidal conditions. $w$ is a weighting function toward the lateral and top boundaries. In the original approach by Wiegelmann (2004), the functional $L$ is iteratively minimized with boundary conditions derived from measurements of the photospheric magnetic field vector. The newly added surface integral term takes into account measurement errors and allows a slow injection (controlled by the Lagrangian multiplier $\nu$) of the boundary data (see Wiegelmann & Inhester 2010, for details). $W(x, y)$ is a diagonal matrix, which is chosen inversely proportional to the transverse magnetic field strength.

During iteration of the NLFFF algorithm, the following quantities are monitored

$$L_1 = \int_V \frac{|(\nabla \times B) \times B|^2}{B^2} dV;$$

$$L_2 = \int_V |\nabla \cdot B|^2 dV;$$

$$\sigma_j = \left( \sum_i \frac{|J_i \times B_i|}{B_i} \right) \left/ \sum_i J_i \right., \tag{2}$$

where $L_1$ and $L_2$ correspond to the first and second terms in Equation (1), respectively. These integrals consider only the inner $236 \times 236 \times 188$ physical region (where the weighting functions are unity) and $\sigma_j$ corresponds to the sine of the current weighted average angle between the magnetic field and
the electric current density. During the iteration, these terms decrease and force the electric current to be parallel to the magnetic field (force-free). For our data sets, $\sigma_j$ finally becomes about $15^\circ$.

The initial potential fields (PFs) are computed with the help of a Green’s function method (Sakurai 1989) and require only the normal component of the photospheric magnetic field. The PF solutions are used as the initial state and also to prescribe the top and side boundaries for the NLFFF algorithm. Our computations are performed in a Cartesian box with a grid of $300 \times 300 \times 160$, which corresponds to physical dimensions of $219 \times 219 \times 117$ Mm$^3$ encompassing the AR on the Sun. As the vector magnetograms of this AR satisfy the force-free consistency conditions approximately (the flux imbalance is less than 1% and force and torque terms are about 5%), preprocessing of the data was not necessary (Wiegelmann et al. 2006, 2012).

After constructing 3D coronal fields, the change in magnetic field line linkage is measured by the strength of QSLs defined as squashing degree $Q$ (Titov et al. 2002; Titov 2007). $Q$ describes the field line mapping gradients and larger values of $Q$ correspond to the cross section of QSLs in any plane. It is computed by tracing two consecutive field lines with footpoints at an extremely small distance and measuring the distance between the respective conjugate footpoints as given by

$$
Q = \sum_{i,j=1}^{2} \left( \frac{X_i}{B_{z,0}/B_{z,1}} \right)^2,
$$

where $X_i (i = 1, 2)$ is the coordinates of the conjugate foot point in the Cartesian system and $B_{z,0}$ and $B_{z,1}$ are vertical field components at the starting and ending footpoints of a field line. For dense points of $Q$, the calculations are performed in a grid of resolution increased by eight times that of extrapolation. We use an iterative scheme as described in earlier studies (Aulanier et al. 2005; Savcheva et al. 2012; Sun et al. 2013). The QSL is defined by $Q \gg 2$, and the value $Q = 2$ is the lowest possible value. The maximum value of $Q$ found in our computation is $\sim 10^{13}$ but much larger values are possible at still higher resolution.

4. FLARE EVOLUTION, MORPHOLOGY, AND MAGNETIC FIELD PROPERTIES

AR 11166 appeared on the northern part of the solar disk on March 3. Although it was already well emerged, it continued to evolve with further flux emergence. During disk transit, the region was very dynamic and harbored several flares and CMEs. The AR and its long-term activity, caused by flux motions and helicity injection, were thoroughly investigated in Vemareddy et al. (2012b). The second X-class flare in the solar cycle 24, X1.5 occurred in this AR on March 9 at 23:13 UT, and we study its structural evolution here. In this context, we focus our investigation on 6 hr of observations around the time of the flare.

Figure 1 shows the observations of the flare event in different wavelength-passbands. As visible in the HMI continuum images (panel 1(a)), the AR consists of sunspots of variable size, which have well developed umbra and penumbra. Two of the sunspots are located in the east (SP1, SP2) and one in the west (SN1) and are large in size. Smaller and fragmented spots are grouped around the center part of the AR. The chromospheric Hα images show the presence of a dark filament with one leg originating from the central portion of the sunspot group and the second leg anchored near sunspot SP1. Signatures of bright ribbon emissions are observed from 20:00 UT onward. They appear only during the flare, however.

From the GOES soft X-ray profile, the flare initiation occurred at 23:13 UT, having peak phase emission in HXRs at 23:21 UT. With progressive reconnection in the corona, emissions eventually form ribbons that start appearing from 23:15 UT onward and exhibit peak emission at about the peak time of the flare (23:23 UT). The light curves of Hα and UV 1700 Å exhibit their maximum flare emission almost at the same time. The EUV emission peak in the 171, 94 Å channels, however, is observed only later, at 23:29 UT, and is associated with post-flare loops, which evolve further for another half hour.

The main flare ribbon RB1 has a “quasi-circular” shape which formed within the sunspot group. RB1 seems to have a close connection to the coronal reconnection site. In addition, two ribbons (RB2 and RB3) formed remotely from RB1 more or less simultaneously. An important aspect of this event is that it has no evident ribbon motions, but it expands within one minute during the impulsive phase. It is assumed that static ribbons are associated with stationary coronal magnetic reconnection. Motions during the progressive reconnection phases are seen, however, for events close to the limb (e.g., Joshi et al. 2009).

