OBSERVATION AND ANALYSIS OF BALLISTIC DOWNFLOWS IN AN M-CLASS FLARE WITH THE INTERFACE REGION IMAGING SPECTROGRAPH

SEAN R. BRANNON

Department of Physics, Montana State University, Bozeman, MT 59717, USA

Received 2016 January 22; revised 2016 August 11; accepted 2016 August 22; published 2016 December 9

ABSTRACT

Despite significant advances in instrumentation, there remain no studies that analyze observations of on-disk flare loop plasma flows covering the entire evolution from chromospheric evaporation, through plasma cooling, to draining downflows. We present results from an imaging and spectroscopic observation from the *Interface Region Imaging Spectrograph* (IRIS) of the SOL2015-03-12T11:50:00 M-class flare, at high spatial resolution and time cadence. Our analysis of this event reveals initial plasma evaporation at flare temperatures indicated by 100–200 km s^{−1} blueshifts in the Fe XXI line. We subsequently observe plasma cooling into chromospheric lines (Si IV and O IV) with ∼11 minute delay, followed by loop draining at ∼40 km s^{−1} as indicated by a “C”-shaped redshift structure and significant (∼60 km s^{−1}) non-thermal broadening. We use density-sensitive lines to calculate a plasma density for the flare loops, and estimate a theoretical cooling time approximately equal to the observed delay. Finally, we use a simple elliptical free-fall draining model to construct synthetic spectra, and perform what we believe to be the first direct comparison of such synthetic spectra to observations of draining downflows in flare loops.

Key words: Sun: chromosphere – Sun: corona – Sun: flares

1. INTRODUCTION

Solar flares are among the most energetic explosive events that occur within the solar system, and have a profound impact on the local space environment within which the Earth resides. The standard picture of the evolution of a solar flare begins with the reconnection of magnetic field lines in the corona (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), forming a series of flare loops. Once reconnected, the loops are then free to retract at the Alfvén speed, compressing and heating the plasma to several tens of megakelvin (MK) near the loop tops (Semenov et al. 1998; Longcope et al. 2009). The energy released during this process is generally thought to be transported down the flux tube from the reconnection site by some combination of non-thermal electron beams (Brown 1973) and thermal conduction (Craig & McClymont 1976; Forbes et al. 1989). Whatever the mechanism, once the energy reaches the transition region (TR) and chromosphere at the flare loop footpoints, it becomes deposited in the cool and dense plasma located there, heating it and resulting in an over-pressure, which drives upflows known as *chromospheric evaporation* (Sturrock 1973). The evaporated chromospheric plasma, now at flare temperatures, fills the loop from one or both footpoints and results in the loop appearing bright in hot coronal spectral lines.

Once the evaporation process has ceased and the flare loop has been filled with hot plasma, it begins to cool through a combination of radiative and conductive energy transfer (Antiochos & Sturrock 1978; Antiochos 1980; Culhane et al. 1994; Cargill et al. 1995). In the case of conduction, the magnetic field constrains the energy transport to be along the loops, moving thermal energy down toward the cooler layers in the chromosphere. The radiative losses, meanwhile, are responsible for the observational appearance of the loop in various wavelengths. Models differ on which of these mechanisms dominate the energy-loss process: for example, Antiochos (1980) finds support for radiatively dominated

cooling, while Antiochos & Sturrock (1978) find support for conduction-dominated cooling, and Cargill et al. (1995) find support for an early conduction phase followed by a later radiative phase. In addition to these two mechanisms, Bradshaw & Cargill (2010) show that, in the presence of bulk plasma flows, the loop can also lose thermal energy through an enthalpy flux. Whatever the mechanism, the result is that the plasma cools, loses its pressure support in the loop, and begins flowing back down toward the footpoints.

The downflowing plasma in coronal loops is often referred to as *coronal rain* (Foukal 1978, 1987). Coronal rain has been observed most frequently in the chromospheric H α line (e.g., Brueckner 1981), but has also been observed in other chromospheric and coronal lines. Schrijver (2001), Winebarger et al. (2001), and Winebarger et al. (2002), for example, all use the *Transition Region And Coronal Explorer* (Handy et al. 1999). Winebarger et al. (2002) also uses the Solar Ultraviolet Measurements of Emitted Radiation (Wilhelm et al. 1995), and Brekke et al. (1997) uses the Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995), both on board the *Solar and Heliophysics Observatory* (SOHO). Brekke et al. (1997) reports flows of ∼60 km s^{−1} along one leg of a loop, indicating possible catastrophic cooling (Cargill & Priest 1982) on one side.

Off-limb observations in H α and other wavelengths have reported a variety of downflow velocities for coronal rain. Schrijver (2001) reports velocities in TR temperatures of ∼100 km s^{−1} and a downward acceleration of ∼80 km s^{−2}, around one-third of the free-fall acceleration under solar surface gravity. Observations of off-limb prominences have also revealed that ballistic (free-fall) plasma flows often occur near the loop apexes, but that the plasma experiences reduced accelerations near the footpoints (Wiik et al. 1996; Malherbe et al. 1997; Liang et al. 2004). Finally, a recent study (Antolin et al. 2015) of off-limb coronal rain using multiple instruments suggested, among other things, that the sub-ballistic velocities commonly observed may be the result of density (and thus

pressure) inhomogeneities within the catastrophically cooling loops.

