NARROW-LINE-WIDTH UV BURSTS IN THE TRANSITION REGION ABOVE SUNSPOTS OBSERVED BY IRIS

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Received 2016 July 5; revised 2016 August 16; accepted 2016 August 16; published 2016 September 29

ABSTRACT

Various small-scale structures abound in the solar atmosphere above active regions, playing an important role in the dynamics and evolution therein. We report on a new class of small-scale transition region structures in active regions, characterized by strong emissions but extremely narrow Si IV line profiles as found in observations taken with the Interface Region Imaging Spectrograph (IRIS). Tentatively named as narrow-line-width UV bursts (NUBs), these structures are located above sunspots and comprise one or multiple compact bright cores at sub-arcsecond scales. We found six NUBs in two data sets (a raster and a sit-and-stare data set). Among these, four events are short-lived with a duration of ~10 minutes, while two last for more than 36 minutes. All NUBs have Doppler shifts of 15–18 km s⁻¹, while the NUB found in sit-and-stare data possesses an additional component at ~50 km s⁻¹ found only in the C II and Mg II lines. Given that these events are found to play a role in the local dynamics, it is important to further investigate the physical mechanisms that generate these phenomena and their role in the mass transport in sunspots.

Key words: line: profiles – methods: observational – Sun: atmosphere – Sun: transition region – sunspots

Supporting material: animations

1. INTRODUCTION

Small-scale structures and activities abound in solar active regions (ARs), including explosive events (Dere et al. 1989; Innes et al. 1997; Huang et al. 2014), blinkers (Harrison et al. 1999; Parnell et al. 2002), small-scale loops (Huang et al. 2015), spicules and fibrils (Wilhelm 2000; Tsiropoula et al. 2012; Pereira et al. 2014; Rouppe van der Voort et al. 2015), to name a few. Thanks to recent high-resolution observations of ARs, activities have been seen on even finer scales. For example, observations made with the High-resolution Coronal Imager (Hi-C; Kobayashi et al. 2014) have indicated signatures of magnetic braids with scales of ~0.2″ in AR loops (Curtain et al. 2013), heating events with a similar size in both moss (Testa et al. 2013) and inter-moss loops (Winebarger et al. 2013), as well as fine loops at sub-arcsecond scales (Peter et al. 2013). Using Hi-C observations, Régnier et al. (2014) reported on the discovery of small-scale brightenings named “EUV bright dots” (EUV BDs) found at the base of large-scale loops rooted at the edge of ARs with a characteristic duration of 25 s and a typical length of ~1″. More recently, the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) has discovered very broad Si IV emission profiles blended by strong absorption lines in small-scale (~1″) compact brightenings in ARs (Peter et al. 2014). These brightenings, named “hot bombs,” were suggested to be signatures of hot plasmas in the photosphere generated by magnetic reconnections. In addition, Tian et al. (2014) reported on sub-arcsecond BDs implicating heating events in the transition region (TR) above umbrae and penumbrae of sunspots underlying ARs. Deng et al. (2016) found that these BDs do not have a chromospheric response and suggested their TR formation. Similarly, BDs in sunspots were also recently reported in Hi-C observations (Alpert et al. 2016). In sunspot umbrae and penumbrae, Kleint et al. (2014) presented IRIS observations of small-scale brightenings associated with supersonic downflows, which were suggested to play a role in heating the TR above sunspots. Penumbral jets have been investigated with IRIS data and were found to be heated to TR temperature (Vissers et al. 2015).

In the present work, we report on a new class of fine-scale structures in ARs, characterized by very bright emissions but extremely narrow profiles in the Si IV line in the TR above sunspots as observed by IRIS. In what follows, we present our observations in Section 2, describe the results in Section 3, and summarize our findings in Section 4 where some discussions are also offered.

2. OBSERVATIONS

The observations analyzed in this study include two data sets. The first (DATA1) is a raster data set taken on 2014 February 16 from 20:19 UT to 21:04 UT when IRIS was targeting AR 11974 and scanned the same area twice with a 0.35″ wide slit and an exposure time of 2 s. The spectral slit scanned a 140″ × 175″ field of view (FOV) with a step size of 0.35″ and an along-slit pixel size of 0.17″, in which several sunspots and their surrounding plages were observed (see Figures 1(b)–(d)).