From the photospheric magnetic field distribution, we understand that the ribbons form along the polarity inversion line (PIL), which separates the two opposite polarities (Figures 1(b) and (c)). This central portion has a peculiar magnetic field distribution: the positive flux of the small sunspot SSP is embedded in a negative flux region associated with the sunspot group SGN (panels (a) and (g) in Figure 1). This flux distribution forms a nearly closed contour of the PIL (thick curve in panel (g)). Such configurations are prone to contain topological structures like null points and are potential locations where current sheets may form (Demoulin et al. 1993, 1997). Despite this complex flux distribution, the overall magnetic configuration of the AR is bipolar (with an imbalance of fluxes less than 1%) with a dominantly negative polarity in the west and a positive one in the east.

In coronal AIA 171 Å images, we see coronal loops connecting the major sunspots of opposite polarity. The magnetic connectivity in the flaring region was somewhat difficult to identify before the event, but at later times, the formation of post-flare loops are well visible. During the peak phase, the emission along the PIL coincides spatially in all AIA channels and with the Hα ribbons. The coronal loops filled with plasma are regarded as tracers of the magnetic field lines and help to determine the structure of the observed magnetic flux distribution. The field line connectivity is clearly visible in the central flaring part of the AR. This gives us some clues about the relation of the coronal field structure and the ribbons. From observations of hot coronal loops in 94 Å, we conclude that the coronal field lines have their footprints located within the observed emission of ribbons.

To relate these emissions along the ribbon with the reconnection site in the corona, HXR sources are overlaid (contours of 80%, 90% of maximum) on EUV images (Figures 1(d)–(f)). The HXR images are reconstructed from the “clean” algorithm (Högboom 1974) at a one minute integration time. The peak HXR emission coincides with that of Hα and UV, implying their spatial and temporal association during the flare. Indeed, the HXR sources in the 6–12, 25–100 kev bands fall in between RB1 and RB2. We co-align the images to an accuracy level of 2–3 arcsec by using magnetic field contours on different instrument images to compute the corresponding shifts. However, due to problems
with projection effects, an ambiguity persists to differentiate between HXR sources from footpoint and loop top sources. These observations imply that RB1 and RB2 are formed by direct impingement of particles from the reconnection site in the corona.

To investigate the flare emission in $H\alpha$ in more detail, we plot light curves from RB1, RB2, and RB3 (not shown in this paper). The curves show that emission from RB1 and RB2 occurs simultaneously; the emission from RB3 is delayed by about one minute when compared to the earlier one. This delayed emission from RB3 could be likely related to its remote presence from the flaring site. All of these observational facts reflect the scenario of the classical flare model: coronal plasma particles become accelerated in the corona by magnetic reconnection and traverse downward along the field lines, thereby bombarding the low coronal dense material, which consequently leads to the formation of ribbons with bright emission.

The vector magnetogram, horizontal field vectors are over-plotted onto the vertical magnetic field map panel 1(g) illuminates the sheared field distribution along the PIL. In the presence of continued slow flux motions as the AR evolves, stress can build up and store energy in the magnetic configuration. Please note that the horizontal field vectors are almost aligned to the PIL and reflect the presence of such stressed field lines. All these observations indicate favorable conditions for a flare (e.g., Vemareddy et al. 2012a).

Several studies (Sudol & Harvey 2005; Petrie & Sudol 2010; Wang & Liu 2010) gave evidence that flares may change the magnetic field configuration significantly in a persistent and permanent manner. The persistence of the observed field changes implies that they are not artifacts of changes in the photospheric plasma parameters (Maurya et al. 2012) during the flare, and the temporal and spatial coincidences between flare emission and field changes suggest that field changes are linked to the flare. To check the presence of such flare-associated field changes, we have scrutinized horizontal field maps ($B_h = \sqrt{B_x^2 + B_y^2}$) as plotted in Figures 1(h) and (i) before (22:12 UT) and after (23:48 UT) the flare. In the insets, large horizontal fields (up to 1500 G) have been distributed along the PIL. Their prominent change spreading in a large area is
identified, however, only at a localized region (small rectangular box). From this small region, the average $B_h$ is evaluated and plotted with respect to time in Figure 2(a). Obviously, the evolution of a horizontal field at this location during the flare delineates that they have undergone a permanent change with a net average increase of about 180 G (see panels 1(g) and (h)). These observations are consistent with recent reports of collapsing fields appearing as increased horizontal fields after reconnection (Wang et al. 2012).

Similarly, the net vertical current ($I = \sum_{N\, \text{pixels}} J_z$) and net line-of-sight flux ($\Phi = \sum_{N\, \text{pixels}} B_z$) in the AR is computed at the north (N) and south (S) polarities, and we show their temporal evolution in Figures 2(b) and (c), respectively. The flux in both N- and S-polarity varies by $0.5 \times 10^{21}$ Mx over the time interval of 6 hr indicating that the variations are likely part of the general evolution but not related to significant flux emergence or cancellation. Since positive (negative) flux is having a dominant positive (negative) signed current, it is likely that the AR magnetic field is right helically twisted (Wang et al. 2004) with positive helicity, which is consistent with the sign of helicity injection rate derived from flux motions (Vemareddy et al. 2012b). This interpretation is in turn supported by the sign of average alpha given by

$$\alpha_m = \frac{\sum J_z(x, y) \text{sign}[B_z(x, y)]}{\sum |B_z|} = (1.27 \pm 0.19) \times 10^{-8} \text{ m}^{-1}$$

computed at the photospheric boundary, which implies an average twist in the AR. The net vertical current, as evaluated from both polarities, increased from 22:00 UT toward their peak values at the end of the day. The net current changed by a similar amount of about $1.8 \times 10^{12}$ A in both signed fluxes, which implies that they are likely generated around the PIL by shearing motions. This significant increase of net currents is usually a precursor for flaring activity (Schrijver et al. 2008; Ravindra et al. 2011).

