IRIS AND SDO OBSERVATIONS OF RECURRENT EXPLOSIVE EVENTS

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ABSTRACT

Observations of recurrent explosive events (EEs) with timescales of 3–5 minutes are reported. These EEs have been observed with the Interface Region Imaging Spectrograph (IRIS) and have a spatial dimension of ~1′/5 along the slit. The spectral line profiles of C ii 1335/1336 Å and Si iv 1394/1403 Å become highly broadened both in red as well as blue wings. Several absorption lines on top of the broadened profiles were identified. In addition, emission lines corresponding to neutral lines such as C i 1351.66 Å, C i 1354.29 Å, and C i 1355.84 Å were identified. The C i 1354.29 Å and C i 1355.84 Å lines were found only during the EEs, whereas C i 1351.66 Å broadens during the EEs. The estimated lower limit on electron number density obtained using the line ratios of Si iv and O iv is about $10^{13.5}$ cm$^{-3}$, suggesting that the observed events are most likely occurring at heights corresponding to a lower chromosphere. To the best of our knowledge, for the first time we have detected short-period variability (30 s and 60–90 s) within the EE bursts. Observations of the photospheric magnetic fields underneath EEs indicate that a negative polarity field emerges in the neighborhood of oppositely directed positive fields that undergo repetitive reconnection (magnetic flux cancellation) events. The dynamic changes observed in AIA 1700 Å, 1600 Å, C ii 1330 Å, and Si iv 1400 Å intensity images correspond very well with the emergence and cancellation of photospheric magnetic field (negative polarity) on a timescale of 3–5 minutes. The observations reported here suggest that these EEs are formed due to magnetic reconnection and are occurring in the lower chromosphere.

Key words: line: profiles – magnetic fields – Sun: atmosphere – Sun: chromosphere – Sun: transition region – Sun: UV radiation

Supporting material: animations

1. INTRODUCTION

The solar atmosphere is highly dynamic, changing on timescales of minutes to hours. Explosive events (EEs) are one of the many prominent phenomena observed in the solar transition region. They were discovered by Brueckner & Bartoe (1983) using the observations recorded by the High-resolution Telescope and Spectrograph (HRTS) on board Black Brant sounding rockets. EEs are characterized by broad line profiles with high-velocity components (~110 km s$^{-1}$), which form around 10$^5$ K. They have a spatial scale of ~1600 km (2$''$) and a lifetime of ~60 s (Dere et al. 1989).

Using the observations recorded from the Solar Ultraviolet Measurements of Emitted Radiation (SUMER; Wilhelm et al. 1995) spectrograph on board the Solar and Heliospheric Observatory (SOHO), Innes et al. (1997b) reported observations of EEs in the chromosphere, which revealed the presence of bi-directional plasma jets as predicted by theoretical models of magnetic reconnection. It was also found that these events often occur in bursts lasting up to 30 minutes, whereas individual events may have typical lifetimes of about 1–6 minutes (Innes et al. 1997a; Chae et al. 1998). EEs may occur at the same location with a period around 3–5 minutes and may be triggered by waves found in the solar atmosphere (Ning et al. 2004; Doyle et al. 2006). It has also been reported that EEs are preferentially located in the regions with weak and mixed magnetic polarity (Chae et al. 1998) and are associated with a canceling magnetic flux (see, e.g., Muglach 2008; Huang et al. 2014).

Recently, Peter et al. (2014) studied similar events using the observations recorded by the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) and found examples of a bi-directional jet from the emission profiles of a Si iv 1394/1403 Å doublet. They also found absorption lines from cooler ions superimposed on these lines, suggesting that these hot events are occurring in the cooler atmosphere of the Sun. Schmitt et al. (2014) also found absorption features from a multitude of cool atomic and molecular lines while studying the broadened profiles of Si iv transition region lines during the brightening events. Huang et al. (2014) studied a single EE along with underlying magnetic field evolution. They found evidence of magnetic flux cancellation and suggested that magnetic reconnection must have taken place during the EE.

In this paper, we present observations of recurrent EEs using the high-resolution spectroscopic and imaging observations from IRIS. We also study the evolution of underlying magnetic field and explore the relationship between the EEs and the presence of waves in the atmosphere. The paper is organized as follows. We describe the observations in Section 2 and discuss the results in Section 3. We summarize the results and draw conclusions in Section 4.