Most of the studies discussed above were limited in similar ways by instrumentation and observational techniques. First, with the exception of Brekke et al. (1997), these studies all depend on feature-tracking methods using imaging observations. These methods require there to be distinguishable density features in the plasma that can be tracked over time. Consequently, they cannot track steady flows with smooth density gradients, and it is generally impossible to determine whether a bright stationary structure is due to a static piece of plasma or to density compression from flows or shocks. In Brekke et al. (1997), the authors attempt to circumvent this issue by using spectroscopic observations from *SOHO*/CDS. As they report, however, the off-limb nature of the prominence makes it impossible to determine whether the flows are upflows or downflows. Finally, the majority of studies involve observations of off-limb prominences, which persist for hours or even days, and thus, the flows described are not relevant to actively flaring loops.

Ideally, the loops involved would be located near disk center and oriented normal to the solar surface, to avoid ambiguities in flow direction, and would either be currently undergoing, or have recently undergone, flaring activity. Unfortunately, such direct spectroscopic observations of flare loop flows are difficult to obtain: the instrument must be pointed directly at the loops as they flare, and limitations in cadence and spatial resolution mean that the loop flows may not be adequately resolved. Studies of cooling plasma in on-disk flare loops that were filled during a flare evaporation event are therefore scarce, despite the importance of direct observations of post-cooling loop flows. One significant example is Czakowska et al. (1999), which reports chromospheric evaporation in flare ribbons in the form of blueshifted Fe XVI and O V lines from a *SOHO*/CDS observation. In Figure 1 of that paper, redshifted O V lines can be noted in the loop arcade in those results. The authors primarily focused on the redshift-to-blueshift gradient across the ribbon boundary, however, and did not address the source of the arcade flows or attempt to fit a model loop velocity profile to the observed data. Additionally, the *SOHO*/CDS observation of the flare loops did not begin for more than an hour after the flare peak. Another, more recent, example is Scullion et al. (2014), which examined the strand width of cooling plasma (a measure of the magnetic field morphology) in on-disk post-flare loops in H α , but did not discuss the flow velocities.

To the best of our knowledge, therefore, no previous studies have reported on the full spectral evolution of on-disk flare loops from evaporative upflows to post-cooling downflows. As a result, there exists no start-to-finish observational confirmation of the standard model of loop filling, cooling, and draining. Launched on 2013 June 23, the *Interface Region Imaging Spectrograph* (*IRIS*; De Pontieu et al. 2014) has high-resolution and high-cadence imaging and spectroscopic instruments, recording several diagnostic lines spanning a wide range of chromospheric, TR, and coronal temperatures, and is an ideal instrument for taking observations of flare loop flows during the evaporation, cooling, and subsequent draining phases of a flare. In this paper we analyze an *IRIS* observation of a near-disk-center flare and the associated flare loops, and use the results to determine the velocity profile of the cooling plasma. The outline of the paper is as follows. In Section 2, we describe

the *IRIS* instrumentation; in Section 3, we give the details of the active region and the particular flare of our interest; in Section 4, we delve into the imaging and spectral data of the flare evolution, calculate Doppler shifts and line widths, and analyze the plasma density and cooling time; in Section 5, we present a simple ballistic flow model and calculate synthetic *IRIS* spectra; finally, in Section 6, we will briefly discuss our results and open questions.

2. INSTRUMENT

IRIS is a NASA Small Explorer mission located in low-Earth orbit, and features two primary instruments: a dual-range ultraviolet (UV) spectrograph (SG) and a four-band slit-jaw imager (SJI). The SG and the SJI have identical pixel size (0".16). The SG slit is 0".33 wide (giving an effective spatial resolution of 0".4) and 175" long, and covers two far-UV (FUV) spectral windows (1332–1358 Å and 1389–1407 Å) and one near-UV (NUV) spectral window (2783–2835 Å). The windows contain spectral lines formed over a wide range of temperatures, from photospheric (5000 K) to coronal (11 MK); however, the primary mission focus is on chromospheric and TR spectral lines. The SG slit may be placed in a single location ("sit-and-stare") or it may be rastered to provide two-dimensional spatial coverage. The SJI is used to provide context and coalignment imaging of the observation region. The SJI field of-view (FOV) is identical to the SG (175" $\times$ 175"), and records in four passbands (1335, 1400, 2796, and 2832 Å). The SJI typically operates at a reduced cadence (1/2 to 1/4) compared to the SG, due to cycling between passbands (De Pontieu et al. 2014).

