Formation and Eruption Process of a Filament in Active Region NOAA 12241

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Abstract

In order to better understand active-region filaments, we present an intensive study on the formation and eruption of a filament in active region NOAA 12241 during the period from 2014 December 18 to 19. Using observations from the Helioseismic and Magnetic Imager (HMI) vector magnetograms, we investigate the helicity injection rate, Lorentz force, and vertical electric current in the entire region associated with the filament. The helicity injection rate before eruption is found to be larger than that after eruption, while the vertical electric current undergoes an increase at first and then a gradual decrease, similar to what the magnetic flux undergoes. Meanwhile, we find that the right part of the filament is formed by magnetic reconnection between two bundles of magnetic field lines while the left part originated from shearing motion. The interaction of the two parts causes the eruption of this filament. The mean horizontal magnetic fields in the vicinity of the magnetic polarity inversion line (PIL) enhance rapidly during the eruption. Another striking phenomenon, where the vertical electric currents close to the magnetic PIL suddenly expand toward two sides during the eruption, is found. We propose that this fascinating feature is associated with the release of energy during the eruption.

Key words: Sun: activity – Sun: evolution – Sun: filaments, prominences

Supporting material: animations

1. Introduction

Solar prominences are common and spectacular features on the Sun, consisting of dense and cool plasma material suspended in the extremely hot corona. When they are observed on the solar disk, they appears as dark filamentary structures called filaments. Based on ground- and space-based observations, filaments are always found above the magnetic polarity inversion lines (PILs), which separate the signs of the magnetic fields on the photosphere (Babcock & Babcock 1955; Howard 1959; Martin 1998; Okamoto et al. 2008, 2009). It is customary to divide filaments into three styles according to their locations on the solar disk: active-region filaments, intermediate filaments, and quiescent filaments (Patsourakos & Vial 2002; Mackay et al. 2010).

The magnetic field, which plays a key role, is always associated with filaments in the corona. This fact helps us understand the formation, dynamic stability, and eruption of filaments. It is widely believed that filaments are supported by the local magnetic field including a “dips” structure (configuration of upward concavity) or a twisted structure against the gravity (Kippenhahn & Schlüter 1957; Kuperus & Raadu 1974; Lee et al. 2000; Liu et al. 2012; Yan et al. 2014, 2015). However, due to the limitations of magnetic field measurements at present, understanding the magnetic configuration of filaments is still debated by different research groups. Based on observations and numerical simulations, Kippenhahn & Schlüter (1957) proposed that the filament is a thin current sheet perpendicular to the surrounding magnetic field and supported by the Lorentz force, while Kuperus & Raadu (1974) suggested that the filament is supported by magnetic forces caused by the photospheric-induced currents. Therefore, two different theories for the magnetic topologies of filaments have been proposed: the sheared arcade model (Kippenhahn & Schlüter 1957; Malherbe & Priest 1983; Antiochos et al. 1994; DeVore & Antiochos 2000; Welsch et al. 2005) and the flux rope model (Kuperus & Raadu 1974; Aulanier & Demoulin 1998; Amari et al. 2000; Guo et al. 2010; Cheng et al. 2014; Priest & Longcope 2017). Both models can clearly explain certain observed properties of filaments, but ambiguous observational evidences could not completely favor either of them.

Another unresolved question is how such dark and dense filaments form in the extremely hot but thin corona. It includes two considerations: material injection and magnetic structure. Chae (2003) reported that the material can be ejected into an active-region filament by a succession of jets and small eruptions through magnetic reconnections. Some researchers also found that cool plasma can be lifted by rising magnetic fields at PILs (Galsgaard & Longbottom 1999; Litvinenko & Wheatland 2005; Kucur et al. 2012; Song et al. 2017). The convergence and cancellation of magnetic flux are considered to play important roles in the formation of the magnetic structure of filaments, which have been reported by some authors (Martin 1998; Wang & Muglach 2007). Based on observations and numerical simulations, many researchers have suggested two distinct ways that filament magnetic structure is formed: surface action (van Ballegooijen & Martens 1989; Martens & Zwaan 2001; Yeates et al. 2008; Yang et al. 2016) and subsurface action (Low 1994; Fan & Gibson 2006; Archontis & Török 2008; Magara 2008). In the former, the magnetic structure connects with sheared flows, rotating motion, and converging flow toward opposite magnetic polarities in the photosphere, and most of these photospheric motions occur in the vicinity of the magnetic PILs. In this sense, the magnetic structures of filaments are formed generally.
through magnetic reconnection between pre-existing magnetic fields, which are driven by photospheric motions. Giauquesaks et al. (1997) reported that the formation of a filament is related to the photospheric motion of its bottom part. Using the data observed by the NVST, SDO, and Hinode observatories, Yan et al. (2015) found that sunspot rotations and shearing motions are responsible for the formation of two homologous active-region filaments in NOAA 11884. In subsurface action, the magnetic structure is associated with magnetic flux emergence and various motions in the convection zone. In this sense, the magnetic structures of filaments are thought to be formed in the solar interior and emerge into the atmosphere through magnetic buoyancy. Although both views can explain some observational characteristics, the complicated processes of filament formation are still not fully understood.