The second data set (DATA2) was taken on 2014 March 10 from 04:10 UT to 10:26 UT, when IRIS targeted NOAA 11998 in a sit-and-stare mode with an exposure time of 15 s. In both data sets, we analyzed the spectral data taken in the Si IV 1394 Å and 1403 Å, C II 1334 Å and 1336 Å, Mg II k 2796 Å and Mg II h 2803 Å lines as well as the continuum around 2832 Å. In both data sets, the slit-jaw (SJ) data with a spatial resolution of 0″34 taken in the 1330 Å and...
1400 Å channels were analyzed. The cadence of these images for DATA1 and DATA2 was 14 s and 33 s, respectively.

In order to determine the rest wavelength of the Si IV line, we used the chromospheric Fe II 1392.82 Å line as a reference to zero Doppler shift, and the vacuum wavelengths of the Si IV 1394 Å and 1403 Å are taken as 1393.76 Å and 1402.77 Å [see IRIS Technical Note 20 for details]. The residual orbital variation has been removed by the new version of the procedure _iris_orbitvar_corr_l2.pro._

### 3. RESULTS

#### 3.1. The Raster Data Set

We started our analysis by deriving the Si IV 1394 Å line widths in the observed FOV of DATA1. To this end, we applied a single Gaussian fit to all the spectra with good signal-to-noise ratios. We excluded those pixels with intensity at line center is lower than that 30 times of the background (taken in the continuum at \(~200\ \text{km s}^{-1}\) Doppler shift), and those pixels
that are spiked by high-energy particles and cosmic rays. The non-thermal velocities were computed by using the instrumental broadening obtained by the pre-flight measurements (31.8 mÅ for SiIV) and by assuming a formation temperature of $T_{\text{max}} = 6.3 \times 10^4$ K as given by CHIANTI (V7.1.3; Dere et al. 1997; Landi et al. 2013). We then produced a two-dimensional histogram of intensities and non-thermal velocities for the two spectral scans (see Figure 1(a)). The SiIV non-thermal velocities in the ARs range from 3 to 50 km s$^{-1}$, with the majority of the pixels lying in the range between 10 and 30 km s$^{-1}$, in agreement with previous studies (e.g., Dere & Mason 1993; Teriaca et al. 1999; De Pontieu et al. 2015, etc.). In addition, Figure 1(a) indicates that despite the spread, there exists a positive correlation between the non-thermal velocities and intensities. A similar tendency has been reported by Chae et al. (1998), who studied a quiet-Sun region using SUMER observations.

From the histogram, a tail in the distribution is clearly visible as denoted by the white square in Figure 1(a), corresponding to relatively strong emissions but very small non-thermal velocities (i.e., line widths). It turns out that the locations of the points in this tail, as given by the green pixels in the raster images (Figures 1(b)–(d)), are clustered around a few specific positions. To better see them, we enclosed these green pixels with solid-line squares and labeled them events 1–5 in Figures 1(b)–(d). An example of the SiIV, CII, and MgII k line profiles averaged over the whole area of event 4 is given in Figures 1(e)–(g). For reference, the profile averaged over the entire FOV is also presented (the insets). From Figure 1(e) one sees that the average line width of the SiIV 1394 Å profile for Event 4, for instance, is 88.8 mÅ (or, equivalently, 8.7 ± 0.7 km s$^{-1}$ in terms of non-thermal velocities), substantially narrower than the reference profile for which a width of 184.0 mÅ (or 23.8 km s$^{-1}$) is derived. In contrast, its intensity is stronger by a factor of $\sim$20 (see also Table 1). For comparison, we note that the line width and integrated intensity of the SiIV 1394 Å line in the sunspots are 64.6 mÅ (or 5.6 km s$^{-1}$) and 45.0 DN/s, respectively. The line width (non-thermal velocity) measured in the sunspot is close to that of the event, while the intensity is much smaller (the intensity of event 4 is about 2750 DN/s; see Table 1). In Figures 1(f) and (g), the CII and MgII k line profiles are fitted by excluding the self-reversal portion (Xia 2003). One sees that the CII profile for event 4 behaves in a similar fashion to SiIV even though the MgII k profile is only marginally narrower than the reference spectrum. The Doppler velocities of events 1–5 range from 15 to 17 km s$^{-1}$ measured in the two SiIV lines.

