EXPLOSIVE EVENTS ON A SUBARCSECOND SCALE IN IRIS OBSERVATIONS: A CASE STUDY

ZHENGHUA HUANG1, MARIA S. MADJARSKA2, LIDONG XIA1, J. G. DOYLE2, KLAAS GALSGAARD3, AND HUI FU1
1 Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai, 264209 Shandong, China; huangzhenghua@gmail.com
2 Armagh Observatory, College Hill, Armagh BT61 9DG, UK
3 Niels Bohr Institute, DK-2100 Copenhagen, Denmark
Received 2014 July 4; accepted 2014 September 22; published 2014 December 3

ABSTRACT

We present a study of a typical explosive event (EE) at subarcsecond scale witnessed by strong non-Gaussian profiles with blue- and redshifted emission of up to 150 km s⁻¹ seen in the transition region Si iv 1402.8 Å, and the chromospheric Mg ii k 2796.4 Å and C ii 1334.5 Å observed by the Interface Region Imaging Spectrograph (IRIS) at unprecedented spatial and spectral resolution. For the first time an EE is found to be associated with very small-scale (∼120 km wide) plasma ejection followed by retraction in the chromosphere. These small-scale jets originate from a compact bright-point-like structure of ∼1.5 size as seen in the IRIS 1330 Å images. SDO/AIA and SDO/HMI co-observations show that the EE lies in the footpoint of a complex loop-like brightening system. The EE is detected in the higher temperature channels of AIA 171 Å, 193 Å, and 131 Å, suggesting that it reaches a higher temperature of log T = 5.36 ± 0.06 (K). Brightenings observed in the AIA channels with durations 90–120 s are probably caused by the plasma ejections seen in the chromosphere. The wings of the C ii line behave in a similar manner to the Si iv’s, indicating close formation temperatures, while the Mg ii k wings show additional Doppler-shifted emission. Magnetic convergence or emergence followed by cancellation at a rate of 5 × 10¹⁴ Mx s⁻¹ is associated with the EE region. The combined changes of the locations and the flux of different magnetic patches suggest that magnetic reconnection must have taken place. Our results challenge several theories put forward in the past to explain non-Gaussian line profiles, i.e., EEs. Our case study on its own, however, cannot reject these theories; thus, further in-depth studies on the phenomena producing EEs are required.

Key words: methods: observational – Sun: activity – Sun: chromosphere – Sun: transition region – techniques: spectroscopic

Online-only material: animations, color figures

1. INTRODUCTION

The solar transition region is the interface between the chromosphere and the corona within which the temperature rapidly rises from 25,000 K to 1 MK. Plasma in the solar transition region appears to be very dynamic, as evidenced by the so-called “explosive events” (EEs). The term “explosive event” describes non-Gaussian mostly transition region line profiles showing Doppler velocities of 50–150 km s⁻¹ (Brueckner & Bartoe 1983). On average the EE size as determined along a spectrometer slit is about 2'-5' with a lifetime of up to 600 s (Dere et al. 1989). From 82 EEs observed by HRTS, Dere et al. (1989) found only one case in which there was evidence for apparent velocities. This result suggests that the velocities of events associated with EEs are non-isotropic, and (some or all) EEs are possibly the spectral signature of jets. EEs are often observed in bursts lasting up to 30 minutes (Innes et al. 1997a; Doyle et al. 2006).

EEs are usually found along the magnetic network at the boundaries of the super-granulation cells (Dere et al. 1989; Porter & Dere 1991; Madjarska & Doyle 2003). They are associated with regions of weak and mixed polarity fluxes (Brueckner et al. 1988; Dere et al. 1991; Chae et al. 1998a; Teriaca et al. 2004; Muguclach 2008). Chae et al. (1998a) studied the magnetic field of 163 EEs identified in Solar Ultraviolet Measurement of Emitted Radiation (SUMER) observations and Big Bear Solar Observatory (BBSO) magnetograms, and found that 103 of these were associated with magnetic flux cancellations. However, the connection between EEs and magnetic cancellation is still under debate. Muguclach (2008) found that only 7 out of 37 EEs were associated with magnetic cancellation sites while the magnetic flux for 62% of EEs did not change during their lifetime, though it is possible that this is due to instrumental limitations. Magnetic reconnection is proposed as the possible mechanism that produces opposite directed jets generating the EE’s blue- and redshifted emission (see, e.g., Dere et al. 1991; Innes et al. 1997b; Chae et al. 1998a; Ryutova & Tarbell 2000; Lee et al. 2000).

The true nature of the events associated with EEs remains unknown as these “events” actually carry only the spectral signature about the observed phenomena. EEs were suggested to be the signature of siphon flows in small-scale loops (Teriaca et al. 2004). They are also believed to be produced by spicules and macrospicules (Wilhelm 2000), and were found to be associated with chromospheric upflow events (Chae et al. 1998b). EEs were found in transient brightenings and X-ray jets (Madjarska et al. 2012). Madjarska et al. (2009) showed that EEs can result from up- and down-flows in a surge. Curdt & Tian (2011) put forward the idea that EEs are produced by swirling jets where a helical motion would be mostly responsible for the blue- and redshifted emission (the Si iii 1206.51 Å line was used in this study).

EEs are typically observed in transition region emission lines with formation temperatures ranging from 2 × 10⁴ K to 5 × 10⁴ K (Brueckner & Bartoe 1983). Dere (1992) reports from HRTS spectra that less than 1% of the EEs observed in transition region lines are also seen in C i 1561 Å (1 × 10⁴ K) while they are weakly seen in C ii 1335 Å (1.6 × 10⁴ K). SUMER observations showed that EEs also appear in lower temperature lines such as O i (1 × 10⁴ K), Lyman 6 to Lyman 11 (1.2 × 10⁴ K; Madjarska & Doyle 2002), and Lyman β (1.2 × 10⁴ K;
Figure 1. Left: cut-off AIA 211 Å image with the contour of the equatorial extension of a polar coronal hole overplotted. The outlined dotted-box region is the IRIS slit-jaw image field of view. The vertical line represents the IRIS slit position. Right: IRIS slit-jaw image on which the dark vertical line in the middle is the location of the slit. The contour plot is the boundary of the coronal hole defined in the AIA 211 Å image.

(A color version of this figure is available in the online journal.)

Figure 2. Radiance images in Mg ii k 2796.4 Å, C ii 1334.5 Å, and Si iv 1402.8 Å (in reversed color). The coronal hole boundary determined from the AIA 211 Å image is marked with a dashed line. The region between the two solid lines marked with “Ref” is where the reference line profiles are obtained. An arrow with “EE” points to the studied explosive event.

