Spectroscopic Observations of High-speed Downflows in a C1.7 Solar Flare

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Abstract

In this paper, we analyze the high-resolution UV spectra for a C1.7 solar flare (SOL2017-09-09T06:51) observed by the Interface Region Imaging Spectrograph (IRIS). We focus on the spectroscopic observations at the locations where the cool lines of Si IV 1402.8 Å (∼10^3.8 K) and C II 1334.5/1335.7 Å (∼10^4.4 K) reveal significant redshifts with Doppler velocities up to ∼150 km s$^{-1}$. These redshifts appear in the rise phase of the flare, then increase rapidly, reach the maximum in a few minutes, and proceed into the decay phase. Combining the images from IRIS and Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, we propose that the redshifts in the cool lines are caused by the downflows in the transition region and upper chromospheric layers, which likely result from a magnetic reconnection leading to the flare. In addition, the cool Si IV and C II lines show gentle redshifts (a few tens of km s$^{-1}$) at some other locations, which manifest some distinct features from the above locations. This is supposed to originate from a different physical process.

Unified Astronomy Thesaurus concepts: Solar magnetic reconnection (1504); Active solar chromosphere (1980); Solar flares (1496); Ultraviolet astronomy (1736)

Supporting material: animation

1. Introduction

Solar flares are some of the most energetic events on the Sun (e.g., Fletcher et al. 2011) and are generally believed to be associated with magnetic reconnection (Kopp & Pneuman 1976; Masuda et al. 1994; Lin & Forbes 2000). In the standard flare model, magnetic reconnection releases massive energy in the corona, which is pre-stored in a nonpotential magnetic structure. The released energy is subsequently transported downward to the lower atmosphere through thermal conduction and/or nonthermal particles. Hence the chromospheric plasma is heated and emits strong radiation that forms flare loops. Due to enhanced thermal pressure, the heated chromospheric material moves upward to the corona and fills the flare loops that are visible in EUV and soft X-ray bands. This process is known as chromospheric evaporation (Brosius & Phillips 2004; Milligan et al. 2006a, 2006b; Doschek et al. 2013). In general, the evaporation is also accompanied by a compression of chromospheric plasma based on momentum balance (Canfield et al. 1990), which is referred to as chromospheric condensation (Fisher et al. 1985; Milligan et al. 2006a; Zhang et al. 2016).

There are several ways to investigate the energetics and dynamics of flares, of which the spectroscopic diagnostics are a classical and important one. Based on the fact that each spectral line is formed in a specific atmospheric layer, we could obtain various information on different layers of the atmosphere by using different lines. For example, the cool lines of Si IV and C II that are formed at ∼10^4.3 K and ∼10^4.4 K, respectively, could be used to diagnose the transition region (TR) and upper chromosphere (e.g., McIntosh & De Pontieu 2009; Tian et al. 2014a; Li et al. 2019). The hot Fe XXI line with a formation temperature of ∼10^7 K could reveal the physical properties of the hot corona (Tian et al. 2014b; Battaglia et al. 2015; Graham & Cauzzi 2015; Li et al. 2015; Polito et al. 2015, 2016; Young et al. 2015; Dudík et al. 2016; Brosius & Inglis 2018). In particular, the Doppler velocity can be derived from line profiles, which are good indicators of the plasma flows during a flare. For optically thin lines, blueshifts are generally due to plasma upflows whereas redshifts imply plasma downflows.

There have been a large number of studies on the blueshifts/redshifts that result from chromospheric evaporation/condensation in solar flares. For instance, blueshifts with velocities ranging from ∼50 to ∼300 km s$^{-1}$ were typically observed in the spectra of highly ionized Fe atoms (e.g., Fe XVI to Fe XXIV) from instruments such as Hinode/EIS and the Interface Region Imaging Spectrograph (IRIS; e.g., Brosius & Phillips 2004; Liu et al. 2006; Chen & Ding 2010; Zhang et al. 2016; Li et al. 2017a). Redshifts with velocities of ∼20–80 km s$^{-1}$ from the relatively cool lines of He II, O III, O V, and Fe XII were also detected owing to plasma condensation (e.g., Wuelser et al. 1994; Ding et al. 1995; Czyzakowska et al. 1999; Brosius 2003; Kamio et al. 2005; Teriaca et al. 2006; Del Zanna 2008; Milligan & Dennis 2009). Note that these blueshifts/redshifts are located on the flare ribbons.

