Flare Energy Release in the Lower Solar Atmosphere near the Magnetic Field Polarity Inversion Line

I. N. Sharykin\textsuperscript{1,2}, V. M. Sadykov\textsuperscript{3}, A. G. Kosovichev\textsuperscript{3}, S. Vargas-Dominguez\textsuperscript{4}, and I. V. Zimovets\textsuperscript{1}

\textsuperscript{1}Space Research Institute (IKI) of the Russian Academy of Sciences, Moscow, Russia
\textsuperscript{2}Institute of Solar-Terrestrial Research (ISTP) of the Russian Academy of Sciences, Siberian Branch, Irkutsk, Russia
\textsuperscript{3}New Jersey Institute of Technology, Newark, NJ, USA
\textsuperscript{4}Universidad Nacional de Colombia, Bogotá, Colombia

Received 2016 March 18; revised 2017 March 5; accepted 2017 April 17; published 2017 May 10

Abstract

We study flare processes in the solar atmosphere using observational data for an M1-class flare of 2014 June 12, obtained by the New Solar Telescope (NST/BBSO) and Helioseismic Magnetic Imager (HMI/SDO). The main goal is to understand triggers and manifestations of the flare energy release in the photosphere and chromosphere using high-resolution optical observations and magnetic field measurements. We analyze optical images, HMI Dopplergrams, and vector magnetograms, and use nonlinear force-free field (NLFFF) extrapolations for reconstruction of the magnetic topology and electric currents. The NLFFF modeling reveals the interaction of two magnetic flux ropes with oppositely directed magnetic fields in the polarity inversion line (PIL). These flux ropes are observed as a compact sheared arcade along the PIL in the high-resolution broadband continuum images from NST. In the vicinity of the PIL, the NST H\textalpha observations reveal the formation of a thin three-ribbon structure corresponding to a small-scale photospheric magnetic arcade. The observational results are evidence in favor of the primary energy release site located in the chromospheric plasma with strong electric currents concentrated near the PIL. In this case, magnetic reconnection is triggered by the interacting magnetic flux ropes forming a current sheet elongated along the PIL.

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

1. Introduction

Magnetic reconnection is believed to be the main mechanism of solar flare energy release (see Priest & Forbes 2000, 2002 and references therein). The most popular standard CSHKP flare model (Carmichael 1964; Sturrock & Coppi 1966; Hirayama 1974; Magara et al. 1996; Tsuneta 1997) assumes that the reconnection occurs in a quasi-vertical current sheet in the solar corona beneath an upward moving plasmoid. In the framework of this model, the primary energy release (magnetic reconnection in the current sheet) and electron acceleration take place in the low-density corona. It is likely that a large fraction of eruptive solar flares follows this scenario (e.g., Krucker et al. 2008; Liu et al. 2008; Fletcher et al. 2011). Obviously, non-eruptive flare events cannot be interpreted in the framework of the standard model. It has been argued that the magnetic reconnection process can be triggered not only in the corona but also in the low, partially ionized, layers of the solar atmosphere (e.g., Georgoulis et al. 2002; Chae et al. 2003). Recently developed models of chromospheric magnetic reconnection (e.g., Leake et al. 2012, 2013, 2014; Ni et al. 2015) have been applied to relatively small-scale phenomena, such as chromospheric jets and Ellerman bombs. However, it is unclear if magnetic reconnection in the chromosphere may play a significant role in solar flares, and what kind of magnetic topology may be involved in the reconnection process. In this respect, investigation of the flare energy release in the lower solar atmosphere is particularly interesting.

It has been known since the observations of Severnyi (1958) that solar flares appear first in the vicinity of the polarity inversion line (PIL) of the line-of-sight (LOS) magnetic field, and that the flare emission spreads outside the PIL as the flare develops. He also found that a considerable gradient of the magnetic field across the PIL is required for the flare appearance. Further observations provided new knowledge about flare processes near the PIL. For example, Wang et al. (1994), Kosovichev & Zharkova (2001), and Sudol & Harvey (2005) showed that the flare onset is often associated with sharp changes of the magnetic field near the PIL. The statistical analysis of SOHO/MDI LOS magnetograms, presented in the work of Welsch & Li (2008), showed that PILs with a strong magnetic field gradient are associated with flux emergence. The most recent statistical study by Schrijver (2016) illustrated that X-class flares are associated with strong-field, high-gradient PILs created during the emergence of magnetic flux into active regions. A detailed 3D modeling of the magnetic field presented in the work of Inoue et al. (2016) revealed the conditions in the vicinity of PIL that are favorable for magnetic reconnection and triggering solar flares. High-resolution observations of the formation of H\textalpha ribbons showed that a flux rope elongated along a PIL in the low solar atmosphere becomes unstable following an enhancement of its twists (Wang et al. 2015). Thus, it is especially interesting to study flare processes in the vicinity of the PIL, as well as connections with the dynamics of magnetic fields and electric currents.

