Magnetic Energy Release and Transients in Solar Flare of July 14, 2000

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ABSTRACT

High-resolution observations of a large solar flare of 14 July 2000 ("Bastille Day Flare") from Michelson Doppler Imager (MDI) instrument on SOHO spacecraft reveal rapid variations of the magnetic field in the lower solar atmosphere during the flare. Some of these variations were irreversible, occurred in the vicinity of magnetic neutral lines and were probably related to the magnetic energy release in the flare. A surprising result is that these variations happened very rapidly on the scale of 10-15 minutes in a large area of ~ 50 Mm^2 at the beginning of the flare. Other, more localized and impulsive magnetic field variations probably related to so-called "magnetic transients" were accompanied by impulses in continuum intensity and Doppler velocity. These impulses have dynamic characteristics similar to Ellerman's "bombs" and Severny's "mustaches" and were probably caused by high-energy particles bombarding the solar surface.

Subject headings: Sun: activity — Sun: flares — Sun: magnetic fields — Sun: sunspots — Sun: X-rays, gamma rays — Sun: photosphere — Sun: particle emission

1. Introduction

It is generally believed that solar flares are a result of release of magnetic energy accumulated in sunspot regions. This energy, typically $10^{28} - 10^{32}$ erg, is released in the form of light, X-ray emission, accelerated particles and high-speed plasma flows. Typically the flares occupy $10 - 100$ Mm^2 on the solar surface and last from several minutes to several hours. However, the mechanism of the flare energy release is not understood mainly because of the incomplete knowledge of magnetic field variations in the flares. While some observers reported decrease in the magnetic field strength after the flares, some others argued that the changes are consistent with a general trend of evolution of active regions (see Sakurai & Heie, 1996, for a review). Most of early observations were carried out with relatively poor temporal resolution with long intervals (an hour or longer) between the magnetic field measurements. Nevertheless, it has been established in the early observations that strong flares mostly occur near neutral lines of the vertical component of the magnetic field with a strong gradient of the field ($\sim$ 1 G/km) and where the horizontal component has strong shear (Severny, 1964; Zvereva & Severny, 1970). It has been also shown that the magnetic energy of the flaring regions estimated from the line-of-sight component decreases after strong flares. Most of the later discussions were about whether the magnetic field variations were the flare energy source or a flare consequence (Svestka, 1976).

Surprising strong impulsive variations of magnetic field during solar flares were detected with a videomagnetograph at the Big Bear Solar Observatory (Patterson & Zirin, 1981). However, the interpretation of these observations was unclear, and the observed variations might be caused by emission in the spectral line (Paterson, 1984; Harvey, 1985; Moore, et al. 1984). These studies were based on measurements of the line-of-sight component of the magnetic field. Observations of the transverse component have also indicated substantial flare-related variations of magnetic shear. However, the results are inconclusive (e.g. Wang et al. 1994; Cameron & Sammis, 1999), sometime showing increases of the magnetic shear contrary to what is expected if magnetic energy is released.

Recently, we have reported on preliminary results of analysis of the flare of May 2, 1998 (Kosovichev and Zharkova, 1999), using magnetic field measurements from the Michelson Doppler Imager (MDI) instrument on SOHO spacecraft (Scherrer et al, 1995). These measurements carried out in the MDI full-disk mode with 2-arcsec pixel spatial resolution and 1-min cadence have provided evidence for a rapid permanent decrease of magnetic energy estimated from the line-of-sight component during the impulsive phase of the solar flare in the vicinity of the neutral line. Here we report on new significantly more detailed MDI observations of the July 14, 2000, flare, carried out in the high-resolution mode with a plate scale of 0.625 arcsec per CCD pixel.

2. MDI Observations

The MDI magnetograms are obtained by measuring the shift of Ni I 6768 Å absorption line in right and left circular polarized light. The difference between the two shifts is a measure of the Zeeman splitting, and proportional to the line-of-sight component of the magnetic field. Four right and left circular polarized filtergrams are taken in pairs to minimize possible intensity variations within the line. The filtergrams are taken every 3 sec, and the magnetic signal is calculated with one minute cadence on board spacecraft. The flare was located not far from the disk center (N22 W07), therefore, the line-of-sight signal represents mostly the vertical component of the magnetic field. The typical noise level of the MDI magnetograms is about 20 Gauss. In addition, the MDI instrument measured Doppler velocity and background intensity with 1 min cadence using the same spectral line. We have used all three quantities in this analysis.