5. CORONAL MAGNETIC FIELD STRUCTURE AND FAN–SPINE TOPOLOGY

In order to derive the magnetic connectivity of the observed boundary distribution of the fields, we constructed the 3D field above the AR using potential and NLFFF approximations as discussed in Section 3. The force freeness of the reconstructed NLFFF solutions is measured by the weighted average angle ($\sigma_x$) between the field and current which is less than 15° and the integrals in Equation (2) are about $L_1 \leq 2.7$ and $L_2 \leq 1.3$ in all time frames. In principle, these terms must vanish for exact force-free equilibria, but due to noise and measurement errors in the boundary data, small residual forces remain. The solutions are still valid for further analysis, however.

Figure 3 shows field lines (color-coded with the vertical currents at their footpoints) at 23:00 UT. From the oblique view in panel 3(a), the field lines connecting the major sunspots are overlying (up to heights of 110 Mm) to those (below 40 Mm) connecting the fluxes at the middle part of the AR. In panel 3(b), the same field lines are plotted onto a 171 Å channel image for comparison with coronal plasma loops as proxies of magnetic field lines. Plasma structures from major sunspots resemble those with fewer current flowing field lines. This indicates that these overlying long loops are almost current free. However, compact, stressed locations are generally observed at flaring sites (the white rectangular region shown in panel 3(c)). These complicated structures are difficult to model even with the NLFFF approximation. As conjectured earlier, sheared field vectors along the PIL around SSP yields stressed (in red) field lines with significant currents along them. It is worth mentioning that this is the only location that differs from the rest when compared to that of PF-based magnetic structures. These elevated structures indicate a non-potential, higher energy state in the flaring region. Those field lines that are somewhat away from the PIL in the surrounding negative flux region are connecting to remote positive flux regions. They are passing over the isolated positive polarity SSP and covering it with a dome-like structure. Such configurations are possible locations for the formation of null points with a specific topology relevant for reconnection. In total, the NLFFF model reproduced field structures that resemble coronal loops at large scales and at small, compact locations the structure is stressed, as expected from the sheared boundary vectors (e.g., Vemareddy et al. 2013).
Finding the null point and topological properties in a noisy reconstructed field structure is a difficult task. The procedure described in Haynes & Parnell (2007) is adopted to find the exact position of the null point. Basically, it involves scanning for the null to locate a possible grid cell and finding the precise position using a tri-linear interpolation with the help of an iterative Newton–Raphson scheme within the grid cell. We found null points in every frame of the PF model from 20:00 UT to 23:36 UT. In the NLFFF model, however, the algorithm did not find any null in a few frames, probably because of noise and computational errors. In the NLFFF field, the location of the null is (78.04, 43.55, 3.76) at 23:00 UT frame in the ROI. In all other frames, the null point is observed about this grid cell at a height of about 2.11 Mm (1 grid cell = 0.725 Mm) and above. The reason we would find no null after 23:36 UT in either model would be likely related to a structural change of the magnetic configuration by reconnection during the flare.

Further, topological properties of null can be obtained from eigenvalues and eigenvectors of the Jacobian matrix \( \delta B = \nabla \cdot B_i = \partial B_i / \partial x_j \) (Lau & Finn 1990; Priest & Titov 1996) in the vicinity of the null. For instance, the eigenvectors

\[
\hat{e}_0 = [-0.4181, 0.2368, 0.8770]^T \\
\hat{e}_1 = [0.6026, -0.7924, 0.0948]^T \\
\hat{e}_2 = [-0.0039, 0.9791, 0.2031]^T
\]

corresponding to eigenvalues \((-222.15, 105.87, 147.47)\) are evaluated for the \( \delta B \) matrix at 23:00 UT frame. As the determinant (product of eigenvalues) of this matrix is negative, the type of null is B or positive (Parnell et al. 1996). The nulls found at different time frames from the NLFFF solution are positive (B-type) whereas in the PF solution, the found nulls are all negative (A-type or the determinant of the Jacobian matrix is greater than zero).

With \( \delta B \), the Lorentz force \( (F) \) and the electric current \( (J) \) can also be estimated locally. The trace of \( \delta B \) must vanish. This is not the case, however, because of numerical errors and linearization. The average relative error (Xiao et al. 2006) for \( \delta B \) is estimated with the ratio given as, \( | \nabla \cdot B | / | \nabla \times B | \approx 10\% \). At this level of precision, the NLFFF approximation is presumed to be a suitable model reproducing and identifying reliable orientation of the fan–spine structure. Boundary data with less noise might lead to more accurate solutions in the form of the averaged angle (~15°) between the current and field in NLFFF solutions.

Two of the eigenvectors (with the same sign for the eigenvalues) define the fan surface and the third one specifies the spine direction. With knowledge of the fan plane orientation, field lines away from the null can be traced in a circle of points on either side of the fan-plane to visualize the local structure of the null. As an exemplary case, these field lines are plotted on an Hα image in Figure 4(a). The inner (cyan) and outer (orange) field lines meet in a circle of points that define the fan plane which is oriented at a tilt angle. The field lines below the fan plane (cyan) are diverging to connect with the photosphere exactly along the ribbon RB1 and those above (orange) are converging to connect at RB3.