In this paper, we present a new investigation of the M1.0 non-eruptive solar flare of 2014 June 12, which started at around 21:00 UT, peaked at 21:12 UT, and ended at approximately 50° southeast from the disk center. This event was previously studied by Kumar et al. (2015) and Sadykov et al. (2015, 2016), who provided a general analyses of the structure and dynamics in the chromosphere and corona, as well as a study of the chromospheric evaporation process. Our specific goal is to investigate in detail the structure and
variations of the magnetic field and electric currents in the PIL. This event was selected for analysis due to the availability of various unique observations of the solar atmosphere made by the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), New Solar Telescope (NST; Goode & Cao 2012) in the Big Bear Solar Observatory (BBSO), the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002), and the Helioseismic Magnetic Imager (HMI; Scherrer et al. 2012) and Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) instruments on board the Solar Dynamics Observatory (Pesnell et al. 2012). This flare showed intriguing activity in the vicinity of the PIL, which was discussed in previous works (Sadykov et al. 2014, 2015; Kumar et al. 2015). Sadykov et al. (2014) first reported observations of a small-scale photospheric flux-ropes structure that started untwisting immediately after the X-ray peak. Kumar et al. (2015) presented detailed morphological evidence of magnetic reconnection in the vicinity of the PIL between two small opposite polarity sunspots. Using NST Hα images, they concluded that an interaction between two J-shaped loops led to the formation of a twisted flux rope along the PIL. They also detected plasma inflows near the PIL, which were recognized as a signature of magnetic reconnection of a flux rope with the overlying magnetic field. The IRIS and RHESSI observations of the selected flare were previously discussed in the paper of Sadykov et al. (2015), who presented a detailed analysis of Doppler shift maps reconstructed for different spectral lines and compared these maps with the RHESSI X-ray images. It was concluded that the chromospheric evaporation was triggered not only by accelerated particles but also by heat flux from the hot coronal plasma. Sadykov et al. (2016) studied the relationship between the chromospheric evaporation flows deduced from IRIS observations and the magnetic field topology of the flare region. Using vector magnetograms from HMI, they reconstructed the magnetic field topology and the quasi-separatrix layer, and found that the upflow (blueshift) regions as well as the H-alpha flare ribbons are magnetically connected to the PIL region via a system of low-lying loop arcades (with height ≲4.5 Mm). This allowed them to propose an interpretation of the chromospheric evaporation based on the geometry of the local magnetic fields and the primary energy source associated with the PIL. However, the processes in the PIL itself were not previously studied. This is the topic of our paper.

In addition to the analysis of the Hα-line wing filtergrams and broadband TiO images (7057 Å) with high spatial resolution, which correspondingly show processes in the lower chromosphere and the photosphere, we use nonlinear force-free magnetic field (NLFFF) modeling to explain some topological peculiarities and energy release of the flare. In particular, NLFFF modeling can help find possible sites of magnetic reconnection, and understand where the current sheet is formed. Magnetic reconnection and flare triggering can be associated with shearing motions, magnetic flux emergence, or cancellation. To detect the plasma flows and compare them with other observational data, we use the HMI Dopplergrams.

Thus, the focus of this paper is a detailed analysis of physical processes in the vicinity of the PIL in the low atmosphere during the solar flare using analysis of the electric current system, evolution of magnetic field topology, and dynamics of plasma flows. This paper is divided into four sections. Section 2 describes the observational data. Section 3 is devoted to analysis of NST images, electric currents, and magnetic field topology (using the HMI data). Discussion and conclusions are presented in Section 4.