Figure 2 presents a zoom-in view of these bright features on the images taken in the SiIV, CII, MgII k, and continuum 2832 Å lines. All pixels in events 1, 3, and 4 are characterized by a narrow profile together with some strong emission in SiIV. However, for the two long-duration events (events 2 and 5), only a fraction of the pixels correspond to strong emissions and narrow line widths, thereby falling into the tail of the histogram in Figure 1(a). While the profiles at the rest pixels are significantly narrower than the reference spectra, the intensities are not as strong. Consider Figures 2(c)–(f). One sees that events 1, 3, 4, and 5 can be clearly seen in both the CII and MgII k radiance images, whereas event 2 can be hardly discerned. Regarding the continuum 2832 Å radiance images (Figures 2(g) and (h)), one can see that all five of these events are associated with sunspots. In particular, events 1 and 4 are located above the umbra of one of the small sunspots in the region, while events 3 and 5 appear above some brighter regions (likely the penumbra of the sunspot). On the other hand, event 2 is located above the umbra of a neighboring sunspot, which formed around February 13. We found that the SiIV line widths of these events are close to that of the spectra averaged from the dark sunspot region (64.6 mÅ), suggesting that the plasmas in these events are probably linked to the sunspot.

These events can also be examined from the perspective of their temporal evolution. For this purpose, we attached an animation to Figure 3, showing these events in the IRIS 1400 Å SJ images (SJIs). In addition, snapshots for individual events are also presented in the top row of Figure 3. The light curves for these events in both SJ 1330 Å and 1400 Å are shown in the bottom row of Figure 3 (see the red and black curves), from which one sees that they are similar in both channels as far as their qualitative behavior is concerned. Interestingly, events 1, 3, and 4 tend to show up in their light curves as a short-lived spike with a duration of $\lesssim$10 minutes. The spectral slit scanned events 1 and 3 in their decaying phase, but traversed event 4 at its peak. Events 2 and 5 show a different behavior in that they actually brightened multiple times, as evidenced by the many spikes in their light curves. These two events have a longer lifetime of $\gtrsim$36 minutes. A closer inspection further indicates that these events are elongated structures and comprise more than one bright cores with scales of $\lesssim$1″. For each individual event, the bright cores tend to flare up simultaneously, and they last from 41 to 297 s with an average of 146 s.

Table 1 lists the parameters for all events, giving their lifetimes, integrated intensities, intensity ratios to the reference region, FWHMs, ratios of their FWHMs to the reference spectra, their non-thermal velocities, Doppler velocities, and areas, as well as the associated intensity ratios of SiIV 1394 Å to SiIV 1403 Å. Note that event 6 is what we identified in the sit-and-stare observation (see Section 3.2). All these strongly emitting events correspond to non-thermal velocities $\lesssim$10 km s$^{-1}$ (see Table 1). They are all small-scale features and their areas in the SiIV raster images are in the range of 6 $\sim$ 36 arcsec$^2$. Furthermore, the associated intensity ratios of SiIV 1394 Å to 1403 Å range from 1.7 to 2.0. For reference, the intensity ratio of the SiIV doublet measured in the reference spectrum is $\sim$1.93. All these values are close to the ratio of a transition probability of 2 (Dere & Mason 1993; Chae et al. 1998), indicative of an optically thin line formation.

The OIV 1401.16 Å is detected in a part of events 2, 3, and 4, while the OIV 1399.77 Å appears only in a part of event 2. The ratio of these two lines in event 2 indicates an electron density of $1.5 \times 10^{10}$ cm$^{-3}$. In these events, we found various types of Mg II triplet profiles (near 2791.6 Å and 2798.8 Å) without any typical behavior. None of them is comparable with those shown in Pereira et al. (2015). We, therefore, do not pursue any further analysis.