In panel 4(b), the same structure is illustrated in oblique 3D view, overplotted onto the photospheric \( B_z \) field. The inner field lines (cyan) form a dome-like structure, which completely covers the isolated positive polarity spot SSP. This fan dome divides the volume into two distinct connectivities. To prove the existence of a null point, we extract the field strength \( |B| \) distribution in two perpendicular planes of slice#1 and slice#2. They are shown in insets with logarithmic scale in the same panel. From the field distribution in these two slice planes, it is obvious that the residual field (yellow) is embedded within the strong fields of the AR and assures the correct identification of the null point.

In addition, we also traced field lines that have footprints lying along the outer edge of ribbon RB1 and are shown in the same panel (in yellow). They connect to the remote ribbons RB2 and RB3, demonstrating their topological relation. The connectivity with the southeast portion of RB3 from RB1 has no exact topological relevance, but the connection with the far away negative flux from RB1 is visible in Figure 3(c). These observations provide straightforward evidence that the identified coronal null point in the magnetic field structure confirms association with a fan–spine topology, which is of specific importance for favoring reconnection.
In panel 4(c), the fan–spine structure in the PF solution is obtained in a small volume of $8 \times 8 \times 8$ Mm$^3$ centered around the null. At this small length scale, the noise in the numerically extrapolated field did not allow us to directly compute the magnetic topology until we smoothed the field with a boxcar of three grid cells. As before, field lines in a circle of radius (0.7 Mm) from the null are traced up and down the side of the fan plane. Not surprisingly, the null point contains two types of isolated field lines called the spine lines. One is below the fan plane (blue) touching the middle part of an isolated sunspot and another is above the fan plane (orange) and extends toward RB3. In the fan plane, both of the field lines (blue and orange) diverge and manifest a separatrix surface in the form of a dome-shaped structure intersecting with the photosphere along the inner edge of the ribbon. This local field structure around the null is reminiscent of a theoretically predicted topology by Lau & Finn (1990, see their Figure 2) with a $\gamma$-line along the spine and a $\Sigma$-surface as the fan. Owing to the type of the null, which is negative (A-type), the field lines in the fan plane are directed away from the null (Parnell et al. 1996). Note that the spine eigenvector is almost normal (an angle deviation of $2^\circ$) to the fan plane, as expected for PF nulls.

Similarly, for the NLFFF solution (panel 4(d)), the existence of a fan–spine topology is obvious, but it is structurally different from the characteristics of a PF magnetic null. The eigenvectors constructing the fan plane subtend a $139^\circ$ angle and the normal has about a $24^\circ$ angle with the spine axis, leading to a tilted orientation of the fan plane. An electric current ($\mathbf{J} \cdot \hat{e}_0 \neq 0$, $\mathbf{J} \cdot \hat{e}_1 \neq 0$, $\mathbf{J} \cdot \hat{e}_2 \neq 0$) flows along the eigenvector directions, which is consistent with the nature of the non-potential null and a non-perpendicular orientation of the fan plane with the spine axis. Moreover, because the type of this null is positive (B-type), the field lines are directed toward the null and we can note from the figure that they are spirally approaching the null. This spiral nature of the field lines around the null delineates twist and currents, forming a complex topological structure that is entirely different from that of the potential case.

Thus, we identify a magnetic null point in the coronal magnetic structure that is associated with a specific fan–spine topology. The intersection of the fan dome with the photosphere...
Figure 5. Iso-surface (level 0.015 Am$^{-2}$) of coronal current distribution $|\mathbf{J}|$ projected onto the photospheric $B_z$ magnetogram in (a) the plane-projected 2D view and (b) the perspective 3D view. Three planes of slice#1, slice#2, and slice#3 [orange rectangular planes], the cross-section of the domed structure of the fan–spine topology, are considered to extract their current distribution (Figure 6). Obviously, the current is concentrated at the localized fan separatrix (see Figure 4(a)) above the PIL in the corona, up to 8 Mm and intersecting along the ribbons at the main flaring location.

(A color version of this figure is available in the online journal.)

along the main flaring ribbon provides potential evidence for the topological relevance of the coronal reconnection location and ribbon emission.

6. QSLs, CURRENT DISTRIBUTION, AND RECONNECTION

Using the three components of the magnetic field, we compute the electric current distribution $|\mathbf{J}|$ above the flaring region and study its evolution. In Figure 5, the iso-surface of $|\mathbf{J}|$ at the 0.015 Am$^{-2}$ level is rendered and plotted onto the $B_z$ magnetogram in top and perspective views. The chosen level of iso-surface indicates a strong current distribution. By comparing these coronal currents with the locations of the Hα flare ribbons, we understand that ribbon RB1 is directly associated with a coronal current layer as a domed structure. The intersection of this current layer at the lower boundary almost traces the path of RB1. Furthermore, its volume distribution is concentrated at the 3D separatrix surface of the domed structure, covering SSP as seen in Figure 4(b). This indicates that the separatrix layers constituted by the domed field lines (Figure 4(b)) are natural locations for current layers, as found in several theoretical studies (Demoulin et al. 1996, 1997). As the ribbon RB1 follows the path of the PIL, which is surrounded by a sheared horizontal field distribution (Figure 1, panels (g)–(i)), the currents are generated by twisted structures along the PIL extending to the corona and forming an almost closed surface. As no flux emergence appeared, the assumed mechanism to build these coronal currents is the motion of flux. At higher values of the current, the iso-surface can still be thinner and lower in height. Two similar locations of the coronal current locations are identified along ribbon RB2. However, above the ribbon RB3, the current is weakly distributed compared to these locations, so that its iso-surface cannot reach prominent levels.