In order to understand the nonpotential evolution of filaments, many researchers tried to find some precursors of filaments, which are used to forecast their appearance and disappearance (Liu et al. 2012; Malanushenko et al. 2014; Liu et al. 2016; Wang et al. 2016). In this paper, we study the formation and evolution process of an active-region filament, which is composed of two parts. The evolutions of some physical parameters (e.g., Lorentz force, helicity, vertical electric current, and so on) are investigated in the active region during the periods related to the formation and eruption of this filament. We also discuss the formation mechanisms of the two filament parts and the eruption process of filament by using the data observed by the SDO, GOES, and Global Oscillation Network Group (GONG) instruments.

2. Observations and Methods
2.1. Observations

The filament was formed in NOAA Active Region 12241, which is located close to the center of the solar disk (about S11°E15°), from December 18 to 19. Full-disk, multi-wavelength, high spatio-temporal observations captured by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Hoeksema et al. 2014) on board the Solar Dynamic Observatory (SDO; Pesnell et al. 2012) are available for this study. The SDO/AIA provides seven extreme ultraviolet and three ultraviolet-visible channel images with a spatial resolution of 0.6 arcsec per pixel and a minimum cadence of 12 s, while the SDO/HMI provides line-of-sight magnetic fields, continuum intensity, Doppler shift, and vector magnetograms (VMs) on the photosphere with a spatial resolution of 0.5 arcsec per pixel, with the cadences of the three former channels being about 45 s and that of the latter one being about 12 minutes. The vector magnetic fields of the HMI are derived using the Very Fast Inversion of the Stokes Vector (VFISV) algorithm (Borrero et al. 2011; Centeno et al. 2014), and the 180° azimuthal ambiguity is resolved with the minimum energy method (Metcalf 1994; Leka et al. 2009). We use the AIA 304 Å images to illustrate the evolution of the filament and utilize the VMs to study the different physical parameters during the period from December 18 12:00 UT to December 19 04:00 UT, while the SDO/HMI magnetograms are used to investigate the magnetic configuration around the filament. Furthermore, the Hα images observed by the GONG (Harvey et al. 1996, 2011) at the National Solar Observatory (NSO), which includes six stations all over the Earth, also allow us to study the filament in detail, with a spatial resolution of 1.05 arcsec per pixel and a cadence of 1 minute. Moreover, the GOES spacecraft provides the soft X-ray flux profile to identify the flare during the eruption of the filament.

2.2. Methods
2.2.1. Magnetic Helicity Injection Rate

As is well known, the magnetic helicity of a field \( B \) within a volume \( V \) is defined as

\[
H = \int_V A \cdot B dV,
\]

where the vector potential \( A \) satisfies

\[
B = \nabla \times A.
\]

The magnetic helicity injection rate, which reflects the time variation of the magnetic helicity, can be deduced as (Berger & Field 1984):

\[
\frac{dH}{dt} = -2 \int_S (A \cdot u) B_n dS,
\]

in which \( S \) denotes the boundary surface of the volume \( V \), \( u \) denotes the velocity of the flux tubes on the boundary (the flux transport velocity, \( u = V_e - (V_n/B_n)B_e \)) (Démoulin & Berger 2003), and \( B_n \) denotes the strength of the normal component of the magnetic field. In general, the magnetic helicity is related to the morphological structure of the closed magnetic field (such as the linkage and twisting of the field), while the magnetic helicity injection rate is associated with the flux emergence and the sheared, vortical, twisting, and rotating motions on the solar surface, which is often thought to be one representation of magnetic non-potentiality. With the acceptable assumption that the solar photosphere \( S \) is planar, Pariat et al. (2005) proposed that the helicity injection rate could be transformed to

\[
\frac{dH}{dt} = -\frac{1}{2\pi} \int_{S'} \int_S \frac{d\theta}{dt} B_n B_n' dS dS',
\]

and

\[
\frac{d\theta}{dt} = \frac{1}{r^2} \left( r \times \frac{dr}{dt} \right) \frac{1}{n} = \frac{1}{r^2} (r \times (u - u'))_n,
\]

where \( r = x - x' \) denotes the vector between two photospheric points defined by \( x \) and \( x' \), and \( u \) and \( u' \) are the homologous velocities of two different points. According to Equations (4) and (5), the vector velocity field should be available to calculate the helicity injection rate. Therefore, we derive the vector velocity field by using the Differential Affine Velocity Estimator for Vector Magnetograms (DAVE4VM) method (Schuck 2008). The DAVE4VM method implements a variational principle with the magnetic induction equation to track the velocity of magnetic footpoints. We adopt 19 × 19 pixels as the window size for DAVE4VM, which is determined by examining the slope, Pearson linear correlation coefficient, and Spearman rank order between \( v_n \cdot (u B_n) \) and \( \Delta B_n / \Delta t \) (Schuck 2006, 2008). Once the vector velocity fields have been derived using the DAVE4VM method, the helicity injection rate \( (dH/dt) \) could be calculated by integrating over the
boundary surface by using the SDO/HMI VMs with the cadence of 12 minutes.