3. Variations of Magnetic Field During the Flare

The flare of July 14, 2000, which occurred in active region NOAA 9077, started at about 10:10 UT and reached the peak of the soft X-ray flux (X5.7) at 10:24 UT. First significant variations in the magnetic field are detected in the MDI measurements at 10:12 UT approximately at the start of the soft X-ray flux recorded by the GOES-10 satellite. During the next 30 minutes magnetic field variations are observed in various areas of the active region. Figure 1a shows the MDI magnetogram taken at the beginning of the flare. The rectangular areas numbered from 1 to 7 indicate places of the most significant variations. These variations are shown in differences between the consequent magnetograms (panels b–f of Fig. 1).

During the initial phase, from 10:12 to 10:20 UT,

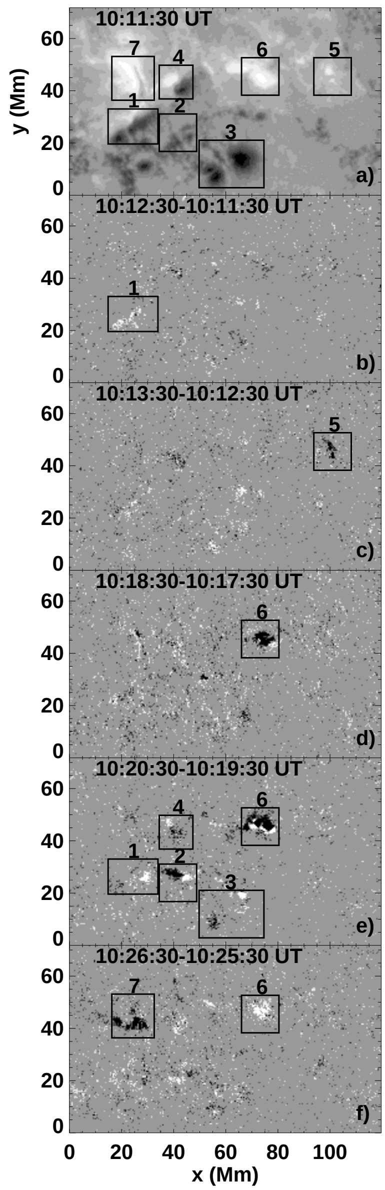

Fig. 1.— Maps of the line-of-sight component of the magnetic field and the differences between the consequent field measurements showing variations during the solar flare of July 14, 2000: a) the MDI magnetogram taken at the beginning of the flare at 10:11:30 UT, the gray scale corresponds to the field strength from -1500 G (black) to 1500 G (white), the rectangular boxes indicate regions (1-7) of some most prominent variations; b)-f) samples of the 1-min magnetic field differences, the gray scale corresponds the range from -70 to 70 G, the white features shows positive variations of 70 G and larger, the black features are the negative variations of -70 G and greater.