It is worth mentioning that there are few observations that have reported the rapid redshifts (say, >100 km s$^{-1}$) in the cool lines on the flare ribbons. Instead, some rapid blueshifts or redshifts were observed on the loops, which could be interpreted as magnetic reconnection outflows. Sadykov et al. (2015) reported a strong jet-like flow with a redshift velocity of ∼100 km s$^{-1}$ in the chromospheric C II and Mg II lines just prior to a flare, which perhaps comes from the magnetic reconnection region. Reeves et al. (2015) detected intermittent fast downflows (∼200 km s$^{-1}$) in the Si IV line as evidence for magnetic reconnection between the prominence magnetic fields and the overlying coronal fields. Moreover, bidirectional outflows with velocities of tens to hundreds of km s$^{-1}$ were observed in the Si IV line in terms of a tether-cutting (TC) reconnection (Chen et al. 2016) or a separator reconnection (Li et al. 2017b). In spite of these, spectroscopic observations of magnetic reconnection are still lacking and the detailed
The Astrophysical Journal, 904:95 (10pp), 2020 December 1

Zhou et al.

physical mechanisms of fast flows appearing in some events are not fully understood yet.

Fortunately, IRIS (De Pontieu et al. 2014) provides high-resolution slit-jaw images (SJJs) as well as spectra for a large number of flares. The subarcsecond observations from IRIS reveal fine structures of flares and illustrate distinct features of plasma flows. In this work, we detect rapid redshifts with a velocity of $\sim 150$ km s$^{-1}$ in the cool SiIV and C II lines at some locations during a C1.7 flare. We also observe gentle redshifts of tens of km s$^{-1}$ in these cool lines at some other locations. Such distinct redshifts are supposed to originate from different processes. In the following, we present the observations in Section 2 and data reduction in Section 3. Then we show the results from IRIS spectral lines in detail in Section 4. In Sections 5 and 6, we give the discussions and conclusions, respectively.

2. Observations

The C1.7 flare under study occurred in the active region NOAA 12673 near the west limb. It started at $\sim 06:51$ UT and peaked at $\sim 06:56$ UT on 2017 September 9. Figure 1 gives an overview of the flare from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) images (Figures 1(a)–(f)) as well as IRIS SJJs (Figures 1(g)–(i)) at different passbands. It is seen that a sigmoid structure (marked by the black arrow) shows up in some low-temperature channels, e.g., SJJs at 1330 Å (Figures 1(g)–(i)) and AIA 1600 Å images (Figure 1(e)). Some bright loops or loop-like structures can also be seen in the images. At an early time ($\sim 06:52$ UT), a few small flare loops appear at $Y \sim -168''$ (around the IRIS slit locations C and D; see the left panels of Figure 1). At later times ($\sim 06:54$ UT and $\sim 06:56$ UT), some smaller loop-like structures show up at $Y \sim -162''$ (around the slit locations A and B, see the middle and right panels of Figure 1 and also the accompanying animation). In Figure 1(h), we overplot the contours of the line-of-sight magnetic field observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012). One can see that the four slit locations A–D are close to the magnetic inversion region. Note that some jet structures accompanying the flare can be seen in the IRIS FOV (at $Y \sim -180''$; see Figures 1(f) and (i)). We also notice that some filament plasma draining in the FOV of IRIS exists, which first appears at $\sim 06:56$ UT (see Figure 1(f), marked by the white arrow) and lasts for $\sim 15$ minutes.