(A color version of this figure is available in the online journal.)

Zhang et al. 2010). These lines have a non-Gaussian shape with a reversed line core surrounded by two emission peaks. In Lyman 6–11, Madjarska & Doyle (2002) found that some of these lines show a stronger self-absorption in EE which is due to an increase of the emission in the wings while the core intensity increase remains weak. In Lyman β, Zhang et al. (2010) found that the self-reversion becomes more significant during EEs with a stronger peak in the blue wing.

Wilhelm et al. (1998) identified two EEs that occurred in an active region and were observed at coronal temperatures (Mg ix 749 Å, 10⁶ K). Teriaca et al. (2002) found that EEs in the quiet Sun do not have a coronal response suggesting that they are not relevant to coronal heating (only two events were analyzed in this study). From the analysis of the energetics of explosive events observed with SUMER, Winebarger et al. (2002) concluded that the energy released in explosive events should be enough to heat the solar atmosphere.

The overview given above shows that our knowledge of the phenomena generating EEs is very uncertain with many open questions that need to be addressed, e.g., what physical phenomena generate EEs’ up- and down-flows, rotation or all simultaneously? Do phenomena associated with EEs contribute directly or indirectly to the mass and energy transfer in the solar atmosphere? What is (are) the physical mechanism(s) driving the phenomena that produce explosive events? Where in the solar atmosphere do phenomena producing explosive-event
**Figure 3.** Explosive event in Si IV. From left to right, top row: radiance image (in reversed color) produced from the total intensity of the Si IV line, Si IV profiles taken from the pixels denoted with diamond symbols as “A,” “B,” and “C” in the radiance image. The dotted line, multiplied by five, is the reference spectrum obtained from the region shown in Figure 2. The Si IV profiles from “A” and “C” are multiplied by two. Bottom row: Doppler velocity image derived from a single Gaussian fit, RB asymmetry of the region of the explosive event at 50–70 km s\(^{-1}\), 90–110 km s\(^{-1}\), and 130–150 km s\(^{-1}\) with the contour of the radiance image overplotted. The dotted lines outline the region from which the temporal variations of RB (Figure 6) are obtained.

(A color version of this figure is available in the online journal.)

**Figure 4.** Explosive event in IRIS Mg II k. From left to right, top row: radiance image (in reversed color) from the total intensity in the Mg II k line, Mg II k line profiles taken from the pixels denoted by diamond symbols as “A,” “B,” and “C,” together with the reference profile overplotted (dotted line). The blue emission peak is marked with k\(_{\text{pr}}\), the red with k\(_{\text{pr}}\), and the absorption core as k\(_{3}\). Bottom row: radiance image (in reversed color) in the line center of Mg II k (i.e., in k\(_{3}\)), RB asymmetry of the region of the explosive event at 50–70 km s\(^{-1}\), 90–110 km s\(^{-1}\), and 130–150 km s\(^{-1}\) with the contour of the radiance image overplotted. The dotted lines outline the region from which the temporal variations of RB (Figure 6) are obtained.

(A color version of this figure is available in the online journal.)
Figure 5. Explosive event in C ii 1334.5 Å. Top row from left to right: radiance image (reversed color), RB asymmetry of the region of the explosive event at 50–70 km s$^{-1}$, 90–110 km s$^{-1}$, and 130–150 km s$^{-1}$. The dotted lines outline the region from which the temporal variations of RB (Figure 6) are obtained. The contours from the Si iv radiance image are overplotted on all images. Bottom row from left to right: C ii 1334.5 Å profile (solid lines) taken from pixels “A,” “B,” and “C” with the reference profile overplotted (dotted line).

(A color version of this figure is available in the online journal.)

line profiles typically originate? The combination of the very recent state-of-the-art mission, the Interface Region Imaging Spectrograph explorer (IRIS), with the excellency of the Atmospheric Imaging Assembly (AIA) and the Helioseismic and Magnetic Imager (HMI) data, provide an unprecedented opportunity that might help us answering the many open questions related to EEs. Our study does not give an answer of all the open questions. However, it provides the first insight into the unique capabilities of IRIS (spectral and imaging chromospheric and transition region data with remarkable spatial and spectral resolution) for unlocking the mystery of what phenomena drive the feature called an “explosive event.”

In the present work, we carry out a case study of an explosive event combining simultaneous IRIS spectroscopic and imaging data together with magnetic field and coronal imaging observations from HMI and AIA on board the Solar Dynamics Observatory (SDO). We report for the first time and in unprecedented detail on the spectral and imaging characteristics of an explosive event on a subarcsecond scale which should give a better understanding on the driving physical mechanism of these phenomena. We also describe the behavior of the observed optically thick lines which is crucial for a radiative transfer modeling of the emission from dynamically evolving atmospheric phenomena. This study will promote an extensive statistical study based on spectral (IRIS) and imaging (IRIS & AIA) data that will be crucial in taking a step toward understanding the solar phenomena that trigger strong non-Gaussian profiles in the solar chromosphere and transition region, i.e., “explosive events,” and their true role in coronal heating. The article is organized as follows: Section 2 describes the observations and the data reduction, the results and discussion are presented in Section 3, and the conclusions are given in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

The observations were taken by IRIS (De Pontieu et al. 2014), AIA (Lemen et al. 2012), and HMI (Schou et al. 2012) on board SDO (Pesnell et al. 2012) on 2013 October 4 from 18:42:09 UT to 19:00:54 UT.