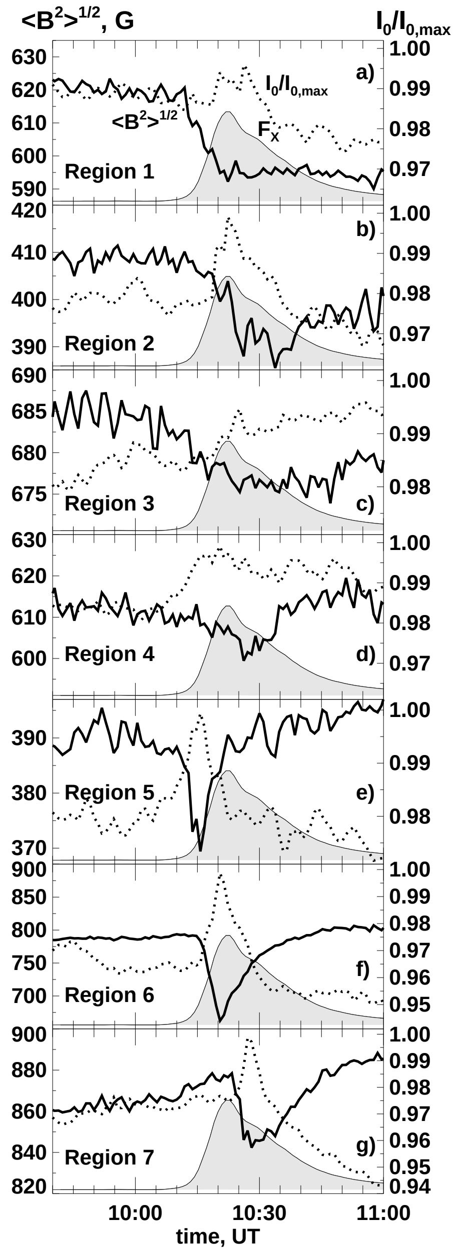

Fig. 2.— Temporal variations of RMS magnetic field, $\langle B^2\rangle^{1/2}$, (thick solid curves), mean relative background intensity, $I_0/I_{0,\max}$, (dotted curves), in each of the 7 rectangular regions of Fig.1, and the soft X-ray flux, F_X (shaded profile) during the flare of July 14, 2000.

the variations occurred in Region 1 (Fig.1b) which contained magnetic fields of the opposite line-of sight polarities (δ-type sunspot), and near two leading unipolar spot in Regions 5 (Fig.1 c) and 6 (Fig.1 d). During the maximal phase at 10:20 - 10:25 UT magnetic field variations were observed in several other regions usually reflecting changes of the strength of the existing magnetic fields. Figure 2 shows the variations of the root-mean-squared of the magnetic field, $\langle B^2\rangle^{1/2}$, in Regions 1-7 as a function of time (thick curves), and the corresponding variations of the mean relative intensity, $I_0/I_{\max}$ (dotted curves) and the GOES-10 1-min averaged soft X-ray flux, F_X (shaded profiles).

Evidently, there were two types of magnetic variations: irreversible in Regions 1-3 (Fig.2 a-c) and transient in Regions 4-7 (Fig. 2 d-g). The first type is characterized by a permanent decrease of $\langle B^2\rangle$ (or the magnetic energy density estimated from the line-of-sight component). It provides evidence of magnetic energy release because $\langle B^2\rangle$ in these regions became permanently lower after the flare. The most significant decrease occurred in Region 1 during the impulsive phase where the RMS of the magnetic field decreased by approximately 30 G. The field variations correlated with intensity increases which, however, did not exceed 1%. In Region 1 the intensity increase started near the middle of the magnetic variation, and continued after the magnetic variation ended. As we have mentioned this region is characterized by magnetic fields of the opposite polarities close to each other. However, another region with two opposite polarities (Region 4) did not show similar irreversible changes, - $\langle B^2\rangle$ only slightly decreased after the flare maximum and then restored approximately to the initial values.

Transient variations of the second type occurred at the beginning of the impulsive phase in Region 5, near the X-ray maximum (Region 6) and during the decaying phase (Region 7). These variations occurred in unipolar areas and were accompanied by impulsive increases of the intensity. The magnetic field strength became smaller in all these transients, and then gradually restored.

After the flare maximum, magnetic perturbations quickly expanded to North-East with a speed of about 200 km/s along the footpoints of the magnetic arcade and were accompanied by the rise of a long postflare arcade observed in the EUV lines by the TRACE mission.

4. Dissipation of Magnetic Fields

The main site of the magnetic energy decrease was in Region 1 (see Fig. 1a,b and 2a). This region includes vertical magnetic fields with opposite polarities. These fields were pushed towards each other before the flare probably by external flows. This resulted in an increase of the magnetic field gradient and hence stronger horizontal electric currents, and eventually led to the flare.

Figure 3a shows the MDI magnetogram (gray-scale image) and the locations of the magnetic neutral line at 9:00:30 UT (thin dashed curve) and 10:11:30 UT (thick dashed curve). This line which separates the two polarities was moved in the South direction with a speed of ~ 200 m/s, with the larger displacement being in the upper part of Region 1. The magnetic field gradient there reached 1.3 G/km (Fig. 3b). Most of the magnetic energy release occurred very close to the high gradient area occupied by the negative polarity. The white contour curves in Fig.3a show the levels of the magnetic energy density decrease at -1.5×10^4 erg/cm^3 (thin curve), -2.5×10^4 erg/cm^3 (medium curve), and -3×10^4 erg/cm^3 (thick curve). These values calculated from only the vertical component of the field do not provide a precise estimate of the magnetic energy release, but certainly serve as good indicators of the energy release site. At the same time, in a relatively small area of the positive polarity the magnetic energy increased (black contours in Fig. 3a). This demonstrates the complexity of the electrodynamic flare processes near the neutral line. The net effect of these variations is consistent with magnetic energy dissipation at the beginning of the flare. The characteristic area of the energy release was $\sim 4.6\times10^{17}$ cm^2, and the integrated magnetic energy density decrease was about 7×10^{21} erg/cm. If the characteristic height of the magnetic field variation was $\sim 10^8$ cm then the total energy dissipated in the vertical field (horizontal currents) in Region 1 during the first 10 min of the flare was $\sim 7\times10^{29}$ erg. This is comparable with the energy of a typical flare.

