EXPLOSIVE EVENTS ASSOCIATED WITH A SURGE

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ABSTRACT

The solar atmosphere contains a wide variety of small-scale transient features. Here, we explore the interrelation between some of them such as surges, explosive events, and blinkers via simultaneous spectral and imaging data taken with the TRACE imager, the SUMER and Coronal Diagnostics Spectrometer (CDS) on board SOHO, and Swedish Vacuum Solar Telescope La Palma. The features were observed in spectral lines with formation temperatures from 10,000 K to 1 MK and with the TRACE Fe ix/x 171 Å filter. The Hα filtergrams were taken in the wings of the Hα 6365 Å line at ±700 mÅ and ±350 mÅ. The alignment of all data in both time and solar XY shows that SUMER line profiles, which are attributed to explosive events, are due to a surge phenomenon. The surge’s up- and downflows, which often appear simultaneously, correspond to the blue- and redshifted emission of the transition region N v 1238.82 Å and O v 629.77 Å lines as well as radiance increases of the C i, S i, and Si ii and Si iii chromospheric lines. Some parts of the surge are also visible in the TRACE 171 Å images which could suggest heating to coronal temperatures. The surge is triggered, most probably, by one or more Elerman bombs which are best visible in Hα ±350 Å but were also registered by TRACE Fe ix/x 171 Å and correspond to a strong radiance increase in the CDS Mg ix 368.07 Å line. With the present study, we demonstrate that the division of small-scale transient events into a number of different subgroups, for instance explosive events, blinkers, spicules, surges or just brightenings, is ambiguous, implying that the definition of a feature based only on either spectroscopic or imaging characteristics as well as insufficient spectral and spatial resolution can be incomplete.

Key words: Sun: activity – Sun: chromosphere – Sun: corona – Sun: transition region – Sun: UV radiation

Online-only material: mp4 animation

1. INTRODUCTION

Over the last decades, the increased use of space observatories such as the Solar and Heliospheric Observatory (SOHO), the Transition Region Corona Explorer (TRACE), and presently Hinode, coupled with ground-based observations, has brought many new features on the Sun to light. What is, however, more important is that the combination of different types of observations, i.e., spectroscopic and imaging, covering a wide wavelength range and having a similar cadence and spatial resolution, provides crucial information on the nature and the physical characteristics of these phenomena.

We now know that the solar atmosphere contains different kinds of small-scale transient events. A particular transient phenomenon, however, is often associated with a specific instrument or a type of instrument, either a spectrometer or an imager. Explosive events (EEs), registered by the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectrometer and the high-resolution telescope and spectrometer (HRTS), for instance, were found to be restricted to transition region temperatures from 2 × 104 K to 5 × 105 K. They were first discovered by Brueckner & Bartoe (1983) in C iv 1548.21 Å data taken with HRTS. They are characterized as short-lived (60–350 s) small-scale (3″–5″ along a spectrometer slit) events identified by Doppler shifts of up to 200 km s−1. It has been suggested that they result from the production of high-velocity bidirectional plasma jets during magnetic reconnection (Dere 1994). They often occur in areas with weak fluxes of mixed polarity or on the border of regions with large concentration of magnetic flux (Chae et al. 1998) and are often observed in bursts lasting up to 30 minutes in regions undergoing magnetic cancellation (Dere 1994; Chae et al. 1998; Pérez et al. 1999; Doyle et al. 2006). Another term often associated with them is bidirectional jets (Innes et al. 1997).

Surges mainly observed in Hα (104 K) and Ca ii K & H (6 × 103 K) as well as extreme-ultraviolet (EUV) and X-ray jets are also assumed to result from the same physical mechanism. Solar surges are associated with active regions and represent an ejection of dense chromospheric material (N ≈ 1011 cm−3) in the shape of straight or arch-shaped collimated streamers seen dark or bright in the Hα line (Roy 1973). The upflows often return to the solar surface along the same trajectory. Their occurrence is associated with Elerman bombs (Elerman 1917) in their footpoints.

The term “blinker” was first used by Harrison (1997) to describe a small-scale (on average 8″ × 8″) brightening in EUV lines observed with the Coronal Diagnostics Spectrometer (CDS) onboard SOHO. They last on average 17 minutes and are preferentially located in the network boundaries (Bewsher et al. 2002). It has been suggested that they represent an observational signature of increased filling factor rather than electron density. Several physical mechanisms have been put forward by Priest et al. (2002), Doyle et al. (2004), and Marik & Erdélyi (2002).