2.1. IRIS

IRIS is a NASA Small Explorer mission, which was launched into a sun-synchronous orbit on 2013 June 27. It takes simultaneous spectra and images of the interface region (i.e., chromosphere and transition region) of the Sun with 0.33–0.4 spatial resolution and as low as 2 s cadence. IRIS observes the far-UV wavelength band in the spectral range from 1331.6 to 1358.4 Å that includes two bright Ci i lines with a spectral sampling of 12.98 mÅ pixel$^{-1}$, and in the range 1380.6–1406.8 Å (containing several Si iv and O iv lines) at 12.72 mÅ pixel$^{-1}$. IRIS also operates in the near UV spectral range from 2782.6 to 2833.9 Å at 25.46 mÅ pixel$^{-1}$ recording two bright Mg ii lines. For comparison, the SUMER spectral sampling is around 44.0–45.0 mÅ pixel$^{-1}$ in the 660–1600 Å, i.e., IRIS has more than three times higher spectral resolution. The instrument is designed in such a way that a slit with a size 0.33 $\times$ 175$^{\prime\prime}$ guides the sunlight into a spectrograph while a reflective coating directs the sunlight outside of the slit into an imaging system making slit-jaw images (SJs). Therefore, the slit position appears as an emission-blocked vertical line on the slit-jaw images (see the example in Figure 1). The slit can either stay in a fixed position to record sit-and-stare spectra or scan a large area with a selected step size. The slit-jaw images can be taken in four different channels, one centered at 1330 Å with a 40 Å bandpass recording chromospheric and strong continuum emission,
one at 1400 Å again with a 40 Å bandpass imaging the lower transition region, one at 2796 Å with a 4 Å bandpass providing images of the upper chromosphere, and one at 2832 Å with a 40 Å bandpass for high-contrast photospheric imaging. The IRIS data set used in this study includes spectral observations taken in a sit-and-stare mode with 8 s exposure time and 9 s cadence, and slit-jaw images taken in the 1330 Å channel with a 4 Å bandpass for high-contrast photospheric imaging. The IRIS data set used in this study includes spectral observations taken in a sit-and-stare mode with 8 s exposure time and 9 s cadence, and slit-jaw images taken in the 1330 Å channel also at 9 s cadence. Four spectral windows were transferred to the ground containing two C ii lines (1334.5 Å and 1335.7 Å, log $T = 4.3 $ K), the Si iv 1402.8 Å line (log $T = 4.8 $ K), and the Mg ii k 2796.4 Å line (log $T = 4 $ K). IRIS was targeting an equatorial extension of a polar coronal hole across its boundaries (Figure 1). Figure 1 shows an overview of the coronal hole in the 211 Å channel of AIA and one of the SJ images. The coronal hole boundaries are defined as the region where the AIA 211 Å emission drops to half of that in the surrounding quiet Sun region. The spectral observations were taken in a sit-and-stare mode, but a compensation for the solar differential rotation was not applied to the data.

The present study uses IRIS level 2 data provided by the IRIS team. These are science products after dark current removal, flat-field, and geometric correction have been applied. We found that spiked pixels are still present in the spectral data. To flag these pixels, we first determined the maxima of the line profiles and the standard deviation ($\sigma$) of the maxima were calculated. The pixels with line profiles that have a maximum exceeding $3\sigma$ were flagged and excluded from any further analysis. A further wavelength correction for the orbital variation of the line position was required due to the temperature change of the detector and the spacecraft–Sun distance variation over the course of an orbit. To correct this, we used the standard program provided by the IRIS team (Tian et al. 2014).

2.2. AIA and HMI

The AIA observations used in this study were taken in the UV channels including the 1700 Å and 1600 Å at about 24 s cadence, and in the EUV 304 Å, 171 Å, 193 Å, 211 Å, 335 Å, 131 Å, and 94 Å passbands at about 12 s cadence. The spatial resolution of the AIA images is 1.2 / 0.6 pixel$^{-1}$. The HMI longitudinal magnetograms analyzed here have a 45 s cadence and were taken from 17:40 UT to 19:17 UT (IRIS observed from 18:42 UT to 19:00 UT) in order to investigate the magnetic field evolution that precedes and follows the IRIS observations. The HMI pixel size is 0.505 and a 1σ noise level is 10 G (Liu et al. 2012).

2.3. Co-alignment

The emission in the three IRIS spectral lines (Mg ii k, C ii, and Si iv) is shifted along the IRIS slit. To correct for this offset we used fiducial emission marks made by various phenomena along the slit. We found an offset between C ii and Si iv of 7 pixels (i.e., Si iv is 7 pixels lower than C ii) and Mg ii k is 4 pixels higher than C ii. The IRIS 1330 Å slit-jaw and the AIA 1600 Å images both have a strong continuum contribution which permits a straightforward alignment between both data sets. The AIA 1600 Å images were then aligned with the HMI data.

3. DATA ANALYSIS, RESULTS, AND DISCUSSION

The IRIS observations present a unique opportunity to study the solar chromosphere and transition region at unprecedented spatial (subarcsecond), spectral, and time resolution. Here, we explore this advantage to analyze at subarcsecond scale a small (close to 1" size) transient phenomenon combining spectroscopic, imaging, and magnetic-field co-observations. An online animation (see Figure 9) provides spatially and temporally combined observations from all the instruments used here, i.e., the SJ 1330 Å images from IRIS, the HMI magnetograms, and the AIA images in the 1600 Å, 304 Å, 171 Å, 193 Å, 211 Å, and 131 Å channels together with the emission along the slit in the three IRIS spectral lines, Mg ii k, C ii, and Si iv. The spectroscopic investigation and results are presented in Section 3.1, the imaging (IRIS and AIA) analysis is given in Section 3.2, and the magnetic field study is described in Section 3.3. We also present our interpretation of the observed spectral and imaging features, the possible physical mechanism, and the challenges brought up by the instrumental limitations.

3.1. IRIS Spectroscopy of the Explosive Event

The IRIS spectral and imaging data were taken at the boundaries of an equatorial extension of a polar coronal hole (Figure 1). The spectral observations obtained in the Si iv line were first analyzed by applying a single Gaussian fit. Then the data set was inspected for strong blue and/or redshifted emission above 50 km s$^{-1}$. We identified one such event with strong non-Gaussian profiles (solar_y = 200'). Judging by its spectroscopic
The Astrophysical Journal, 797:88 (14pp), 2014 December 20

Huang et al.

Figure 7. Light curves in the blue (top) and red (middle) wings of Si\textsc{iv}, C\textsc{ii}, and Mg\textsc{ii}k in the range 20−100 km s\(^{-1}\), and the line center from −5 km s\(^{-1}\) to 5 km s\(^{-1}\) (for all three lines, bottom). Please note that the slit was crossing the event from west to east (see Section 3.1 for more details).

(A color version of this figure is available in the online journal.)

Figure 8. Mg\textsc{ii}k and C\textsc{ii} profiles taken from the regions where a line center increase is observed (see the bottom left panel of Figure 4). Top panel: profiles taken at 18:44:58 UT. Bottom panel: profiles taken at 18:52:51 UT. The dashed lines indicate the area from which the line profile plots are produced. The C\textsc{ii} profiles are enlarged by a factor of 10 in order to fit them to the same radiance axis as Mg\textsc{ii}k. The overplotted dotted lines are the average line profiles of the "REF" region in Figure 2.

appearance, the event carries all the observational characteristics of the EE (see Section 1 for more details). The EE measures \(\approx 1.5''\) along the \textit{IRIS} slit. In the radiance images, produced from the sit-and-stare slit observations, it appears as a bright compact structure in the Mg\textsc{ii}k, C\textsc{ii}, and Si\textsc{iv} lines (Figure 2). Note that because compensation for the solar differential rotation was not applied during the \textit{IRIS} observations, at these heliographic coordinates the slit scans an area of 1'' in 460 s. For an event with a size of 1.5'', it will take approximately 11 minutes to be scanned from west to east. In the SJ images, the EE appears as a compact bright-point-like structure, which is visible during the whole observing period, i.e., 18 minutes 46 s.

