RELATIONSHIP BETWEEN CHROMOSPHERIC EVAPORATION AND MAGNETIC FIELD TOPOLOGY IN AN M-CLASS SOLAR FLARE

VIACHESLAV M SADYKOV1, ALEXANDER G KOSOVICEV1,2,3, IVAN N SHARYKIN1, IVAN V ZIMOVETS4, and SANTIAGO VARGAS DOMINGUEZ5

1 Department of Physics, New Jersey Institute of Technology, Newark, NJ 07102, USA
2 NASA Ames Research Center, Moffett Field, CA 94035, USA
3 W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
4 Space Research Institute (IKI) of Russian Academy of Sciences, Moscow 117997, Russia
5 Universidad Nacional de Colombia, Sede Bogotá, Observatorio Astronómico, Carrera 45 # 26-85, Bogotá, Colombia

Received 2016 April 5; revised 2016 June 22; accepted 2016 June 23; published 2016 August 23

ABSTRACT

Chromospheric evaporation is observed as Doppler blueshift during solar flares. It plays a key role in the dynamics and energetics of solar flares; however, its mechanism is still unknown. In this paper, we present a detailed analysis of spatially resolved multi-wavelength observations of chromospheric evaporation during an M 1.0-class solar flare (SOL2014-06-12T21:12) using data from NASA’s Interface Region Imaging Spectrograph and HMI/SDO (the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory), and high-resolution observations from VIS/NST (the Visible Imaging Spectrometer at the New Solar Telescope). The results show that the averaged over the flare region Fe XXI blueshift of the hot (10^7 K) evaporating plasma is delayed relative to the C II redshift of the relatively cold (10^5 K) chromospheric plasma by about one minute. The spatial distribution of the delays is not uniform across the region and can be as long as two minutes in several zones. Using vector magnetograms from HMI, we reconstruct the magnetic field topology and the quasi-separatrix layer, and find that the blueshift delay regions as well as the Hα flare ribbons are connected to the region of the magnetic polarity inversion line (PIL) and an expanding flux rope via a system of low-lying loop arcades with a height of ≤4.5 Mm. As a result, the chromospheric evaporation may be driven by the energy release in the vicinity of PIL, and has the observed properties due to a local magnetic field topology.

Key words: Sun: activity – Sun: chromosphere – Sun: flares – Sun: magnetic fields – Sun: UV radiation – techniques: spectroscopic

1. INTRODUCTION AND MOTIVATION

Spectroscopic observations provide a very powerful tool to study atmospheric properties and dynamics of solar flares. The long history of these studies includes observations from numerous satellites and rocket missions (Fletcher et al. 2011; Milligan 2015). NASA’s currently operating Interface Region Imaging Spectrograph (the IRIS satellite; De Pontieu et al. 2014) observes the chromosphere and chromosphere–corona transition region with high spatial, temporal, and spectral resolutions. The IRIS spectral coverage includes several strong lines formed in the upper chromosphere: Mg II h&k 2796 Å and 2803 Å (T = 8–10 × 10^5 K) and in the lower transition region: C II 1334/1335 Å (T = 1 – 2 × 10^4 K) and Si IV 1403 Å (T = 5–10 × 10^4 K). In the hot plasma of solar flares, IRIS can observe the Fe XXI1354.1 Å line, which corresponds to a forbidden transition and is formed at 1.1 × 10^7 K. This line appears during flares in the IRIS O1 spectral window.

Among various physical processes occurring during solar flares, one of the most important is chromospheric evaporation. According to the standard flare model (Carmichael 1964; Sturrock 1968; Hirayama 1974; Kostiuk & Pikelner 1975; Kopp & Pneuman 1976; Priest & Forbes 2002; Shibata & Magara 2011), this process is initiated by the rapid heating of dense layers of the solar atmosphere to coronal temperatures, creating an overpressure region. The dynamical expansion of this region is accompanied by upflows of the hot plasma into the corona, and often by downward motions of relatively cold plasma and shocks. A recent overview of the chromospheric evaporation processes can be found in the paper of Milligan (2015).

