MULTI-WAVELENGTH HIGH-RESOLUTION OBSERVATIONS OF A SMALL-SCALE EMERGING MAGNETIC FLUX EVENT AND THE CHROMOSPHERIC AND CORONAL RESPONSE

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ABSTRACT

State-of-the-art solar instrumentation is now revealing magnetic activity of the Sun with unprecedented temporal and spatial resolutions. Observations with the 1.6 m aperture New Solar Telescope (NST) of the Big Bear Solar Observatory are making next steps in our understanding of the solar surface structure. Granular-scale magnetic flux emergence and the response of the solar atmosphere are among the key research topics of high-resolution solar physics. As part of a joint observing program with NASA’s Interface Region Imaging Spectrograph (IRIS) mission on 2013 August 7, the NST observed active region NOAA 11,810 in the photospheric TiO 7057 Å band with a resolution of pixel size of 0.034 arcsec and chromospheric He i 10830 Å and Hα 6563 Å wavelengths. Complementary data are provided by the Solar Dynamics Observatory (SDO) and Hinode space-based telescopes. The region displayed a group of solar pores, in the vicinity of which we detect a small-scale buoyant horizontal magnetic flux tube causing granular alignments and interacting with the preexisting ambient field in the upper atmospheric layers. Following the expansion of distorted granules at the emergence site, we observed a sudden appearance of an extended surge in the He i 10830 Å data (bandpass of 0.05 Å). The IRIS transition region imaging caught ejection of a hot plasma jet associated with the He i surge. The SDO/HMI data used to study the evolution of the magnetic and Doppler velocity fields reveal emerging magnetic loop-like structures. Hinode/Ca ii H and IRIS filtergrams detail the connectivities of the newly emerged magnetic field in the lower solar chromosphere. From these data, we find that the orientation of the emerging magnetic field lines from a twisted flux tube formed an angle of ∼45° with the overlying ambient field. Nevertheless, the interaction of emerging magnetic field lines with the pre-existing overlying field generates high-temperature emission regions and boosts the surge/jet production. The localized heating is detected before and after the first signs of the surge/jet ejection. We compare the results with previous observations and theoretical models and propose a scenario for the activation of plasma jet/surges and confined heating triggered by buoyant magnetic flux tubes rising up into a magnetized upper environment. Such process may play a significant role in the mass and energy flow from the interior to the corona.

Key words: Sun: activity – Sun: atmosphere – Sun: chromosphere – Sun: granulation – Sun: magnetic fields