In Figure 3 (top and bottom left) we show the radiance and the Doppler-shift images obtained from the Si\textsc{iv} line. The Doppler-velocity image was produced by applying a single Gaussian fit. Away from the EE, the line is dominated by noise due to the low count rate of Si\textsc{iv} but the emission in the EE has a good signal-to-noise ratio allowing reliable calculation from a single Gaussian fit. As we mentioned above the spectral information obtained during the event is both spatial and temporal, although the observations are in a sit-and-stare mode. While the EE moves under the \textit{IRIS} slit, first a redshift dominated emission is registered for the time between 18:45:27 UT and 18:46:42 UT, i.e., during 75 s. The Sun would rotate under the \textit{IRIS} slit for this period of time by approximately 0.16'', i.e., \(\sim 118\) km. An example of the redshifted Si\textsc{iv} line profile is given in Figure 3 (top row, 2nd panel—"A"). Gradually blueshifted emission is seen to increase from 18:46:57 UT to 18:47:49 UT, (i.e., in 52 s) until the emission in both wings is almost equal (Figure 3, top row, 3rd panel—"B"). From 18:47:58 UT until 18:51:55 UT (237 s), the emission is blueshift dominated (Figure 3, top row, 4th panel—"C"). The phenomenon was scanned in 388 s, which means that the size of the EE in the Si\textsc{iv} line (i.e., transition region) is \(\approx 0.84''\). Considering the projection angle, the EE should have a size of 0.94'' on the solar surface.

The Doppler-shift pattern seen in the single Gaussian images was further investigated using the red–blue (RB) asymmetry method. RB asymmetry is defined as the difference of the emission in the red and blue wing of a spectral line at the same Doppler velocity (or Doppler-velocity range) and is given by

\[
RB_{\Delta \lambda_1} = \int_{\lambda_0 + \Delta \lambda_1 - \delta \lambda_0}^{\lambda_0 + \Delta \lambda_1 + \delta \lambda_0} I_\lambda d\lambda - \int_{\lambda_0 - \Delta \lambda_1 - \delta \lambda_0}^{\lambda_0 - \Delta \lambda_1 + \delta \lambda_0} I_\lambda d\lambda,
\]

where \(\lambda_0\) is the wavelength of the line center, \(I_\lambda\) is the intensity of the spectral line, \(\Delta \lambda_1\) is the offset from the line center, and \(\delta \lambda_0\) is the wavelength range over which the RB asymmetry is determined. This method has been widely used in optically thick spectral-line analysis (e.g., in Har, Madjarska et al. 2009; Huang et al. 2014, and the references therein), and it was also
introduced to emission lines (De Pontieu et al. 2009). A variant of this method that differs in the determination of the line center is discussed in Tian et al. (2011). In the present study, the line center is obtained from an average profile in the region indicated in Figure 2. In Figure 3, bottom row, we show images of the RB asymmetry in the Si iv line in three Doppler-shift ranges: 50–70 km s$^{-1}$, 90–110 km s$^{-1}$, and 130–150 km s$^{-1}$. The temporal variations of the RB asymmetry obtained by averaging over the EE along the slit in the Si iv line are given in the top panel of Figure 6. We clearly see from both figures that the RB asymmetry of the EE is positive only in the lowest velocity range (50–70 km s$^{-1}$). The blueshift dominant emission is found in the central part of the EE. Again we have to keep in mind that the information is space-time combined and the excess up-flow may later be followed by a down-flow or vice-versa. As seen by Madjarska et al. (2009) in the case of a surge, simultaneous plasma up- and down-flow along adjacent field-lines would produce simultaneous blue and/or redshifted emission with the appearance along the spectrometer slit depending on the line of sight.

The observations show that the redshifted emission is weaker than the blueshifted emission, indicating that less plasma at the formation temperatures of the three lines falls back toward the chromosphere. One explanation could be that the plasma is ejected from the chromosphere and part of it is heated to transition region and/or coronal temperatures. After the plasma deposits the heat in the upper atmosphere, it falls back to the chromosphere at different speeds and over a longer period of time. Another possible interpretation is that the plasma is ejected along looped magnetic-field lines thus leaving the field-of-view of the spectrometer slit.

The event also appears as a compact bright structure in the Mg ii k and C ii radiance images (Figures 4 and 5) similar to Si iv. Both lines appear with a central absorption core surrounded by two emission peaks. The Mg ii k blue peak is sometimes referred to as k$_1$, and the red as k$_2$, while the line core is k$_3$. Here, we will simply refer to k$_{2r}$ and k$_{2b}$ as blue and red wings. The line profiles of the two absorption lines at three sampling pixels ("A," "B," and "C") in bottom rows of Figures 4 and 5 are red-wing-dominated, with equal wings, and blue-wing-dominated respectively, i.e., the same as for the Si iv profiles. The RB asymmetry in the two chromospheric lines is derived as for the Si iv line and is shown in Figures 4 and 5. The RB temporal variations are given in Figure 6. Note that Doppler shifts in the wings of the Mg ii k line are reported to be a signature of flow velocities as found by Leenaarts et al. (2013a, 2013b) and Pereira et al. (2013). The Mg ii k and C ii RB asymmetry images show very similar to behavior as the Si iv asymmetry with the only difference in the Doppler velocity range 130–150 km s$^{-1}$. That may be due to a blend in the red wing of these two lines (Mg ii k is blended by an unidentified line, and C ii 1334.5 Å is blended by the blue wing of C ii 1335.7 Å). Our results demonstrate that above 50 km s$^{-1}$ during a very dynamic event the wings of the chromospheric lines studied here carry identical information as the optically thin Si iv line.

To investigate in more detail the radiance behavior in the wings and centers of the three lines, we produced lightcurves in their blue and red wings and line centers (Figure 7). The response in the wings of C ii is almost identical to the Si iv wing emission with only a small delay of 9 s for the blue wing of C ii to reach peak emission (top panel in Figure 7). This indicates that the wings of the two lines form at a similar temperature.