Figure 2 shows the spectra of Si IV, C II, Mg II, and Fe XXI along the IRIS slit at four times. It is seen that the cool Si IV, C II, and Mg II lines show evident redshifts at locations A–D during the flare. Note that strong continuum emission and narrow cool lines also show up at locations A and B (see the first column). In addition, one can see some evident emission of the hot Fe XXI line at locations A and B, which shows clear redshifts at some times (say, 06:55:17 UT and 06:56:06 UT for location A, also see the line profiles in Figures 4(e) and (g)) except for some blueshifts at location B in part of the time. By contrast, the Fe XXI line at locations C and D are much weaker but exhibit evident blueshifts (see Figure 2(p) as well as Figures 4(f) and (h)). In this work, we select these four locations to study the typical features of the flare region, which can be divided into two groups, i.e., one for locations A and B and the other for locations C and D. These two sets of locations exhibit some distinct spectral features on the moment maps as well as in the line profiles as described in Section 4.

3. Data Reduction

The C1.7 flare was observed by IRIS and the Solar Dynamics Observatory (SDO). The IRIS slit was used to perform a medium sit-and-stare spectral observation with a high time cadence of 9.8 s. The slit has a width of 0.733 and the pixel scale along the slit is 0.06166. The spectral resolutions are 0.051 Å and 0.025 Å for NUV and FUV spectra, respectively. IRIS SJJs at 1330, 2796, and 2832 Å have a field of view (FOV) of $60'' \times 62''$ and a cadence of 28 s. The former two passbands are characteristic of the upper chromosphere and lower transition region (De Pontieu et al. 2014). The AIA on board SDO obtained UV and EUV images for this flare with a spatial resolution of 1″2 (or 0.06 pixel−1) and temporal resolutions of 24 s and 12 s, respectively. The UV and EUV bands are sensitive to plasmas at different temperatures. For example, the 131 Å, 193 Å, and 171 Å bands are for coronal plasmas with their responses peaking at $\sim 10$ MK, $\sim 1.6$ MK, and $\sim 0.6$ MK, respectively, while the 304 Å and 1600 Å bands are for chromospheric and TR plasmas with formation temperatures of $\sim 0.05$ MK and $\sim 0.1$ MK, respectively. Note that here, we use the AIA 1700 Å images and SJJs 2832 Å to make a coalignment, both of which show clear sunspot features. The uncertainty of the coalignment is estimated to be $\sim 1''$. We mainly use the Si IV 1402.8 Å line that has a formation temperature of $\sim 10^{4.8}$ K in this work. The C II lines at 1334.5 Å and 1335.7 Å ($\sim 10^{4.4}$ K), the Mg II k line at 2796.4 Å ($\sim 10^{4.0}$ K), and the Fe XXI line at 1354.1 Å ($\sim 10^{7.1}$ K) are referred to as well. For the Si IV line, we make a moment analysis to derive the total intensity (the zeroth moment) and Doppler velocity (the first moment) for the following two reasons. (1) The Si IV line profiles are very complicated in this flare, i.e., showing two or even more emission peaks (see Figure 3). (2) The ratio of the two Si IV lines at 1393.8 and 1402.8 Å somewhat deviates from 2 (ranging from $\sim 1.4$–$2.1$ at locations A–D) during the flare, indicating that the Si IV line suffers from an opacity effect (e.g., Peter et al. 2014; Yan et al. 2015; Kerr et al. 2019). For the optically thin Fe XXI line that is mainly contaminated by the C I 1354.3 Å line, we use a double Gaussian function to fit the two lines. Note that we also apply a triplet Gaussian fitting to these two lines when the C I line exhibits a red asymmetry during the flare. In order to calculate the Doppler velocity, here we use some photospheric or chromospheric lines over a relatively quiet region before the flare onset to determine the reference wavelength. For the Si IV line, the S1 1401.5 Å line is used for calibration. For the Fe XXI line, the O I line at 1355.6 Å and the C I line at 1355.8 Å are used. The reference centroids of the Si IV and Fe XXI lines are obtained to be 1402.77 Å and 1354.08 Å, respectively. The uncertainty in the Doppler velocity is thus estimated to be $\sim 1$ km s$^{-1}$, which is consistent with the velocity accuracy as reported in De Pontieu et al. (2014) and Wülser et al. (2018).