We found that a weak response in the AIA 304 Å, 171 Å, and 211 Å channels is associated with these events. We believe that this response is caused by the TR emission contamination of the coronal channels (see O’Dwyer et al. 2010 for more details). We will investigate this issue in a future dedicated study using simultaneous EIS and IRIS data.
Table 1
Parameters of the Bright Features

| ID | Lifetime \(a\) (minutes) | Channel (Å) | Intensity (DN/s) | \(R_a\)^b | FWHM\(^c\) (mA) | \(R_b\)^d | \(V_{\text{mean}}\) (km s\(^{-1}\)) | \(V_{\text{disp}}\) (km s\(^{-1}\)) | Area (arcsec\(^2\)) | \(I_{1394}/I_{1403}\) |
|----|-----------------|-------------|-----------------|-------------|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 1  | \(\sim 6\)      | Si IV 1394  | 727             | 5.0          | 65.9            | 0.3          | 5.6 ± 0.8       | 16.0 ± 1.1      | 6.4             | 1.9             |
|    |                 | Si IV 1403  | 380             | 5.0          | 66.3            | 0.4          | 5.6 ± 0.7       | 16.2 ± 1.0      |                 |                 |
|    |                 | C II 1334   | 474             | 7.9          | 98.4            | 0.5          |                 |                 |                 |                 |
|    |                 | C II 1336   | 672             | 8.3          | 104.1           | 0.5          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 1643            | 1.1          | 273.5           | 0.6          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 1319            | 1.2          | 246.7           | 0.6          |                 |                 |                 |                 |
| 2  | \(> 36\)        | Si IV 1394  | 579             | 4.0          | 72.5            | 0.4          | 6.8 ± 0.8       | 15.1 ± 1.4      | 36.3            | 1.7             |
|    |                 | Si IV 1403  | 347             | 4.6          | 66.0            | 0.3          | 5.6 ± 0.5       | 15.9 ± 1.5      |                 |                 |
|    |                 | C II 1334   | 12              | 0.2          | 107.7           | 0.6          |                 |                 |                 |                 |
|    |                 | C II 1336   | 16              | 0.2          | 91.3            | 0.4          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 392             | 0.3          | 231.9           | 0.5          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 282             | 0.3          | 213.4           | 0.5          |                 |                 |                 |                 |
| 3  | \(\sim 3.5\)    | Si IV 1394  | 2138            | 15.2         | 85.4            | 0.5          | 7.9 ± 1.3       | 17.0 ± 2.7      | 16.9            | 1.9             |
|    |                 | Si IV 1403  | 1151            | 15.9         | 80.7            | 0.4          | 7.5 ± 1.3       | 17.2 ± 2.7      |                 |                 |
|    |                 | C II 1334   | 300             | 5.0          | 134.5           | 0.7          |                 |                 |                 |                 |
|    |                 | C II 1336   | 422             | 5.2          | 155.5           | 0.7          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 3144            | 2.1          | 455.2           | 1.0          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 2625            | 2.4          | 421.5           | 1.0          |                 |                 |                 |                 |
| 4  | \(\sim 10\)     | Si IV 1394  | 2754            | 19.6         | 88.8            | 0.5          | 8.7 ± 0.7       | 16.9 ± 3.5      | 7.5             | 1.9             |
|    |                 | Si IV 1403  | 1470            | 20.3         | 86.5            | 0.4          | 8.4 ± 0.9       | 16.9 ± 3.4      |                 |                 |
|    |                 | C II 1334   | 608             | 10.1         | 118.0           | 0.6          |                 |                 |                 |                 |
|    |                 | C II 1336   | 844             | 10.4         | 138.5           | 0.6          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 2510            | 1.7          | 410.8           | 0.9          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 2058            | 1.9          | 371.4           | 0.9          |                 |                 |                 |                 |
| 5  | \(> 45\)        | Si IV 1394  | 682             | 4.8          | 84.5            | 0.5          | 8.4 ± 0.8       | 15.4 ± 1.8      | 23.0            | 1.8             |
|    |                 | Si IV 1403  | 370             | 5.1          | 84.2            | 0.5          | 8.3 ± 0.9       | 15.6 ± 1.9      |                 |                 |
|    |                 | C II 1334   | 159             | 2.7          | 128.0           | 0.7          |                 |                 |                 |                 |
|    |                 | C II 1336   | 210             | 2.6          | 155.5           | 0.7          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 3104            | 2.0          | 414.1           | 0.9          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 2501            | 2.3          | 381.7           | 0.9          |                 |                 |                 |                 |
| 6  | \(\sim 14\)     | Si IV 1394  | 158             | 9.1          | 56.8            | 0.4          | 3.6 ± 1.0       | 16.7 ± 2.2      | 1.0             | 2.0             |
|    |                 | Si IV 1403  | 79              | 8.8          | 61.3            | 0.4          | 4.4 ± 1.2       | 18.0 ± 2.2      |                 |                 |
|    |                 | C II 1334   | 58              | 3.8          | 159.3           | 1.1          |                 |                 |                 |                 |
|    |                 | C II 1336   | 91              | 4.1          | 207.5           | 1.2          |                 |                 |                 |                 |
|    |                 | Mg II k 2796| 469             | 0.9          | 455.0           | 1.1          |                 |                 |                 |                 |
|    |                 | Mg II h 2803| 285             | 0.8          | 341.7           | 1.0          |                 |                 |                 |                 |