IRIS provides a unique opportunity for the chromospheric evaporation studies (see, e.g., Tian et al. 2014, 2015; Battaglia et al. 2015; Brosius & Daw 2015; Graham & Cauzzi 2015; Li et al. 2015a, 2015b; Polito et al. 2015; Sadykov et al. 2015; Young et al. 2015). In particular, the Fe XXI line appearing only during flares detects the hot upward-moving plasma flows as an Fe XXI blueshift. The chromospheric evaporation is also observed in the IRIS UV chromosphere and transition region lines. However, the interpretation of the Doppler shift is less straightforward and depends on the energy transfer mechanism and heating rates resulting in “gentle” and “explosive” types of evaporation (see papers of Antiochos & Sturrock 1978; Zarro & Lemen 1988 and simulations of Fisher et al. 1985a, 1985b, 1985c for the details).

The chromospheric evaporation process is still not well understood. Despite many numerical simulations (e.g., Kostiuk & Pikelner 1975; Livshits et al. 1981; Fisher et al. 1985a; Kosovichev 1986; Liu et al. 2009; Reep et al. 2015, 2016; Rubio da Costa et al. 2015a, 2015b), some details of the process could not be reproduced. One of the most disputed effects is a time delay of the coronal evaporation flow relative to the chromospheric response observed as redshift of relatively cold UV lines corresponding to the downflowing plasma. Graham & Cauzzi (2015), Battaglia et al. (2015), and Young et al. (2015) found the delays of about 60 s using IRIS spectroscopic data. The simulations of Rubio da Costa et al. (2015b) are the most successful in reproducing this effect. The delays between the maximum of the upflow plasma velocity...
and the maximum of the downflow velocity can reach ≈ 45 s for a low heating model with the maximum temperature less than 10^7 K. However, most of the numerical simulations of the standard “thick-target” flare model predict that both phenomena should occur almost simultaneously.

There have been some attempts to explain this discrepancy. Emission of the Fe XXI line might be very weak at the initial and supposedly blueshifted stages of the evaporation, and then became stronger but less blueshifted. This situation is clearly illustrated in the paper of Graham & Cauzzi (2015). The weak Fe XXI emission may happen due to non-equilibrium ionization effects (Battaglia et al. 2015). In particular, Figures 6–8 of Bradshaw (2009) demonstrate that for the number density of 10^8–10^9 cm\(^{-3}\) the characteristic ionization time can reach ≈ 60 s for Fe XIX and higher ionization degree ions, which may cause the blueshift delays for about one minute. However, the theory cannot explain the observed delays for a couple of minutes or longer.

In this paper, we focus on a detailed spatio-temporal analysis of the chromospheric evaporation during an M 1.0 class flare that occurred on 2014 June 12 from 21:01 UT to 21:19 UT in active region NOAA 12087. At this time, the active region was located southeast (heliocentric coordinates S22E49) on the solar disk, and the flare event was well-covered by the IRIS observations in the coarse-raster mode (the IRIS observational set started long before the flare beginning and continued long after the flare decay). The eight slit positions run in a cyclic order with a high cadence (≈ 20 s for the full cycle), which allowed us to study the flare spectra in most of the flare region. Some general properties of the chromospheric evaporation during this flare have already been studied in our previous paper (Sadykov et al. 2015). Dynamical and magnetic processes in the vicinity of the magnetic polarity inversion line (PIL) have been studied by Kumar et al. (2015) and Sharykin et al. (2016). In this paper, we study the process of chromospheric evaporation and its relations to the flare magnetic geometry in more detail.