Figure 4 shows the variations of the mean gradient of the vertical magnetic field in Region 1 as a function of time. It is clear that the gradient was growing before the flare and then suddenly decreased at the beginning of the flare.

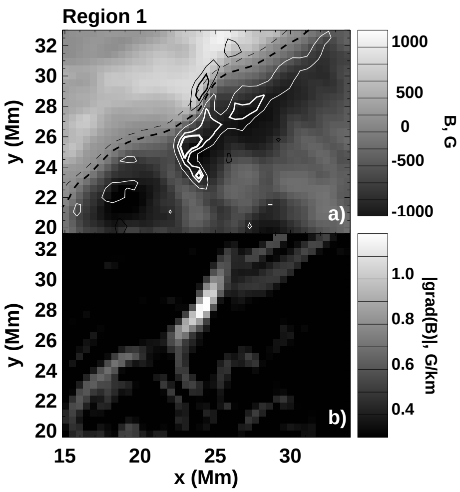

Fig. 3.— a) Locations of the neutral magnetic line in Region 1 at 9:00:30 UT (thin dashed curve) and 10:11:30 UT (thick dashed curve), and contour lines of the difference between the 20-min averaged magnetic energy density, $\langle B^2/4\pi \rangle$) estimated before (9:42:30-10:11:30 UT) and after (10:23:30-10:42:30 UT) the flare from the vertical component of the field (white contour show negative energy variations, black contours show the positive variations); the gray-scale image is the MDI magnetogram at 10:11:30 UT); b) the map of the absolute gradient of the vertical component of the magnetic field at the start of the flare, 10:11:30 UT.

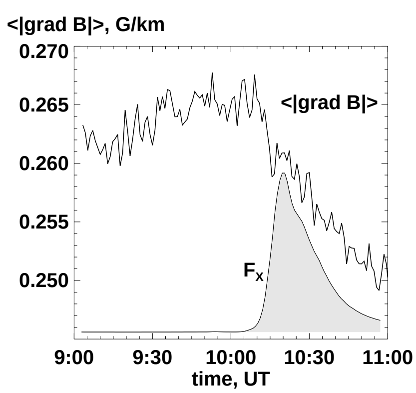

Fig. 4.— The mean absolute gradient of the vertical magnetic field, $\langle |\mathrm{grad} B| \rangle$, in Region 1 (Fig. 1) as a function of time. The lower shaded curve shows the flare soft X-ray flux, F_X.