Notes.

\(a\) The lifetime determined from the IRIS 1400 Å SJIs. Events 2 and 5 are both visible during the entire observing period.

\(b\) The intensity ratios of the events to the reference spectra.

\(c\) FWHM of the line profiles subtracted by the instrumental width (31.8 mA for Si IV, 28.6 mA for C II and 50.54 mA for Mg II).

\(d\) The ratios of the FWHMs of the events to the reference spectra.

3.2. The Sit-and-stare Sequence

We also analyzed a sit-and-stare sequence, in which an event with very small line widths and strong intensities is observed. The two-dimensional histogram and the Si IV radiance image are given in Figures 1(h) and (i). From the histogram, one readily discerns a tail marked by the white square in Figure 1(h), which corresponds to a brightening event labeled “6” in Figure 1(i).

In Figure 4 and the animation, we present the temporal variation of event 6 seen in C II, Si IV, Mg II k, and SJ 1400 Å (Figure 4). The event appears as a compact brightening and lasts for \(\sim 14\) minutes, having a size of 1.0 arcsec\(^2\) (determined from the SJ 1400 Å image). The temporal variation of Si IV line width and intensity are given in Figure 4(f), from which one sees a dramatic decrease in line width accompanying a drastic increase in intensity. The line width of this event decreases by \(\sim 80\%\) while the intensity increases by a factor of \(\sim 20\) (see Figure 4(f)). Note that the \(R_1\) and \(R_2\) of this event listed in Table 1 were given based on the reference spectra averaging from the entire FOV. This event is found to be located above the penumbra of a sunspot seen in the IRIS SJ 2832 Å. Again, the intensity ratio of the Si IV doublet is 2 (see Table 1), suggesting optically thin emission.

In event 6, the Si IV spectra are regularly Gaussian, and the Doppler shifts are measured as \(\sim 17\) km s\(^{-1}\) (redshifted). An interesting characteristic of event 6 is that the C II and Mg II k show a clear enhancement in the red-wing at about 50 km s\(^{-1}\) (see an example given in Figure 4(h) and more in the animation). The red-wing enhancement can be better demonstrated by the C II and Mg II k red–blue asymmetry (De Pontieu...
et al. 2009; Tian et al. 2011) of the region at 45–55 km s$^{-1}$ (see Figures 4(b) and (d)). This indicates a supersonic downflow in the chromosphere. We note that supersonic downflows above sunspots have also been seen in IRIS observations (Kleint et al. 2014; Kwak et al. 2016). However, in contrast to the narrow line profiles, these supersonic flows reported previously show broad TR spectra.

4. DISCUSSION AND CONCLUSIONS

In this work, we identified six events with strong emissions but narrow spectral profiles in the IRIS Si IV spectral data obtained in ARs. These events were found to occur in compact regions in the corresponding radiance images, and are therefore named as narrow-line-width UV bursts (NUBs). We identified five events in raster data and one in a sit-and-stare sequence. These phenomena appear as one or a group of sub-arcsecond compact brightenings, either in the form of some short-lived bursts with a duration of $\sim$10 minutes (events 1, 3, 4, and 6) or as a series of brightenings lasting for $\sim$30 minutes (events 2 and 5). We suggest that the phenomena studied here are of the same class, given their similar characteristics. The different appearance from event to event is possibly due to different plasma conditions and magnetic topology. To make an appropriate classification, further investigations are required. The intensity ratios of the Si IV doublet are close to 2, indicating optically thin line formation. The Doppler velocities range from 15 to 18 km s$^{-1}$. Compared to the reference spectra, the NUBs possess only about half of the line width and emissions enhanced by a factor of 4–20. The average non-thermal velocities of these events range from 3.6 to 8.7 km s$^{-1}$ in Si IV.