In the successive stages of the quasi-static evolution, the stress in the photospheric fields develops possibly by slow flux motions, which in turn build up coronal currents. These stressed field lines about the closed PIL construct a domed coronal current distribution. It is important to note that the null is located within this dome structure. When reconnection commences at this coronal null, the currents at the associated separatrices will dissipate and power the flare. In order to capture the effect of dissipation, we have extracted $|\mathbf{J}|$ in the planes of arbitrarily chosen slices#1, 2, and 3, cross-sectioning the dome structure as depicted in Figure 5 (orange planes). The obtained current distribution in these slice planes from the time frames before (22:00 UT), during (23:12 UT), and after (23:48 UT) the flare are plotted in Figure 6. The height of the current distribution extends to 8 Mm (the contour level 0.01 Am$^{-2}$ is marked) in the corona. Note that slice#1 is almost in the plane containing the coronal null and crosses the localized region involving photospheric field enhancement, as noted in the previous section.

This coronal current distribution in slice#1 evolves toward a constricted shape at 23:12 UT, thereby forming a cusp-shaped distribution appearing at lower height at 23:48 UT. A similar evolution is seen mildly in the current distribution of slices#2 and #3. As the coronal current evolution is affected more in slice#1, having a magnetic null point, it confirms further that reconnection occurs in the corona in this plane, but not in the planes across ribbon RB1, which do not contain nulls. Note that reconnection of magnetic fields is a dynamical effect and occurs in thin current sheets which are not resolvable by present observations. The coronal current shown here has been computed from the curl of the slow evolving coronal fields.

It is highly difficult to trace the same single field line in every frame exactly to trace its connectivity change during the reconfiguration for several reasons. Because the reorganization of the fields happens in the corona, the photospheric fields would respond to such an effect in the line-tied scenario. However, this effect of coronal reconfiguration on the photosphere is small, localized, and sometimes not present at all. One can better investigate such changes by computing a number of collected field lines from a localized region. The coronal field evolution in the domed structure is shown in the panels of the last column in Figure 6. Field lines above the PIL at two different heights (1 Mm and 4 Mm) are traced and plotted. Their configuration indicates a sheared nature and provides evidence for coronal
Evolution of coronal current distribution in the planes of slices#1, #2, and #3 which are cross-sectioned (Figure 5) across the dome-shaped fan structure before, during, and after the flare. All panels are scaled within [0, 0.04] Am\(^{-2}\) and contain a contour level of 0.01 Am\(^{-2}\). First column: the slice plane is extracted across the PIL with unambiguous horizontal field change (Figures 1(g)–(i)), pre-existing coronal currents build up further to form stressed structures with a cusp-shaped current distribution (dissipation of these currents may drive reconnection). Second and third columns: distribution of currents located somewhat outside the flaring region, which only slightly changed during the flare in comparison to their pre-flare distribution. Note that the two vertical concentrations of the currents in all panels correspond to a coronal separatrix layer intersecting with ribbon RB1. Last column: the corresponding coronal field evolution above the sunspot SSP depicting the scenario for the coronal current generation. Field lines over the PIL are up to 1 Mm in height (red) and overlying lines (in orange) are up to 4 Mm in height. Note that some of the open field lines get closed at 23:48 UT.

(A color version of this figure is available in the online journal.)

Figure 6.

Evolution of coronal current distribution in the planes of slices#1, #2, and #3 which are cross-sectioned (Figure 5) across the dome-shaped fan structure before, during, and after the flare. All panels are scaled within [0, 0.04] Am\(^{-2}\) and contain a contour level of 0.01 Am\(^{-2}\). First column: the slice plane is extracted across the PIL with unambiguous horizontal field change (Figures 1(g)–(i)), pre-existing coronal currents build up further to form stressed structures with a cusp-shaped current distribution (dissipation of these currents may drive reconnection). Second and third columns: distribution of currents located somewhat outside the flaring region, which only slightly changed during the flare in comparison to their pre-flare distribution. Note that the two vertical concentrations of the currents in all panels correspond to a coronal separatrix layer intersecting with ribbon RB1. Last column: the corresponding coronal field evolution above the sunspot SSP depicting the scenario for the coronal current generation. Field lines over the PIL are up to 1 Mm in height (red) and overlying lines (in orange) are up to 4 Mm in height. Note that some of the open field lines get closed at 23:48 UT.

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currents in the form of ridges (obtained in slice planes across the dome) as shown in the other panels of the same figure. The overlying field lines (orange) connect to distant fluxes around the PIL and some of them are open to converge with the spine from the null location. In successive time frames, these open overlying field lines (very few from the localized region where horizontal fields have undergone a permanent change; see Figures 1(h) and (i)) become closed after reconnection at 23:48 UT. During this reorganization, the stress in the coronal field releases and magnetic energy becomes redistributed from higher to lower heights that contain a cusp-shaped current distribution and a closed field configuration.