There have been attempts to unify some of these terminologies, e.g., blinkers have been suggested as a generic term for EUV network and cell brightenings (Harrison et al. 2003). Chae et al. (2000) stated that blinkers and EEs were the same phenomenon, while Madjarska & Doyle (2003) found them to be two separate unrelated events, as did a statistical study by Brkić & Peter (2004). Madjarska & Doyle (2003) also speculated that blinkers may simply be the on-disk signature of spicules. Their work later led to the suggested notion that some
blinkers and macrospicules are the same phenomenon (O’Shea et al. 2006; Madjarska et al. 2006).

The uniqueness of the present study lies in the exploration of small-scale transient phenomena using simultaneous EUV high-cadence and the highest existing spatial and spectral resolution data currently available, together with ground-based Hα observations. We analyzed numerous small-scale transient features seen along a SUMER slit in chromospheric (Ca i, Si i, Ca ii, and S ii), transition region (N v and O v), and coronal (Mg x) spectral lines, and their counterparts in the Swedish Vacuum Solar Telescope (SVST) Hα filtergrams and TRACE 171 Å images. Our main objective is to derive the spectral characteristics of these events and compare them with their image appearance at coronal and chromospheric temperatures, which should provide their correct identification and evaluation of their plasma quantities and dynamics, and could suggest a possible physical mechanism of their generation.

2. SUMER, CDS, TRACE, AND SVST LA PALMA OBSERVATIONAL MATERIAL

All data were obtained on 1999 June 1 in active region NOAA 8559 with the SUMER slit placed over the plage area. The standard data reduction procedures were applied to all observational material. The SUMER dataset (Wilhelm et al. 1995) was taken from 09:03:23 UT to 11:01:42 UT with the solar rotation compensation mode turned on. The slit 0′′ × 120′′ was used, exposing for 25 s the bottom part of detector B. A list of the analyzed spectral lines is given in Table 1. The CDS data were taken with a 25 s exposure time resulting in a 34 s cadence in a sit-and-stare mode with a 2′′ × 181′′ slit. The observed spectral lines are also reported in Table 1. The TRACE 171 Å dataset (Handy et al. 1999) was obtained from 09:15:44 UT to 10:39:56 UT, exposing for 5.8 s resulting in 10–40 s cadence. The images were derotated to a reference time of 08:17 UT. The Hα 6563 Å filtergrams were made with the SVST in La Palma. The Hα data were registered at ±350 mÅ and ±700 mÅ and have a pixel size of 0.083 arcsec pixel−1. The cadence of the Hα=350 mÅ and −700 mÅ data is 1m14s ± 1s and of the Hα+350 mÅ and +700 mÅ data is 1m11s ± 2s. In Figure 1, we show an overview of the region observed by

Table 1

| Ion     | λ Å−1 | log(Tmax) K−1 | Comment |
|---------|-------|----------------|---------|
| N v     | 1238.82 | 5.3 |         |
| Ca i    | 1249.00 | 4.0 |         |
| O iv/2  | 1249.24 | 5.2 | blend   |
| Si x/2  | 1249.40 | 6.1 | blend   |
| C i     | 1249.41 | 4.0 |         |
| Mg x/2  | 1249.90 | 6.1 | blend   |
| O iv/2  | 1250.25 | 5.2 | blend   |
| P ii    | 1249.81 | 4.2 | blend   |
| Mg ii   | 1249.93 | 4.1 | blend   |
| Si ii   | 1250.09 | 4.1 | blend   |
| Si ii   | 1250.41 | 4.1 |         |
| C i     | 1250.42 | 4.0 | blend   |
| S ii    | 1250.58 | 4.2 |         |
| Si ii   | 1251.16 | 4.1 |         |
| C i     | 1251.17 | 4.0 | blend   |
| O iv/2  | 1251.70 | 5.2 |         |
| C i     | 1252.21 | 4.0 |         |
| S ii    | 1259.53 | 4.2 | blend   |
| O iv/2  | 1259.54 | 5.4 |         |
| O iv/a  | 629.77  | 5.4 |         |
| Mg ii/a | 368.057 | 5.8 | blend   |
| Mg ii/a | 368.070 | 6.1 |         |
| He i/a  | 584.33  | 4.7 |         |

Notes. The expression “/2” means that the spectral line was observed in second order. The comment “blend” means that the spectral line is blended with a close-by line.