2. OBSERVATIONS

Data analyzed in this work were obtained by IRIS on 2014 March 4 between 12:39 UT to 14:37 UT using sit-and-stare mode. The top left and middle panels of Figure 1 show the location of the IRIS slit above the slit-jaw images (SJI) obtained in C ii 1330 Å and Si iv 1400 Å. The top right, bottom left, and middle panels show corresponding images taken in the 1600, 171, and 193 Å passbands of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO). The bottom right panel displays the line of sight (LOS) magnetic field measurement obtained from the Helioseismic and Magnetic Imager (HMI; Schou...
et al. 2012), also on board SDO. The arrows in all the panels mark the locations of the recurrent EEs.

IRIS spectra were obtained with an exposure time of 4 s, resulting in a cadence of approximately 5 s, whereas SJIs were obtained with an exposure time of 4 s and effective cadence of 15 s. In this study, we have used IRIS level-2 data provided by the IRIS team. The IRIS SJIs from different filters and detectors are already coaligned for level-2 data. We also used the fiducial mark along the slit and SJIs to correct any offset between them. The wobble effect due to thermal flexing between the guide telescope and the main IRIS telescope is already corrected in regular IRIS operations based on the orbital wobble tables (De Pontieu et al. 2014, and H. Tian 2015, private communication). This correction may still leave an uncertainty of about 1–2 pixels, which will not be important for the analysis performed over several spatial pixels.

Data obtained from AIA and HMI have also been utilized in this work. IRIS and AIA observations were coaligned using IRIS–SJI Si iv 1400 Å and AIA 1600 Å images. All the HMI and AIA images obtained in different filters were coaligned and derotated with respect to the AIA 1600 Å image obtained at 14:09:52 UT using the standard Solar Software (SSW) routines. The obtained data set provides a unique opportunity to study the time evolution of recurrent EEs using both imaging and spectroscopic observations, and to study the evolution of underlying magnetic field.

3. RESULTS AND DISCUSSIONS

Transition region EEs are identified by very broad emission line profiles that show non-Gaussian enhancements in both the wings (Brueckner & Bartoe 1983). We identified one such small-scale bright structure (with spatial width <1′′5) in the SJIs of C ii 1330 Å and Si iv 1400 Å at the locations [348°07′, −121°44′]. The identified EE is marked with arrows in all the panels in Figure 1. A corresponding animation is provided. An enhancement in intensity corresponding to the locations and times of EEs identified in C ii 1330 Å and Si iv 1400 Å images is observed in the AIA 1600 Å image (top right panel). The enhancement can also be identified in images taken in the AIA 171 Å and AIA 193 Å images, though not as clearly as in the...
The bottom right panel displays a magnetic field map. The arrow locates a small-scale negative polarity region (average field strength 350 G) surrounded by the positive magnetic polarity regions, which spatially and temporally correspond to the identified EEs. The vertical white line in the IRIS SJII locates the IRIS slit. Fortuitously, the slit was located right at the location where the EE occurred, allowing us to perform detailed spectroscopic study. Below we discuss the spectroscopic properties of this feature.

3.1. Evolution of Spectral Line Profiles

We selected a small portion of IRIS slit data corresponding to the spatial location of the EE during the time interval of 14:09 UT to 14:36 UT. In Figure 2 we plot the time evolutions of the spectral line profiles of the C II 1335/1336 Å doublet, Si iv 1394 Å, and 1403 Å (see panels (I), (J) and (K), respectively). An analysis of the time evolution of the profiles revealed that the EE occurred in multiple bursts, with a time period of 3–5 minutes and each burst lasted for approximately 2–3 minutes. The time evolution of the event is indicated by the enhancement in the intensity and width corresponding to each burst (see panels (I), (J), and (K)).

In the beginning, for the first few bursts, the enhancement in the intensity was by a factor of 4–12 whereas for later events the enhancement in intensity was about a factor of 20–40 with respect to the pre-EE phase at the same location (see Section 3.2). As can be seen in the animation with Figure 1, since the spatial extent and locations of the bursts changed with time, a few bursts in the beginning and at the end could only be observed marginally.