In addition to the spectroscopic data, the knowledge of the magnetic field topology is very important for the understanding of the flare dynamics. The magnetic field and corresponding electric current systems are the primary energy sources of solar flares. They can store the magnetic energy and convert about 10^30–10^32 erg (Emslie et al. 2012) into the kinetic energy of moving plasma and accelerated particles via magnetic reconnection, Joule heating, and other mechanisms. Thus, it is especially important to know the magnetic field configuration. Nowadays, it is possible to obtain photospheric vector magnetograms from the SDO/HMI telescope (Scherrer et al. 2012) and reconstruct the magnetic field in the solar atmosphere under certain assumptions. One of the key characteristics of the magnetic field structure is the Quasi-Separatrix Layer (QSL, Démoulin et al. 1996, 1997). From the physical point of view, the QSL is a relatively thin surface where the magnetic field connectivity exhibits strong gradients (Aulanier et al. 2006), which can work as a channel of magnetic energy dissipation.

Nowadays, it is also possible to analyze flares with high-resolution using observations with large ground-based telescopes. One of the most breakthrough ground-based facilities is the New Solar Telescope (NST, Goode & Cao 2012) at the Big Bear Solar Observatory. The 1.6 m primary mirror and implemented adaptive optics provide diffraction-limited images and resolve features that are smaller than 0.1. The studied flare was observed by the NST, and in this work we utilize the NST observations obtained in the H\(\alpha\) line core.

2. METHODOLOGY

The IRIS observation temporarily covered the entire event for more than one hour from the appearance of the first signs of flaring activity until the end of the decay phase. The instrument obtained spectra in several wavelength windows in each point of the region with ≈ 20 s temporal and 0′.33 × 2″ spatial resolution. To analyze the large amount of spectroscopic data, we implemented the following techniques of the line profile analysis.

For each IRIS line formed in the chromosphere and chromosphere–corona transition region, the center-of-gravity approach used in our previous paper (Sadykov et al. 2015) can be implemented. We decided to use the C II 1334.5 Å line as a representative of the colder chromospheric layer response to the flare heating. The C II line is formed at \(T = 1–2 \times 10^5\) K. It is not overexposed in this flare unlike the Si IV line, and its shape is simpler than that of the Mg II lines. For each C II line profile, the following characteristics are calculated: (1) the line peak intensity and (2) the Doppler shift defined as a difference between the center of gravity of the line and the reference wavelength for this line \((\lambda - \lambda_{\text{ref}}) = \int \Delta \lambda d\lambda / \int \Delta \lambda d\lambda - \lambda_{\text{ref}}\). The reference wavelength of the C II line was calibrated using observations of several quiet-Sun areas before the flare and was chosen to be equal to 1334.56 Å. Obviously, the implemented technique cannot be applied to blended spectral lines. An example of such a line is, in fact, the IRIS Fe XXI 1354.1 Å line that is formed in the 1.1 × 10^7 K hot plasma, and is very important for our study. The blends of this line are discussed by Tian et al. (2014, Figure 2) and Young et al. (2015, Appendix A). We decided to take into account only the strongest blend, the C I 1354.3 Å line. Our previous study (Sadykov et al. 2015) did not reveal significant Doppler shifts of this line during the flare. Thus, for the Fe XXI line, we performed a double-Gaussian fitting with a fixed peak wavelength of the second Gaussian profile corresponding to the reference wavelength of the C I line \(\lambda_{\text{ref}} = 1354.34\) Å. This reference wavelength was also determined from observations of several quiet-Sun regions before the flare. We kept the wavelength difference between Fe XXI and C I lines the same as in Vilhu et al. (2001), and obtained the Fe XXI reference wavelength equal to 1354.146 Å. Parameters of the Fe XXI line obtained by Gaussian fitting are used to estimate its intensity (as the amplitude of the Gaussian) and its Doppler shift (difference between the wavelength corresponding to the peak of the Gaussian and the reference wavelength). Using the procedures described above, we determined the temporal and spatial behavior of the Doppler shift of the lower transition region C II 1334.5 Å and coronal Fe XXI 1354.1 Å lines that are essential for studying the chromospheric evaporation.