The behavior of the Mg ii k wings is similar to that of the C ii. However, the emission in the wings of Mg ii k in addition to the Doppler shift is possibly also affected by emission related to wing formation in the lower chromosphere. The above is not valid, however, for the line centers. The line center of C ii is clearly reversed. We obtained the lightcurves in the line center of the Mg ii k and C ii lines, summing the emission from −5 to 5 km s$^{-1}$. The line-center emission of these two lines show the same behavior which is very different from the emission in the center of the Si iv line (Figure 7, bottom panel). The only difference between C ii and Mg ii k is the later response of Mg ii k (18 s) when a sudden intensity increase at the edges of the brightening linked to the EE is observed. This clearly shows that the line centers of both chromospheric lines are emitted from plasma at similar temperatures.

A line center reversal in the C ii has been seen in HRTS (0.05 Å spectral resolution) data but has never been reported in SUMER (0.045 Å) observations (Figures 9 and 10 in Avrett et al. 2013). We made an automatic scan of all the C ii data in the SUMER archive visually searching for C ii profiles showing explosive event line profiles. We found numerous examples of EE where C ii shows a central reversal but only in stronger events. One of the reasons that a central reversal is now clearly seen in the IRIS data is apparently due to the IRIS higher spatial resolution. In SUMER, a small central reversal will not be visible but instead a flat profile peak will be registered.

An emission increase is clearly seen in the line center of Mg ii k and C ii at the west (the start of the scanning of the event as observed in a sit-and-stare mode) and east (end of the scanning) edge of the event. In Figure 4 (bottom row, first panel), we show the Mg ii k line-center radiance image where the two brightenings are seen. After careful investigation we found that this increase is not due to a line center emission increase but rather to a shift of the wings of both the C ii and Mg ii k lines toward the line center. On the west site of the event the intensity in the red wing increases and shifts toward the line center (shorter wavelength) while on the other edge (east or end of the scanning) of the event the intensity in the blue wing rises shifting again toward the line center (longer wavelength) (Figure 8). This behavior appears temporally and spatially where the Si iv line-wing-emission excess is observed, and it suggests that an intensity increase toward the line center is related to the plasma dynamics. Radiative transfer calculations are only available under the assumption of ionization equilibrium, therefore, these are not entirely valid for the atmospheric conditions in the presence of a highly energetic event (Leenaarts et al. 2013a, 2013b; Pereira et al. 2013). Doyle et al. (2013) showed that for dynamic bursts with a decay time of a few seconds, the Si iv line can be enhanced by a factor of two to four in the first fraction of a second with the peak in the line contribution function occurring initially at a higher electron temperature due to transient ionization compared to ionization equilibrium conditions.

3.2. IRIS and AIA Imaging of the Explosive Event

IRIS provides a unique opportunity to study solar phenomena in simultaneously taken spectroscopy and imaging data. Figure 10 displays the evolution of the event seen in the 1330 Å slit-jaw filter. At the beginning of the observations (18:42:08 UT), a brightening system with three bright cores can be seen in the area (see the arrows in the first panel of Figure 10). The EE is distinctly present in the AIA UV 1600 Å and 1700 Å channels with the same general shape. The three cores, however, are
impossible to distinguish due to the lower (up to 3–4 times) spatial resolution of AIA. The event is seen in the AIA 1600 Å images from 17:54 UT to 19:19 UT, i.e., for 85 minutes.

The event was also investigated in the 304 Å, 171 Å, and 211 Å channels shown in Figure 11. In the AIA 304 Å and 171 Å images a dynamically evolving bright complex feature is present. During its evolution some loop pattern becomes apparent, but to clearly identify individual loops and to link to the underlying magnetic field configuration is close to impossible. One of the footpoints of the complex brightening is rooted in the three-core 1600 Å feature where the EE is also found to originate. The investigation of the associated HMI magnetograms shown in Figure 14 indicates that the EE is located above two opposite-polarity-canceling magnetic features (see the online animation with Figure 9). It also shows that the HMI resolution is too low to make any reliable field extrapolations for more detailed investigation of the magnetic field structures and associated small-scale dynamics. The bright core feature linked to the EE appears very dynamic in the IRIS 1330 Å images and a very close look reveals that continuously small-scale ejections take place during the entire IRIS observation period. Most of the ejections have a mini-jet-like shape. They propagate in random directions, and some of them (as the clear example shown with a black arrow in image at 18:56:20 UT of Figure 10) have a width of one pixel (i.e., 0′′.166). Such fine scale jet structures have so far only being seen with ground-based telescopes, e.g., Ellerman bombs (e.g., Watanabe et al. 2011). Part of the ejected material appears to contract back to the source region toward the end of the 1330 Å image series a disk projection of what appears to be a small cloud-like feature is ejected after which the source region becomes weaker. To follow this evolution please view the online close-look SJ 1330 Å image animation (Figure 10). Chae et al. (1998b) found an association between EEs observed in Si XIV 1402 Å and chromospheric upflows identified as a blueshifted Hα profile at 1′′ spatial resolution. No jet features were observed but rather “dark dots” with a size of 2′′–3′′ and lifetime of 1–2 min were identified in the Dopplergram with an upflow velocity of 15–30 km s⁻¹. The authors suggested that the “chromospheric upflow events may be the manifestation of cool plasma material flowing into magnetically diffusive regions, while explosive events represent hot plasma material flowing out of the same regions” (see the abstract of the article).

In the top panel of Figure 12, we present the lightcurves in the three spectral lines together with the lightcurve of the event in the SJ images (see the remarks in Figure 10). The lightcurves of the emission in the AIA EUV channels are shown in the panels below and are obtained from the boxed region overlaid on the...
first column in Figure 11. The region selected for producing the lightcurves is larger (7′′65 × 7′′35) in comparison to the event because we need to account for the movement of the feature and for the activity in its close proximity (perhaps triggered by the EE), see Figure 10. Thus the lightcurves are formed partially by the EE source region and also by the loops rooted in it. The lightcurves are smoothed by three frames. We need to point out that the dip in the SJ lightcurve during the peak of the event seen in the spectral lines is purely instrumental (see Section 2 for more details). The slit is obscuring the event during this period of time and because of the small size of the event at least one-third of its emission is blocked.