2.2.2. Lorentz Force and Electric Current Calculation

With the reasonable assumption that if the upper surface and the side walls of the volume are sufficiently distant from the active region, then the magnetic field contribution from those boundaries can be negligible, the Lorentz force acting on the upper solar atmosphere can be deduced as (Fisher et al. 2012):

$$ F_r = \frac{1}{8\pi} \int_{A_{ph}} (B_r^2 - B^2) dA, \quad (6) $$

and

$$ F_h = -\frac{1}{4\pi} \int_{A_{ph}} B_r B_h dA, \quad (7) $$

where $B_r$ is the radial field component, $B_h$ indicates the transverse field component, and $A_{ph}$ is the area of the photospheric surface covering the active region. $F_r$ and $F_h$ denote the radial/upward and horizontal components of the Lorentz force, respectively. Note that the Lorentz force is a global quantity, meaning that the Lorentz force is meaningful only for the entire active region. We utilize the Lorentz force to investigate the relationship between the evolution of the active region and the force acting on the upper atmosphere. On the other hand, the corresponding changes in the Lorentz force vector components acting on solar interior which is equal and opposite to the one acting on upper atmosphere can be deduced by Equations (6) and (7):

$$ \delta F_r = \frac{1}{8\pi} \int_{A_{ph}} (\delta B_r^2 - \delta B^2_h) dA, \quad (8) $$

and

$$ \delta F_h = -\frac{1}{4\pi} \int_{A_{ph}} \delta (B_r B_h) dA. \quad (9) $$

These equations are often employed to investigate the breakback reaction of eruption from the atmosphere to the interior (Petrie 2012, 2013; Wang et al. 2012b; Xu et al. 2016). Petrie (2013) argued that it is useful to estimate the spatial distributions of the Lorentz force vector when the distributions of the calculation field are the major, well-resolved magnetic structure. Therefore, we can derive the spatial distribution of the Lorentz force changes $\delta F_r$ and $\delta F_h$ by integrating pixel by pixel based on Equations (8) and (9) during the eruption of the filament.

Another nonpotential quantity, electric current, plays an important role in filaments. As is well known, the electric current density can be calculated by Ampere’s law:

$$ J = \frac{1}{\mu_0} (\nabla \times B), \quad (10) $$

where $\mu_0$ denotes the magnetic permeability of vacuum, $J$ indicates the electric current density vector, and $B$ is the magnetic field vector. According to Equation (10), by neglecting the effect of the electric displacement current, the electric current density component perpendicular to the solar surface can be derived by the following equation:

$$ \mathbf{j}_l = \frac{1}{\mu_0} (\nabla \times \mathbf{B})_l = \frac{1}{\mu_0} \left( \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} \right), \quad (11) $$

where $B_x$ and $B_y$ are the two perpendicular components of the horizontal magnetic fields. According to Equation (11), the spatial distributions of the vertical electric current density perpendicular to the solar photosphere can be derived by using SDO/HMI VM data with a cadence of 12 minutes. To reduce the noise influence from the measurement, we only consider the field with a transverse component stronger than 100 G (the value of measuring error in the transverse magnetic field) to calculate the Lorentz force and the vertical electric current density.

2.2.3. A Nonlinear Force-free field Model Extrapolation

In order to illustrate the morphological characteristics of the filament’s magnetic field, we reconstruct the coronal magnetic field through a nonlinear force-free field (NLFFF) model based on the photospheric VMs. The extrapolated field derived by the NLFFF model extrapolation is thought to match well the magnetic structures of the observational images (Wiegelmann et al. 2005). The NLFFF extrapolation is based on the “minimized optimization” approach (Wheatland et al. 2000), which was implemented by Wiegelmann (2004) with a weighting function to reconstruct the coronal magnetic field. This method uses the photospheric magnetic field vector observed by the solar instrument and the potential field derived from the vertical component of the field with a Green’s function algorithm as a boundary condition to reconstruct three-dimensional magnetic fields. Before the extrapolation, we use a $2 \times 2$ rebinning of the boundary data to 0.72 Mm pixel$^{-1}$, the same as some authors (Sun et al. 2012; Wiegelmann et al. 2012; Liu et al. 2013). On the other hand, a preprocessing procedure is used for the photospheric vector magnetograph data, which drives the boundary data toward being more consistent with the assumption of a force-free field (Wiegelmann et al. 2006). In this study, the region for extrapolation is within a box of $300 \times 171 \times 171$ uniform grid points, which corresponds to about $216 \times 123 \times 123$ (Mm$^3$) (See Figure 1(b)).

3. Results

3.1. Long Evolution of the Active Region Associated with the Filament

Active region NOAA 12241, located in the south hemisphere, exhibited a complex distribution of magnetic fields, wherein the leading sunspot in the west was dominated by a positive magnetic field and a compound field was present in the east of the active region (see Figure 1(a)). From the SDO/AIA 304 Å and GONG H$_\alpha$ images in panels (c) and (d) of Figure 1, the filament had not yet really formed until about 12:00 UT on 2014 December 18, but some discontinuous filamentary structures could already be seen in the vicinity of the magnetic PIL, particularly in the left blue box in panel (c) of Figure 1. At about 21:24 UT, the mature filament appeared on the PIL (see Figures 6(a) and (b)). Most of the filament erupted away in a magnetic eruption that started at about 21:41 UT and produced a halo coronal mass ejection (CME) together with a GOES M6.9 flare (SOHO LASCO CME Catalog). The detailed
The evolutionary process of this active region is shown by the animated version of Figure 1. The photospheric VM at 11:58 UT is displayed in panel (b) of Figure 1, which corresponds to the region of NLFFF extrapolation, and shows the different calculated physical parameters such as magnetic helicity injection, Lorentz force, and electric current density.