2. Observational Data

To investigate the fine spatial structure of the flare energy release site, we use Hα data from the Visible Imaging Spectrometer (VIS) as well as TiO filter (7057 Å) images from the Broadband Filter Imager (BFI), obtained at the 1.6 m NST (Goode & Cao 2012; Varsik et al. 2014) and available from the BBSO Web site (http://bbso.njit.edu/). The new system of adaptive optics, the large aperture, speckle-interferometry post-processing (Wöger et al. 2008), and good seeing conditions made it possible to obtain images of the Sun with high spatial resolution up to the diffraction limit. The pixel size of the VIS images is about 0′′029, which is approximately three times smaller than the telescope diffraction limit λ/α ≈ 0′′084. The pixel size of the BFI TiO images is about 0′′034 with the diffraction limit ≈0′′09. The time cadence between two subsequent Hα line scans in five wavelength bands (6563 Å ± 1.0, ±0.8, and ±0.4 and the line core) is ≈15 s.

In this paper, we do not discuss X-ray and ultraviolet observations in detail as it was made earlier by Sadykov et al. (2015) and Kumar et al. (2015); we focus on the processes near the PIL in the lower solar atmosphere.

To understand the flare energy release, it is extremely important to determine the magnetic field topology of the PIL as magnetic reconnection can be triggered in a magnetic field configuration different from the CSHKP model. We study the magnetic field structure using observations of HMI (Scherrer et al. 2012). The HMI makes spectropolarimetric observations of the magneto-sensitive Fe I line (6173 Å) using two different cameras in six wavelength filtergrams covering the whole line profile. Calculations of the optical continuum intensity, LOS magnetic field, and Doppler velocity with the time cadence of 45 s and the spatial resolution of ~1″ are based on the right and left circular polarization measurements. To obtain the full magnetic field vector with the time cadence of 720 s, the HMI also makes measurements of the linear polarization profile. The spatial resolution of the vector magnetograms is the same as that in the case of the LOS magnetograms. In our data sets, the time cadence of the Hα filtergrams from NST is the shortest. Thus, we consider physical processes on timescales longer than 15 s.

The 3D structure of the magnetic field in the flare region was reconstructed using the NLFFF optimization method (Wheatland et al. 2000) available from the package SolarSoft. For the boundary condition, we used the disambiguated HMI vector magnetograms (Centeno et al. 2014).

3. Results

3.1. Fine Structure of the PIL Region

Detailed images of the flare region in the vicinity of the PIL are displayed in Figure 1. The TiO images in the left column show the temporal dynamics of an elongated structure (which looks like a small twisted flux rope, or an arcade, and indicated by the red ellipse) separating two sunspots of opposite magnetic polarity (“δ-type” configuration). We will refer to this structure as the TiO arcade hereafter. It had been described by Sadykov et al. (2015) and Kumar et al. (2015). The visible width of this structure has a tendency to grow with time. The
Figure 1. Zoomed NST images of the region with a highly twisted magnetic field. TiO images are shown in the left column. The blue-wing and red-wing Hα filtergrams are presented in the central and right columns, respectively. The twisted TiO magnetic structure called the TiO flux rope is marked by the red ellipse in the top-left and bottom-left panels.
two other columns in Figure 1 show images in the red and blue wings of the Hα line. At the beginning of the flare, before the impulsive phase, we observe tiny Hα ribbons and brightenings in the vicinity of the TiO arcade. At 21:06:25 UT, the most intensive Hα ribbons surround the TiO arcade (which may correspond to a magnetic flux rope). A very intriguing peculiarity is that we observe a three-ribbon structure: two relatively wide ribbons (with width \( \sim 1" \)) and a tiny thread (width \( \sim 0.75" \)) located between them. The tiny ribbon directly corresponds to the TiO flux rope, which is located inside the twisted magnetic structure seen in the Hα line core. These observations are presented in Figure 2 in more detail, where the Hα (line wing) emission sources (shown by the yellow contour lines) are compared with the TiO and Hα (line core) images. The thin ribbon was stable while the others moved away from each other with the speed of \( \sim 5-10 \) km s\(^{-1}\).

3.2. Dynamics of Photospheric Plasma Flows

In this section, we present analysis of the Doppler LOS velocity in the flare region, measured by HMI. It is worth noting that the detected flows do not correspond to the upflows and downflows directly as the solar flare is located \( \sim 640" \) from the disk center. Thus, the LOS velocities are composed of horizontal (along the solar surface) and vertical components. However, we will define the positive and negative LOS velocities as “downflows” and “upflows.”