* Denotes lines registered by CDS.

TRACE and SVST with the locations of the SUMER and CDS slits. The alignment of SUMER and CDS to the TRACE data with a precision of ±1″ was done as described by Doyle et al. (2005), using TRACE 171 Å images and a CDS Mg ix 368 Å raster. The coalignement of the Hα data to TRACE was done according to the technique given in de Pontieu et al. (1999).

3. RESULTS AND DISCUSSION

First, we inspected the SUMER spectral line profiles looking for radiance increases and/or line broadenings. Figure 2 shows

Figure 1. Overview of the observed region taken (from left to right) with the TRACE 171 Å filter, Hα=−350, +350, −700, and +700 mÅ. The vertical solid line indicates the SUMER slit location, while the vertical dashed indicates the CDS slit position. The arrow indicates the elongated structures which were identified as a surge. Although SUMER and CDS were commanded to point at the same solar disk coordinates, the two slits are actually offset by 14″−15″. One possible explanation is that SUMER had lost motor steps during the pointing procedure (W. Curdt 2007, private communication). The TRACE image is shown with reversed color table, i.e., darker structures mean stronger emission.
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Figure 2. Radiance variations of the O \( v \) (left) and N \( v \) (right) lines along the SUMER slit. The horizontal lines indicate the area used to analyze the spectral line profile variations. The light curves shown in Figures 5 and 6 were produced from this region.

Figure 3. Doppler images from H\( \alpha \) 6365 Å ±350 mÅ (first from the left) and ±700 mÅ (second), followed by O \( v \) 629 Å, N \( v \) 1238 Å, and the spectral window covering Mg \( x \) 625 Å and several chromospheric lines, as indicated on the image (see also Table 1). The vertical solid line indicates the SUMER slit location, while the dashed vertical line indicates the CDS slit position. The horizontal solid line indicates the region from which the SUMER light curves were produced. The arrow points at the surge.

The radiance variations of the transition region O \( v \) 629 Å and N \( v \) 1238 Å lines. Brightenings are clearly seen in the area indicated with the horizontal dashed lines. The line profiles reveal a different response of the two transition region lines O \( v \) and N \( v \), which will be discussed later in the paper. The images were produced from the peak radiance of the spectral lines obtained from a single Gauss fit with the continuum emission removed. This helps to separate the intensity variation in the spectral line from the continuum emission changes. The increase in the continuum emission during explosive events is a well-known fact (Madjarska & Doyle 2002).

The next step of our analysis was to produce animated time sequences from some of the available data (see the movie file available in the online journal). The movie consists of TRACE 171 Å images, the SUMER spectral windows of O \( v \) 629 Å, Mg \( x \) 625 Å together with several chromospheric lines, plus N \( v \) 1238 Å, and SVST H\( \alpha \) 6365 Å filtergrams taken at −350 mÅ. Additional movies can be seen at http://www.arm.ac.uk/~madj/outgoing/Surge.

The SUMER spectral line profiles during the brightening events show all the hallmarks of explosive events, i.e., non-Gaussian profiles and only blue- or redshifted emission or both. An example of these profiles is shown in Figure 3. When coupled with the TRACE 171 Å images, the SUMER spectral windows of O \( v \) 629 Å, Mg \( x \) 625 Å together with several chromospheric lines, plus N \( v \) 1238 Å, and SVST H\( \alpha \) 6365 Å filtergrams taken at −350 mÅ. Additional movies can be seen at http://www.arm.ac.uk/~madj/outgoing/Surge.

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the Hα images help to cross-correlate the feature as seen in TRACE with the dark and bright Hα features from the surge and its footpoints. Jiang et al. (2007) presented in great detail the relation between Hα surges, EUV and X-ray jets, which resemble very much the event analyzed here (Figure 4). They concluded that each surge consisted of a cool Hα component and hot, EUV or soft X-ray component which showed different evolution in space and time. The cadence of our Hα data does not permit such an analysis. However, the SUMER data do not show evidence for a different spatial behavior of the chromospheric and transition region emission. This could be due to the difference in the spatial resolution between the SVST and SUMER data, as well as the fact that slit spectrometer data have their limitation for space analysis. Not all features seen in the transition region lines, however, have their counterpart in the chromospheric lines, which suggests that plasmas were heated to higher temperatures. Unfortunately, the lack of magnetic field data makes it impossible to discuss the photospheric magnetic field configuration.