Online-only material: color figures

1. INTRODUCTION

Activity of the solar atmosphere entails numerous multiscale processes, magnetic structuring of which is controlled by photospheric and subphotospheric evolution and dynamics. Building blocks for these processes are thought to occur at very small (subarcsecond) spatial and short (a few minutes) temporal scales. The 1.6 m New Solar Telescope (NST; Goode et al. 2010) operating at the Big Bear Solar Observatory (BBSO) provides such high-resolution capabilities. The ground-based observations reaching the diffraction limit through the use of adaptive optics systems in combination with the current satellite facilities, i.e., Interface Region Imaging Spectrograph (IRIS), Solar Dynamics Observatory (SDO), and Hinode, allow us to investigate the linkage between different layers of the solar atmosphere from the photospheric surface to the corona in order to detail the finest evolutionary stages of solar activity and to understand the physical mechanisms driving it. Emerging flux regions (EFRs) are of great interest because of their impact on the solar atmosphere. Many observational and theoretical approaches (e.g., Zwaan 1985; Lites et al. 1998; Magara 2001; Kubo et al. 2003; Stein et al. 2011) have been developed to establish how magnetic fields are generated in the solar interior, emerge in the photosphere, and shape the structure and dynamics of atmospheric layers. It is thought that magnetic reconnection may play a particularly important role in shaping the response of the solar chromosphere to the emerging magnetic flux associated with different phenomena, such as brightenings, dimmings, jets, surges, among others. Some recent models suggest that flux emergence and subsequent reconnection with the background magnetic field can be important for injection of mass and energy into upper atmospheric layers (Archontis et al. 2005; Isobe et al. 2008; Martínez-Sykora et al. 2008). Heating and eruption of chromospheric material associated with granular-scale EFRs in the vicinity of active regions have been observed in locations displaying surges (Guglielmino et al. 2010; Wang et al. 2014), jets (Guo et al. 2013; Schmieder et al. 2013), Ellerman bombs, and various brightenings (Pariat et al. 2007; Vargas Domínguez et al. 2012). These observations suggested that magnetic reconnection between newly emerged and preexisting field lines can release energy and drive ejection of chromospheric plasma, supporting a simple two-dimensional configuration scenario proposed by some authors (e.g., Yokoyama & Shibata 1995). In this scenario, the emerging magnetic field lines are anti-parallel to the pre-existing field lines. However, in the real three-dimensional (3D) geometry, the orientation of interacting field lines may be more complex and significantly affects the dynamics and energetics of the process, as pointed out by Galsgaard et al. (2007). The complex dynamics of small-scale and “hidden” fields in the photosphere is claimed to be important for balancing radiative energy losses of the chromosphere (e.g., Trujillo Bueno et al. 2004). However, the key ingredients of
the small-scale emerging flux and its interaction with the solar atmosphere are still not understood. In this paper, we present a multi-wavelength analysis of observations, acquired with the NST, the SDO (Lemen et al. 2012), the IRIS (De Pontieu et al. 2014), and the Hinode mission (Kosugi et al. 2007), of a transient emerging flux event of 2013 August 7, resulting in generation of a surge/jet and compact heating at coronal-height locations. We compare our observational findings with realistic MHD numerical modeling of magnetic field emergence from the convection zone into the chromosphere and corona. In particular, we find remarkable similarities with the evolution of buoyant flux tubes in 3D numerical experiments of Cheung et al. (2007) and Tortosa-Andreu & Moreno-Insertis (2009), in which the equations of MHD and radiative transfer are solved self-consistently. We interpret the observational results as evidence of emergence of a horizontal small-scale magnetic flux tube into the overlying magnetized environment and discuss the generation of the plasma jet as a result of the interaction of both the emerging and ambient magnetic fields.

2. OBSERVATIONS AND DATA ANALYSIS

The emerging magnetic flux event was observed in the vicinity of active region NOAA AR 11810 at solar disk location S26W18 (263°, −501°) on 2013 August 17. The NST was pointed at the region from 17:00 UT to 19:00 UT acquiring filtergrams in the photospheric TiO 7057 Å line (bandpass: 10 Å) pixel size of 0.034 using Broadband Filter Imager and narrow-band images in the He i 10830 Å line (bandpass: 0.5 Å) with the IRIM instrument (Cao et al. 2012). In addition, observations in the Hα 6563 Å line at the blue/red (−0.2 Å + 0.2 Å) wings were acquired with the NST Visible Imaging Spectrometer (VIS; Cao et al. 2010). The adaptive optics correction system, AO308, and the speckle image reconstruction processing technique (Woger & von der Lube 2007) provided diffraction limited images, allowing us to resolve small-scale plasma structures in the photosphere and chromosphere. Time cadence of the processed NST data is 15 s. Simultaneous observations from space telescopes IRIS, SDO, and Hinode were also used in the analysis. The IRIS data included the Mg ii K line (2796 Å) imaging the upper chromosphere, the Si iv transition region (1400 Å), and C ii transition region (1330 Å), The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Heliospheric Magnetic Imager (HMI; Scherrer et al. 2012) on board SDO were used for analyzing EUV emitting coronal plasma and the photospheric magnetic field evolution, respectively. G-band and Ca ii H filtergrams acquired with the Solar Optical Telescope on board Hinode were also utilized in the multi-wavelength study together with the Hinode X-Ray telescope (XRT) observations. Data from all telescopes and instruments are carefully co-aligned, and the region of interest (ROI) is spatially and temporally extracted from the different channels.

3. RESULTS

The multi-wavelength data allow us to simultaneously investigate solar events from the photosphere up to the corona. Figure 1 illustrates the context of the NST images (available through the online Data Catalog at http://www.bbso.njit.edu), displaying a large part of NOAA AR 11810. The figure shows the extracted portions of the chromospheric filtergrams (NST/ VIS and IRIS), and coronal (SDO/AIA and Hinode/XRT) images in the vicinity of a group of solar pores.