Figure 2. Zoom-in view of the events in the Si IV ((a) and (b)), C II ((c) and (d)), Mg II k ((e) and (f)), and continuum 2832 Å ((g) and (h)) radiance images in DATA1. The contour (green lines) taken from the Si IV radiance images (only the areas around the events are considered) are superimposed on all images taken from the same raster to illustrate the locations of the events.

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Figure 3. Events 1–5 identified in DATA1 seen in IRIS SJ 1400 Å (panels (a1)–(e1)). They are marked by the solid-line squares (yellow) and contoured by green lines. Their IRIS SJ 1400 and 1330 Å light curves are given as black and red lines in panels (a2)–(e2). The dashed lines denote the period of the IRIS spectral slit scan. (An animation of this figure is available.)

Figure 4. Evolution of event 6 (in DATA2) seen in C II (a), C II RB asymmetry at 45–55 km s$^{-1}$ (b), Mg II k (c), Mg II k RB asymmetry at 45–55 km s$^{-1}$ (d), Si IV (e), and SJ 1400 Å (g). The temporal variation of the Si IV intensity and line width are shown with black and blue lines in (f), respectively. The dashed lines denote the period when the event occurred. Example profiles (taken from the location marked by a plus symbol in panels (a)–(e)) of C II (red) and Mg II k (black) are shown in (h). (An animation of this figure is available.)
which are significantly smaller than the reference non-thermal velocity of ≈22 km s\(^{-1}\) from DATA1 andDATA2. They are much lower than the value obtained with SUMER as well (27.65 km s\(^{-1}\) measured by Teriaca et al. 1999).

What makes the NUBs interesting is that their intensities tend to be inversely correlated with their line widths. We note that a similar inverse correlation has also been found in sunspot plumes. These are bright regions in the TR above sunspots as viewed in spectral lines formed at 10\(^5\)–10\(^6\) K, often related to large coronal loops rooted in sunspot umbrae (Foukal et al. 1974; Foukal 1976; Raymond & Foukal 1982). The densities of sunspot plumes tend to be significantly lower than in plages, whereas the temperatures tend to be one or two magnitudes lower (Foukal et al. 1974). They are dominated by downflows (Dere 1982; Brynildsen et al. 2001; Doyle & Madjarska 2003) exceeding 25 km s\(^{-1}\) at temperatures close to 200,000 K (Brynildsen et al. 2001). A comprehensive review of sunspots and sunspot plumes can be found in Solanki (2003). Using SUMER O\(\nu\) observations, Doyle & Madjarska (2003) also reported that the non-thermal velocities in a bright sunspot plume are 5 to 10 km s\(^{-1}\) lower than that in its neighboring regions. In contrast to sunspot plumes, the NUBs reported in this work are more dynamic and smaller. The possible relationship between NUBs and sunspot plumes is worth a dedicated investigation, which is, however, beyond the scope of this Letter. Nonetheless, it is certain that the NUBs we reported are located above sunspots and have similar line widths to sunspot materials. Further investigations are therefore necessary for understanding the generation mechanisms that generate these NUBs and the roles they play in the local dynamics of ARs and mass cycling in sunspots.

We thank the anonymous referee for very constructive and practical comments and suggestions, Drs. Hui Tian and J. Chae for useful discussions. This research is supported by the 973 program 2012CB825601 and National Natural Science Foundation of China (41404135, 41274178, 41474150, 41174154, 41274176, and 41474149). Z.H. thanks the Shandong provincial Natural Science Foundation (ZR2014DQ006) and the China Postdoctoral Science Foundation. M.M. acknowledges the Leverhulme Trust. 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 through an ESA PRODEX contract. Z.H. and M.M. thank ISSI for supporting the team on “Solar UV bursts—a new insight to magnetic reconnection.”

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