With the methods described in Section 2.2, we analyze the evolutions of the different parameters during the period from 12:00 UT on December 18 to 4:00 UT on December 19, a duration covering the formation and eruption process of the filament. Figure 2 shows the variation of different parameters, where the red vertical dashed line denotes the onset of the filament eruption. These physical parameters are derived by integrating over the whole region of Figure 1(b). Panel (a) shows the time variations of magnetic fluxes integrated from the vertical component of the VMs. The black line represents the positive magnetic flux while the blue line represents the negative magnetic flux. Both polarities of the magnetic flux increased until about 19:00 UT and decreased gradually after that. The filament had not completely formed until 19:00 UT (See Section 3.2). It means this filament was forming in the periods that covered the growth and decay of the active region. Panel (b) shows the evolution of the helicity injection rate and accumulated helicity. The accumulated helicity is calculated by the time integral of the helicity injection rate, and we set it to be zero at the beginning of the investigating time. Generally, the active region had a positive helicity injection at all times. This feature agrees with the well-known hemispheric pattern that positive (negative) helicity is dominant in the southern (northern) hemisphere (Pevtsov et al. 1995; Mackay & van Ballegooijen 2005; Zhang & Low 2005). Another noticeable feature is that the helicity injection rate experienced a decrease after the filament eruption. In other words, the magnetic helicity during the periods of formation and static process of the filament was injected more quickly into the upper atmosphere from the photospheric subsurface than the one after the filament eruption. The transverse Lorentz force \( F_x \) acting on the upper atmosphere, from Equation (7), is shown in panel (c) (the black line), while the blue line indicates the direction angle \( \theta = \arctan \left( \frac{F_y}{F_x} \right) \) between the transverse Lorentz force and the solar west (positive direction of the X-axis on the heliographic coordinate). The transverse Lorentz force displayed a decrease during the long evolution of the active region, while the direction angle kept increasing the entire time. An interesting feature is that the longitudinal component of the transverse Lorentz force \( F_z = F_y \sin \theta \) was always positive, which means that the upper atmosphere was always forced into the northern direction by the Lorentz force. This fascinating feature may be related to the drift of the active region, but it needs more investigations to confirm. In panel (d), the evolution of the vertical electric currents derived from Equation (11) are shown. The positive electric current is calculated by integrating the positive electric current density over the entire region, while the negative electric current is calculated by integrating the negative electric current density. We find that the line profiles of the vertical electric currents
increased before 20:20 UT, and then gradually decreased later. This variation was similar to the evolution of magnetic fluxes.

3.2. Formation of the Filament

Although some dark filamentary structures existed in the vicinity of the magnetic PIL, there was no filament at 12:00 UT on December 18. As the active region evolved, the filament gradually appeared and then matured. In this complex process, the right part of the filament first appeared at about 18:00 UT while the left part appeared fully at about 21:00 UT. In order to investigate the formation of this filament, we divide the filament into two parts, the left part and the right part (see the two blue dashed boxes in Figure 1(c)).

3.2.1. The Right Part of the Filament

In this part, using SDO/AIA 304 Å observations, we can see clearly that some dark structures primarily appeared in the right region. It extended to the left region later and became a long filament structure. Figure 3 shows the formation process of this part. The SDO/AIA 304 Å images in the top row display three different moments of the formation process, while the middle row is the homologous vector magnetic field and the bottom row shows the magnetic field lines derived by NLFFF model extrapolation. At 12:07 UT, no filament structures existed in the vicinity of the magnetic PIL. At 14:30 UT, some dark material appeared in the right part. At 18:10 UT, a long and thin filament formed and appeared in panel (c).

According to the characteristics of this process, we propose that the two bundles of the magnetic field lines became a long filament structure through magnetic reconnection. First, two bundles of magnetic field lines appeared separate from each other at the beginning. Second, the right footpoints of the left bundle and the left footpoints of the right bundle gradually approached close to each other. Third, as the right/left footpoints of the two bundles became close enough, magnetic reconnection will happen in the PIL. Then, the long magnetic structure of the filament formed. The magnetic field lines based on NLFFF model extrapolation completely support this proposal (see the bottom row of Figure 3).