The rest wavelengths of spectral lines recorded by the *IRIS* SG are dynamically shifted due to the orbital motion and thermal variations of the spacecraft. The absolute wavelength calibration of the FUV and NUV spectral windows must therefore be corrected for each spectra. To calculate this correction, we use the SSWIDL (Freeland & Handy 1998) routine `iris_orbitvar_corr_l2`, which fits the Ni I 2799.474 Å line (which, as a photospheric line, is generally expected to be unshifted when averaged over sufficient area and time) to determine the wavelength shift for the FUV spectral windows (De Pontieu et al. 2014; Tian et al. 2014). We note that this calibration technique generally leaves a residual error in the wavelength shift of 1–2 km s⁻¹ shift, which, for the purposes of this study, we choose to ignore.

3. FLARE DETAILS

The data for this paper were taken from the *IRIS* observation on 2015 March 12 that began at 05:45:19 UT and ended at 17:40:59 UT. This observation was a sit-and-stare flare watch, with a cadence of ~ 5 s for the SG and ~ 15 s for each passband of the SJI (1330, 1400, and 2832 Å). The SJI FOV was 120" $\times$ 119" and was initially centered at $[-235'', -190'']$. The target for this particular observation was a NOAA active region (AR) 12297, which on that day was a large active region located somewhat south and east of disk center. In Figure 1(a), we show the magnetogram (standard color table) taken at 11:34:14 UT by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on board the *Solar Dynamics Observatory* (*SDO*; Pesnell et al. 2012), which shows the line-of-sight (LOS) magnetic field of the region. AR 12297 rotated around the solar east limb on 2015 March 6, and at that time already

Figure 1. (a) Image of the *SDO*/HMI magnetogram (standard color scale) for NOAA AR 12297, taken shortly before the flare start at 11:34:14 UT. (b) Image of the flare ribbons taken by *SDO*/AIA 1600 Å during the flare at 12:02:40 UT. (c) Image of the flare loop arcade taken ~ 40 minutes after the flare peak by *SDO*/AIA 171 Å. (d) Full-FOV image from the *IRIS* SJI 1400 Å passband taken during the flare at 12:02:44 UT (approximately the same time as plot (b)); the SG slit is visible as a pale line running vertically down the center of the image. Color scale for all plots is RLBW (defined in Section 3). In plots (a)–(c), the *IRIS* SJI FOV is indicated for context by the solid box and the SG slit pointing is indicated by the vertical dashed line. The solid box in plot (d) indicates the zoom region for Figure 2.

possessed a complex magnetic geometry with several polarities and polarity inversion lines. During the *IRIS* observation on 2015 March 12, a strongly bipolar region centered at $[-170'', -170'']$ can be seen dominating the eastern side of the AR in Figure 1(a), with a negative polarity in the north and positive polarity in the south (an intrusion of positive polarity within the negative region can also be seen, which appeared and vanished several times during the preceding days).

Numerous flares occurred within AR 12297 during the week of 2015 March 12. Several flares occurred within the *IRIS* SJI FOV during the course of this observation, and the SG slit was well positioned over the polarity inversion line for the strong bipolar region mentioned above (see Figure 1(a)). Some of

these flares produced flare ribbons and/or loops that were crossed by the SG slit; these include a C4.3 at 08:15 UT (all times refer to GOES peak X-ray flux), a C8.4 at 09:14 UT, an M1.6 at 11:50 UT, and an M1.4 at 12:14 UT. The flare we have chosen to analyze in this paper was the M1.6 flare (SOL2015-03-12T11:50:00), which initiated at 11:38 UT and continued until the initiation of the subsequent M1.4 flare at 12:09 UT. This flare produced two chromospheric ribbons, one on either side of the polarity inversion line, which were easily visible in 1600 Å. In Figure 1(b), we show the 1600 Å image taken at 12:02:40 UT by the Atmospheric and Imaging Assembly (AIA; Lemen et al. 2012) on board *SDO*, which shows these northern and southern ribbons; note that we use a

reversed $\log_{10}$ black–white (RLBW) color scale, where white (black) is lowest (highest) intensity.

We also note several tenuous strands of 1600 Å emission that appear to connect the two ribbons. The strands generally follow paths leading from northeast to southwest, and are much fainter than the ribbons. These strands appear to coincide with the paths of the flare loops, as can clearly be seen by inspecting the *SDO*/AIA 171 Å image in Figure 1(c) (also RLBW). Note that the time for this image is 12:28:47 UT, which is ~ 26 minutes later than the 1600 Å image. This is due to significant saturation of pixels in the 171 Å passband at earlier times, and also to the fact that cooling flare plasma typically appears in 171 Å later than the formation of the loop by the flare. We see, however, that the flare loops are clearly visible arcing from northeast to southwest between the northern and southern ribbons along very similar trajectories as the strands in 1600 Å. Combined with the fact that the strands appear in 1600 Å only after the flare peak at 11:50 UT, this leads us to believe that the strands are in fact emission from the flare loops, despite the TR temperature $\log T = 5.0$ of the C IV lines that dominate the 1600 Å passband (Lemen et al. 2012).