3.1. Chromospheric Surge Observed in He i and Hα Lines

The NST He i images reveal very rich chromospheric dynamics and a plethora of small-scale activity. An exceptionally enhanced and elongated absorption feature (surge) drew our attention to the region, and we decided to investigate it in detail. Such surges, sometimes more powerful, are quite common (Zirin 1988). Figure 1 (upper leftmost panel) shows the surge (inside the black rectangular box) at the moment of its maximum intensity contrast. Although the field of view (FOV) is not large enough to fully cover the length of the surge, its apparent length is at least 23 Mm. Figure 2 is a time-slice plot displaying the evolution of the surge throughout the time series of He i images (various notable evolutionary stages are indicated by a set of arrows). The total lifetime of the surge is approximately 1 hr. The evolution of the surge shows periods of enlargement and retraction. Possibly, there were three subsequent eruptions, separated by about 30 minutes. Some dark multi-threaded features are observed, in particular, between the first and second eruptions. The limitations in the FOV did not allow us to determine the entire extension of the surge, but the outbursts seem to follow the same trajectory, which may indicate an oscillatory behavior. Up to a dozen superfluous threads can be individually resolved in the surge in some of the images. The maximum thickness of the surge was about ~2.2 Mm, and the width of every resolved fiber is from 100 to 200 km. From the longitudinal growth shown in Figure 2, we can estimate the longitudinal expansion velocity of about 30 km s⁻¹ for the first ejection and ~10 km s⁻¹ for the following retraction–ejection periods. The chromospheric response peaks about three minutes after the initiation of the surge. This will be discussed in detail in Section 3.3. In the NST/Hα images taken in the blue and red wings, the corresponding dark-absorbing feature appears very enhanced (see images in Figure 1), and the images clearly manifest that the surge runs parallel to other much brighter fibrilar structures in the region, reflecting the geometry of the ambient magnetic field.

3.2. Photospheric Activity and Magnetic Flux Emergence

The TiO images show an intense activity of bright features, particularly in the nearest vicinity around the pores (see upper middle panel of Figure 1). We find good agreement in the location of these bright structures (TiO photospheric bright points) and the G-band bright points observed in simultaneous Hinode/G-band images. These bright structures host magnetic flux tubes of the order of kG (Ishikawa et al. 2007). The enhanced brightness photospheric structures match the locations where He i dark-absorbing features seem to be rooted, as pointed out in some previous works (Zeng et al. 2013; Yurchyshyn et al. 2010). At about 18:00 UT, time series of the photospheric TiO images reveal an area of intense granular alignments (GAs) occurring immediately before and during the development of the surge, suggesting a connection between the two phenomena. To track the photospheric plasma dynamics, we applied the local correlation tracking (LCT) method (November & Simon 1988) to the series of TiO images. Figure 3 (upper left panel) shows a flow field map computed over the large white-boxed region in Figure 1 (upper panels) by using a correlation tracking window with an FWHM of 1° and averaging over a 1 hr time period. The flow field is dominated by a large area of diverging flows (highlighted with red arrows). Prior to the LCT analysis, the time series were subsonically filtered to eliminate p-modes of solar oscillations. Arrows in the figure represent horizontal
velocities, and although the velocity magnitude depends on the time averaging, the general pattern can be used to track the surface flows (e.g., Vargas Domínguez et al. 2008). Different 20 minute time-averaging windows were used to compute the flow maps before and after the interval shown in Figure 3 (17:52–18:52 UT). Only the flow maps calculated during this time interval display the large diverging region. During this time, the granule exploded and grew up to five times the size of a normal granule. The region of red arrows is hereafter referred to as the GA site. Some intense photospheric bright points are observed in the closest vicinity, inside and around the GA site. We used an intensity thresholding procedure for masking the location/area of bright features. Figure 3 (upper right panel) plots the variation of the area (Mm²) covered by bright features. For further analysis, we extracted a ROI around the GA site (smaller white box in Figure 1 and red box in Figure 3). Small panels in Figure 3 (lower row) show the extracted TiO frame in the ROI at the time of the maximum area coverage (18:11:00 UT) and the corresponding mask (where black areas show the location of bright features in the FOV). The black contour outlines the GA site found in the flow map. The time evolution in the plot shows a sharp increase in the area of bright features starting 10 minutes before the GA activation and up to the maximum (17:42–18:11 UT). The time of the area maximum coincides