The Dopplergrams are compared with the LOS magnetograms in Figures 3(A)–(D). Before the flare onset (Figure 3(A)), we observe a system of upflows surrounded by downflows near the PIL. This flow system was observed during the whole flare process without significant changes. The flare initiation is associated with the appearance of new downflows (Figures 3(B)–(D)) near another region of the PIL (marked by an arrow) with a speed value up to 1 km s\(^{-1}\), which corresponds to the TiO arcade.

In Figure 3(E), we demonstrate the dynamics of the flow speed distribution. Colors from black to red indicate the number of HMI pixels in particular speed ranges indicated along the y-axis. In Figure 3(D), we show by the yellow contour an area where the distribution of Doppler speeds was calculated. This place includes the TiO arcade and a surrounding region with enhanced Doppler flows. One can notice that after the flare onset (marked by the vertical line in panel (E)), the distribution of the Doppler speeds changes. The thick black curve is the Doppler speed (\( \sim 1 \) km s\(^{-1}\)) averaged over all pixels inside the yellow contour in Figure 3(D). This line also indicates the changing average flow speed (from 1 to \( 0.75 \) m s\(^{-1}\)) in the region of our interest, associated with the flare onset and marked by the dashed white line in Figure 3(E).

3.3. Electric Currents in the Flare Region

To calculate the vertical currents, \( j_z \) (component perpendicular to the solar surface), we use the HMI vector magnetograms and Ampère’s law (e.g., Guo et al. 2013; Musset et al. 2015):

\[
  j_z = \frac{c}{4\pi} (\nabla \times B)_z = \frac{c}{4\pi} \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right),
\]

where \( B_x \) and \( B_y \) correspond to the east–west and south–north components of the magnetic field.

Since the flare was located far from the disk center, the observed LOS PIL may deviate from the exact position of the PIL of the \( B_z \) component (vertical to the solar surface) due to the projection effect. Using the HMI vector magnetograms, we recalculated all \( B \) components from the local helioprojective Cartesian system to the Heliocentric Spherical coordinate system. The recalculated values are used for the calculations of \( j_z \) shown in Figure 4. The figure also shows the comparison of the LOS PIL (thin black line) with the exact PIL (thick black line) in the helioprojective Cartesian coordinate system.

There are several places along the PIL where electric currents are intensified. In the region of the TiO flux rope, electric currents are intensive and experience changes that can be visually detected in Figure 4. To quantify the changes, we
calculate the total electric current through the region shown by the blue box in Figure 5(A). The temporal dynamics of the total $I_z$ is shown in Figure 5 in panels (C)–(E). We present the total positive (black) and negative (red) currents, calculated above three threshold values: $1\sigma$, $3\sigma$, and $5\sigma$, where $\sigma$ is the standard deviation of the $j_z$ distribution fitted by a Gaussian (see Figure 5(B)) outside the flare region (red rectangle area in Figure 5(A)) chosen to characterize noise in the $j_z$ measurements. One can note that the total current changes during the flare. The absolute negative and positive $I_z$ values for all three cases decrease just before the X-ray impulse. This can be interpreted as dissipation of electric currents resulting in the flare energy release. The decrease of $I_z$ was the largest for the $1\sigma$ threshold value, and was about $1.6 \times 10^{12}$ A for both the
negative and positive components. The smallest value of the $I_z$ reduction was about $0.5 \times 10^{12}$ A for the $s_{5}$ threshold. Thus, the change in the total electric current is mostly due to changes of relatively weak electric currents in the $\Delta f$ region. However, the largest relative change in the total electric current was for the $s_{5}$ threshold $D \approx 0.6$, while this value for the $s_{1}$ threshold was 0.21. One can also note that $I_z$ begins to increase during the growth of the GOES X-ray light curve, caused by a subsequent flare that occurred in the same region.

3.4. Topology of the Magnetic Field

In this section, we present results of the analysis of the magnetic field structure using the NLFFF magnetic field extrapolations. Our interest is concentrated on the region surrounding the photospheric PIL. We consider the HMI magnetograms that are projected in the Heliographic spherical coordinate system. These magnetograms (after some spatial smoothing) are used to reconstruct the magnetic field before and after the flare using the NLFFF method. The selected regions are marked by boxes in the top panels of Figure 6, which show the original HMI magnetograms in the solar disk coordinates. The reconstructed magnetic field topology of the flare region (marked by the red box in the top panels) is shown in Figure 6 (mid panels). The twisted magnetic field structure follows the PIL. The magnetic field topology does not change significantly during the flare energy release, as follows from comparison of the preflare and postflare NLFFF extrapolations.