We performed a further spectroscopic analysis in order to gather more information on the relation between explosive events and surges. In order to analyze the temperature response of the surge plasma, we produced normalized light curves (Figure 5) from spectral lines covering a large range of formation temperatures (see Table 1). The light curves were obtained by binning the partition along the SUMER slit outlined by two horizontal lines in Figure 2, corresponding to 18 pixels (~18″). The TRACE light curve was obtained by binning over an array of 4″ × 4″ at Solar X = 382″ and Solar Y = 400″, where the SUMER slit crosses the event(s) as indicated in Figure 1. All light curves were normalized to the maximum value of the radiance during the studied time interval. The TRACE 171 Å passband, although dominated by the Fe IX and Fe X lines, has some transition region lines in the range of 171.5–174 Å, e.g., O V and O VI, though, as shown by Doyle et al. (2003), their effect is small unless there is a substantial departure from a Maxwellian velocity distribution. Among the observed spectral lines is the coronal Mg X 625 Å (1 MK) line. Its light curve in Figure 5 shows no clear evidence for enhanced emission except around 09:25 UT and 09:55 UT. Comparing with the chromospheric light curve in Figure 5, we found that these increases in the Mg X emission are due to the blend from several cooler lines (see Table 1) rather than Mg X itself (Toriaca et al. 2002). Another possible explanation is that Mg X has very slow ionization and recombination time scales, as described by Golub et al. (1989). We cannot speculate on the decrease in the light curve of the chromospheric lines for the time period 10:30–11:00 UT.

Chae et al. (1998), using SUMER data in Si IV 1402 Å and Big Bear Solar Observatory (BBSO) Hα spectrograph observations, found that chromospheric upflow events arising in intranetwork
areas are related to transition region explosive events. Madjarska & Doyle (2002), studying high-cadence (10 s) data during explosive events in the chromospheric Ly 6 960.75 Å line (20,000 K) and the transition region S vi 933.38 Å (200,000 K) line, found a time delay in the response of the S vi line with respect to the Ly 6 line, with Ly 6 responding 20–40 s earlier. Consequently, the authors suggest heating from chromospheric to transition region temperatures, i.e., a chromospheric origin of explosive events. The complexity of the event(s) analyzed in the present work makes it impossible to temporally resolve the connection of cold and hot plasmas. It is also possible that the time resolution of the present data is not sufficient for such analysis.

We examined in more detail a few selected time intervals, namely A, B, and C from the light curves, in the different spectral lines (Figure 5) as well as in the blue and red wings and the cores of the N v 1238 Å and O v 629 Å lines (Figure 6). During the time interval A, we noticed only a signature of line radiance increases/broadenings in the chromospheric and the N v lines (see their corresponding light curves in Figures 5 and 6). No response was registered in O v or TRACE 171 Å. In the time interval from 09:40–09:55 UT (B), the ejection is first seen in N v and the chromospheric lines and 5 minutes later in O v. The Hα images around 09:44 UT show a narrow dark jet (Figure 4, upper images). The peak of the O v emission corresponds to a decrease/plateau in the N v and the chromospheric lines with these lines increasing again after O v starts to decrease. A sudden rise in the N v and the chromospheric lines just before 09:55 UT has no counterpart in the O v line. A strong brightening in the footpoint of the jet precedes its occurrence. This brightening was identified as an Ellerman bomb(s) and it is best seen first in Hα−350 mÅ and later in Hα +350 mÅ. Importantly, a strong brightening is seen in the TRACE image at the same position (Figure 4). This brightening lasted and evolved for around 30 minutes, triggering a series of jets. The jets crossing the SUMER slit produced explosive events. To find out whether there is really a coronal response during the Ellerman bomb, we studied the light curves of the CDS lines. The Mg ix 368 Å line (the blend by Mg vii was removed using a double Gauss fit) shows a significant radiance increase together with CDS O v 629 Å and He i 584 Å (Figure 7). The changes correlated very well with the radiance variations of the TRACE emission from the same area. Time interval C (10:08–10:30 UT) displays first a strong blueshifted emission in N v trailed by O v and then follows a strong redshifted emission in the N v and a more modest one in O v. That is followed by another strong rise in the blue wing and the core radiance of N v and O v. We found that the Ellerman bomb(s) occurs at around 10:00 UT as a sudden radiance increase in all CDS spectral lines and the TRACE (Figure 7). At around 10:10 UT the SUMER spectral lines (Figures 5 and 6) show a strong dynamics as described above corresponding to a plasma ejection triggered by the Ellerman bomb(s). This complex behavior of the spectral lines...
during A, B, and C time intervals reflects a well-known event—a surge (Newton 1942).