Panels (L), (M), and (N), respectively, show the spectral line profiles of the C II doublet and two Si iv lines (1394 and 1403 Å) at different times. The solid lines show the spectra at

**Figure 2.** Wavelength–time plot of the observed EEs in the C II 1335/1336 Å doublet, Si iv 1394 Å, and Si iv 1403 Å spectral lines (panels (I), (J), and (K)). Typical spectral line profiles at various locations are shown in panels (L), (M), and (N), where continuous lines show the line profile at the peak of the event (position C in panel (J)), the dotted–dashed line indicates the profile during the quiescent time (position A in panel (J)), and the dashed line is for intermediate time (position D in panel (J)). Vertical continuous and dashed lines in panels (L), (M), and (N) indicate the more prominent and less prominent absorption lines from known ions, whereas dotted lines indicate the absorption features from unknown ions.

AIA 1600 Å. The bottom right panel displays a magnetic field map. The arrow locates a small-scale (≈2'' × 2'') negative polarity region (average field strength 350 G) surrounded by the positive magnetic polarity regions, which spatially and temporally correspond to the identified EEs. The vertical white line in the IRIS SJII locates the IRIS slit. Fortuitously, the slit was located right at the location where the EE occurred, allowing us to perform detailed spectroscopic study. Below we discuss the spectroscopic properties of this feature.
the peak time of EE (labeled as C in panel (J)) and the dashed line shows the spectra for the time labeled as D in panel (J). For comparison, we have also overplotted the spectra at a quiescent time (labeled as A in panel (J)) with a dashed–dotted line. As can be inferred from the plots, during the quiescent phase the C II 1335/1336 Å doublet line shows an extremely weak self-absorption feature (almost non-existent) in the line center, which could be due to large opacity as was pointed out by Peter et al. (2014). At the times when EEs have started, the profiles of C II and Si IV have strongly broadened. This is essentially due to the enhancement in both the wings, which were sometimes observed to be asymmetric. During the burst phase, self-absorption features in highly broadened C II lines increase sharply and bifurcate the spectral line in two (see panel (L), the solid line and the dashed line). The O IV 1401 Å spectral line shows only about a 50% enhancement in the intensity during the peak phase of the EEs, unlike the spectral lines of C II and Si IV, where the enhancement is much higher.

During the initial times, when EEs were marginally caught by the IRIS slit, profiles showed mostly blueshifted emission (or blue wing enhancement). However, during the later times, profiles became very broad with enhancements in both the red and blue wings. We fitted the complete C II doublet with two positive and two negative amplitude Gaussian functions and each Si IV line with a single Gaussian function. While fitting, we used error bars, which were provided by IRIS level-2 data on the measured data numbers (DN). As EEs are believed to have highly non-Gaussian profiles, the reduced χ² and the residuals of the fit were generally higher during the peak activity of the EEs. We measured the Doppler velocity and width (FWHM) of the line with respect to the corresponding average line center position obtained at the quiescent phase (at position A labeled in panel (J)). The Doppler width at the quiescent phase is about 35 km s⁻¹ for both C II and 25 km s⁻¹ for both Si IV lines.

Both of the prominent Si IV lines show almost identical Doppler velocity and width variation with time. The Doppler velocity and width measured from both the Si IV lines exceeds −50 and 150 km s⁻¹ at the peak of activity around 14:25 UT. However, at the same location and time, C II lines measured Doppler velocity and width exceeding −35 and 140 km s⁻¹ at the peak activity time, whereas C II self-absorption lines measured −10 and 65 km s⁻¹, respectively. Unlike the two Si IV lines, the two C II emission lines do not show similar Doppler velocity and width. The C II 1335.7 Å emission line consistently shows lower Doppler velocity and width as compared to C II 1334.5 Å. The lower values of the Doppler shift and width in C II 1335.7 Å may result from the presence of a strong Ni II 1335.2 Å absorption line.

From Figure 2, we identify the presence of several absorption features in the emission line profiles. The most prominent absorption feature corresponds to the Ni II 1353.20 Å line observed on the top of the broadened emission line profile of C II 1335.71 Å. The absorption features of Ni II 1393.33 Å and Fe II 1403.10 Å were also observed very prominently on the top of the profiles of Si IV 1393.76 Å and 1402.77 Å, respectively. These lines are marked with vertical solid lines. Other less prominent absorption features were also found at 1334.82 Å, 1353.07 Å, 1335.41 Å, 1336.07 Å, Fe II 1392.81 Å, Fe II 1393.21 Å, Fe II 1393.59 Å, Si IV 1393.80 Å, 1394.17 Å, 1402.35 Å, and Si IV 1402.77 Å. The identified absorption lines are marked with vertical dashed lines, whereas unidentified lines are marked with vertical dotted lines. Many of these absorption features were reported very recently by Schmit et al. (2014), Peter et al. (2014) and Yan et al. (2015). Some of them have also reported the presence of self-absorption lines on the top of broadened profiles of C II 1334.54 Å and 1335.71 Å, Si IV 1393.76 Å and 1402.77 Å during the EEs.