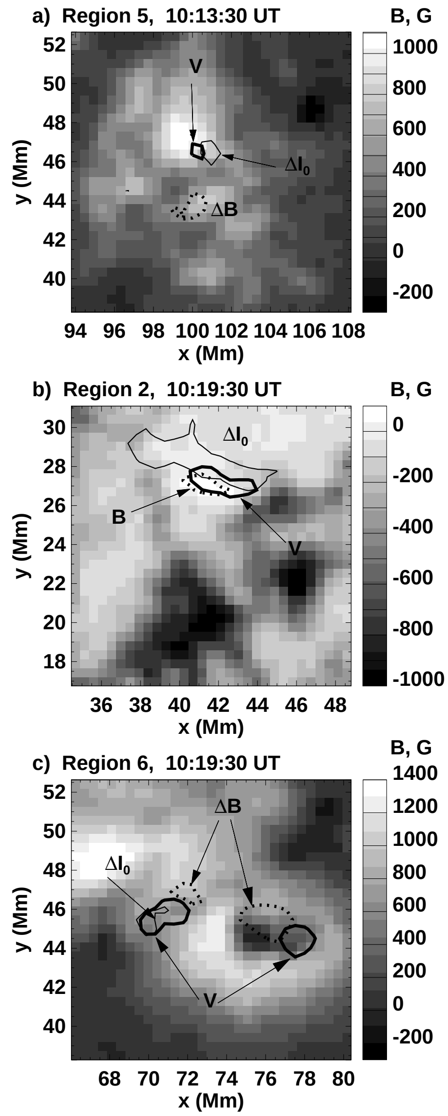

Fig. 5.— Maps for three magnetic transients showing locations of strongest variations at the transient maxima. The gray-scale images are MDI magnetograms. Thick solid contours show the strongest negative velocities: a) -0.5 km/s, b) -1.1 km/s, c) -1 km/s. Dotted contours shows the places of strongest magnetic field variations (ΔB is the difference between two consequent magnetograms): a) ΔB=-70 G, b) B=40 G, c) ΔB=-500 G. Thin solid contours show places of maximal intensity, $\Delta I_0/I_{0,\max}$=0.8.

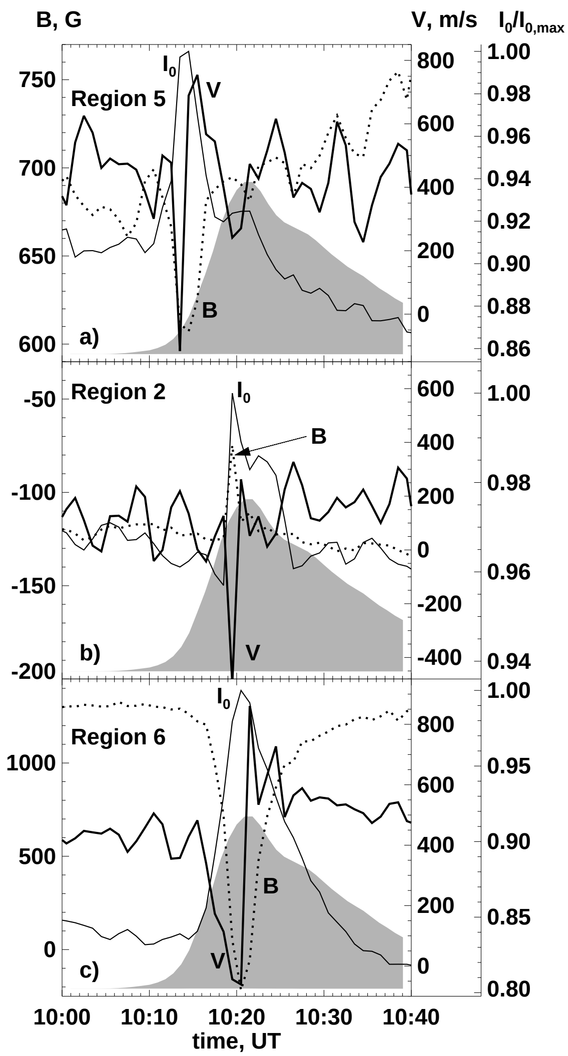

Fig. 6.— Vertical magnetic field, B, (dotted curves), vertical velocity, V, (thick solid curves) and the relative continuum intensity, $I_0/I_{0,\max}$, (thin solid curves) as functions of time for the three magnetic transient events shown in Fig. 5. The shaded area shows the soft X-ray profile.

5. Magnetic Transients

Sudden impulsive variations of the magnetic field were observed during the flare mostly in unipolar areas of various magnetic field strength. These variations resulted in sharp temporary decreases of the magnetic field strength. After these events lasting 1–10 minutes the magnetic field strength is returned to the initial values. The transients occurred at different distances from the energy release site and different times during the flare.

The first and relatively weak transient event occurred at the very beginning of the explosive phase at 10:13 UT in Region 5, approximately 80 Mm from the energy release site in Region 1. For this event locations of the strongest variations of the velocity, V, intensity, I_0, and magnetic field, B with respect to the background magnetic field near the peak of the velocity signal, at 10:13:30 UT, are shown in Fig.5a The highest negative velocity variation ($\simeq -0.7$ km/s) and intensity increase ($\simeq 20\%$) occurred at a boundary of the leading sunspot. The variations of V, I_0 and B did not coincide but were close to each other. The strongest magnetic field variation ($\Delta B \approx -70$ G) occurred ≈ 2 Mm south from the strongest intensity and velocity variations. Nevertheless, these variations were not completely separate. In Fig. 6a we show the variations of V, $I_0/I_{\max}$ and B in a small area of 3x3 CCD pixels (2 Mm^2) as a function of time. It shows a sharp negative velocity signal (Doppler blue shift) lasting only 1 min followed by a smaller positive signal. This is consistent with an upflow followed by a graduate downflow. The corresponding magnetic field and intensity variations peak later and lasted longer, ≈ 4 min.