As mentioned before, it is especially important to study the delay of the evaporated hot plasma flow observed as blueshift of the hot coronal lines relative to the chromospheric response (observed as redshift or blueshift of the cooler chromospheric or transition region lines). The IRIS raster scans provide an opportunity to study the spatial configuration of the delays across the flare region. For this analysis, the following procedure was performed. First, the Doppler shift of the C II 1334.5 Å line was estimated at every point for each time
moment of the IRIS scans in the region, and the same was done for the Fe XXI 1354.1 Å line. After this, the temporal evolutions of the redshift and blueshift in each point were plotted and smoothed with a 50 s running window for better estimation of their peak times. The peak times of the redshift and blueshift maxima were determined visually from the plotted curves. In places where the redshifts or blueshifts did not show any peak, we set the delay to zero. Also, the delay was determined only in the flare “bright points,” where the averaged over time magnitude of the C ii 1334.5 Å line was greater than one-eighth of the mean magnitude of this line across the flare region. The uncertainties of the measured delays are \(\approx 20\) s because of the time needed for the IRIS to scan the eight spatial positions.

To reconstruct the magnetic field for the studied event, we followed the approach of Wheatland et al. (2000) implemented in the Nonlinear Force-Free Field (NLFFF) package of the Solar Software (SSW) for Interactive Data Language. The algorithm finds the solution for the NLFFF approximation assuming that all electric currents flow along the field lines. For the boundary conditions, the 12 minute full-Sun vector magnetograms obtained by the HMI/SDO instrument (Scherrer et al. 2012) were used. We reconstructed the magnetic field for eight time moments covering the flare period from 20:22:25 UT to 21:46:25 UT with 12 minutes cadence. For the magnetic force line tracing, a tri-linear interpolation technique implemented in the SSW NLFFF package was used. To estimate topological peculiarities of the magnetic field in the flare region, we applied a method of QSL calculation (Démoulin et al. 1997). The QSLs mark areas in the extrapolated field with sharp variations of magnetic field connectivity. To make a quantitative estimate of the connectivity changes at a point \(P(x, y, z)\), we use a parameter called the Squashing factor \(N(x, y, z)\), which is calculated as

\[
N(x, y, z) = \sqrt{\sum_{i=1}^{3} \left( \frac{\partial X_i}{\partial x} \right)^2 + \left( \frac{\partial X_i}{\partial y} \right)^2 + \left( \frac{\partial X_i}{\partial z} \right)^2}.
\]  

Here \(X_1\) and \(X_2\) are components of the vector connecting the point where the field line crossing point \(P(x, y, z)\) is directed outward from the photosphere with the point where the same line is directed down into the photosphere. The coordinate derivatives \(\partial_x, \partial_y, \) and \(\partial_z\) characterize variations of magnetic connectivity from point to point.

In addition, we analyzed the flare X-ray data from the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI, Lin et al. 2002) and compared the 12–25 keV X-ray sources reconstructed by using the CLEAN algorithm with the magnetic field topology. Data from the detectors 1F–7F are used for the reconstruction. RHESSI observations covered the entire flare event, from \(\approx 21:40\) UT till \(\approx 21:35\) UT. The X-ray flux above 25 keV was very weak and insufficient for the source reconstruction.

3. RESULTS

3.1. Behavior of the Integrated Redshifts

The integrated (averaged over the flare region) intensities and Doppler shifts of the C ii 1334.5 Å and Fe XXI 1354.1 Å lines are displayed in Figure 1. For the C ii line, the intensity is measured at its peak, and the Doppler shift is estimated using the center-of-gravity approach discussed in Section 2. For the Fe XXI line, the intensity and the Doppler shift corresponds to the amplitude and the mean shift of the corresponding Gaussian (see Section 2 for the details). The mean intensities and Doppler shifts are plotted with different colors (see caption of Figure 1 for the color code).