The lightcurves in Figure 12 show two periods of brightening increase. The first lasts for ~8 minutes but is actually composed of several intensity peaks each with duration between 90 and 120 s. The second brightening has the same duration as the individual spikes of the first brightening. These intensity variations are clearly linked to the small-scale ejections and brightness increase in the source region. The first intensity increase starts in the AIA 304 Å channel at ~18:44 UT and ends at ~18:53 UT. The start in the SJ images cannot be defined because of the spectroscopic observations. In the 171 Å channel the flaring of the EE begins later, i.e., ~18:46 UT, and stops earlier at ~18:52 UT. The event is first seen in the AIA 193 Å channel at the same time as in AIA 304 Å. In AIA 131 Å, it appears to be delayed by one minute with respect to the 304 Å and 193 Å channels but this can also be due to the weak signal in this channel. The start of the brightening in the 211 Å channel is impossible to determine.

At 18:55 UT, the EE starts to flare up again (only seen in the imaging data) and reaches maximum in the IRIS 1330 Å slit-jaw images at 18:56:01 UT. During this stage, the event shows a clear jet-like structure seen in IRIS 1330 Å SJ images (black arrow in image at 18:56:20 UT of Figure 10), and can also be followed in the AIA UV/EUV channels (arrows in the 3rd column of Figure 11). The time of the emission maxima are 18:56:55 UT in 304 Å, 18:57:47 UT in 171 Å (44 s later with respect to AIA 304 Å), 18:57:42 UT in 193 Å (102 s), 18:57:47 UT in 211 Å (102 s), and 18:58:32 UT for 131 Å (152 s). Because of the 12 s cadence of the AIA data, the 171 Å, 193 Å, and 211 Å actually respond simultaneously. Only the 131 Å channel is delayed with respect to the other coronal temperature channels by ≈50 s. The emission recorded in the 131 Å channel is known to be dominated by Fe VIII and several transition region lines. Therefore, the later response can be related to a cooling rather than heating during the EE.
The Astrophysical Journal, 797:88 (14pp), 2014 December 20
HUANG et al.

Figure 11. Explosive event in the AIA channels. From top to bottom: 1600 Å, 304 Å, 171 Å, and 193 Å. The dotted lines in the first column outline the region from which the lightcurves (Figure 12) are calculated. The contour of the magnetic flux density is overplotted on the second column of the images (black: $-20 \text{ Mx cm}^{-2}$, cyan: $20 \text{ Mx cm}^{-2}$). The arrows in the third column of AIA 304 Å, 171 Å, and 193 Å images denote the brightening associated with the EE. The full cadence of the images (including 211 Å and 131 Å channels) is provided in an online animation.

(A color version of this figure is available in the online journal.)

The 171 Å channel is dominated by Fe$^{ix}$ but if a feature at low temperature is observed, the recorded emission will be at temperatures $\log T (K) < 5.7$ (Vanthinathan et al. 2012; Brooks et al. 2011). Although the AIA 193 Å channel is dominated by three Fe$^{xii}$ lines, it has a significant transition region emission contribution from non-identified lines (Del Zanna et al. 2011). The AIA 211 Å channel is also known to record transition region emission, a lot coming from Fe$^{viii}$ lines. However, 50% of the lines emitting in this channel remain unidentified (Del Zanna et al. 2011). Only in active regions we do have a strong contribution from Fe$^{xiv}$. To conclude, the AIA channels do not give a straight answer on the temperature of the observed explosive event.

The clear intensity increase in AIA 171 Å, 193 Å, 211 Å, and 131 Å suggests that during the explosive event, plasma was ejected reaching temperatures to which all of these channels are sensitive. To determine this temperature, we used the emission measure (EM) Loci method (see, e.g., Winebarger et al. 2011; Alexander et al. 2013, etc.). The EM loci curves are constructed from the channel response functions calculated using the method described in Del Zanna et al. (2011) and the emission at around 18:58 UT. The resulting curves are shown in...
Figure 12. IRIS and AIA lightcurves of the region outlined by the dotted line in Figures 10 and 11. The lightcurves of the spectral lines are produced by integrating over the whole line during the time interval when the slit was crossing the event. The vertical dotted line denotes the time from which the emission of AIA 171 Å, 193 Å, 211 Å, and 131 Å is used to calculate the EM Loci (Figure 13).

(A color version of this figure is available in the online journal.)

Figure 13. The EM loci suggests that $\log T = 5.36 \pm 0.06$ (K) is the most probable temperature of the event. The second loci-curve clustering at $6.18 \pm 0.1$ K is less plausible following the discussion above on the temperature response of the AIA EUV channels. An EUV active-region jet was reported by Chae (2003) in TRACE 1600 Å (transition region and continuum emission) and 171 Å. The jet, which was much larger than the jets reported here, had a temperature of $2-3 \times 10^5$ K. The temperature of the jet was obtained from a TRACE filter ratio method.

3.3. Magnetic Field of the Explosive Event

Having now the great opportunity provided by IRIS to observe spectroscopically the Sun at subarcsecond resolution, we face the challenge of having both incompatible coronal imaging and also magnetic field data. Nevertheless, we analyzed in detail the only available data from HMI. After the magnetic field associated with the explosive event was identified, we tracked its evolution starting an hour before the IRIS observations. A selection of HMI images is shown in Figure 14 and an animation in the online journal (Figure 9). At the start of the selected data set (i.e., 17:40 UT), a bipolar region is found in the area of the EE with one negative polarity fragment and a few positive ones. The distance between the two closest negative and positive fragments is $\sim 2''$. The positive and negative fragments are moving toward each other while at the same time the positive flux increases, which is either due to flux emergence or convergence (the spatial scale and sensitivity of HMI does not permit a judgment as to which one of the two mechanisms is at work). Magnetic flux cancellation associated with EEs has been previously reported by Chae et al. (1998a) and Muglach (2008). In both studies, however, only around 63% and 19% (103 out of 165 and 7 out of 37), of the EEs resulted from flux cancelation, respectively. As in the present case, instrumental limitations could be the reason for this result and possibly larger or even all EEs are associated with magnetic flux cancellation. Thus studies using higher magnetic field resolution and sensitivity data are required, as will be discussed further below. Jet-like phenomena of various sizes and temperatures have been related to magnetic flux cancellation (e.g., Chae et al. 1999; Chae 2003; Chifor et al. 2008; Madjarska et al. 2012; Huang et al. 2012; Adams et al. 2014). The authors of all these studies suggest magnetic reconnection as the most probable driving mechanism.