In order to further illustrate this scenario, we investigate the magnetic flux under the filament indicated by the yellow dashed box in the panel (d) of Figure 3. Due to the complexity of the negative magnetic flux in this place, we only calculate the positive magnetic flux. The evolution of the positive magnetic flux is exhibited in panel (d) of Figure 4. One can see that the positive magnetic flux was obviously decreasing during the periods of formation. This means that magnetic cancellation...
occurred in this place. Furthermore, the brightening can also be found near where the two bundles crossed one another at different times, which are marked by the white arrows in panels (a)–(c) of Figure 4. These two features suggest that magnetic reconnection occurred in places where the two bundles of magnetic fields crossed, which were accompanied by brightening and resulted in the production of the long and short magnetic field lines. Subsequently, the long magnetic field lines rose up and became the filament magnetic structure, while the short ones sank into the subsurface and resulted in magnetic cancellation. In this formation process, the transverse magnetic fields in the vicinity of the magnetic PIL became weaker, marked by the red arrows in panels (a)–(f). This may be the result of the sinking of the short magnetic field structure and the rising of the long magnetic field one after magnetic reconnection.

3.2.2. The Left Part of the Filament

As mentioned previously in this paper, some dark filamentary structures exited this part (see Figure 1(c)) at 12:00 UT. Therefore, we just care about how this dark filamentary structures evolved as a long filament structure rather than the origin of this dark structure. Figure 5 exhibits the evolutionary process of this part. The SDO/AIA 304 Å images reveal the filament configuration in panels (a) and (b). As shown, some discontinuous filamentary structures were present at 12:40 UT, while the discontinuous structures joined together to form the completed filament structure at 21:26 UT.

Panels (c) and (d) of Figure 5 present the SDO/HMI continuum intensity images, which show the motions of the two main magnetic polarities linked by white lines. From panel (d), in comparison to panel (c), the white line became more horizontal at 21:22 UT. The angle between the two white lines is about 14°. This indicates that the shearing motion appeared in the vicinity of the magnetic PIL. The horizontal velocity fields derived by the DAVE4VM method are exhibited in panels (e) and (f). The green arrows indicate the horizontal velocities on the photosphere. The shearing motion can also be exhibited in the vicinity of the magnetic PIL. The homologous vector magnetic fields on the photosphere are shown in panels (g) and (h). The blue arrows indicate the transverse magnetic fields, while the background field is the radial magnetic field, and the white color denotes the magnetic field with positive polarity and the black color denotes the magnetic field with negative polarity. The transverse magnetic fields underneath Figure 3. Formation process of the right part. (a)–(c) The evolution in the SDO/AIA 304 Å images. (d)–(f) The corresponding vector magnetograms from SDO/HMI. The background denotes the radial magnetic field while blue arrows denote the transverse magnetic field. The red arrows indicate the decrease of the transverse magnetic field and the yellow rectangle in panel (d) shows the region for Figure 4(d) to calculate the flux. (g)–(i) The corresponding radial magnetic field and magnetic field lines derived using the NLFFF model.
the filament marked by a red circle in panel (h) are enhanced a little.

Based on the above description, we suggest that the formation process of this part was the result of shearing motion influencing the pre-existing magnetic field structure. The pre-existing magnetic field structures resided in the vicinity of the magnetic PIL. As the opposite polarities moved toward opposite directions, where positive polarities moved toward the northwest and negative polarities moved toward the southeast, the pre-existing magnetic fields stretched and became more sheared. Sequentially, the magnetic structures of the filament gradually formed above the magnetic PIL. This shearing motion on the photospheric surface also caused the enhancement of the transverse magnetic fields in the vicinity of the magnetic PIL.

3.3. Eruption of the Filament

This filament erupted and released the energy when it was out of stability, accompanying the M6.9 flare. The flare started at 21:41 UT and peaked at 21:58 UT. The variation of the soft X-ray (1–8 Å) fluxes obtained by the GOES observation (the green line in Figure 8(e)) also shows details about this flare.

Figures 6(a) and (b) illustrate the structure of this filament before eruption in the SDO/AIA 304 Å and GONG \( H_* \) images, respectively. Although the GONG \( H_* \) observation is not very good, we can clearly distinguish the two parts of the filament with these two images. The magnetic structures of the filament derived by NLLFF model extrapolation also match well with the observations (see Figure 6(e)). The chosen magnetic field lines of the filament are shown by the blue lines, which also shows that the filament consists of two parts. Panel (c) of Figure 6 displays the corresponding vector magnetic fields. Panel (d) of Figure 6 shows the \( H_* \) image during the eruption of the filament. There were three brightening regions, which correspond to the two footpoints of each part and the junction point of the two parts, respectively. Therefore, we suspect that the filament eruption was caused by interaction between the two parts. Magnetic reconnection appeared at the junction of the two parts, and then the heated plasmas were accelerated toward each footpoint along the magnetic field. In order to investigate the change in the magnetic fields, we compared the transverse fields (Figure 6(f)) pre-flare and post-flare. The contours indicate that the horizontal fields increase by 100 G after the eruption. We can find an obvious feature that the horizontal fields increased in the vicinity of the magnetic PIL after the eruption. This feature agrees well with a previous study (Sun et al. 2012).

According to Equations (8), (9), and (11), the spatial distributions of the Lorentz force change and the vertical electric current density can be derived from the vector magnetic fields. One fascinating feature, where the negative \( \delta F_z \) experienced a rapid increase and \( \delta E_z \) became parallel to the magnetic PIL after the eruption (see Figures 7(a) and (b)), is...
That means the Lorentz force acting on the interior abruptly increased and became more parallel to the magnetic PIL after the eruption. The same feature was also found by some authors (Wang & Liu 2010; Fisher et al. 2012; Petrie 2012, 2013; Wang et al. 2012b). On the other hand, we also find another striking feature: the vertical electric current density near the magnetic PIL suddenly expanded toward the two sides after the eruption (see Figures 7(c) and (d), and the animated version of Figure 7). In other words, the positive vertical current density extended toward the positive magnetic polarity, while the negative one expanded toward the negative magnetic polarity. This interesting phenomenon might be connected with the release of energy accompanying the flare.