Panel (a) of Figure 1 represents the Fe XXI 1354.1 Å line intensity and Doppler shift integrated over the flare region. A delay of the Fe XXI line intensity relative to its Doppler shift is very obvious, and, probably, occurs because of the gradual filling of the magnetic loops by the hot evaporated plasma. Panel (b) of Figure 1 displays the mean intensity and Doppler shift of the C ii line. The delay between the high-temperature Fe XXI line and low-temperature C ii emission of about six minutes is not a surprising result: the same types of delays were observed in several works, e.g., by Brosius & Phillips (2004) and Brosius & Holman (2009). One can notice an increase of the C ii redshift during the flare, and its correlations with the X-ray 12–25 keV light curve from RHESSI. Previously (see Sadykov et al. 2015 for details), it was found that the slowly varying redshifts mainly represent some background activity in the region. Figure 1 shows that we observe a superposition of the relatively steady downflows and fast varying downflows due to the flare energy release.
Panel (c) in Figure 1 displays the C II and Fe XXI normalized Doppler shifts fitted with cubic splines. The tension of splines was chosen to smoothly fit all the significant features of the time curves. Additionally, the normalized derivatives of these splines are plotted in Figure 1(c). Despite the first peaks of the C II line redshift and Fe XXI line blueshift, marked as two dotted vertical lines in Figures 1(a) and (b), are separated in time by about a minute, these curves started to rise almost simultaneously as one can see from the derivatives in Figure 1(c). This is in good correspondence with the expectations of the “thick-target” model, in which the chromosphere is heated by a beam of accelerated electrons. Two dotted vertical lines in Figures 1(a) and (b) correspond to the first peaks of the C II line redshift and Fe XXI line blueshift. One can see that the peak of the Fe XXI blueshift is delayed with respect to the C II line redshift for about one minute.

The typical values of the C II line redshifts are \( \sim 30\text{–}50 \text{ km s}^{-1} \), and the typical blueshifts of the Fe XXI line are \( \sim 50 \text{ km s}^{-1} \). In the previous paper (Sadykov et al. 2015), we mentioned that the evaporation process in this flare can be characterized as of the “gentle” type because of the subsonic velocities of the evaporated plasma according to Antiochos & Sturrock (1978). However, the integrated redshift of the C II line (Figure 1) starts increasing at the beginning of the flare activity, which may be a sign of the explosive evaporation according to Fisher et al. (1985a). Figure 1 also reveals significant background steady plasma downflows obvious before and after the flare. It is possibly that the evaporation in this region has a very complex structure, and cannot be classified as a pure explosive or gentle type, according to the models.

3.2. Spatial Structure of Chromospheric Evaporation

The distribution of the Fe XXI 1354.1 Å blueshift maximum delay relative to the C II 1334.5 Å redshift maximum across the flare region is demonstrated in Figure 2. The procedure which we have performed to measure the delays is described in Section 2. The result is presented in the form of the contour lines corresponding to the delays of 30 s, 60 s, 120 s and 240 s. The underlying IRIS 1330 Å SJ image is shown for better representation of the chromospheric activity.

As one can see, the delays distributed across the flare region can be longer than two minutes, which is longer than the previously reported one minute delays (Battaglia et al. 2015; Graham & Cauzzi 2015; Young et al. 2015). The delays are distributed along the flare ribbon visible in the background IRIS 1330 Å SJ image, and are not uniform. Flare ribbons are thought to be closely connected to the magnetic field configuration in the region. In the standard flare model, it is assumed that because of the deposit of energy of accelerated particles and heat flux along the flare loops, the plasma emission becomes stronger near the loop footpoints that becomes visible as the flare ribbons. Thus, we have decided to study the magnetic field properties in the region in order to better understand their relationship to the observed delay distribution.

3.3. Flare Process and Field Topology

For the magnetic field reconstruction, we use the NLFFF method of Wheatland et al. (2000) and vector magnetograms from HMI/SDO as the boundary conditions. Figure 3 represents the reconstructed magnetic field structure. In panel (a), this structure resembles the flux rope, which was observed in the NST images and reported by Sadykov et al. (2014) and Kumar et al. (2015). The underlying gray-scale image represents the radial magnetic field (white for the positive and black for the negative polarity regions). As one can see, the field lines of the flux rope are twisted, reflecting a nonpotential nature of the magnetic field in the studied region with the currents embedded. This configuration is located exactly at the PIL. The detailed structure and dynamics of this region, which is likely to be the primary energy source for the flare, is discussed in a separate paper by Sharykin et al. (2016).