To evaluate the magnetic activity during the EE, we produced the temporal variations of the total positive and negative magnetic flux from the boxed region in Figure 14. A limited field of view was used around the region of the EE. The temporal variations shown in Figure 15 reveal that a flux increase starts prior to the event in both the positive (from $\sim 18:27$ UT until 18:43 UT) and the negative (from 18:18 UT until 18:25 UT) polarities. The increase of the positive flux is at a rate of $2.7 \times 10^{15}$ Mx s$^{-1}$, while the increase of the negative is $1.6 \times 10^{15}$ Mx s$^{-1}$. At the beginning of the IRIS observations at 18:42 UT, the distance between the negative and positive magnetic fragments is within one HMI pixel when the magnetic-field cancellation was already ongoing. The cancellation rate is $4.7 \times 10^{14}$ Mx s$^{-1}$ for the positive flux (linear fit to the curve between 18:39 UT and 19:17 UT), and $5.9 \times 10^{14}$ Mx s$^{-1}$ for the negative flux (linear fit to the curve between 18:25 UT and 18:59 UT). We should stress here that these estimations are only a low limit because of instrumental limitations. The cancellation rates are close to those found for an X-ray jet (Huang et al. 2012), and much smaller than those recorded during a GOES C4.3 flare.
Figure 14. HMI magnetograms of the explosive event. The overplotted dashed line square is the region from where the magnetic flux is calculated in Figure 15.

Figure 15. Temporal variations of the positive (left) and negative (right) magnetic fluxes. The red lines represent the linear fit to the period of flux emergence and cancellation.

(A color version of this figure is available in the online journal.)
as discussed in Huang et al. (2012), this flux cancellation rate strongly suggests that the event observed here results from an impulsive energy release most possibly magnetic reconnection. To compare, Chae et al. (2002) found $3.6 \times 10^{14} \text{ Mx s}^{-1}$ and $9.7 \times 10^{14} \text{ Mx s}^{-1}$ of flux cancellation rate for two cancellation sites, which the authors suggest to be consistent with a Sweet–Parker magnetic reconnection model. In the present case, the combined changes of the locations and the flux of different patches will result in reconfiguration of the field line connectivity that can only take place through magnetic reconnection. To fully understand the dynamical evolution of this event, reliable 3D models of the magnetic field are required. With the small size of this event, which represents only a few HMI pixels, a representation of the small-scale magnetic field is not possible to obtain by any extrapolation models. Without this, a detailed understanding of the underlying mechanism that drives this event is very challenging.

4. CONCLUSIONS

The real nature of explosive events is still under debate. Jets produced by magnetic reconnection, siphon flows in small-scaled loops and swirling jets have been proposed as the phenomena causing explosive-event line profiles. Please note that none of these interpretations was confirmed by imaging information until present. Here, we analyze an explosive event witnessed by strong non-Gaussian profiles with up to 150 km s$^{-1}$ blue- and redshifted components in the Si iv line. The EE was associated with a small ($\sim 1.5''$) compact bright-point-like structure in the IRIS unprecedented high-spatial, temporal, and spectral resolution observations combining them with imaging and magnetic field data from AIA and HMI, respectively. We found, for the first time, that an “explosive event” phenomenon is associated with continuous small-scale plasma ejections and retractions on a subarcsecond scale (jet width of $0.166$ or 120 km) observed in the solar chromosphere (IRIS SJ 1330 Å).

In the AIA 304 Å and 171 Å channels, the explosive event appears to be located in the footpoints of a complex multiple loop system, which is also confirmed by the HMI magnetograms. Magnetic flux emergence or convergence followed by flux cancellation at the location of the explosive event was found, suggesting that magnetic reconnection producing high-velocity plasma outflows was taking place. Brightenings observed in the AIA 304 A, 171 A, 211 A, and 131 Å channels with duration between 90 s and 120 s are most probably produced by the plasma ejections (also responsible for the explosive event) seen in the SJ 1330 Å images.

The Mg ii k and C ii lines observed by IRIS show self-reversed profiles, with the explosive event affecting the line wings (i.e., the emission peaks) but not the absorption dips (the line centers). The wings of the C ii line, above 50 km s$^{-1}$ behave as the Si iv line wings, suggesting that the wings of these two lines are formed at similar temperatures while the wings of Mg ii k are affected by both Doppler-shift and emission contribution possibly related to their formation in the lower chromosphere. A predominantly strong redshifted emission is observed in all lines at one edge (west) of the small-scale ($1.5''$) bright structure (as seen in the SJ images) while at the opposite edge (east) the emission is predominantly blueshifted suggesting a down- and up-flow, respectively, on a scale as low as $0.16''$ (or 118 km). A particular feature was observed at the west edge of the SJ bright feature, where the Mg ii k and C ii lines show profiles with a strong emission increase in the red peak but blueshifted toward the line center with the opposite being observed in the east edge (i.e., blue wing increase shifted toward the line center). Because of the lack of radiative transfer calculation in the presence of very energetic events, to speculate about what causes these profiles is not presently possible. This challenges the radiation transfer calculation of these two optically thick lines.

RB asymmetry analysis of the Mg ii k, C ii, and Si iv suggests that the flows (jets) producing the explosive event originate in the low chromosphere. The plasma up-flows clearly dominate the down-flows, which indicates that plasma heated to high temperatures is ejected and after depositing energy in the high transition region or corona falls back to the chromosphere. The temperature of the event derived using the EM Loci method is $log T = 5.36 \pm 0.06$ (K). The phenomena associated with the EE, therefore, directly contribute to the heating of the solar transition region. Their impact on coronal heating is still to be investigated. As we mentioned in the introduction, the only study that has concluded on the direct coronal contribution of EEs (Teriaca et al. 2002) is based only on two events.

Although our case study cannot answer all the questions listed in the Introduction, it moves our knowledge a step forward by demonstrating one of the possible phenomena producing EEs. The present study provides a wealth of information on the behavior of chromospheric lines in non-equilibrium ionization. A future forward chromospheric C ii and Mg ii k, and transition region Si iv modeling studies (including non-equilibrium ionization effects, see Doyle et al. 2013) can then provide important clues on the physical mechanism(s) in action during phenomena witnessed by explosive events.

The temporal behavior of the chromospheric and transition region lines clearly demonstrates that the scenario suggested by Chae et al. (1999) where chromospheric upflows represent cool plasma material flowing into magnetically diffusive regions, while explosive events represent hot plasma material outflow from the reconnection site, is not valid in the present case. The imaging data on the other hand show that the plasma up- and down-flows are produced by plasma ejection and retraction rather than bi-directional reconnection outflows as suggested by Dere et al. (1991) and Innes et al. (1997b). The present phenomenon does not support the scenario of a swirling upflow (Curdt & Tian 2011) as a possible phenomenon witnessed by EEs. We would like to stress that although our case study does not endorse these interpretations, they still remain plausible explanations for other EE-associated phenomena. To really extend our knowledge on small-scale events using high-resolution IRIS observations, we need in parallel much higher resolution magnetograms than those are currently available.