In order to deeply investigate the eruption of the filament, we analyze the variations of different parameters in the vicinity of the magnetic PIL during the eruption. We choose an interesting region, which was not only in the vicinity of the magnetic PIL.

Figure 5. Evolutionary process of the left part. The left column is pre-formation while the right column is post-formation. (a) and (b): SDO/AIA 304 Å images. (c) and (d): SDO/HMI continuum intensity images. White lines in panels (c) and (d) indicate the motion of the main polarities. The white solid lines link the two main polarities, while the white dotted line in panel (d) is parallel to the white line in panel (c). (e) and (f): Horizontal velocity field derived by DAVE4VM. The green arrows denote the horizontal velocities. The background is homologous vertical magnetic fields. (g) and (h): Vector magnetograms observed by SDO/HMI. The red circle marks the region where the transverse field increased after the formation of the left part.
but also almost contained the filament and main region of the horizontal field change, to calculate some parameters (see the black box in panel (f) of Figure 6). Figure 8 shows the temporal variations of the different parameters (such as helicity, magnetic flux, vertical electric current, and so on) in the box of interest during the period from 18:48 UT on 2014 December 18 to 00:48 UT on 2014 December 19. The green line in panel (e) shows the profile of the soft X-ray 1–8 Å fluxes. The red vertical dashed line represents the onset of the filament eruption.

As panel (a) of Figure 8 shows, the helicity injection rate \( \frac{dH}{dt} \) underwent a rapid decrease after eruption, while the accumulating helicity stopped increasing. About half an hour after the eruption, the helicity injection rate increased to the same value before the eruption. In panel (b), the profiles of the lines show the variations of the unsigned magnetic flux and mean horizontal magnetic field, respectively. The black line indicates the evolution of the unsigned magnetic flux, while the blue dashed line is the mean horizontal magnetic field. The unsigned flux gradually increased until about 21:10 UT and had a relatively rapid decrease before the eruption. However, it experienced a bit of an increase during the eruption. After about 22:10 UT, it gradually decreased. On the other hand, the mean horizontal field enhanced rapidly after the eruption, a feature that had been found by many authors (Petrie 2012; Wang et al. 2012b, 2016; Yan et al. 2015; Xu et al. 2016). This enhancement of the horizontal field can be explained by the submergence of the magnetic field after eruption (Wang et al. 2012a). The vertical Lorentz force acting on the solar interior is shown in panel (c) of Figure 8. The black line indicates positive change in the Lorentz force while the blue dashed line indicates a negative change; these are derived from the integration of the positive and negative changes of the Lorentz force over the region of interest, respectively. A distinctive characteristic is found: the negative change of the Lorentz force underwent an abrupt increase after the eruption, while the positive change of the Lorentz force was almost invariant. This means that the vertical Lorentz force close to the PIL acted downward after the filament eruption. This might be associated with the reaction acting on the solar interior when eruptive phenomena appeared in the upper atmosphere.

Panel (d) of Figure 8 shows the changes in the vertical electric current in the box of interest as a function of time. The black/blue dashed lines indicate positive/negative electric current in the vertical direction. Both vertical currents began to enhance before the eruption and reached a peak at the same time as the flare peak (see the green line in panel (e) of Figure 8). Figure 8(e) shows the positive/negative magnetic flux as a function of time, which are represented by the black/blue dashed lines, respectively. The positive/negative magnetic flux changed little during the eruption. This suggests that the eruptive action had little influence on the magnetic fluxes.
4. Conclusion and Discussion

In this paper, we studied the formation and eruption process of a filament in the active region NOAA 12241. We divide the filament into two parts to investigate the formation of this filament. We find that the right part of the filament was formed by reconnection between two bundles of magnetic field lines, while shearing motion played an important role in the formation of the left part. Therefore, we suggest that the surface effect acting on the magnetic field to change its configuration plays an important role in the formation of the filament, particularly in mature and decaying active regions. On the other hand, the transverse field in the vicinity of the magnetic PIL shows different patterns in the formation of the two parts: in the right part the transverse field decreases, but in the left part it slightly increases. This suggests that the transverse fields in the vicinity of the magnetic PIL is not uniform, with a tendency to change during the formation of the filament. Further, the evolution of the entire active-region associated with the filament was also investigated. The main results are as follows.

1. During the long evolution of the active region, the helicity injection rate before the eruption is higher than the one after the eruption. The transverse Lorentz force acting on the upper atmosphere exhibits a decreasing pattern. The profiles of the vertical electric currents (positive/negative electric currents) are similar to the magnetic fluxes, which increase before about 20:00 UT on December 18 and then gradually decrease later.