Panels (b) and (c) of Figure 3 illustrate the reconstructed magnetic field structure and the flare ribbons observed in the IRIS SJ 1330 Å image. For a better understanding the structure, only the magnetic field lines reaching a certain range of heights (\( 2''\text{–}6'' \), or 1.5–4.5 Mm) are presented. The higher magnetic field lines have their footpoints far away from the flare ribbons, and thus do not participate in the energy transfer during the flare. The underlying image is the IRIS 1330 Å SJ image for 21:04:43 UT. The field lines corresponding to the flux rope mentioned above are shown in green in this figure. One can see that almost all the lines starting from the flare ribbons have their other footpoint near the flux rope region at the PIL.

One of the possibilities to understand changes of the magnetic field topology and its connection with the observed delays is to reconstruct the so-called QSL (Démoulin et al. 1996, 1997). We have already described the computational procedure in Section 2. It was found that the QSL evolves with height very smoothly. Thus, we decided to utilize the QSL at a height of \( \approx 1000 \text{ km} \) above the photosphere, and calculated the squashing factor for the comparison.

The QSL structure presented in Figure 4 is mostly stable before (from 20:22:25 UT to 20:58:25 UT) and after (from 21:22:25 UT to 21:46:25 UT) the flare. However, during the flare impulsive phase the QSL undergoes significant changes in
the region marked by the red dashed ellipse. The magnetic field neutral line also undergoes significant changes restricted to the marked region. Because of the 12 minute integration time of the SDO/HMI vector magnetogram data, we cannot determine when exactly during the period from 21:04:25 UT to 21:16:25 UT the QSL evolved.

We compare the QSL chromospheric structure with the flare ribbons visible in the IRIS 1330 Å SJ images and the NST Hα line core images. The result is presented in Figure 5. The observing times are shown for each panel. One can notice a correspondence between the flare ribbons and the QSL cross-section. Also, the evolution of both the QSL and the flare ribbons (for both NST and IRIS observations) demonstrates similar patterns, confirming the idea that the flare energy transport along the QSL forms the flare ribbons (Schmieder et al. 1997; Masson et al. 2009; Chandra et al. 2011).

To understand when exactly the evolution of the flare ribbons occurred, we studied the behavior of the Hα flare ribbon in more detail. We found that the motions of the flare ribbon occurred during the period from 21:12 UT to 21:15 UT, i.e., after the impulsive phase of the flare. This time interval is within the uncertainty interval determined for the QSL change (from 21:04:25 UT to 21:16:25 UT). Also, only the north-eastern part of the ribbon changed, the other parts were mostly stable (see Figures 5(g) and (h)).

Figure 6 demonstrates the distribution of the delays across the flare region with the QSL chromospheric cross-section and the magnetic field lines originating from the delay regions. For convenience, only the field lines corresponding to the main arcade are plotted. The NST Hα-line core image is displayed in the background. Additionally, we plot the RHESSI 12–25 keV contours for different integration times in the same figure. Similarly to Figure 3, the height of most of the field lines does not exceed 4.5 Mm (or 6°). So, the lines connecting the flux rope site and the delay regions do not extend high into the solar corona. The RHESSI 12–25 keV sources evolve along the
reconstructed arcade with time as illustrated in Figure 6(b) and (c). For 21:04:00 UT–21:05:40 UT the primary source is located near the flux rope region (solid contours in Figure 6(b)), while at 21:05:40 UT–21:06:16 UT it appears closer to the southeastern part of the flare ribbon (dashed contours). The X-ray sources do not match the flare ribbons and arcade footpoints. During the further periods, shown in Figure 6(c), the X-ray source is slightly moving toward the top of the arcade and becomes more diffuse. Perhaps, it represents the emission of the hot evaporated plasma. Thus, from the observations, we cannot confirm that the chromospheric evaporation observed in the flare ribbons is caused by the accelerated electrons, as predicted by the standard model. Unfortunately, the flux above 25 keV does not allow us to analyze higher energy sources.