The transients in Regions 2 and 6 occurred almost simultaneously, both peaking approximately at 10:19:30 UT, (see Fig. 5b,c and 6b,c) but were separated from each other by ≈ 40 Mm (Fig. 1a,e). The event in Region 6 started earlier, at $\approx$ 10:17 UT, and was much stronger and longer. While the transient in Region 6 occurred in a sunspot penumbra with strong magnetic field, the Region 2 transient occurred in an area of a very weak background magnetic flux of ≈ 100 G (Fig. 5b), far from sunspots. It lasted only 1 min in V and B and about 7 min in I_0 (Fig. 6b). In all our cases the strength of the magnetic field irrespective of its sign was decreased; and the Doppler line shift was consistent with upflow motions followed by much weaker downflows.

The strongest transient associated with the flare was observed in Region 6. It was located at both the East and West sides of a sunspot, with stronger variations being at the West side (Fig. 5c) where the MDI magnetic field signal detected a variation of about 1500 G, so that the magnetic polarity was even briefly reversed at the peak of the transient. The Doppler velocity variation was negative at the beginning of the transient ($\Delta V \simeq -0.6$ km/s), and then suddenly changed to positive ($\Delta V \simeq 0.4$ km/s) when the magnetic variation reached its maximum. This velocity variation is again consistent with an upflow followed by a downflow.

6. Interpretations and Discussion

Using the high-resolution data of the July 14, 2000, solar flare from the MDI instrument on SOHO space mission we have observed two types of magnetic field variations: a permanent decrease of the magnetic field strength near the magnetic neutral line during the rising phase of the flare, and transient variations of magnetic field, Doppler velocity and intensity during the impulsive phase. We suggest that the permanent change was related to the magnetic energy release in this flare, and that the transients were caused by beams of energetic particles hitting the solar photosphere.

Our results are in agreement with the initial magnetic field measurements in solar flares by Severny (1964) and his colleagues at the Crimean Observatory, and later observations by Moore et al (1984). A sudden permanent decrease of a satellite polarity during a flare was observed by Paterson & Zirin (1981). A surprising results of our investigation is that the irreversible magnetic field variation occurred very quickly during 10 min in a large area just at the beginning of the flare, releasing a significant amount of energy, comparable with the total energy of solar flares. This variation occurred in the vertical component of the magnetic field, which often is considered as non-changing during solar flares.

The properties of the magnetic transients observed by the MDI are quite similar to the transients observed by Paterson & Zirin (1981) and Zirin & Tanaka (1981) using a BBSO videomagnetograph. There were concerns that magnetograph signals can be unreliable because of rapid variations in the line emission during solar flares, and fine unresolved structure of this emission (Patterson, 1984; Harvey, 1985). Since simultaneous spectral data are not available it cannot be ruled out that the magnetic field measurements are contaminated by a spurious signal caused by a flare emission. However, it is unlikely that these measurements are completely spurious because the MDI measurements show that the variations of magnetic field, Doppler velocity and intensity do not completely coincide both spatially and temporary. However, some cross-talks among the MDI signals cannot be excluded.

It is intriguing that the velocity signal of the transients is similar to "mustaches" (or Ellerman "bombs") - extended spectral line features - studied in detail by Severny (1968) and his colleagues who also found associated polarization signals which may correspond to impulsive variations of magnetic field. Mustaches are often observed in the chromosphere during flares. Also similar weaker events are observed around sunspots, thus representing a broader class of impulsive phenomena. Mustaches can be explained by streams of energetic particles penetrating in the solar chromosphere (Ding et al, 1998). Therefore, we suggest that our transients observed much closer to the photosphere might be caused by beams of particles accelerated to much higher energies and thus penetrated into much deeper layers than the energetic particles in mustaches. Details of this interpretation are not developed yet. We hope that these observations will stimulate further observational and theoretical studies of solar flare effects in the lower atmosphere of the Sun.

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