4. Results

4.1. Line Profiles and Moment Maps

Figures 3 and 4 show the line profiles at the four selected locations for some noticeable times when the Doppler velocity of Si IV shows a peak or subpeak, as indicated by the vertical dashed–dotted lines in Figures 6 and 7. It is seen that at locations A and B, the Si IV line are mostly redshifted with the Doppler velocity being over 100 km s$^{-1}$ (Figures 3(a) and (b)).
For the cooler CII and MgII lines at location A (and also at location B), they show a much stronger red-peak emission with an unshifted line core (or a central reversal; see Figures 4(a) and (c)). Note that the two CII resonance lines are blended due to a large redshift. By contrast, at locations C and D, the SiIV line profiles show two components or a red asymmetry with the Doppler velocity lower than 100 km s\(^{-1}\) (Figures 3(c) and (d)). In particular, the CII and MgII lines exhibit a redshifted line core at these two locations (Figures 4(b) and (d)). Moreover, weak but blueshifted emission is detected in the hot FeXXI line at location C (Figures 4(f) and (h)). However, at location A, the FeXXI line emission is relatively stronger and shows evident redshifts with a velocity of a few tens of km s\(^{-1}\) (Figures 4(e) and (g)).

Figure 1. Overview of the evolution of the C1.7 solar flare in AR 12673. Panels (a)–(f) are for AIA UV and EUV images, while panels (g)–(i) are for IRIS SJIs. In each panel, the two purple bars (marked by A and B) and two blue bars (marked by C and D) represent four locations that are selected for study in the work. In panels (a)–(f), the green dashed box refers to the FOV of the IRIS SJIs as shown in panels (g)–(i) and the black dashed line marks the position of the IRIS slit. The black arrow in panels (c) and (g)–(i) denotes the sigmoid structure. In panel (f), the white arrow indicates the filament plasma draining. The purple and green contours in panel (h) indicate the positive and negative magnetic fields observed from HMI, respectively. An animation of the AIA 131 Å and the IRIS SJI 1330 Å images is available in the online Journal. The animated images are annotated with the IRIS slit and the four study locations. The animation runs from 06:52:06 UT to 06:59:06 UT.

(An animation of this figure is available.)
Figure 2. IRIS spectra of the Si IV, C II, Mg II, and Fe XXI lines at four selected times during the flare. The vertical dashed–dotted lines in each panel refer to the reference centers for each of the lines. The four horizontal dashed lines (purple and blue) refer to the four locations (A–D) that are selected for study. Note that the spectra of the Si IV and Fe XXI lines are saturated to show the continuum emission.
Figure 5 gives the space–time diagram of the SiIV line intensity. One can see that locations A–D show significant brightenings that exhibit an apparent motion toward the north over time. From the Doppler velocity map of the SiIV line in Figure 5(b), it is seen that all these locations display evident redshift features that correspond to the brightenings (see the overplotted contours). However, the redshift velocities at locations A and B can be as high as 150 km s$^{-1}$, which seem to be uncommon in observations. By contrast, the redshift velocities at locations C and D are only a few tens of km s$^{-1}$, which are often observed and reported in previous studies. Note that there appear to be some notable blueshifts at the bottom part, which are supposed to be caused by the flare-accompanied jet eruptions.

4.2. Kinematic Features of the Downflows

Figures 6 and 7 show the temporal evolutions of the total intensity (the solid line marked with stars) as well as the Doppler velocity (the solid line marked with diamonds) of the Si IV line at the four locations. Here we also plot the GOES 1–8 Å soft X-ray (SXR) emission (the dashed line) and its time derivative (the dotted line) to show the evolution of the whole flare. It is seen that the time derivative of SXR emission exhibits two peaks, one at $\sim$06:54:30 UT and the other at $\sim$06:55:40 UT, which may indicate two episodes of energy release.