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**Figure 1.** Selected images of NOAA 11810 observed on 2013 August 7 with ground-based (NST) and space telescopes (SDO, IRIS, and Hinode). Upper row: NST/IRIM/He\textsc{i} image (left panel) displaying a dark-absorbing feature (surge) and almost simultaneous NST/TiO photospheric image (middle panel), and NST/VIS/H\textsc{a} images in the blue/red wing (right panels). Lower row: chromospheric and coronal observations of the region framed by the large white boxes in the upper panels. Images correspond to instances of peak intensity values in the sub-regions framed by the small white boxes. Equal color palettes are used to display images observed with the same instrument/telescope. Colored triangles in some of the images in the figure, as well as in Figures 3 and 5, denote various relevant stages of the event that are presented in Figure 2.

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**Figure 2.** Time-slices plot displaying the evolution of the chromospheric dark-absorbing feature (surge) from the NST/IRIM/He\textsc{i} observations. Black rectangle framing the surge in Figure 1 (top left panel) shows the portion extracted from the time series to generate the plot with a time interval of 30 s between every pair of images. The figure highlights remarkable evolutionary stages throughout the lifetime of the surge, outcomes from the analysis of all different instruments and channels. Slices with colored arrows denote various stages of the event that are displayed as individual images labeled with the corresponding $\triangle$ in Figures 1, 3, and 5.

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with the very first signs of the plasma surge in He\textsc{i} 10830 Å line shown in Figure 2 and is close to the moment of the jet enhancement observed in the \textit{IRIS} data. In the next section, we will comment more on the chromospheric and coronal response. By using the \textit{SDO}/HMI data, we can follow the evolution of the photospheric magnetic field and Doppler velocities in the GA site. Figure 4 shows one of the context line of sight (LOS) magnetograms (saturated at 200 G), in which positive magnetic polarities (in white) are dominant and correspond mainly to the magnetic field of the pores. The structure of the ambient magnetic fields can be inferred from the NST chromospheric images (also in \textit{IRIS} and \textit{Hinode} images, e.g., panels of Figure 1), and they display organized quasi-parallel spatial distribution. The ROI displays some negative-polarity magnetic elements; see, for instance, the ROI box in the magnetogram in Figure 4 close to the moment of the detected surge eruption. From the \textit{SDO}/HMI observations, we have vector magnetic field data (magnetic field strength, inclination, and azimuth angles) every 12 minutes from 17:00 to 19:48 UT. We calculate the transversal and longitudinal magnetic fields and track their evolution. In the transverse magnetograms, we find an imprint of the horizontal component of the emerging field lines (apex), e.g., see the elongated structure shown in the central part of the image displaying transversal magnetic field magnitudes shown in Figure 4 (middle panels). Figure 4 (bottom panel) plots histograms for the transversal and LOS magnetic field components computed for two instances: before and during the main emergence of magnetic flux (17:48 and 18:12 UT, respectively). Comparing to the magnitude of the longitudinal magnetic field (above the noise level), we do not find significant changes for both intervals, whereas there is a substantial increase of the transversal component from the first to the second instance (increment of \(\sim 100\) G in the mean value). We also use a reference box extracted from a quiet-Sun region (QS box) to measure the same quantities and found that the distribution of horizontal magnetic field strength is shifted to lower values compared to those for the ROI box (longitudinal components are predominantly below the noise level). Figure 5 (upper left and lower right panels) shows two selected TiO images with overlying contours of positive/negative (blue/red) LOS magnetic field. Doppler velocities in the LOS are computed from \textit{SDO}/HMI data. Upflow (negative) and downflow (positive) values...
are measured after correcting from the orbital velocity of the spacecraft. Contours of Doppler velocities are overplotted in both frames (upflows/downflows in green/yellow). The white contour outlining of the GA site is included as a reference. Regions of a weaker magnetic field in the lower part of the FOV display larger magnitudes of upflows and downflows up to 400 and 1400 m s$^{-1}$, respectively. The FOV is dominated by positive magnetic fields with maximum mean values of $\sim$300 G throughout the entire time coverage (17:32–18:51 UT). More intense photospheric bright points host stronger magnetic field reaching almost kG values. By the moment of initiation of the GA event, inferred from the flow map, confined upflows surrounded by downflows start to appear with bipolar magnetic patches neighboring them (at 17:53:15 UT). During the emergence of the magnetic flux, the area of upflows increases together with growing regions displaying positive/negative magnetic polarities. Approximately 15 minutes after the initiation, the granules become very distorted and “sandwiched,” forming a lineal structure (see TiO frame at 18:09:45 UT in Figure 5). By this time, an enhanced jet structure is detected in the IRIS 1330 Å data together with the first signs of the surge in He I images (Figure 2), as shown in the corresponding IRIS panel of Figure 5. The magnetic flux emergence process appears to continue for another 35 minutes with recurrent upflows with neighboring downflows. Fragmentation of polarities is visible at some stages of this process, but in general, upflows were encompassed by positive and negative small-scale ($2''$) patches with the field strength of 50 G. The location of some particular regions in the FOV are labeled as P1, P2, P3, and P4 (see the lower right panel of Figure 5). P1 indicates the location where the surge eruption initiates (as inferred from the time-slice plot in Figure 2 and the IRIS image in Figure 5). Points P2 and P4 are characterized by localized negative magnetic patches, while P3 by a more extended positive-polarity area. There is a significant increase of the magnetic field strength in P2, P3, and P4 as the region evolves. From 18:20 UT onward, the negative patch at P4 shrinks and seems to be canceling out with a neighboring large positive magnetic area, while the negative path at P3 does the same with its surrounding positive patch. At the end of the sequence (18:51:48 UT), the upflows vanished, and a large patch of positive polarity covered a substantial part of the FOV. The rapid evolution of the magnetic field and plasma vertical velocities occurs mostly inside the region described as the GA site (within the white contours in the sequence of TiO images in Figure 5).