We have also identified several emission lines coming from neutral atoms such as Cl I 1351.66 Å, C I 1354.29 Å, C I 1355.84 Å, and O I 1355.60 Å. All of these lines except the O I 1355.60 Å indicate the presence of either self-absorption or absorption features (see Figure 3) during the peak activity time of the EEs. To the best of our knowledge, this is the first report of the appearance of self-absorption features in the emission
lines of neutral atoms. However, we note that the associated error bars on the data points are relatively large. Therefore, a more detailed investigation is required to confirm that these are indeed self-absorption features. The C\textsc{i} 1354.29 Å and 1355.84 Å lines were not present during the quiescent phase and were detected only during the EE, whereas the C\textsc{i} 1351.66 Å line was present during the quiescent phase and broadened during the EEs. The O\textsc{i} 1355.6 Å was present both during the quiescent phase as well as during the EEs. However, we surprisingly did not find any absorption features or noticeable line broadening of the O\textsc{i} 1355.6 Å line at any time, such as C\textsc{i} 1351.66 Å, C\textsc{i} 1354.29 Å, and C\textsc{i} 1355.84 Å during the EEs in the \textit{IRIS} spectra.

3.2. Intensity Evolution of EEs

\textit{IRIS} records both the spectroscopic and imaging data of the solar atmosphere simultaneously. While spectra recorded with the slit have a very limited field of view, \textit{IRIS} SJIs can record data in the larger field of view. As mentioned in Section 3.1, the \textit{IRIS} slit caught a few bursts marginally. Thus we also use SJI images obtained in the 1330 and 1400 Å passbands of \textit{IRIS} to study the full time evolution of the entire EE sequence. We also looked into the different AIA passbands to find any signatures of these events in the upper layers of the atmosphere.

In the top panels of Figure 4 (see the accompanying animation), we show an area chosen to study the intensity evolution in the \textit{IRIS} 1330 Å and 1400 Å passbands. The middle panel of Figure 4 displays the change in the intensity with time as recorded by the \textit{IRIS} spectrometer. The light curves clearly reveal that the first and last few bursts were weak. The strongest bursts were seen starting around 14:24 UT. In the bottom panel of Figure 4, we plot the intensity obtained in the chosen area with the time in different passbands of \textit{IRIS}. Recently, Martínez-Sykora et al. (2015) found that \textit{IRIS} passbands have significant contributions from the continuum. However, continuum effects will be significant only when signals in the C\textsc{ii} and Si\textsc{iv} lines are too weak to explain the presence of observed features in the 1300 and 1400 Å SJIs. In the case of EEs, signals in C\textsc{ii} and Si\textsc{iv} profiles are very strong (stronger by a factor of 4–40), which are seen in the SJIs; thus the contribution from the continuum may be ignored. The light curve for two \textit{IRIS} passbands shows very similar evolutionary characteristics. The light curve obtained from \textit{IRIS} passbands indicates that the total intensity of EEs was increasing with time in the beginning and started decreasing only after 14:28 UT.
Figure 5. Wavelet analysis result for the intensity variation with time (starting from 14:21:28 UT) as recorded by IRIS C ii 1335/1336 Å spectral lines. The top panel shows the intensity variation with time. The bottom left panel shows these color-inverted wavelet power spectrum with 99% confidence-level contours, while the bottom right panel shows the global wavelet power spectrum with 99% global confidence level drawn. The periods P1 and P2 at the locations of the first two maxima in the global wavelet spectrum are shown above the global wavelet spectrum.

Figure 6. Same as Figure 5 but for the Si iv 1394 Å spectral line.

whereas in this analysis, we found intensity variabilities of the order of 1 minute and less within the individual EEs extended over several spatial pixels. Therefore, instrumental wobble has not affected our analysis and thus the obtained short-period intensity variabilities.