As shown in the top panel of Figure 6, at location A, the Si IV line intensity starts to rise at $\sim$06:54:20 UT. It shows two peaks with the first one (at $\sim$06:55:17 UT) prior to the main peak of the time derivative of GOES SXR emission, and the second one (at $\sim$06:56:05 UT) slightly after that (see the two vertical dashed–dotted lines). The temporal variation of the redshift velocity resembles that of the line intensity, only that the velocity increases a little bit earlier than the intensity. The velocity rises rapidly from $\sim$06:53:40 UT and reaches its maximum ($\sim$150 km s$^{-1}$) at $\sim$06:55:17 UT. After the velocity reaches its second peak ($\sim$140 km s$^{-1}$) at $\sim$06:56:05 UT, it gradually decreases to nearly zero at $\sim$07:00:05 UT. The variation behavior at location B (the bottom panel of Figure 6) is similar to that of location A except for a slight difference in timing. The redshifts at location B first appear at $\sim$06:54:10 UT and rise up to the first peak ($\sim$150 km s$^{-1}$) at $\sim$06:54:30 UT. Like at location A, the Doppler velocity at location B shows two peaks in coincidence with two peaks in intensity (as indicated by the two vertical dashed–dotted lines). By comparison, the Doppler velocity at location B reaches its first peak about one minute earlier than that at location A. The second peak of the velocity, however, appears at the same time for both locations A and B.

The time profiles of line intensity and Doppler velocity at locations C and D (see Figure 7) are distinct from those mentioned above. It is seen that, at location C, the intensity increases at $\sim$06:54:00 UT and shows some fluctuations. For the velocity, it starts to rise earlier at $\sim$06:52:10 UT and decreases to zero at $\sim$06:58:50 UT, also showing some fluctuations with amplitudes ranging from $\sim$30 to $\sim$50 km s$^{-1}$. Location D also reveals a fluctuation behavior in the time profiles of intensity and velocity. Compared with the redshift
velocities at locations A and B, the velocities at locations C and D are much smaller.

5. Discussions

As shown above, the two sets of locations exhibit some distinct spectral features that are supposed to originate from different processes. As the C1.7 flare studied here is small in size and especially complex in morphology, it is somewhat difficult to determine the precise positions of the four selected locations, i.e., whether at flare ribbons or on flare loops, from the present data. In this section, we only provide some possibilities or speculations for the physical origin of the redshifts and blueshifts observed at these locations.

Figure 4. Line profiles of C II 1334.5 Å and 1335.7 Å, Mg II 2796.4 Å, and Fe XXI 1354.1 Å at locations A and C. The vertical dashed–dotted line in each panel refers to the reference center of each line. In panels (a)–(d), the solid and dashed curves represent the observed line profiles at two different times that are marked in Figures 6 and 7. In panels (e)–(h), the observed line profiles are plotted in solid curves, while the fitted line profiles and the Fe XXI 1354.1 Å components are plotted in dotted and dashed curves, respectively. Note that in panels (e) and (g), the observed line profile is fitted by a triplet Gaussian function when the C I line shows a red asymmetry. The positive and negative velocities labeled in panels (e)–(h) refer to the redshift and blueshift velocities from the Fe XXI 1354.1 Å line, respectively.
For locations A and B, continuum emission and cool narrow lines show up, which seems to support that they correspond to flare ribbons. However, such high-speed (∼150 km s$^{-1}$) redshifts have scarcely been reported in the cool lines at flare ribbons and seem to be hard to explain using the ribbon scenario. In particular, relatively strong emission as well as evident redshifts are detected in the hot Fe XXI line at these two locations, which most likely originate from flare loops (e.g., Tian et al. 2014b, 2016; Young et al. 2015; Polito et al. 2018). In fact, some loop-like structures can be seen in the SJIs as well as AIA images at these two locations. Based on all of these factors, we conjecture that the flare loops probably overlap with the flare ribbons along the line of sight at locations A and B. In the following, we consider several possibilities for the origin of the high-speed (>100 km s$^{-1}$) redshifts or downflows at these two locations presuming that they are mainly contributed by flare loops: (1) projection effect, (2) filament plasma draining, (3) hot plasma cooling down, and (4) reconnection outflows.

First, considering that the flare under study is near the solar limb, we need to check the possible consequence of the projection effect. Sometimes, a particular viewing angle could attain redshifts for actual upflows. However, this is not the case here, since the angle between the line of sight and the loop axis seems to be still acute.