Following the procedure described in Section 3, the distribution of \(Q\) on the photosphere (\(z = 0\)) is calculated and compared with the photospheric vertical current and the \(\text{H}\alpha\) ribbon locations (Figure 7). The computed values of \(Q\) are distributed in the range between 20 and 10\(^3\) with a grid size, eight times finer than the original model grid. At further fine resolutions, the values of \(Q\) may be still higher, which becomes computationally expensive. It is inferred that when \(Q\) reaches the order of 10\(^9\), the thickness of the QSLs is small enough to allow reconnection (Demoulin et al. 1996, 1997). Therefore, the resolution at which we compute \(Q\) is small enough to locate important QSLs, which are taking part in reconnection. We show logarithmic \(Q\) maps, scaled within the minimum and maximum of the \(Q\) distribution. The NLFFF model shows a more complex field structure compared with the PF model, and consequently, the \(Q\) pattern differs. The noisier transverse field, used as the boundary condition for the NLFFF model, contributes significantly to the patchy \(Q\) structure, contrary to noiseless, smooth structures usually found in analytical configurations (e.g., Demoulin et al. 1996; Titov 2007). To identify the important QSLs, which are relevant for the topology, Savcheva et al. (2012) conjectured that the significant QSLs have both high \(Q\) values and a high current density \(|J|\). The authors used the product of \(Q\) and \(|J|\) to compare with flux rope structures. However, the \(QJ\) plots are not well proved to be identify the main QSLs and the current density for the PF is zero; consequently, we do not use them here. They also suggested computing \(Q\) at different heights above the photosphere to avoid patchiness.

In both models of the field extrapolations, the strongest \(Q\) values (black lanes of panels 7(a)–(c)) form a structure like a tadpole in the strong field regions in addition to other patchy lanes related to noise, small magnitude, and fragmented fields across the AR. We note the deviation of these small-scale patterns between PF and NLFFF models by the presence of sheared horizontal fields in the latter. The high \(Q\) of this tadpole head is almost lying along the inversion line of the magnetic field and also traces the inner edge of the quasi-ellipsoidal ribbon RB1 (see panel 7(g)). The tail of this tadpole \(Q\) pattern extends to RB2 through RB3. Note that the southeast part of RB3 does not have much relevance with RB1, however, the fluxes away from RB1 do have continuous mapping, as stated in earlier sections. Furthermore, the footprints of fan field lines (plotted in panels 4(a) and (b)) fall along this elliptical high \(Q\) which implies that the domed separatrix surface associated with the null is surrounded by a gradual connectivity gradient generalizing separatrices to QSLs.

To compare these \(Q\) maps, we also plotted the vertical current \((J_z)\) in panel 7(i). The distribution of \(J_z\) is in the range of...
Figure 7. Spatial distribution of squashing degree $Q$, which defines QSLs and its association with flare ribbons. The $Q$ at the photospheric boundary ($z = 0$) is calculated with (a) the potential field, (b)–(c) NLFFF approximations, and displayed in logarithmic gray scale. Noticeably, high $Q$ values form a tadpole-like pattern in both models. The $Q$ pattern differs at small scales, especially at the tadpole head portion in PF and NLFFF solutions. An obvious change in $Q$ between 23:00 UT and 23:48 UT, marked at the arrowed position, is shown in the enlarged insets, (d)–(f). The corresponding vertical cross-sections of $Q$ in a plane are indicated by a solid line in panels (a)–(c). The maximum height of $Q$ decreased by 2.37 Mm from 23:00 UT to 23:48 UT. In all panels, the values of $Q$ ranged from the lowest (in white) 20 to the highest $10^3$ but scaled appropriately for better visibility. (g) An overlay of contours of log($Q$) on an Hα image illuminating the spatial association of $Q$ and ribbons. (h) AIA 94 Å channel image with $B_z$ contours showing the coronal connectivity of ribbons and fluxes. (i) Spatial distribution of vertical current ($J_z$) also depicting large values around the positive flux sunspot SSP. Iso-contours of $B_z$ at ±150 G are shown in red/blue. The FOV in panels (a)–(c) and (g)–(i) is same as that indicated by the white rectangular box (ROI) in Figure 1.

Interestingly, there is a clear change in the trace of $Q$ (marked by a blue arrow) in the head portion of the tadpole in the frames just before the flare at 23:00 UT and after the flare at 23:48 UT (panels 7(b) and (c)). The locus of $Q$ transforms from a more zigzag path to a smoother one. Note that the change of this geometric path is more than 1 arcsec and it is in the south part of the PIL, which is associated with the coronal field reconfiguration. The north part of the PIL also has a similar zigzag path, but does not change during the flare. Reorganization during magnetic reconnection releases high stress from the fields and therefore the path of $Q$ and the QSLs change significantly around the flare time. Moreover, the squashing degree distribution is evaluated in the vertical cross section plane of the tadpole head, i.e., in the dome structure to construct coronal QSL shapes (see Figures 7(d)–(f). The overall shape of the QSL follows ±150 mAm$^{-2}$; the higher values are located along the PIL of the flaring region. Concurrently, the large values of the vertical current in the form of ridges around the SSP also spatially coincide with this large elliptical $Q$ value (especially the head part of the tadpole). The AIA 94 Å image, which captures the hot coronal plasma loops (~6 MK), is shown in panel 7(h). A comparison of the $Q$ map with the Hα flare ribbons is depicted in panel 7(g).
field lines in the dome structure with one of its legs located at one side of the quasi-elliptical PIL and the second one on other side; the legs are connected by a straight line across the tadpole $Q$ pattern. The middle section of this QSL is rooted close to the central part of the SSP (as a downward spine) intersecting with the outer legs in the corona. Their shape also resembles the coronal current distribution (Figure 6) obtained in similarly oriented planes. Specifically, the QSL extends to higher heights (maximum height is 6.8 Mm) in the NLFFF model than in the PF model (maximum height is 3.4 Mm), because of currents in twisted fields.