The bottom panels of Figure 6 show the absolute value of the horizontal component of the electric current density calculated from the extrapolated magnetic field. We see that the strongest horizontal currents with values up to $0.2 \text{ A m}^{-2}$ are concentrated in the vicinity of the PIL. One can notice that the TiO arcade corresponds to the region of strong $j_h$. The preflare value of $j_h$ is weaker than the postflare value.

The region of our particular interest is where the TiO arcade and preflare activity were observed (this place is marked by ellipse in Figure 6). In Figure 7, we present the magnetic field extrapolation results for this region. The starting points of the magnetic field lines are selected in the region of the TiO arcade. Before the flare, we see two interacting twisted flux tubes near the PIL. Such magnetic configuration is favorable for magnetic reconnection. The approximate place of the interaction of the magnetic flux tubes is localized at heights up to $\sim$2 Mm above the photosphere, which is in the upper chromosphere. After the flare, a small arcade is formed between these flux tubes, probably due to magnetic reconnection. The next section describes this scenario of magnetic reconnection in more detail.

The results of the NLFFF modeling are consistent with the TiO and Hα images (Figure 1). In Figures 7(A) and (B), we show the magnetic field gradient $\nabla B_z = \sqrt{(\partial B_z/\partial x)^2 + (\partial B_z/\partial y)^2}$. The strongest value of $\nabla B_z$ ($\sim 1 - 2 \text{ kG/Mm}$) is found along the PIL and concentrated near the region where the TiO flux rope with downflows was observed. One can notice that the area of enhanced $\nabla B_z$ was reduced after the flare (from seven HMI pixels to one pixel, where $\nabla B_z \gtrsim 1.3 \text{ kG Mm}^{-1}$).

Figure 4. Sequence of four red–blue images showing the evolution of the vertical component of the electric current density. Green and cyan contours show upflows ($-0.8, -0.6, -0.4$ and $-0.2 \text{ m s}^{-1}$) and downflows ($0.2, 0.4, 0.6, 0.8 \text{ km s}^{-1}$) according to the HMI Doppler measurements. Thin black contours show the LOS PIL, while the thick black lines mark the reconstructed PIL reconstructed from the HMI vector magnetograms. Orange ellipse marks the region of TiO arcade.
It is important to trace changes in the magnetic field strength and the electric current density in the vicinity of the PIL. In Figure 8, we demonstrate the distribution of the different physical quantities derived from the NLFFF magnetic extrapolations along the slice intersecting the PIL in the vicinity of the TiO arcade. We show these distributions for pre-flare (left panels) and post-flare (right panels) times.

The magnetic field strength at chromospheric heights reaches ~2 kG. The strength of the magnetic field components along the slice is shown by different colors. We found that the $B_z$ component increases from 800 to 1500 G at the photospheric level, and from 400 to 600 G at the height of 1.1 Mm above the photosphere. We also show the sign inversion line of the $B_z$ component in the plane of the slice by the black line (panels (B) and (C)). This line experiences some changes in the region of the TiO arcade.

There are no significant changes in the distribution of the electric current component $j_{\text{perp}}$ perpendicular to the slice shown in panels (B1) and (B2) of Figure 8. To trace the changes of the electric current density, we present Figure 9. Here we show three slices intersecting the PIL in different places. The strongest electric currents (with current density greater than 0.3 A m$^{-2}$) were concentrated in an area less than 1 Mm$^2$. One can notice that in the region of the TiO arcade (slice C) the magnitude of the electric current density is decreased from 0.37 to 0.3 A m$^{-2}$, and that the height of the maximal current density is also decreased, while the other slices do not show significant changes. Thus, this analysis confirms that the changes of the electric current density are associated with a small region near the PIL, where we observe the TiO arcade.

The decreasing electric currents can be explained by their dissipation during the magnetic reconnection. It is worth noting that we calculated the electric current density on the scale of the HMI resolution (∼1 arcsec/pixel), and thus, the obtained $j_z$ value represents a low limit. In reality, the $j_z$ magnitude can be greater due to unresolved fine structures of the electric current.