2. To analyze the formation process of the filament in this active region, the filament is divided into two parts in the formation. We deduce that the right part of the filament is formed by magnetic reconnection between two bundles of magnetic field lines driven by photospheric motion. In the meantime, we find that the shearing motion plays an important role in the formation of the left part. This suggests that the surface effect is a main mechanism in the formation of the filament. Furthermore, it is also found that the transverse magnetic fields display different patterns during the formation of the two parts, showing a decreasing pattern in the right part and an increasing pattern in the left part.

3. The magnetic reconnection that occurred in the junction of the two parts should be responsible for the filament eruption. After the eruption of the filament, the negative vertical Lorentz force change ($\delta F_z$) acting on the solar interior experiences an abrupt increase, and the vertical electric currents suddenly expand toward the two sides in the vicinity of the magnetic PIL.

4. The mean horizontal magnetic field close to the magnetic PIL enhances rapidly during the eruption. The change of the negative Lorentz force close to the magnetic PIL goes through an abrupt increase after the eruption. On the other hand, the positive/negative vertical electric currents are increasing before the eruption and reach the peak at the same time as the flare peak.

The positive helicity injection in the entire active region is consistent with a hemispheric pattern (Pevtsov et al. 1995), with positive/negative helicity injection domains in the southern/northern hemisphere. The vertical electric currents covering the entire region have a variation tendency similar to the magnetic fluxes. Sun et al. (2012) found that the vertical electric current of the active region increases with the emergence of unsigned magnetic flux in AR 11158. In addition, Wang et al. (2016) found that the vertical electric current in the entire active region is gradually decreasing as the active region is declining. According to the above features, we suspect that the vertical electric currents in the entire active region exhibit the same behavior as the magnetic fluxes. The $y$-component of the Lorentz force ($F_y$) acting on the upper
atmosphere always remains positive. Furthermore, it is worth noting that the active region is located in the southern hemisphere. Whether or not this noticeable feature is associated with the northward drifting of the active region needs more in-depth studies in the future.

The mechanism of solar filament formation is still indistinct. Two styles of formative mechanisms proposed by many researchers (van Ballegooijen & Martens 1989; Low 1994; Martens & Zwaan 2001; Magara 2008), are surface effect and subsurface effect. Recently, Yan et al. (2016) proposed that the surface effect (such as sunspot motion, magnetic reconnection) is main mechanism for forming an inverse S-shaped active-region filament in active region NOAA 11884. In this study, magnetic reconnection and shearing motion play an important role in formation of this active-region filament. Thus, we verified again that surface effect mechanism is responsible for the formation of solar filament. Two different patterns in transverse magnetic field in the vicinity of the magnetic PIL during the formation of the filament, which is decrease/increase in right/left part, manifesting that filament formation can be connected with either decrease or increase of transverse magnetic field strength below the filament.

After the eruption of the filament, the transverse magnetic field close to the magnetic PIL exhibits an increasing pattern, which has been found by many authors (Liu et al. 2012; Petrie 2012; Sun et al. 2012; Wang et al. 2016; Xu et al. 2016). A reasonable explanation, that the collapse of the magnetic field after the flare/eruption is responsible for the enhancement of the transverse magnetic field, has been proposed (Liu et al. 2012). On the other hand, the helicity injection rate in the vicinity of the magnetic PIL decreases to almost zero after the eruption. As is well known, the eruption of the filament releases not only magnetic energy but also magnetic helicity into the volume. The total helicity injection should be equal to the released helicity during the eruption subtracted from the helicity injection crossing the photosphere. Therefore, the

Figure 8. Variation of the different parameters in the box of Figure 6(f) as a function of time. The red vertical dashed line indicates the onset of filament eruption. (a) Helicity injection rate (black solid line) and accumulating helicity (blue dash line). (b) Unsigned flux (black solid line) and mean horizontal field (blue dash line). (c) The change in the vertical Lorentz force. The positive and negative changes are represented by the black solid line and blue dashed line, respectively. (d) Vertical electric currents. The positive and negative vertical currents are represented by the black solid line and blue dashed line, respectively. (e) Magnetic fluxes. The positive and negative magnetic fluxes are represented by the black solid line and blue dashed line, respectively. The green line is GOES flux in 1–8 Å.
The vertical current experiences an expanding behavior during the eruption. This feature was not found by Sharykin & Kosovichev (2015) and Wang et al. (2016). We deduce that the abrupt expansion in vertical currents is associated with the energy released by the flare. Before the eruption, the magnetic energy is mainly stored in the filament located above the magnetic PIL. When the filament erupts, the energy stored in the filament is released and expanding in the moment. Due to the influence of the energy release and expansion during the eruption, the non-potentiality of the ambient field should increase suddenly. On the other hand, the electric current is nonpotential. Therefore, the electric current expanding toward the two sides can be seen as the result of the increasing non-potentiality of the field surrounding the magnetic PIL.