### 3.3. Chromospheric and Coronal Response

Simultaneous observations from IRIS, SDO, and Hinode allow us to track the response of the chromospheric/corona to the flux emergence event. Time sequences of images displaying the evolution of the solar atmosphere were generated from 19 spectral different channels. Chromospheric and coronal responses are determined by measuring brightness enhancements in the ROI in the corresponding filtergrams. Figure 6 (upper row) shows the intensity variations (light curves) in some of the channels. The SDO/AIA time interval spans from 17:00 to 20:00 UT. The profiles are normalized to their peak intensities. The coronal response is the strongest at 18:03 UT (304 and 193 Å), whereas chromospheric emission measured in 1600 and 1700 Å AIA channels peaked at 18:13 UT. These two moments were used as references for the other panels of Figure 6 (indicated by vertical lines). For the IRIS and Hinode data, the peak values are reached around the same time. We recall the inception of the jet/surge occurred at 18:09 UT, between the two reference times. The coronal maximum response occurred six minutes before the jet/surge first appearance and prior to the peak of localized heating of chromospheric layers. The chromospheric Ca II H observations, acquired less than five minutes after the jet ejection, reveal the enhanced ultrafine loops of plasma heated at this atmospheric level. The shape of the emerging arch...
Figure 5. Sequence of selected NST (TiO and He i) and IRIS images displaying the evolution of the region where granular alignments are detected (GA site; see the text for details). The large FOV corresponds to the small white boxes in the upper panels in Figure 1, the same boxed portion in Figure 2 (left panel). Colored contours are extracted from SDO/HMI and represent the LOS–magnetic field (±40 G) and Doppler velocities (±160 m s$^{-1}$) according to the color code shown. The white contours in the TiO images represent the GA site. He i 10830 Å is shown at the time the jet is visible in IRIS 1330 Å (right). The IRIS contour is overplotted in white in the He i frame. In the right frame, arrows indicate the location of points of interest (P1, P2, P3, and P4). Inclined solid lines are shown as references compared with IRIS image where the jet is observed. The axis of the emerging flux tube and the direction of the emerging magnetic field lines are denoted by inclined dashed lines in the first and third frames, respectively. The direction of the ambient field can be inferred from the He i 10830 Å image (see the dotted red line). Purple triangles indicate these images are used to describe the evolutionary plot of the surge in Figure 2. Time labels are in UT.