A surge analyzed by Tziotziou et al. (2005), employing data from the Dutch Open Telescope (DOT) and TRACE 1600 Å, suggested that the temperature of the surge was in the region of $10^4$ to $10^5$ K; however, without access to additional data from higher temperatures, this was only an approximation. Here, we have data from O $\nu$ 629 Å and N $\nu$ 1238 Å which suggest heating to coronal temperatures.

We performed an identification to see how many of the brightenings seen in the N $\nu$ and O $\nu$ lines (Figure 2) can be categorized as blinkers. The radiance plots in Figure 6 show several radiance increases over the threshold value (1.5 times the background emission), which can be categorized as blinkers. The blinkers, however, also have EEs characteristics as described above.

How can we explain the different behavior of N $\nu$ and O $\nu$? Looking at Skylab data (Vernazza & Reeves 1978), it can be seen that N $\nu$ increases by a factor of eight for an active region and 11.5 for a very active region, while the O $\nu$ only increases by factors of 3.2 and 4.2, respectively. As noted by Doyle et al. (2005), these lines are density sensitive due to density-dependent ionization/recombination. For example, considering density-dependent ionization/recombination from metastable levels, we get that for electron densities above $10^{11}$ cm$^{-3}$ the N $\nu$ line can be enhanced by almost a factor of two over that obtained using stage-to-stage ionization. Similarly, the O $\nu$ is reduced by almost a factor of two, therefore giving a factor of $\approx 3$ difference in the response of N $\nu$ and O $\nu$ lines in high-density plasmas. This, however, applies only to a plasma in ionization equilibrium. For a plasma that is undergoing rapid heating, these ratios are very different. For example, for a high-density plasma of $10^{11}$–$10^{12}$ cm$^{-3}$ at a temperature of $T_e = 5.1$ K $\nu$ is at 70% of its peak, while O $\nu$ is only at 25% (see Figure 4 of Doyle et al. 2005); hence, the O $\nu$/N $\nu$ ratio of the contribution functions is reduced by $\approx 3$, very close to what is observed during the surge (see Figure 6). More work is clearly needed in this area, for example, to address whether a plasma can be maintained for say several minutes at temperatures close to $T_e = 5.1$ in order to have these low O $\nu$ 629 Å to N $\nu$ 1238 Å line ratios. In Figure 6 (the bottom panel), we present the radiance ratio of O $\nu$ versus N $\nu$ during the surge.

An alternative explanation is absorption due to the Lyman continuum (Kanno et al. 1984), although others (Raymond & Doyle 1981) suggest that the effect is minimal. In this case, an optical thickness $\tau_{H} \approx 2$ is required to reduce the O $\nu$ 629 Å line by a factor of two. There are, however, intervals where the O $\nu$ 629 Å line is not reduced in intensity, which would imply a highly variable absorption, but without access to additional spectral lines, we are unable to rule out the Lyman absorption.

4. CONCLUSIONS

The present study demonstrates an interrelation between a surge observed in He 6563 Å and SUMER explosive events registered at transition region temperatures. Although some parts of the surge are seen in the TRACE 171 Å images where the SUMER slit is positioned, the SUMER Mg x 625 Å does not show any response. The surge is triggered by Ellerman bombs occurring in the region from where the surge originates. We found that the Ellerman bombs reached temperatures of 1 MK from TRACE 171 Å and CDS Mg x. They are believed to be the result of magnetic reconnection happening in the low-chromosphere triggering a surge occurrence. With the present study we demonstrate that the division of small-scale transient events into a number of different subgroups, for instance explosive events, blinkers, spicules, surges, or just brightenings, is ambiguous, implying that the definition of a feature based only on either spectroscopic or imaging characteristics as well as insufficient spectral and spatial resolution can be incomplete.

In the light of present findings, we believe that it is of great importance to examine in detail the interrelation between different transient phenomena in the solar atmosphere using simultaneous Hinode and ground-based data. Hinode’s Extreme-ultraviolet Imaging Spectrometer (EIS) has presently the best capabilities to provide coronal spectral diagnostics. Equally, we believe that further exploration of these events by using Hinode and the forthcoming Solar Dynamic Observatory data is crucial for evaluating the contribution of these events to the coronal heating and slow solar wind generation.

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