The *IRIS* SJI observations of this flare confirm many of the same features noted above in the AIA images. In Figure 1(d), we show the full-FOV image for the *IRIS* SJI 1400 Å passband taken at 12:02:44 UT (approximately the same time as for Figure 1(b)) in RLBW. In the image the SG slit can be seen as a pale line running vertically down the center at $-182''$. For context with the *SDO* images, note that in Figures 1(a)–(c) we have indicated the *IRIS* SJI FOV by the solid black inset boxes and the SG slit position by the vertical black dashed lines. We note first that the fortuitous positioning of SG slit, perpendicular to the polarity inversion line, provides excellent coverage over both ribbons and loops for this flare. In Figure 1(d), we can see both the northern and southern flare ribbons running east to west and crossing the slit at approximately $y = -160''$ and $y = -175''$, respectively. Connecting the ribbons, we again see the flare loop strands, discussed above for the 1600 Å image, clearly visible running from northeast to southwest in 1400 Å and crossing the SG slit at multiple positions between the two ribbons. We also observe that the loop strands are significantly more distinct in this image than in Figure 1(b); we conjecture that this may be because the 1600 Å passband has a significant continuum component that obscures the flare loop emission (Lemen et al. 2012).

4. RESULTS

4.1. Flare Evolution

In order to investigate the detailed evolution of the SOL2015–03–12T11:50:00 flare, in Figure 2, we have plotted the SJI 1400 Å images (left column) for the inset box in Figure 1(d), taken at four representative times during the evolution of the flare (Row 1: 11:43:19 UT; Row 2: 11:50:09 UT; Row 3: 11:55:24 UT; and Row 4: 12:03:16 UT). The SG slit can again be seen as a pale vertical line in the center of each plot. We have also plotted the SG data along the slit (at the same times) for the O I 1355.598 Å (middle column) and Si IV 1402.772 Å (right column) spectral windows. The O I 1355.598 Å spectral window contains the Fe XXI 1354.067 Å spectral line at $\log T = 7.0$, and the Si IV 1402.772 Å spectral window is dominated by the Si IV 1402.772 Å spectral line at $\log T = 4.8$, but also contains the O IV 1399.780 Å and O IV

1401.157 Å spectral lines at $\log T = 5.2$ (De Pontieu et al. 2014). The x -axes for the spectral data are in km s^{-1} , calibrated to respectively place the Fe XXI 1354.067 Å and Si IV 1402.772 Å rest wavelength at 0 km s^{-1} , and the rest wavelength is indicated in each plot by the vertical dashed lines. All plots use the RLBW color table.

In the first row (11:43:19 UT), the flare is already several minutes in progress. We note a bright flare ribbon running roughly east to west and crossing the slit at $-160''$, and another ribbon located off the slit in the southwest corner of the image. As in the *SDO*/AIA 1600 Å image, various flare loops connecting the two ribbons can be already be observed, even though the SJI 1400 Å images primarily represent plasma at $\log T = 4.8$. Meanwhile, in the Fe XXI spectral window, we observe a bright horizontal line of emission, co-spatial with the northern ribbon position crossing the slit in the SJI at $-159''$, that stretches across the entire spectral window. This bright line is also visible in the Si IV window, and is most likely an enhancement of the continuum due to energized plasma at the flare ribbon. We also note a brightening of the Si IV 1402.772 Å line at that same position that is strongly redshifted, most likely due to chromospheric condensation. Other regions of intermittent Si IV 1402.772 Å emission, mostly redshifted, are visible between $-160''$ and $-170''$, one of which (around $-168''$) also shows O IV 1399.780 Å and O IV 1401.157 Å emission. Finally, we note a distinct “comma” shaped patch of Fe XXI 1354.067 Å emission, located between $-160''$ and $-166''$, with strong ($100\text{--}200 \text{ km s}^{-1}$) blueshift in the north transitioning to stationary farther south. We believe this to be the signature of chromospheric evaporation at the northern footpoints; presumably there is similar evaporation occurring at the southern footpoints, but the southern ribbon does not cross the SG slit at this time.

In the second row (11:50:09 UT), we note many of the same features persisting from Row 1. The loops are visible at similar intensities and have much the same paths from northeast to southwest as before. The southern ribbon remains mostly off the slit in the southwest, although it has extended somewhat toward the northeast, and the redshifted emission in the Si IV 1402.772 Å line at $-173''$ suggests it may be beginning to cross the SG slit. The continuum enhancement from the northern ribbon also persists in both SG windows, and it continues to do so for the remainder of the rows. The Si IV and O IV features south of the ribbon are still present, but have intensified. The most notable change, however, is in the Fe XXI 1354.067 Å line, which has lost the strong blueshifts in the north, extended farther south, and intensified to become a wide ($>100 \text{ km s}^{-1}$ half-width) region of bright flare plasma emission.