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filament system can be traced from the filtergrams (see orange contours in frame 18:14:15 UT in Figure 5). Locations of P2, P3, and P4 correspond to footpoints where the most prominent emerging loops seem to be rooted, in agreement with the presence of intense photospheric bright points. The compact coronal brightening is confined to the location of the jet (P1), whereas the chromospheric brightenings cover a curved path connecting the location of the jet eruption (P1) and a negative-polarity patch with intense photospheric emission in TiO images (P2). The direction of the jet/surge is parallel to the overlying ambient field lines as marked by the red dotted line in the upper right image in Figure 5. The IRIS image in the same figure shows that the direction of the ejection and the emerging magnetic field lines (white dotted line) form an angle of $\sim$45°. At some frames in the Ca ii H time sequence, before the detected plasma ejection, some dark round-shaped areas (cool patches) are visible with a size resembling the photospheric granular pattern.

4. COMPARISON WITH MODELS

Magnetic field emergence on the granular and mesogranular scales and exploding granules have been studied both observationally (Palacios et al. 2012 and references therein) and using numerical MHD simulations (e.g., Cheung et al. 2007, 2008; Martínez-Sykora et al. 2008; Stein & Nordlund 2012). Multi-wavelength high-resolution data from several ground- and space-based instruments gave us an opportunity to investigate in detail the structure and evolution of these events from the photosphere to the corona and compare the observational results with state-of-the-art simulations. The morphology of the distorted-granulation pattern generally agrees with the emergence of a buoyant horizontal magnetic flux tube from the upper convection zone across granular convection cells. Differing from the case of an $\Omega$-loop-shaped tube with the buoyancy concentrated in a localized part in which the distorted granules form a cluster coinciding with the upper part of the $\Omega$ loop, the rise of a horizontal
tube is observed crossing the photospheric level while forming a lane. Therefore, in the later case, large and dark granules appear when the magnetic domain reaches the photosphere, and they are organized along a more longitudinal arrangement that demonstrates the geometry of the initial magnetic tube (Cheung et al. 2007). The 18:09:45 TiO frame in Figure 5 displays a sequence of distorted and squeezed granules. The fact that the GA are at about 40° from the tube axis shows that the emerging region contains some considerable twists, similar to the case simulated by Cheung et al. (2007). Furthermore, the alignment direction of the oversized granules is considered to reflect the overall orientation of the emerging fields. Our observations show that the emerging magnetic field lines form an angle of ∼45° with respect to the direction of the surge, as well as to the orientation of the overlying ambient field lines, as commented on in the previous sections. Prior to the development of the GA, weaker and fragmented magnetic patches were detected in that region, in accordance with the previous initial arrival of the less strong magnetized components at the more external part (periphery) of the flux tube. Once the more magnetized volume of a flux tube reaches the photosphere, an excess of magnetic pressure can lead to oversized granules (Tortosa-Andreu & Moreno-Insertis 2009, hereafter TM2009). Our observations support this scenario, with GAs covering an estimated maximum area of ∼50 Mm² (with an area of individual granules up to 8 Mm²), which is very similar to the value of ∼7.5 Mm² obtained by TM2009) and lasting for about 45 minutes (18:00–18:47 UT). The observed darker and wider intergranular lanes formed by exploding aligned granules are in agreement with the simulations and also with other observations (Otsuji et al. 2007). Downflows are well correlated with the location of intergranular lanes, yet in some scarce cases they are co-spatial with photospheric bright points. In general, the population of vertically magnetized pixels is more numerous in the intergranular lanes, including new lanes that are created in the process of fragmentation of aligned granules. Downflows are dominant during the entire time series, as reported to be the case in plage regions (Ishikawa et al. 2008). Panel (e) of Figure 6 plots the variation of the mean LOS Doppler velocity (black line) and the evolution of the mean unsigned LOS magnetic field (red line) within the GA site. There is an increase in the unsigned magnetic flux peaking at 18:02 UT, close to the starting time period used to calculate the horizontal flow map in Figure 3, i.e., at a time of strong diverging motions coming from the exploding aligned granules. A very steep intensification of unsigned magnetic field occurred between 17:39 and 18:01 UT. This seems to be the main emergence responsible for the generation of GAs’ strong diverging plasma flows and for bringing up the strongest amount of magnetic flux (unsigned) to the photosphere. Prior to this intensification of the magnetic flux brought to the photospheric surface, the evolution of the mean Doppler velocity shows a sharp rise (beginning at about 17:38 and peaking at 17:51, i.e., 10 minutes before the same behavior is detected in the variation of unsigned magnetic field), as also reported in some studies of the photospheric dynamics of emerging magnetic flux (e.g., Kosovichev 2009). After the so-called main emergence phase, i.e., ~two minutes after the peak in the unsigned magnetic field, we identified the period of maximum coronal and chromospheric response (see Section 3.3), as marked by the two vertical lines in panel (e) of Figure 6. The different periods of intensification/decrease of unsigned magnetic flux are possibly related to the different stages in the emergence of the flux tube (TM2009) and cancelation between emerging polarity patches with ambient opposite-polarity areas that we detect during the evolution of the region. To analyze the distribution of vertical velocities, we plot histograms over 10 minute windows for three periods: before, starting, and during the main emergence. Panel (f) of Figure 6 shows the corresponding plots where, in general, the positive velocity values
(downflows) are not changing much, in contrast with the negative velocities (upflows) reaching much higher magnitudes during the emerging phase compared to the period before emergence begins (i.e., maximum velocity magnitudes of upflows doubles from about 500–1000 m s\(^{-1}\); mean values increase about 200 m s\(^{-1}\)). The vertical and horizontal velocity values are in general lower (by 50%) compared to the numerical experiment of TM2009.