A recently started statistical study covering events in various regions on the Sun should provide a lot of the missing pieces of the puzzle “explosive event.” New recently obtained magnetic field and Hα observations from the Swedish Solar Telescope together with IRIS may also shed more light on how exactly the small-scale jets producing explosive events are generated.

This research is supported by the China 973 program 2012CB825601, and the National Natural Science Foundation of China under contract 41274178, 41404135. Research at the Armagh Observatory is grant-aided by the Northern Ireland Department of Culture, Arts, and Leisure. We thank STFC (grant ST/J001082/1) and the Leverhulme Trust for the financial support. We thank the anonymous referee for critical and constructive comments. We thank Dr. Hui Tian for many useful discussions. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at
NASA Ames Research center and major contributions to downlink communications funded by the Norwegian Space Center (NSC, Norway) through an ESA PRODEX contract. AIA and HMI data are courtesy of SDO (NASA).

Facilities: SDO (AIA, HMI)

REFERENCES

Adams, M., Sterling, A. C., Moore, R. L., & Gary, G. A. 2014, ApJ, 783, 11
Alexander, C. E., Walsh, R. W., Régnier, S., et al. 2013, ApJL, 775, L32
Avrett, E., Landi, E., & McKillop, S. 2013, ApJ, 779, 155
Brooks, D. H., Warren, H. P., & Young, P. R. 2011, ApJ, 730, 85
Brueckner, G. E., & Bartoe, J.-D. F. 1983, ApJ, 272, 329
Brueckner, G. E., Bartoe, J.-D. F., Cook, J. W., et al. 1988, ApJ, 335, 986
Chae, J. 2003, ApJ, 584, 1084
Chae, J., Moon, Y.-J., Wang, H., & Yun, H. S. 2002, SoPh, 207, 73
Chae, J., Qiu, J., Wang, H., & Goode, P. R. 1999, ApJL, 513, L75
Chae, J., Wang, H., Lee, C.-Y., Goode, P. R., & Schuehle, U. 1998a, ApJL, 497, L109
Chae, J., Wang, H., Lee, C.-Y., Goode, P. R., & Schühle, U. 1998b, ApJL, 504, L123
Chifor, C., Isobe, H., Mason, H. E., et al. 2008, A&A, 491, 279
Curtin, W., & Tian, H. 2011, A&A, 532, L9
Del Zanna, G., O’Dwyer, B., & Mason, H. E. 2011, A&A, 535, A46
De Pontieu, B., McIntosh, S. W., Hansteen, V. H., & Schrijver, C. J. 2009, ApJL, 701, L1
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Dere, K. P. 1992, in Solar Wind Seven Colloquium, ed. E. Marsch & R. Schwenn (Oxford: Pergamon), 11
Dere, K. P., Bartoe, J.-D. F., & Brueckner, G. E. 1989, SoPh, 123, 41
Dere, K. P., Bartoe, J.-D. F., Brueckner, G. E., Ewing, J., & Lund, P. 1991, JGR, 96, 9399
Doyle, J. G., Giunta, A., Madjarska, M. S., et al. 2013, A&A, 557, L9
Doyle, J. G., Popescu, M. D., & Taroyan, Y. 2006, A&A, 446, 327
Huang, Z., Madjarska, M. S., Doyle, J. G., & Lamb, D. A. 2012, A&A, 548, A62
Huang, Z., Madjarska, M. S., Koleva, K., et al. 2014, A&A, 566, A148

Innes, D. E., Brekke, P., Germerott, D., & Wilhelm, K. 1997a, SoPh, 175, 341
Innes, D. E., Inhester, B., Axford, W. I., & Wilhelm, K. 1997b, Natur, 386, 811
Lee, C.-Y., Chae, J., & Wang, H. 2000, ApJ, 545, 1124
Leenaarts, J., Pereira, T. M. D., Carlsson, M., & De Pontieu, B. 2015, ApJ, 772, 89
Leenaarts, J., Pereira, T. M. D., Carlsson, M., & De Pontieu, B. 2013b, ApJ, 772, 90
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Liu, Y., Hoeke, R. T., Scherrer, P. H., et al. 2012, SoPh, 279, 295
Madjarska, M. S., & Doyle, J. G. 2002, A&A, 382, 319
Madjarska, M. S., & Doyle, J. G. 2003, A&A, 403, 731
Madjarska, M. S., Doyle, J. G., & De Pontieu, B. 2009, ApJL, 701, 253
Madjarska, M. S., Huang, Z., Doyle, J. G., & Subramanian, S. 2012, A&A, 545, A67
Muglach, K. 2008, ApJ, 687, 1398
Pereira, T. M. D., Leenaarts, J., De Pontieu, B., Carlsson, M., & Uitenbroek, H. 2013, ApJ, 778, 143
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Porter, J. G., & Dere, K. P. 1991, ApJ, 370, 775
Ryutova, M. P., & Tarbell, T. D. 2000, ApJL, 541, L29
Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, SoPh, 275, 229
Teriaca, L., Banerjee, D., Falchi, A., Doyle, J. G., & Madjarska, M. S. 2004, A&A, 427, 1065
Teriaca, L., Madjarska, M. S., & Doyle, J. G. 2002, A&A, 392, 309
Tian, H., DeLuca, E., Reeves, K. K., et al. 2014, ApJ, 786, 137
Tian, H., McIntosh, S. W., De Pontieu, B., et al. 2011, ApJ, 738, 18
Vannanathan, K., Madjarska, M. S., Scullion, E., & Doyle, J. G. 2012, SoPh, 280, 425
Watanabe, H., Vissers, G., Kitai, R., Rooppelle van der Voort, L., & Rutten, R. J. 2011, ApJL, 736, 71
Wilhelm, K. 2000, A&A, 360, 351
Wilhelm, K., Innes, E. E., Curdt, W., Kliem, B., & Brekke, P. 1998, in Solar Jets and Coronal Plumes, ed. T.-D. Guyenne (ESA Special Publication, Vol. 421; Paris: ESA), 103
Winebarger, A. R., Emslie, A. G., Mariska, J. T., & Warren, H. P. 2002, ApJ, 565, 1298
Winebarger, A. R., Schmelz, J. T., Warren, H. P., Saar, S. H., & Kashyap, V. L. 2011, ApJ, 740, 2
Zhang, M., Xia, L.-D., Tian, H., & Chen, Y. 2010, A&A, 520, A37