In the third row (11:55:24 UT), several important changes have occurred in both the SJI and the SG over the intervening 5 minutes. First, the northern ribbon has significantly lower intensity than in the previous row, although it maintains a very similar shape. The southern ribbon, meanwhile, has continued to extend to the northeast, and has begun to clearly cut across the SG slit, and we see a notable enhancement in the redshifted Si IV 1402.772 Å emission at the same position of $-173''$ as before. The flare loops in the SJI have still not significantly altered their shapes, but they have become brighter than before, and thus are more distinct. The Fe XXI 1354.067 Å emission remains stationary or slightly redshifted, but has faded somewhat over the intervening 5 minutes. The most significant change, however, is in the Si IV and O IV lines located between

Figure 2. Time series of *IRIS* SJI and SG images, in RLBW color table, for four different times (by row: 11:43:19 UT, 11:50:09 UT, 11:55:24 UT, 12:03:16 UT) showing the imaging and spectral evolution during the flare described in Section 4.1. The SJI 1400 Å images (left column) correspond to the solid inset box from Figure 1(d). The two SG spectral windows shown are O I 1355.598 Å (middle column), which contains the Fe XXI 1354.067 Å spectral line, and Si IV 1402.772 Å (right column), which also contains the O IV 1399.780 Å and O IV 1401.157 Å spectral lines. The x-axes for the spectral plots are in km s^{-1} , calibrated to respectively place the Fe XXI 1354.067 Å and Si IV 1402.772 Å rest wavelength at 0 km s^{-1} . The rest wavelength is indicated in each plot by the vertical dashed lines.

–160" and –170". These lines have all brightened, quite significantly in the case of the Si IV 1402.772 Å line, and have adopted a distinct quarter-circle shape with fainter redshifts in the north (–162") and bright stationary plasma farther south (–165").

In the final row (12:03:16 UT), we see that the southern ribbon has finally cut all the way across the SG slit, resulting in a horizontal line of continuum enhancement at –174" similar to the one in the north. Both ribbons have continued to fade in intensity, and the connecting loops have now begun to fade somewhat as well. The Fe XXI 1354.067 Å emission has faded significantly since the previous image. However, the Si IV 1402.772 Å, O IV 1399.780 Å, and O IV 1401.157 Å lines between –160" and –170" have continued to evolve into distinct "C"-shaped arcs with bright stationary emission near the center at –165" and fainter (but still bright) redshifted ($40\text{--}50\text{ km s}^{-1}$) regions to the north and south. Although we do not show the SG images for other times in this paper, we observe that this "C" shape in these three spectral lines persists for up to 20 minutes starting at $\sim 11:56$ UT and continuing, albeit at fading intensity, until $\sim 12:16$ UT.

4.2. Spectral Intensity Evolution

One technique for investigating the evolution of a plasma is to plot the total intensity for a given spectral line as a function of position and time. In plots (a) and (b) of Figure 3, we show the resulting time–distance stack plots of total intensity during the flare for the Fe XXI 1354.067 Å (a) and Si IV 1402.772 Å (b) spectral lines (integrated over a 1 Å window centered on each line). The x -axis is time in UT (between 11:36 UT and 12:36 UT), and the y -axis is Solar-Y in arcsec along the SG slit (between –155" and –180"). The color table for both plots is RL BW, and the color scale is shown to the right of each plot.

Several features are readily apparent in these two stack plots. First we note two bright, roughly horizontal, bands located in both plots at –159" and –175". These correspond to the northern and southern ribbons respectively, which is confirmed by inspection of the ribbon locations from Figure 2. The northern ribbon emission brightens abruptly at $\sim 11:42$ UT, however the southern ribbon does not significantly brighten in the SG until ~ 12 minutes later (although fainter emission can be seen back to 11:42 UT as well); this is true for both spectral windows. The delay is explained by recalling from Figure 2 that the southern ribbon does not begin to cut across the SG slit until after 11:50 UT. We additionally note that the emission for both ribbons appears to fluctuate in intensity during the flare (this is more apparent for Si IV 1402.772 Å). We speculate that this behavior may be related to the quasi-periodic fluctuations in footpoint ribbon emission, described in detail in Brannon et al. (2015) and Brosius & Daw (2015).

Between the two ribbons in both plots is a large diffuse region of emission, located between –160" and –173", which corresponds to the flaring loops seen in Figures 1(c) and 2. This loop emission appears first in the hotter Fe XXI line between –160" and –165", shortly after the northern ribbon brightens at 11:42 UT. Subsequently, the Fe XXI emission moves southward and expands to fill most of the region between the ribbons. We note two particularly intense loop emission events, occurring at –163" and –168" respectively, during the time interval between 11:48 UT and 11:54 UT, with the more northern one occurring first and followed shortly thereafter by the southern brightening. After $\sim 11:57$ UT, we observe that the

Fe XXI emission in the loops begins to fade (although significant emission remains in the parts of the loops until after 12:06 UT).

The loop emission in Si IV 1402.772 Å follows a similar pattern of evolution to that of Fe XXI, albeit shifted forward somewhat in time. From Figure 3(b), we see that the Si IV emission appears first at –165" and 11:53 UT (~ 11 minutes after the Fe XXI first appears) before expanding north and south to fill the inter-ribbon region. We observe particularly intense emission events at –165" and –168", co-spatial with the Fe XXI emission events mentioned above and of similar durations but ~ 6 minutes later. Finally, we note that the Si IV emission begins to fade after $\sim 12:12$ UT, although a distinct band of emission remains between –167" and –168" until well after 12:36 UT.