4. DISCUSSION AND CONCLUSION

In this paper, we studied the chromospheric evaporation event during the M 1.0 GOES class flare, which occurred on 2014 June 12 from 21:01 UT until 21:19 UT. The evaporated plasma flows were detected in the hot Fe XXI 1354.1 Å line, and the response of the “colder” layers was studied with the help of the lower transition region C II 1334.5 Å line. The main focus was on the distribution of the chromospheric evaporation delay time between the C II Doppler shift maximum and the Fe XXI blueshift maximum. In addition, the magnetic field lines were reconstructed from the photospheric vector magnetograms, and the QSL was computed and compared with the flare ribbons. Let us summarize the main observational findings mentioned in this study.

1. The averaged over the region C II redshift presented in Figure 1 is correlated with the flare activity observed in the X-ray 12–25 keV energy range. The onsets of the Fe XXI blueshift and the C II redshift are almost simultaneous. The Fe XXI blueshift maximum is delayed relative to the C II redshift maximum for about one minute.
2. The detailed spatially resolved study demonstrates that the delays are distributed in many points along the flare ribbon, and in some places can be longer than two minutes (see Figure 2). The distribution of the delays across the initially observed flare ribbon (in both IRIS 1330 Å and NST Hα line core observations) is not uniform.

3. The reconstructed magnetic field lines originating from the delay regions mostly connect the flare ribbon with the flux rope structure. The height of the magnetic arcades rarely exceeds 4.5 Mm, revealing their low-lying nature.

4. The X-ray 12–25 keV sources demonstrate a dynamic behavior along the main bundle of the reconstructed field lines. Initially located near the flux rope region, the sources later appear closer to the southeast flare ribbons, and then move toward the top of the reconstructed arcade (Figures 6(b) and (c)).
5. The evolution of the QSL and flare ribbons detected in the 1330 Å and Hα line core images demonstrate the same patterns: a mostly stable configuration with a rapid change in the northeast part of the region. This region is the only one along the initial QSL where the delays were not detected due to the weak Fe XXI signal.

The spatio-temporal properties of the chromospheric evaporation reveal very strong delays of the blueshift of the hot evaporating plasma relative to the redshifts of the cold chromospheric plasma across the flare region. While the average over the region blueshift of the Fe XXI line (see Figure 1) demonstrates the delay for about one minute, the spatially resolved delays are found to be even more than two minutes in several zones along the flare ribbon. Thus, the delay averaged over the region represents the superposition of many spatially distributed delays that occurred in different zones and were caused by the excitation of the chromospheric evaporation process in different loops. In this sense, the observed situation corresponds to the “multithread” model (Warren 2006), proposing a sequence of independently heated threads that occurred in different loops. As is clearly seen from Figure 7, in our previous work (Sadykov et al. 2015), the chromospheric excitation took place in different points across the region at different times. Thus it is not surprising that we have received the same kind of behavior for the delays. A “multithread” model was considered for the chromospheric evaporation studies in the work of Rubio da Costa et al. (2016), where the authors used the RADYN code and the superposition of evaporation events occurred in several loops at different times to adequately model the observed signals.

The reconstructed magnetic field geometry also corresponds to the multithread model, but reveals an interesting complex configuration. As was observed from Figure 3, the magnetic configuration of the region represents twisted small-scale loops constructing a magnetic flux rope located at the PIL, and the bundles of more large-scale magnetic field lines with one footpoint located near the flux rope and the other footpoint located in the flare ribbons, i.e., connecting the flare ribbons and evaporating regions with the flux rope. This magnetic flux rope was studied in more details in the paper of Sharykin et al. (2016). One of the conclusions was that the dissipation processes in this region can be the primary energy source for this flare. It is obvious from the reconstructed magnetic field configuration that accelerated particles and heat flux can spread from the flux rope region to the observed flare ribbons along the field lines. Injections of the particles and heat flux into different loops produce the chromospheric evaporation in different spatial zones as we find in the observations. Thus, the flux rope region at the PIL may play the role of the “energy source” for the event.