4. Flare Energies

We found that the flare energy release developed near the PIL, where the magnetic field is highly twisted and strong electric currents are concentrated. To show that the flare energy was stored in the PIL region, one needs to estimate the flare energetics and compare it with the released magnetic energy in the PIL.
The studied solar flare is not eruptive and, thus, there is no CME energy in the total flare energetics. To calculate the total flare energetics, one can integrate the flare emissions. The total integrated soft X-ray radiation losses are estimated as \( \int \nu \frac{dL}{d\nu} d\nu \approx 2 \times 10^{39} \text{ erg} \) according to the GOES data. We use the data from https://solarflare.njit.edu (Sadykov et al. 2017), where the background subtraction method of Ryan et al. (2012) was applied. This energy was estimated by time integration of \( \int \frac{dL}{d\nu} d\nu \), where \( \frac{dL}{d\nu} \) is the radiative loss function (Rosner et al. 1978). The emission measure \( EM \) and plasma temperature \( T \) are calculated according to the method described in the work of Thomas et al. (1985). A significant part of the flare radiation is also in the UV and EUV parts of the electromagnetic spectrum (Emslie et al. 2012; Milligan et al. 2014). We applied standard DEM analysis (Aschwanden et al. 2015) to estimate the radiation losses and the maximum thermal energy using the AIA observations. This analysis covers plasma temperatures from \( 10^5 \) to \( 10^6 \) K. The estimated radiation losses are \( L_{\text{rad}}^{\text{DEM}} \approx 7 \times 10^{37} \text{ erg} \), which is smaller than \( L_{\text{rad}}^{\text{GOES}} \).

The total internal plasma energy is calculated as \( U_{\text{th}} = 3k_b T \sqrt{EM} \cdot V \), where \( k_b \) is the Boltzmann constant and \( V \) is the plasma-emitting volume, which is estimated from the X-ray or EUV images depending on the \( T \) and \( EM \) estimation. For the GOES data and the flare volume (\( \approx 10^{27} \text{ cm}^3 \)) estimated in the work of Sadykov et al. (2015), the maximum thermal energy is \( U_{\text{th}}^{\text{GOES}} \approx 3 \times 10^{39} \text{ erg} \). To estimate the volume of EUV-emitting plasma, \( V \approx 4 \times 10^{27} \text{ cm}^3 \), we also used the AIA images. The DEM analysis results in a maximum \( U_{\text{th}}^{\text{DEM}} \approx 2.4 \times 10^{30} \text{ erg} \), which is much smaller than \( U_{\text{th}}^{\text{GOES}} \), as in the work of Aschwanden et al. (2015) for the flares.

To estimate the total energy of nonthermal electrons, we use results from the work of Sadykov et al. (2015). Taking the spectral index of nonthermal electrons as \( \delta = 7.5 \) and total flux \( F(E > E_{\text{low}}) = 3 \times 10^{35} \text{ electrons s}^{-1} \) \( (E_{\text{low}} = 13 \text{ keV}) \), one can determine the nonthermal energy \( P_{\text{non}} \approx \Delta t F E_{\text{low}} \) \((\delta - 1)/(\delta - 2) \approx 2 \times 10^{39} \text{ erg s}^{-1} \), where \( \Delta t \approx 30 \text{ s} \) is a characteristic duration of the HXR pulse above 12 keV.

To calculate the dissipation of the energy stored in the magnetic fields generated by local electric currents, one can estimate the free energy, which is \( E_{\text{free}} = E_{\text{all}} - E_{\text{pot}} \), where \( E_{\text{all}} \) is the total energy of magnetic field extrapolated from the HMI vector magnetogram data using the NLFFF technique, and \( E_{\text{pot}} \) is the corresponding energy of the potential (no electric currents) magnetic field with the minimum possible energy. The total magnetic energy is calculated by integrating
over the volume shown in the top two panels in Figure 6 with a height of 10 Mm. For the preflare state, $E_{\text{diff}} = 4.87 \times 10^{31}$ erg, $E_{\text{pot}} = 6.27 \times 10^{30}$ erg, and $E_{\text{free}} = 4.24 \times 10^{31}$ erg. After the flare, the magnetic energies were the following: $E_{\text{diff}} = 4.66 \times 10^{31}$ erg, $E_{\text{pot}} = 6.69 \times 10^{30}$ erg, and $E_{\text{free}} = 3.99 \times 10^{31}$ erg. Thus, the change in the free magnetic energy in the PIL region was $\Delta E_{\text{free}} = 2.48 \times 10^{30}$ erg, enough to explain the total flare energetics.