To aid in our subsequent analysis of the flare loops, we have identified the Si IV emission, which we believe to be associated with the loops by the cyan contour in Figure 3(b) (also plotted for context in Figure 3(a)). The contour begins with the appearance of significant Si IV emission at 11:52 UT near –165", and then extends north and south eventually encompassing all SG pixels between –160" and –173". Note that we have deliberately excluded the ribbon emission at the footpoints to the north and south, since the emission there is likely complicated by the more complex chromospheric footpoint geometry. We end the contour arbitrarily at around 12:19 UT, by which point the majority of the Si IV emission has faded. Due to its shape, we shall henceforth refer to this contour as the "bullet," and we will refer to all points (in space and time) as "pixels."

4.3. Doppler Velocities and Line Widths

The SG images for the Si IV 1402.772 Å window, shown in Figure 2 and discussed above, reveal a variety of different behaviors for the spectral lines in that window, which vary in both space and time during the flare. For a more detailed look at the spectral data, we have selected the Si IV 1402.772 Å spectral profiles for nine different pixels located within the bullet and plotted them in Figure 4. A copy of the Si IV intensity stack plot and cyan bullet contour is provided at the top of Figure 4 for context, and the spectral data for each pixel is plotted below. The nine pixels we selected are indicated in the context map by the "+" symbols, and we have labeled these "1"–"9" corresponding to the labels at the top of each spectral plot. The x -axes for all plots are in km s^{-1} calibrated to the reference wavelength of Si IV 1402.772 Å (indicated by the vertical dotted line at $v=0\text{ km s}^{-1}$), and the y -axes are in DN s^{-1} . Finally, we note that the times for pixels 2–3, for pixels 4–6, and for pixels 7–9 are identical within each of those three sets.

We comment first on many of the same features we have already discussed above. Early in the bullet, the Si IV line is nearly stationary, with very slight redshifts of $<10\text{ km s}^{-1}$. A few minutes later, positions away from the bullet center begin to indicate redshifted plasma and in some positions (pixel 3) increased intensity. Then, as time passes, the spectral profiles mature into the structure noted in Figure 2, with pixels to the north (4 and 7) and south (6 and 9) displaying strongly redshifted plasma and broader line widths and pixels in the center (nearer to the loop tops) displaying spectral lines that are narrower, more intense, and generally stationary. In addition to these properties, we note that the Si IV profiles of many pixels

Figure 3. Time–distance stack plots showing the evolution for (a) Fe XXI 1354.067 Å spectral intensity; (b) Si IV 1402.772 Å spectral intensity; (c) Si IV 1402.772 Å Doppler shift; and (d) Si IV 1402.772 Å NTB, as described in Sections 4.2 and 4.3. The x-axis for all plots is in UT, and the velocity color tables are shown at right of each plot. The “bullet” described in Section 4.2 is indicated by the cyan contour in plots (a)–(c) and by the white contour in plot (d).

(e.g., pixels 4, 6, 7, and 9) generally possess significant redshifted wings and/or multiple peaks that do not conform to the standard single Gaussian spectral line profile.

For this reason, as well avoiding the bookkeeping difficulties of multiple components, we have opted to utilize a moment-based analysis to obtain quantitative measurements of the line properties, rather than using a single or multiple Gaussian fitting routine. First, we select the wavelength range 1401.837–1403.707 Å (± 200 km s^{−1}) and set a lower data bound of 5 DN s^{−1} (to eliminate the background) to create a reduced data set for each pixel. We then use the SSIDL routine `moment` to extract the first four statistical moments of the reduced data. In Figure 4 we have plotted the first two moments for the data in each plot, with the mean $\bar{v}$ as the vertical dashed lines and the standard deviation σ (actually $\bar{v} \pm \sqrt{2}\sigma$) as the vertical dash-dotted lines. We note that, for all pixels, the mean tracks very closely with the spectral peak, and we shall thus refer to the mean velocity simply as “the Doppler shift” of that pixel. Likewise, we shall refer to the

quantity $\sqrt{2\sigma}$ as “the line width,” even though in some pixels (e.g., pixel 1) it actually appears to be somewhat wider than the actual $1/e$ line width (acting as an upper bound).

We can now examine the evolution of the Si IV 1402.772 Å spectral line for the bullet. In Figure 3(c), we plot the time–distance stack plot for the Doppler shift found using the above analysis. The bullet pixels are indicated with the cyan contour, and the velocity scale is given at the right. We immediately note the strong redshifts in the north and south at the positions of the ribbons observed in Figure 3. These redshifts appear at all times for the ribbons, indicating that even early in the flare the Si IV plasma at $\log T = 4.8$ is flowing down toward the footpoints characteristic of chromospheric condensation flows. Within the bullet, we observe that the plasma located near the center (near $-165''$) is stationary, whereas plasma located farther north and south of the center becomes increasingly redshifted toward the edges reaching Doppler redshifts of 40–50 km s^{−1}. Interestingly, the sound speed in a $\log T = 4.8$ plasma (as for Si IV) is 50 km s^{−1}, and thus the flows near the

Figure 4. Si IV 1402.772 Å spectral lines for nine different pixels selected from within the bullet defined above. The Si IV 1402.772 Å intensity stack plot from Figure 3 and the cyan bullet contour is provided at top for context, with the nine selected pixels indicated by the “+” symbols and labeled “1”–“9.” The x-axis for each spectral plot is in km s^{-1} , calibrated to the Si IV 1402.772 Å rest wavelength (indicated by the vertical dotted line). Note that the times for pixels 2–3, for pixels 4–6, and for pixels 7–9 are identical within each of those three sets. The vertical dashed and dash-dotted line are the Doppler velocity and line width, respectively, as described in Section 4.3.

loop footpoints at the edge of the bullet are approaching supersonic.