Second, we notice that there appears to be some filament plasma draining in this C1.7 flare as revealed by AIA 304Å images. However, after a careful check of the images, we find that the draining starts to appear in the FOV of IRIS at ∼06:56 UT, and then moves through the IRIS slit at ∼06:59 UT (Figure 8), when the high-speed redshifts at locations A and B have almost disappeared. Therefore, this filament plasma draining is unlikely to be responsible for the origin of the high-speed downflows.

Third, when some hot plasma, say, the evaporation plasma, cools down, it will produce significant redshifts, particularly in the decay phase of the flare. However, we notice that the downflows mostly appear before the SXR emission peak time, i.e., in the rise phase of the flare. Hence the cooling plasma may not be the cause of the high-speed redshifts in the rise phase.

Finally, the remaining possibility is that the high-speed downflows are a result of magnetic reconnection. This is illustrated in Figure 9. At the initial time, two coronal loops L1 and L2 are observed around the IRIS slit (Figure 9(a)). A few minutes later (∼06:54 UT), these two loops approach and
magnetic reconnection occurs between them, which produces a small flare loop Ls as well as the sigmoid structure S (Figures 9(b) and (c)). The reconnection heats the plasma and drives plasma outflows that move along the newly formed flare loop Ls. One of the outflows is located near the slit positions A and B, while the other is out of the slit region. The sigmoid structure then loses its balance and undergoes a subsequent eruption in the corona. The illustration here is in accordance with the TC model proposed by Moore et al. (2001). The high-speed redshifts are likely due to the outflow of the magnetic reconnection near the footpoint of Ls. Such high-speed Doppler velocities have also been reported by Chen et al. (2016, in which, however, the reconnection is supposed to take place in the lower atmosphere due to magnetic cancellation. Here it should also be mentioned that the accompanied redshifts in the hot Fe XXI line might be caused by a retracting of hot flare loops (e.g., Tian et al. 2014b) or termination shocks (e.g., Polito et al. 2018; Shen et al. 2018).

Locations C and D might correspond to flare loops, and their behaviors could be suitably explained by a loop scenario. The gentle blueshifts in the hot Fe XXI line as well as redshifts in the cool lines of Si IV, C II, and Mg II exhibit some fluctuations throughout the flare time, which are likely caused by hot plasma filling and cool plasma draining in the flare loops, respectively.

6. Conclusions

In this paper, we have presented spatio-temporal variations of the intensity and Doppler velocity of several UV lines including Si IV, C II, Mg II, and Fe XXI in a C1.7 flare observed by IRIS. Two sets of locations (A and B; C and D) are selected to reveal the typical features of the flare in detail. It is found that both sets of locations show evident brightenings but some distinct features in the line profiles, Doppler velocities, and their temporal evolutions. At the first set of locations A and B, the cool Si IV, C II, and Mg II lines exhibit significant redshifts with velocities as high as 150 km s\(^{-1}\). In the mean time, the hot Fe XXI line shows redshifts with a velocity of a few km s\(^{-1}\). The strong redshifts in the cool lines mainly show up in the rise phase of the flare, then increase rapidly, and proceed into the decay phase. By contrast, at the second set of locations C and D, the cool lines primarily show gentle redshifts with the velocities only up to tens of km s\(^{-1}\). Simultaneously, the hot Fe XXI line is blueshifted. The time profiles of line intensity and Doppler velocity at the second set of locations display some fluctuations throughout the flare period. All these distinct
features suggest that different physical processes play a role at different flare regions. The high-speed redshifts in the cool lines, most likely originating from flare loops, is thought to be caused by magnetic reconnection outflows, while the gentle redshifts in the cool lines could be regarded as a result of plasma draining in the flare loops.
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Figure 9. SJI 1330 Å showing the evolution of the reconnection process. In each panel, the dashed line refers to the position of the IRIS slit, on which four bars mark four locations that are selected for study. The cyan lines in panel (a) delineate two coronal loops (L1 and L2) in the initial phase of the flare, while the blue line in panels (b) and (c) shows the small flare loop (Ls) that is formed during the magnetic reconnection. The cyan curve S in panels (b) and (c) shows the sigmoid structure after reconnection.