The repetitive natures of EEs and jets with periodicities of 3–5 minutes have been previously reported (see e.g., Ning et al. 2004; Doyle et al. 2006) and have been attributed to the presence of magnetohydrodynamic (MHD) waves in the atmosphere with similar periods. However, to the best of our knowledge, this is the first time a short-period variability with periods of 30 and 60–90 s has been detected in EEs. Recently, using Hi-C data, Pant et al. (2015) found evidence of short-period (30 and 53–73 s) oscillations in a braided magnetic region, providing evidence in favor of a connection between short-period waves and bursts. However, at this point we can not conclude whether oscillations are driving burst events or vice-versa.

3.3. Electron Density in EEs

To estimate electron density during the EEs, a density sensitive O iv 1401 Å and 1399 Å line pair may be used, (although see Dudík et al. 2014). Both these lines are very weak in the IRIS spectra. By binning over a few pixels the signal-to-noise ratio (S/N) for O iv 1401 Å can be improved. However, this does not improve the S/N for O iv 1399 Å.

Based on the suggestions provided by Peter et al. (2014), we estimated electron density using O iv 1401.16 Å and Si iv 1393.76 Å (see, however, Doyle et al. 2013), which only provides a lower limit of the electron density. Since our goal is to get an order-of-magnitude estimate for the electron density, the method suggested by Peter et al. (2014) will serve our purposes. For this calculation we have used the photospheric abundances of Grevesse & Sauval (1998) and CHIANTI ionization equilibrium (Landi et al. 2012).

In order to improve the S/N, we binned spectra over seven pixels along the direction of the slit. The top two panels in Figure 7 show two examples of O iv 1401 Å line profiles at two different times. As can be seen from the line profiles there are still not enough counts to fit to a Gaussian, therefore, we summed over the profile (wavelength range from 1400.94 to 1401.50 Å) and subtracted the contribution of continuum to
estimate the O IV 1401 Å contribution. Although the Si IV 1393.76 Å line is strong enough to fit a Gaussian and obtain the Gaussian integrated intensity, for consistency we have used the same method to obtain the intensity as for O IV 1401 Å. The resulting intensity variations of both the lines are plotted in the middle panel of Figure 7. Electron number densities estimated during the quiescent time are around $10^{11.7}$ cm$^{-3}$, which increases to $10^{13.5}$ cm$^{-3}$ during the peak of the activity (see the bottom panel of Figure 7). We note that since the intensities derived for O IV 1401 Å are the upper limit, the densities obtained here are essentially the lower limit. This estimated lower limit on the electron number density together with appearance of neutral lines (C I 1354.29 Å, and C I 1355.84 Å) during the EE strongly suggests that the event probably occurred somewhere in the lower chromosphere, as was also pointed out by Peter et al. (2014).

3.4. Comparison with AIA Observations

To study if there were any hotter counterparts to the repetitive EEs, we examined the different AIA passbands. Figure 8 displays AIA images taken just after the peak at 14:28 UT, as seen in the bottom panel of Figure 4 in all its passbands. For complete time evolution, see the animation with Figure 8. The observations recorded using the 1700 and 1600 Å passbands show appearances and movements of EEs at a full extent—marked by a rectangular box—that is similar to that seen in IRIS–SJI images (see the light curves plotted in Figure 9). The light curves are plotted using normalized intensities, which were obtained as $\{(I(\tau) - \min(I(\tau))) = \max(I(\tau) - \min(I(\tau)))\}$. However, the hotter channels of AIA show only a small but distinguishable brightening that is spatially correlated with that of the EEs. These brightenings are located in the images using a square box. The full extent of these brightenings is not clear in these hotter channels. Also, there is a time lag of about 5 minutes in the appearance of these brightenings in hotter channels. This makes us wonder if these brightenings are similar to those observed using SJI’s as well as the AIA 1700 Å and 1600 Å images. We would also like to point out that coronal loops that connect to more southern negative fluxes from the sunspot are more likely to cross the field of view. As pointed out by Peter et al. (2014), EUV radiation is strongly attenuated by overlying hydrogen so it would not be surprising to see no signature of the events in the AIA passbands at the same time. However, as time progresses more energy is released, resulting in the ionization of hydrogen with time, thus, we see the response of EEs in the AIA passbands for later events.