We also calculate the non-thermal broadening (NTB) for Si IV 1402.772 Å, given by

$$\sigma_{\text{nt}} = \sqrt{\sigma^2 - \sigma_{\text{th}}^2 - \sigma_{\text{inst}}^2}, \quad (1)$$

where σ is the total $1/e$ line half-width, $\sigma_{\text{th}} = 6.86 \text{ km s}^{-1}$ is the thermal broadening, and $\sigma_{\text{inst}} = 3.9 \text{ km s}^{-1}$ is the instrumental broadening for Si IV 1402.772 Å (De Pontieu et al. 2015). The calculated NTB is shown in Figure 3(d), with the bullet indicated by the white contour and the color scale shown at the right. For most pixels within the bullet, we find the NTB varies between 10 and 60 km s^{-1} . This value is somewhat higher than the previously reported 15–20 km s^{-1} NTB for Si IV in active regions (De Pontieu et al. 2015), although NTB of 60–80 km s^{-1} have been reported for other TR temperature spectral lines (e.g., He II, O VI) during flares (Milligan 2011).

4.4. Plasma Density

It has been well established that the O IV 1399.780 Å and O IV 1401.157 Å lines, which are recorded in the Si IV 1402.772 Å window, are a density-sensitive line pair for chromospheric and TR plasma at $\log T = 5.2$ (Flower & Nussbaumer 1975; Keenan et al. 2009). For the approximate density range $10^8 \text{ cm}^{-3} < n_e < 10^{13} \text{ cm}^{-3}$, the ratio of spectral intensities for these lines correlates in a one-to-one manner with the total electron number density n_e . Strictly speaking, the electron number densities found using this method are only valid for the portion of the plasma at the formation temperature of O IV. That said, if we assume that the plasma that appears in O IV is the same plasma initially heated and evaporated by the flare that appeared earlier in Fe XXI, and subsequently cooled sufficiently to appear in O IV and Si IV, then it is reasonable to extrapolate the densities obtained using this method to the whole of the plasma, including the portions appearing in Fe XXI and Si IV. Additionally, we note that thermal conduction (which we discuss in more detail in Section 4.5) will serve to rapidly smooth out any initial temperature inhomogeneities, meaning that the entire loop may be considered to be at a single temperature (for any given time) during the subsequent evolution.

We begin by considering a wavelength band of 0.5 Å on either side of the two O IV lines, corresponding to $N = 38$ or 39 data bins in each band, as well as a “continuum” band λ_{cont} from 1403.705 and 1404.640 Å (taken to be the generally flat spectral region between the Si IV 1402.772 Å line and the O IV 1404.806 Å line). For the continuum band, we calculate a median continuum intensity I_{cont} by first finding the median of the data over the band and then multiplying by the number of spectral bins N . For the two O IV bands, we first sum the data in each band, subtract the continuum intensity I_{cont} from each total, and divide to obtain the “absolute” intensity ratio $R = I_{1400}/I_{1401}$.

In many pixels one or both of the O IV lines are too weak to be reliable, and we set a lower bound criterion of (I_{1400}, I_{1401}) > 40.0 corresponding to approximately 1 DN s^{-1} per spectral bin above the continuum. In other pixels, the ratio can fall outside of the range corresponding to $10^8 \text{ cm}^{-3} < n_e < 10^{13} \text{ cm}^{-3}$, and cannot be reliably correlated with a density. We flag pixels violating these criteria as “unreliable.” For all other pixels, we use an interpolated

Figure 5. Time–distance stack plot showing the evolution of the plasma electron number density within the bullet, derived from the ratio of the O IV spectral intensities, as described in Section 4.4. The x-axis is in UT, and the color table values are displayed at right, with black indicating unreliable pixels. The bullet is indicated by the white contour.

density-ratio function obtained from the CHIANTI routine `density_ratio` (Dere et al. 1997; Del Zanna et al. 2015) to calculate the electron number density for the plasma in that pixel. In Figure 5, we plot the resulting densities for the same range of positions and time as for Figure 3. Unreliable pixels are colored black, and all other pixels are assigned according to the color bar on the right. The bullet is indicated by the white contour. Note that the majority of pixels outside the bullet have O IV lines that are unreliable; within the bullet, however, we find that the majority of pixels ($\sim 77\%$) are reliable.