5. Discussion and Conclusions

In this section, we will try to draw a picture of the physical processes in the flare region. First of all, we summarize the main observational results. All preflare activity in the low solar atmosphere was located near the PIL in a compact region, according to the NST data. The flare observed in the NST images was accompanied by changing magnetic fields near the PIL, which is clearly seen in the HMI vector magnetograms. The TiO and Hα images reveal the formation of a small (≈3 Mm) arcade-like magnetic structure in the photospheric and chromospheric layers of the solar atmosphere. A magnetic field of this structure is approximately 1000 Gauss. The Hα emission sources near this place were observed as a three-ribbon structure with the thinnest ribbon (seen only in the wings of Hα line) located between the thicker ones. This thin ribbon was stationary while the others moved away from each other during the flare with speed $\sim 5$–10 km s$^{-1}$.

In the same region as the small magnetic arcade, we found intensification of Doppler downflows across the PIL, which
was associated with the flare onset. The strongest intensification of electric currents estimated from the HMI vector magnetograms is also located near the PIL. The observed flows near the PIL are connected with the flare energy release as their distribution and average speed experiences changes during the flare time. The flows could be triggered by magnetic reconnection as the plasma attached to the magnetic field lines in the arcade moves downward.

NLFFF modeling reveals the interaction of oppositely directed magnetic flux tubes in the PIL. The strong electric current was concentrated near the PIL, and its strongest value is achieved in the region of the TiO arcade. Before the flare onset, the interaction of the magnetic fluxes extended from the photospheric up to the chromospheric layers. These two interacting magnetic flux tubes in the low layers of the solar atmosphere are observed as the TiO arcade, which is in accordance with the NST observations. To explain results of the NLFFF modeling and the NST observation, we present a possible scheme of the magnetic reconnection and magnetic field topology in the PIL, which is illustrated in Figure 10. The reconnection is developed in the chromospheric region with a strong magnetic field codirectional to the electric current. Footpoints of the formed arcade (which is seen as the arcade in the NST/TiO images) may correspond to the observed Hα.
ribons. How can we explain the appearance of the third thin ribbon located between the thick ones in the low solar atmosphere, elongated along the PIL, and cospatial with the TiO arcade? This Hα emission could originate from a thin channel (possibly a part of the current sheet) where the electric current dissipates and heats the plasma, causing its emission.

In the introduction, we mentioned an EUV jet in the region of the TiO arcade, which was discussed in the papers of

Figure 9. Distribution of the absolute value of $j$ along slices (B)–(D) shown in the top two panels with the $B_z$ map before the flare (left panels) and after the flare (right panels) times. Panels (B)–(D) correspond to slices (B)–(D). Contours mark the electric current density levels with values 15, 37, 75, 150, 224, 298, 336, and 373 mA m$^{-2}$. The red line is the PIL in the plane of the slices.
Sadykov et al. (2015) and Kumar et al. (2015). In the framework of the discussed model, this jet can be associated with the reconnected magnetic field lines and ejected plasma moving in the upward direction.

How can we explain the formation of the large-scale emission ribbons discussed by Kumar et al. (2015) and Sadykov et al. (2015)? Can the energy be transferred from the site in the PIL in the lower atmosphere to the flare ribbons? Perhaps, it is possible to organize the energy transfer by accelerated particles spreading along the magnetic field lines and filling the large-scale magnetic field structure. Heat conduction fluxes can be also responsible for the energy transfer. The observations and NLFFF modeling presented in the paper of Sadykov et al. (2016) show that the flare ribbon emission source is connected with the PIL region by low-lying ($\lesssim 4.5$ Mm) magnetic field lines that could serve as channels for energy transfer from the primary energy release site.

Similar magnetic field topologies of the magnetic reconnection as in Figure 10 have been discussed previously (e.g., Priest & Forbes 2002). The main feature of our scheme is that the magnetic reconnection in this flare develops in low layers of the solar atmosphere with a strong magnetic field component along the PIL in the current sheet between two interacting flux ropes.

The presented observational results are evidence in favor of the location of the primary energy release site in the chromosphere where plasma is partially ionized, in the region of strong electric currents concentrated near the PIL. Magnetic reconnection may be triggered by two interacting magnetic flux tubes with a forming current sheet elongated along the PIL, resembling the classical model of Gold & Hoyle (1960), where two interacting twisted magnetic tubes were considered. The reconnection process develops in the presence of a strong magnetic field $\sim 1000$ Gauss and, probably, large radiative losses due to the high density. The observed small magnetic arcade can be a result of chromospheric magnetic reconnection.