Regarding the thermal structuring of the lower and mid-chromosphere, a wide variety of features described in simulations, in particular, cool patches, hot filaments, and high-temperature points reported by TM2009 (found at 700 km above the photospheric level in their simulation run), are all found in our data set (IRIS 1330 Å and Hinode/CaII H). These structures are described by these authors as consequences of the emergence of magnetic flux tubes and their interaction with the convective granular motions. The situation described with our observations asserts the emerging magnetic field interacts with the overlying ambient field and generates an extra response of the chromosphere and coronal, as evidenced by the cool surge, the hot jet, and the response in the light curves and filtergrams from transition region and coronal observations around the time of activation of these highly dynamic features. The localized heating at the coronal heights occurs ~five minutes before the first signs of the surge/jet at the ejection site (P1), whereas the response of transition region/chromosphere occurs ~five minutes after it. During that period of about 10 minutes, vertical electric currents, computed from the SDO/HMI transversal and longitudinal photospheric magnetic field components, experienced a substantial increment (panel (d) of Figure 6). Plasma flows have previously been reported occurring in UV lines earlier, up to 10 minutes, than the corresponding Hα surges (Jian et al. 2007), in agreement with our detection.

5. CONCLUSIONS

Our findings give new observational insights into the process of emergence of small-scale magnetic flux that rises from the subsurface layers, crosses the photospheric level, deforms the granular pattern, and generates energetic and dynamics responses at different heights of the atmosphere. Heating and plasma acceleration in the chromosphere are boosted by emergence of a small-scale magnetic volume, resembling the case of a horizontal flux tube rising up from the upper convection zone. One possibility of such a response is a reconnection scenario, like the ubiquitous small-scale reconnection argued by Shibata et al. (2007), which perhaps can explain the production of a cool surge and hot plasma jet, together with the heating of localized point-like regions up to one million degrees in the corona. In this scenario, once the newly emerging magnetic field reconnects with the existing overlying fields, energy is released and thus the reconnection site is heated. Hot plasma moves upward along the resulting open field lines and may create the high-temperature jet and UV emission. Another fraction of the plasma goes downward along the closed loop created after the reconnection process and could be responsible for the small-scale brightenings, frequently known as micro-flaring events. Closed loops can also generate magnetic tension. Low-temperature surges are caused by the upward motion of cold plasma along open magnetic field lines generated by this tensile force. The relative inclination of the emerging and ambient fields can stimulate the reconnection process and the energetic outcome. The Hε surge exhibits repeated ejections all along the same trajectories, as previously reported for Hα surges (Schmieder et al. 1984). The NST HeI has demonstrated to be of significant relevance for probing, with unprecedented detail, the response and evolution of the solar chromosphere.

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