In order to understand the nature of the small brightenings seen in the AIA hotter channels, we performed a differential
emission measure (DEM) analysis to obtain the differential emission measure distribution using the regularized inversion method of Hannah & Kontar (2012). The DEM was obtained using the AIA 131 Å, 171 Å, 193 Å, 211 Å, 335 Å, and 94 Å intensities recorded at the nearby time of 14:29:54 UT when emission in the AIA 193 Å channel peaked. The obtained DEM curve is plotted in Figure 10. The red curve is the DEM before background subtraction and the blue curve is after the background subtraction. Background intensities are intensities obtained at the EE location just before the brightenings start appearing in AIA images. As expected the overall DEM values decrease after the background subtraction. The DEM curve shows a rather strong dip at $\sim$1 MK after the background subtraction. However, the peak emission still comes from a temperature of $\log T = 6.3$. This suggests that the brightening seen in the AIA channels is at a coronal temperature. There is also another peak at $\log T = 5.8$. However, the error bars are much bigger at this location in the plot.

If the brightenings seen in hotter AIA channels are related to those seen in the IRIS–SJI as well as the AIA 1600 Å and 1700 Å images, then the plasma must be heated to about 2 MK. As mentioned earlier, the time analysis shows that there is a lag of about 5 minutes in the appearance of these brightenings in hotter channels. Also we note that by the time these brightenings appear in hotter channels, they disappear from the SJI images. However, at this point, we are not able to conclude whether or not these brightenings are exactly related to each other.
3.5. Magnetic Field Evolution of EE

We analyzed HMI/SDO magnetogram data to study the evolution of the photospheric magnetic field during the EE. Figure 11 (see the accompanying animation) shows the presence of a small-scale negative field (enclosed with a rectangular box) surrounded by the positive field at the location of EE. We have studied the temporal evolution of positive and negative magnetic fields as well as the flux in the boxed region and have plotted these data in Figure 11. As can be seen from the plots, negative polarity field and flux (solid lines in bottom panels) increase and decrease during the EEs on the timescale of 3–5 minutes, whereas the positive polarity field and flux (dashed lines in bottom panels) show somewhat of a decay during that time.

To find any correlation between fluctuations in the magnetic field measured from the HMI and in the intensity during the EEs measured from AIA and IRIS, we perform a correlation analysis at different time delays. The HMI magnetogram is obtained at photospheric height whereas AIA 1700 Å is formed at photospheric and temperature-minimum height and thus are more suitable for a direct correlation study. The correlation of intensity fluctuations obtained from AIA 1600 Å, and IRIS 1330 Å and 1400 Å are performed with respect to those obtained from AIA 1700 Å. The cadence of the HMI is 45 s, whereas the cadences of AIA 1600 Å and 1700 Å, and IRIS 1330 Å and 1400 Å are 24 and 15 s, respectively. We interpolated AIA 1700 Å with respect to the HMI time sequence using spline routines. We also interpolated AIA 1600 Å and IRIS 1330 Å and 1400 Å light curves with respect
to the time sequence of the original AIA 1700 Å. Thus, we obtained cross-correlation coefficients at different time delays for the pairs of the HMI magnetogram (negative polarity) and the AIA 1700 Å light curve; AIA 1700 Å and 1600 Å; AIA 1700 Å and IRIS 1330 Å; and AIA 1700 Å and IRIS 1400 Å. We plot respective pairs of light curves and correlation coefficients at different time delays in Figure 12. The maximum correlation value between the HMI magnetogram (negative polarity) and the AIA 1700 Å light curve is about 0.77 at a time delay of 135 s, which corresponds to three HMI time frames. However, the maximum correlation value between AIA 1700–1600 Å, AIA 1700–IRIS 1330 Å, and AIA 1700–IRIS 1400 Å pairs are about 0.84, 0.82, 0.79, respectively, at a time delay of 0 s. The maximum cross-correlation coefficient between AIA 1600 Å and IRIS 1330 Å, and 1400 Å are above 0.90 at a time delay of 0 s (not shown here). Thus the obtained results suggest that intensity fluctuations as recorded from AIA 1600 Å and 1700 Å and the IRIS passbands are connected to fluctuations in photospheric magnetic fields as recorded from the HMI with a time delay of about 135 s. The increase in flux and field could be related to flux emergence, whereas the decrease in magnetic field and flux could be associated with magnetic flux cancellation resulting from magnetic reconnection. Magnetic flux cancellation events underneath EEs had been previously reported by Chae et al. (1998) and recently by Huang et al. (2014). However, to the best of our knowledge, this is the first time we report such a correlated change in AIA 1700 Å, 1600 Å, C II 1330 Å, and Si IV 1400 Å intensity with photospheric magnetic field (in this case negative polarity) on a timescale of 3–5 minutes during the recurrent bursts of EEs.