The studied event is a good illustration of a chromospheric non-eruptive flare which does not fit into a standard model. It motivates us to investigate magnetic reconnection in physical conditions far from those that are assumed in the frame of the standard model. To develop the idea of chromospheric magnetic reconnection, we need new detailed numerical simulations whose results can be compared with high-resolution multil wavelength observations of solar flares.

This work was partially supported by the Russian Foundation for Basic Research (grants 15-32-21078 and 16-32-00462), and by NASA grant NNX14AB68G. The authors acknowledge the BBSO observing and technical team for their contribution and support. The BBSO operation is supported by Njit, US NSF AGS-1250818, and NASA NNX13AG14G grants, and the NST operation is partly supported by the Korea Astronomy and Space Science Institute and Seoul National University and by the strategic priority research program of CAS with grant No. XDB09000000.

References

Aschwanden, M. J., Boerner, P., Ryan, D., et al. 2015, ApJ, 802, 53
Carmichael, H. 1964, NASSP, 50, 451
Centeno, R., Schou, J., Hayashi, K., et al. 2014, SoPh, 289, 3531
Chae, J., Moon, Y.-J., & Park, S.-Y. 2003, JKAS, 36, 13
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Emslie, A. G., Dennis, B. R., Shih, A. Y., et al. 2012, ApJ, 759, 71
Fletcher, L., Dennis, B. R., Hudson, H. S., et al. 2011, SSRv, 159, 19
Georgoulis, M. K., Rust, D. M., Bernasconi, P. N., & Schmieder, B. 2002, ApJ, 575, 506
Gold, T., & Hoyle, F. 1960, MNras, 120, 89
Goode, P. R., & Cao, W. 2012, in ASP Conf. Ser. 463, Second ATST-East Meeting: Magnetic Fields from the Photosphere to the Corona, ed. T. R. Rimmele et al. (San Francisco, CA: ASP), 357
Guo, Y., Demoulin, P., Schmieder, B., et al. 2013, A&A, 555, A19
Hirayama, T. 1974, SoPh, 34, 323
Inoue, S., Hayashi, K., & Kusano, K. 2016, ApJ, 818, 168
Kosovichev, A. G., & Zharkova, V. V. 2001, ApJL, 550, L105
Krucker, S., Battaglia, M., Cargill, P. J., et al. 2008, A&A, 16, 155
Kumar, P., Yurchyshyn, V., Wang, H., & Cho, K.-S. 2015, ApJ, 809, 83
Leake, J. E., DeVore, C. E., Thayer, J. P., et al. 2014, SSRv, 184, 107
Leake, J. E., Lukin, V. S., & Linton, M. G. 2013, PhPl, 20, 061202
Leake, J. E., Lukin, V. S., Linton, M. G., & Meier, E. T. 2012, ApJ, 760, 109
Sadykov, V. M., Vargas Domínguez, S., Kosovichev, A. G., et al. 2015, *Apl*, 805, 167
Sadykov, V. M., Vargas Domínguez, S., Kosovichev, A. G., & Sharykin, I. N. 2014, arXiv:1412.0172v1
Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, *SoPh*, 275, 207
Schrijver, C. J. 2016, *Apl*, 820, 103
Severnyi, A. B. 1958, *SvA*, 2, 310
Sturrock, P. A., & Coppi, B. 1966, *Apl*, 143, 3
Sudol, J. J., & Harvey, J. W. 2005, *Apl*, 635, 647
Thomas, R. J., Crannell, C. J., & Starr, R. 1985, *SoPh*, 95, 323
Tsuneta, S. 1997, *Apl*, 483, 507
Varsik, J., Plymate, C., Goode, P., et al. 2014, *Proc. SPIE*, 9147, 91475D
Wang, H., Cao, W., Liu, C., et al. 2015, *NatCo*, 6, 7008
Wang, H., Ewell, M. W., Jr., Zirin, H., & Ai, G. 1994, *Apl*, 424, 436
Welsch, B. T., & Li, Y. 2008, in ASP Conf. Ser. 383, Subsurface and Atmospheric Influences on Solar Activity, ed. R. Howe et al. (San Francisco, CA: ASP), 429
Wheatland, M. S., Sturrock, P. A., & Roumeliotis, G. 2000, *Apl*, 540, 1150
Wöger, F., von der Lühe, O., & Reardon, K. 2008, *A&A*, 488, 375