Interestingly, the maximum height of the QSL structure decreased by 2.37 Mm during the evolution from 23:00 UT to 23:48 UT. This significant decrease in height is similar to the evolution of the coronal current distribution in slice#1 of Figure 6. The change in the height distribution of $Q$ and $|J|$ is most likely caused by a reconfiguration of the field structure as explained earlier. With this characteristic finding, it is evidently clear that coronal QSLs are natural locations of currents, facilitating reconnection in them, and their signatures appear as ribbons in the lower chromosphere as a consequence of particle acceleration.

From this comparison, it is evidently clear that the domed-shaped field lines from ribbon RB1 are mapped to RB2 and RB3. Their association infers that the photosphere satisfies line-tied conditions, in which case the flare ribbons are created at the footpoints of QSLs and photospheric currents appear at locations of the flare ribbons similar to those found here. Flare ribbons are generally locations defined by a high vertical current distribution (Vemareddy et al. 2012a) and their relation with QSLs (quantified by their $Q$ values) is topologically (Savcheva et al. 2012; Janvier et al. 2014) found to be well associated. These observations imply a direct association of the QSL, ribbons, and current distribution both at the photosphere and in the corona, as predicted from standard flare models.

7. DISCUSSION

Magnetic fields of the AR evolve quasi-statically under slow motions of line-tied footpoints to the photosphere. By modeling the AR magnetic field with a force-free model, we studied the evolution of the magnetic structure covering the pre- and post-phases of a flare. However, during the time of the flare, rapid changes in magnetic fields cannot be investigated with such an equilibrium model. Assuming a coronal Alfvén velocity of 1000 km s$^{-1}$, the timescale for an Alfvén wave traveling through the entire AR (300 arcsec) is less than 4 minutes. Consequently, dynamic features within this timescale cannot be reproduced in this model, as a quasi-static condition for fields is not valid here. Nevertheless, by following the magnetic system evolution in the AR with a 12 minute time step, where quasi-static approximation remains valid, key information about the stability of the system, e.g., free energy, and the location of the current sheets can be obtained.

Magnetic reconnection can be induced at null points with a fan–spine structure. Numerical simulations show that flux emergence and line-tied shearing boundary motions and rotational motions can induce current sheets near a 3D null point (Pontin et al. 2007; Pariat et al. 2009; Edmondson et al. 2010). The flux systems below and above the fan are then able to interact near the null by magnetic reconnection.

The present confined flare event occurred in the magnetic configuration of an AR with a fan–spine topology, similar to previous studies (Masson et al. 2009; Sun et al. 2012, 2013). The dome-shaped fan separatrix is observed to intersect almost along quasi-elliptical ribbon RB1 and the spine field lines connect to remote ribbon RB3 (we assume this location belongs to RB3). Footpoints of field lines originating from the outer edge of the quasi-elliptical ribbon explain the extended regions of remote ribbons RB2 and RB3. Furthermore, within the six-hour time span, there is no evident flux emergence from the flaring region. Nevertheless, flux motions up to 1.2 km s$^{-1}$ (Vemareddy et al. 2012b) are observed at this central part of the AR. These slow, continuous footpoint motions are the only supposed factors causing the build-up of current layers in the coronal quasi-separatrices in the form of stress in field lines and they further induce reconnection at the coronal null. A predominant increase of the net current before the initiation of a flare (see Figure 2) in both polarity fluxes, but without appreciable flux emergence also supports this presumption. Also, time-dependent MHD simulations for photospheric line-tying conditions (Karpen et al. 1990, 1991) confirmed the formation of quasi-static current sheets near separatrices. Therefore, these findings tend to suggest that line-tied footpoint motions perturbed the fan–spine system, inducing null point reconnection, resulting in flare emission at the footpoints of fan field lines and constituting a quasi-elliptical ribbon.

The observations of this flare are very similar to that in Masson et al. (2009), except that flux emergence was identified in that study. Their interpretations of the prominent observational features with the aid of MHD simulations suit our case and are useful for drawing possible conclusions. Indeed, their simulation results helped Wang & Liu (2012) to analyze five cases of circular flare ribbons, which are often associated with jets, using solely Hα observations. Many observed features of flare ribbons may be difficult to explain with static models, due to the dynamic nature of the reconnection at the null point. Therefore, we will discuss them in connection with their simulation results.

During the reconnection, the field lines break and reconnect instantaneously at the separatrices or quasi-separatrices, slipping across each other. Aulanier et al. (2006) demonstrated slipping (when field line velocities are sub-Alfvénic) and slip running (when field line velocities are super-Alfvénic) reconnection within the QSLs using numerical simulations. Evidence of this slipping reconnection was reported by Aulanier et al. (2007) showing the coronal soft X-ray loops having opposite footpoint motions realizing slipping reconnection.

When the reconnection phase commences at the coronal null point, emissions are expected to originate at the footpoints of underlying fan and spine field lines. According to the above simulation results, field lines closer to the null would reconnect first and the slipping motion toward the null could then account for the counter-clockwise propagation of the circular ribbon emission. The same reasoning applies here for the emission of ribbon RB1.