It was found that almost all the magnetic field lines connecting the blueshift delay regions with the flux rope are low-lying (see Figure 6). Their height rarely exceeds 4.5 Mm, thus, these loops mainly do not expand high into the corona. This means that all the delays were observed in the low-lying loops. The delays are non-uniformly distributed along the flare ribbon (upper panel of Figure 6), but without any obvious patterns. One of the possible explanations of the delays based on the non-equilibrium ionization of the highly ionized Fe atoms (Bradshaw 2009; Battaglia et al. 2015; Graham & Cauzzi 2015) was discussed in the introduction. The results presented in Figures 6–8 of Bradshaw (2009) show that the Fe XIX ion population reaches equilibrium for the considered durations of the heating phase (up to 60 s), but the Fe XXIV ions are out of equilibrium with a low population. There are no results presented for Fe XXI, and it is hard to understand how the Fe XXI ion population behaves during the heating phase. However, the highly ionized Fe fractions (including Fe XIX and Fe XXIV) are in the equilibrium conditions during the thermal conductive cooling phase. The non-equilibrium ionization explanation of delays becomes suitable only in the case of very long continuous heating (for more than two minutes). This may contradict the impulsive nature of solar flares. The strong growth of the C II intensity light curve in Figure 1, and results presented in Figure 7 of Sadykov et al. (2015) support the idea that the chromosphere heating was impulsive. Thus, the non-equilibrium ionization mechanism may be partly, but not fully responsible for the observed delays.

The only region where the delays are not present or not possible to calculate is a part of the flare ribbon located in the upper left corner of Figure 6. Figures 4 and 5 clearly show that this region is the only one where a rapid motion of the flare ribbon and the QSL chromospheric cross-section was observed. We looked at the spectra of this region in detail and revealed the following: the C II redshift was significant, but the weak signal in the Fe XXI line made it impossible to measure the delay. As shown in panels (a), (d), (e), and (h) of Figure 5, the computed QSL cross-section fits the observed flare ribbons quite accurately before and after the impulsive phase of the flare. Thus, one can assume that the QSL evolved at the same time as the flare ribbons—i.e., from 21:12 UT to 21:16 UT. The first 12–25 keV X-ray pulse occurred at ~21:06 UT (the first 12–25 keV peak corresponds to the first peak in the C II integrated light curve in Figure 1). However, at the time when the flare ribbon motion was observed, the 12–25 keV curve, as well as the C II integrated light curves, shows the decay phase. It could be that the motion of the flare ribbons corresponds to the process called “slipping magnetic reconnection” (Aulanier et al. 2012; Janvier et al. 2013). This model is quite new but already found observational evidence (Janvier et al. 2014; Li & Zhang 2015). However, it seems that the studied flare was not driven by the slipping magnetic reconnection mechanism. Despite the fact that the ribbon motion was observed, it definitely occurred after the impulsive phase of the flare. Even if the slipping mechanism is responsible for this motion, it happened after the impulsive phase and could not support the idea that the flare energy is released by this mechanism.

Of course, the found relationship between the chromospheric evaporation delays and the magnetic field configuration is based only on one studied event. Further statistical study is needed to confirm the proposed dependences.

The authors acknowledge the BBSO, IRIS, and SDO mission teams 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. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at the NASA Ames Research Center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre. The authors thank NASA’s SDO HMI team for the availability of...
the high-quality scientific data. The authors also thank the anonymous referee for valuable comments. The work was partially supported by NASA grants NNX14AB68G, NNX14AB70G, and NNX11AO736; NSF grant AGS-1250818; RFBR grants 15-32-21078 and 16-32-00462; and an NJIT grant.

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