In order to get further insight into the magnetic field evolution, we performed a long-term study of the sunspot region, i.e., from the time when it first emerged on the east limb in 2014 February 25, AR 11990 until the time of the analyzed EEs using the HMI observations. The region appeared as a simple sunspot (with negative polarity) within which an emergence of a positive field region was detected. This positive field region evolved with time and developed as a complete sunspot with positive polarity, suggesting a highly complex field evolution and formation of a delta-sunspot (G. R. Gupta & Tripathi, 2015, in preparation). With the evolution of the sunspot, various moving magnetic features (MMFs) were observed. Therefore, in this context it is plausible to conclude that the active region is relatively young, with several small-
scale MMFs around the sunspot. The EEs studied in the current paper were related to one of the MMFs.

4. SUMMARY AND CONCLUSIONS

In this paper we studied observations of recurrent EEs using simultaneous spectroscopic and imaging observations recorded by IRIS, AIA images, and the HMI magnetogram. To the best of our knowledge, this is the first report of such recurrent EEs using IRIS data. The recurring timescale of these EEs was about 3–5 minutes. During the event, line profiles of C II and Si IV showed enhanced broadening, with the Doppler velocity and width exceeding more than −50 and 150 km s\(^{-1}\), respectively. In addition, we identified several absorption lines on top of the broadened emission lines of C II and Si IV. Moreover, we also found a few neutral atom lines such as Cl I 1351.66 Å, C I 1354.29 Å, and C I 1355.84 Å with possible self-absorption features. While the C I 1354.29 Å and 1355.84 Å lines appeared only during the EEs, the Cl I 1351.66 Å, which was present before the EEs, showed broadening during the EEs. The lower limit on electron densities obtained using the method proposed by Peter et al. (2014) was about 10\(^{13.5}\) cm\(^{-3}\). Using the high cadence spectroscopic observations we also discovered short-period variability (∼30 and 60–90 s) within the EE bursts.

The analysis of the LOS photospheric magnetic field measured by the HMI underneath EEs indicated the emergence as well as the cancellation of the magnetic flux. The negative

Figure 12. Cross-correlation analysis between the intensity evolution of EEs obtained from AIA 1700 Å (continuous line, all panels) with the HMI magnetogram (negative polarity, top panel, dashed line), AIA 1600 Å (second panel, dashed line), IRIS 1330 Å (third panel, dashed line), and IRIS 1400 Å (bottom panel, dashed line). Cross-correlation coefficient values obtained with an original signal at different time delays are plotted in the right panels for the respective light curve pairs.

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neath the photosphere and expansion in the upper layers explained by the resistive emergence of magnetic reconnection. We believe that these features can be supports the idea of the formation of these features due to magnetic polarity magnetic flux showed continuous increase with periodic fluctuations, suggesting localized cancellations (see the bottom panels of Figure 11). The changes in AIA 1700 Å, 1600 Å, C II 1330 Å, and Si IV 1400 Å intensities correlated extremely well with the changes in the negative polarity magnetic flux on a timescale of 3–5 minutes during the recurrent bursts of EEs, which has not been reported earlier, to the best of our knowledge.

The observations of strong broadening in the C II and Si IV spectral lines, along with self-absorption and estimated high-electron density, suggest that these are lower chromospheric spectral lines, along with self-absorption and estimated high-polarity magnetic flux under-neath the photosphere and expansion in the upper layers (see, e.g., Pariat et al. 2004; Isobe et al. 2007). This concept has successfully explained the formation of Ellerman Bombs, which were originally detected in Hα observations (Ellerman 1917). In this scenario, a number of Ω loops rise due to well known Parker’s instability from underneath the photosphere and expand. During the emergence and expansion they interact with each other and the process of magnetic reconnection occurs. The process of reconnection may produce the EEs and heat the plasma locally. This process may result in cool material being stacked upon locally heated material, thus resulting in cool absorption lines superimposed on the hot emission lines as proposed by Peter et al. (2014). Therefore the observed EEs are most likely the upper atmospheric counterpart of Ellerman Bombs. This concept, however, needs to be thoroughly verified using observations recorded in the Hα line core and wings, along with IRIS observations and forward modeling of the spectral lines using MHD simulations of realistic solar atmosphere.

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Facilities: SDO (AIA, HMI).

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