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References

Amari, T., Luciani, J. F., Mikic, Z., & Linker, J. 2000, ApJL, 529, L49
Antiochos, S. K., Dahlburg, R. B., & Klimchuk, J. A. 1994, ApJL, 420, L41
Archontis, V., & Török, T. 2008, A&A, 492, L35
Aulanier, G., & Demoulin, P. 1998, A&A, 329, 1125
Babcock, H. W., & Babcock, H. D. 1955, ApJ, 121, 349
Berger, M. A., & Field, G. B. 1984, JFM, 147, 133
Borrero, J. M., Tomczyk, S., Kubo, M., et al. 2011, SoPh, 273, 267
Centeno, R., Schou, J., Hayashi, K., et al. 2014, SoPh, 289, 3531
Chae, J. 2003, ApJ, 584, 1084
Chae, J. 2010, ApJ, 714, 618
Cheng, X., Ding, M. D., Zhang, J., et al. 2014, ApJL, 789, L35
Démoulin, P., & Berger, M. A. 2003, SoPh, 215, 203
DeVore, C. R., & Antiochos, S. K. 2000, ApJ, 539, 954
Fan, Y., & Gibson, S. E. 2006, ApJL, 641, L149
Fisher, G. H., Bereik, D. J., Welsch, B. T., & Hudson, H. S. 2012, SoPh, 277, 59
Gaizauskas, V., Zirker, J. B., Sweetland, C., & Kovacs, A. 1997, ApJ, 479, 448
Galsgaard, K., & Longbottom, A. W. 1999, ApJ, 510, 444
Guo, Y., Schmieder, B., Démoulin, P., et al. 2010, ApJ, 714, 343
Harvey, J. W., Bolding, J., Clark, R., et al. 2011, BAAS, 43, 17.45
Harvey, J. W., Hill, F., Hubbard, R. P., et al. 1996, Sci, 272, 1284
Hoeksema, J. T., Liu, Y., Hayashi, K., et al. 2014, SoPh, 289, 3483
Howard, R. 1959, ApJ, 130, 193
Kippenhahn, R., & Schlüter, A. 1957, Zap, 43, 36
Kuckein, C., Martinez Pillet, V., & Centeno, R. 2012, A&A, 542, A112
Kuperus, M., & Raadu, M. A. 1974, A&A, 31, 189
Lee, S., Yun, H. S., Kim, J.-H., et al. 2000, BAAS, 32, 01.48
Leka, K. D., Barnes, G., Crouch, A. D., et al. 2009, SoPh, 260, 83
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Litvinenko, Y. E., & Wheatland, M. S. 2005, ApJ, 630, 587
Liu, C., Deng, N., Lee, J., et al. 2013, ApJL, 778, L36
Liu, C., Deng, N., Liu, R., et al. 2012, ApJL, 745, L4
Liu, R., Kliem, B., Titov, V. S., et al. 2016, ApJ, 818, 148
Liu, W., Berger, T. E., & Low, B. C. 2012, ApJL, 745, L21
Low, B. C. 1994, PSPL, 1, 1684
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, ApJL, 778, L36
Malanushenko, A., Schrijver, C. J., DeRosa, M. L., & Wheatland, M. S. 2014, ApJ, 783, 102
Malherbe, J. M., & Priest, E. R. 1983, A&A, 123, 80
Martens, P. C., & Zwaan, C. 2001, ApJ, 558, 872
Martin, S. F. 1998, SoPh, 182, 107
Metcalf, T. R. 1994, SoPh, 155, 235
Okamoto, T. J., Tsuneta, S., Lites, B. W., et al. 2008, ApJL, 673, L215
Okamoto, T. J., Tsuneta, S., Lites, B. W., et al. 2009, ApJ, 697, 913
Pariat, E., Demoulin, P., & Berger, M. A. 2005, A&A, 439, 1191
Patsourakos, S., & Vial, J. C. 2002, SoPh, 208, 253
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Petrie, G. J. D. 2012, ApJ, 759, 50
Petrie, G. J. D. 2013, SoPh, 287, 415
Pevtsov, A. A., Canfield, R. C., & Metcalf, T. R. 1995, ApJL, 440, L109
Priest, E. R., & Longcope, D. W. 2017, SoPh, 292, 25
Schuck, P. W. 2006, ApJ, 646, 1358
Schuck, P. W. 2008, ApJ, 683, 1134
Sharykin, I. N., & Kosovichev, A. G. 2015, ApJ, 808, 72
Song, H. Q., Chen, Y., Li, B., et al. 2017, ApJL, 836, L11
Sun, X., Hoeksema, J. T., Liu, Y., et al. 2012, ApJ, 748, 77
van Ballegooijen, A. A., & Martens, P. C. H. 1989, ApJ, 343, 971
Wang, H., & Liu, C. 2010, ApJL, 716, L195
Wang, J., Yan, X., Qu, Z., et al. 2016, ApJ, 817, 156
Wang, S., Liu, C., Liu, R., et al. 2012a, ApJL, 745, L17
Wang, S., Liu, C., & Wang, H. 2012b, ApJL, 757, L5
Wang, Y.-M., & Liu, C. 2010, ApJL, 716, L195
Wang, X., & Wang, H. 2012, ApJ, 757, L5
Yang, B., Jiang, Y., Yang, J., Yu, S., & Xu, Z. 2016, ApJ, 816, 41
Yeates, A. R., Mackay, D. H., & van Ballegooijen, A. A. 2008, SoPh, 247, 103
Zhang, M., & Low, B. C. 2005,ARA&A, 43, 103

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