During sequential occurrence of slip and slip-running reconnection within the fan and null point reconnection, depending on the distance of the field lines from the spine, they slip or slip-run in directions and over distances that are compatible with the dynamics of a remote ribbon at the spine footpoints. As the observed remote ribbon RB3 is far away from the main ribbon RB1 of null-point reconnection, the delayed emission of RB3 by one minute can therefore be explained. The observed dynamics of ribbons are explained by slip and slip-running reconnection of field lines in the QSL. However, there is no a priori reason
for both QSLs and separatrices with nulls to co-exist in a given magnetic structure and connectivity. To explain this, the idea of separatrices embedded in larger QSLs was proposed by calculating gradients of connectivity with a squashing degree (Masson et al. 2009). We can see from Figure 7 that the tadpole-like pattern of very large values of $Q (10^{13})$, separatrices) is extended by intermediate values of $Q$ (i.e., QSLs). Specifically, in the region of the tadpole head, the fan separatrix (large $Q$) facilitates null-point reconnection and the extended QSL (intermediate $Q$) regions allow field lines to slip and slip-running reconnection to explain the ribbon dynamics.

After the impulsive phase of the flare, i.e., the plasma loops evolved to post-flare arcades. This gives us the impression of a disbursted fan–spine topology toward the relaxed state of PFs. For this reason, the null point disappears in the frames after 23:36 UT in either model (PF and NLFFF). When field lines are subjected to imposed boundary motions, which further brought them to a threshold level of sheared configuration, the fan–spine system collapses toward null-point reconnection. Then these field lines are subjected to slip and slip-running reconnection. As a consequence, more field lines in the fan separatrix along the southern part of the PIL become closed. As a consequence, more field lines in the fan separatrix along the southern part of the PIL become closed (Figure 6). With this change in coronal field connectivity, the corresponding signatures, such as a decreased height of the QSL in a vertical cross-section, a change in the footpoints of the QSL at the boundary (Figure 7), and photospheric horizontal field enhancement (Figures 1(h)–(i)) at a localized region are predominantly noted.

8. SUMMARY

We present a detailed study of an X1.5 flare using a force-free coronal magnetic field model. We focus especially on the coronal connectivity of the observed ribbon emission, caused by reconnection-accelerated particles toward lower layers of the solar atmosphere. We envisioned the existence of a particular type of topological structure associated with a magnetic null point. The existence of null points in the magnetic structure of the AR is of fundamental significance for the 3D reconnection process. The main findings of this study are as follows.

1. The AR has an overall bipolar magnetic configuration with a small positive sunspot SSP surrounded by a group of small sunspots of negative polarity at the center. This central region forms an almost closed contour of the PIL and sheared horizontal fields are located along it.

2. An X1.5 flare occurred, forming a quasi-elliptical Hα ribbon RB1 along the exterior of the closed PIL, and remote ribbons RB2 and RB3. Emission in UV 1700 Å spatially coincides with the Hα ribbons and has a peak emission at 23:23 UT. Temporal and spatial association of HXR sources with these flare ribbons suggests that reconnection at the coronal null point above SSP is likely to have a field line linkage with ribbons, which is further ensured by coronal loop connections in hot 94 Å observations.

3. Coronal PF and NLFFF models unveiled the presence of fan–spine topology associated with a single null point above the SSP. The flare location of the HXR emission coincides well with the null point location, implying the possibility of null-point reconnection. Moreover, ribbon RB1 is almost co-spatial with the intersection of the fan surface with the lower boundary, and the outward spine connects to ribbon RB3. Field lines from the outer edges of RB1 are linked to extended regions of remote ribbons RB2 and RB3, thereby explaining the topological relevance of observed ribbon emissions.

4. With the continued slow footpoint motions, shear stresses the field lines located along the PIL and leads to the formation of current layers (Figure 5) around the fan separatrix surface. These layers facilitate reconnection that dissipates coronal currents appearing as cusp-shaped structures at lower heights. Reconnection releases energy and results in field lines close to a PF.

5. At the lower boundary, the spatial distribution of field line connectivity gradients quantified as squashing degree $Q$ have large values, forming a tadpole-like pattern. The head part of this pattern outlines the PIL and the inner edge of RB1, and the tail part extends to RB2 through RB3. Furthermore, the high $Q$ values of this pattern are extending to intermediate values, indicating separatrices of discontinuous connectivity embedded in QSLs of continuous field line connectivity gradients. These embedded separatrices in QSLs will facilitate slip and slip-running reconnection (Aulanier et al. 2006; Masson et al. 2009).

6. While reconnection reorganizes field line connectivity, the footpoints of separatrices/QSLs at the boundary showed a transition from a zigzag path to a straight one in the southern part of RB1. At the same time, the maximum height of the coronal QSL structure decreased by 2.37 Mm during pre-to-post flare evolution. These significant changes suggest a clear topological change of the magnetic structure as the consequence of magnetic reconnection.

7. With knowledge from previous numerical studies (Masson et al. 2009; Pariat et al. 2009) and the findings here, we suggest that line-tied footpoint motions perturbed the fan–spine system and caused null-point reconnection, resulting in flare emission at the footpoints of the fan field lines lying in the quasi-elliptical ribbon RB1. During sequential reconnection at the null, the slipping motion of field lines toward the null explains the counter-clockwise emission of RB1 and slip and slip-running reconnection of field lines toward the outer spine can explain the one-minute delayed emission of RB3 compared to that of RB1.

Studying quasi-static evolution of coronal magnetic fields provides plenty of understanding about how the AR magnetic system stores and releases energy. It also provides details of the topological structure, which was appropriate for reconnection, thereby explaining several aspects of the standard flare model. In other words, it successfully attempts to provide 3D details of 2D images of the flare seen in different wavelengths using a force-free coronal magnetic field model. This kind of modeling of the slow evolution of the AR magnetic fields is also useful for identifying the gaps between observations and theoretical predictions, which can be tested by dynamical MHD simulations.

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