A visual inspection of the reliable bullet pixels in Figure 5 reveals that most fall in the green-to-yellow range, corresponding to a density of 10^{11} cm^{-3} , which is very similar to expected values for flare loops. We confirm this observation with a histogram of the electron number density (with bin size $\log n_e = 0.1$) for the reliable bullet pixels in Figure 6, where we note a peak in the distribution at $n_e = 10^{10.8} \text{ cm}^{-3}$. Based on this, for the remainder of this paper we will treat the plasma density within the loops as approximately uniform in space and constant in time, with a value of $n_e \approx 10^{11} \text{ cm}^{-3}$.

4.5. Cooling Time

As noted in Section 4.2, the loop emission appears first in Fe XXI and subsequently appears ~ 11 minutes later in Si IV and O IV. The similar spatial location and appearance of the intensity features discussed above in Figure 3 suggests that the Si IV emission originates from the same evaporated plasma as the Fe XXI emission, which has subsequently cooled into the cooler spectral lines. Further, the nearly constant density in the loops (noted above) suggests that the cooling process is approximately isovolumetric.

To estimate the cooling time, we recall from Aschwanden (2005) that the radiative and conductive cooling times (in seconds) are given, respectively, by

$$\tau_{\text{rad}} = \frac{m_p c_v T}{n_e \Lambda(T)} = (3.4 \times 10^3) \frac{T^{3/2}}{n_e} \quad (2)$$

Figure 6. Histogram of plasma electron number densities (with bin size $\log n_e = 0.1$) for reliable pixels located within the bullet.

and

$$\tau_{\text{cond}} = \frac{L^2 n_e m_p c_v}{\kappa_0 T^{5/2}} = (3.7 \times 10^{-10}) \frac{n_e L^2}{T^{5/2}}, \quad (3)$$

where T is the plasma temperature (in K), n_e is the electron number density (in cm^{-3}), and L is temperature gradient length scale (in cm); we have also defined the proton mass m_p , the heat capacity at constant volume c_v , the conductive coefficient $\kappa_0 = 1.1 \times 10^{-6}$, and the radiative loss function $\Lambda(T) = (1.2 \times 10^{-19}) T^{-1/2}$ (Aschwanden 2005). For our purposes, we will approximate the temperature gradient length scale as the loop half-length. From inspection of Figure 1(c) (which best shows the coronal loops), we find that the footpoint separation for the loops that cross the slit is about $21''7$. As this observation was relatively close to disk center at the time of the flare, for the purposes of this study we will adopt a conversion factor of $730 \text{ km arcsec}^{-1}$ to obtain a footpoint separation of $\sim 15.8 \text{ Mm}$ and a loop half-length (assuming a elliptical loop with eccentricity $e = 0.8$; see Section 5 for our explanation of this choice) of $\sim 10.1 \text{ Mm}$.

From Equations (2) and (3) we note that, for a 10.1 Mm loop that begins at $\sim 11 \text{ MK}$ at density $\sim 10^{11} \text{ cm}^{-3}$, the conductive cooling time is significantly shorter than the radiative cooling time and will dominate the energy losses. As noted above, thermal conduction will quickly eliminate any initial temperature inhomogeneities that were present in the loop, resulting in the loop possessing a uniform temperature structure. Later, by the time the loop plasma has cooled sufficiently for significant Si IV and O IV emission to appear, it is the radiative energy losses that dominate. To estimate a timescale for the overall cooling from the $\sim 10 \text{ MK}$ to $\sim 80,000 \text{ K}$, we equate these two timescales and solve for T . This yields an approximate crossover temperature, T^* , at which the two energy-loss processes are approximately equal, given by

$$T^* = (5.7 \times 10^{-4}) \sqrt{n_e L}. \quad (4)$$

For a loop as described above, this yields a crossover temperature of $T^* \approx 5.7 \text{ MK}$, and substituting back into Equations (2) or (3) above gives a timescale for the loop cooling from the Fe XXI temperatures to Si IV temperatures of $\tau^* \approx 7.8$ minutes, which is somewhat faster than the observed timescale.

The above estimate is obtained by considering each mechanism independently. The actual cooling process involves both mechanisms acting together, governed by the energy equation for a plasma (Aschwanden 2005),

$$\frac{dT}{dt} = -\frac{T^*}{\tau^*} \left[\left(\frac{T}{T^*} \right)^{-3/2} + \left(\frac{T}{T^*} \right)^{5/2} \right], \quad (5)$$

for T^* and τ^* as defined above. We can solve this approximately for the cooling timescale by rearranging and integrating to obtain the relation

$$\int_0^{\tau_{\text{cool}}} dt \approx -\int_0^\infty \frac{dT}{(dT/dt)} = \tau^* \int_0^\infty \frac{dx}{x^{-3/2} + x^{5/2}}, \quad (6)$$

where we have substituted $x = T/T^*$. Numerically integrating the final relation above, we obtain $\tau_{\text{cool}} \approx 0.85 \cdot \tau^* \approx 6.6$ minutes.

One final note regarding the cooling process: note that the radiative timescale, given in Equation (2), matches the sound-transit time,

$$\tau_{\text{st}} = \frac{L}{c_s} = (5.9 \times 10^{-5}) \frac{L}{T^{1/2}}, \quad (7)$$

when each is roughly $\tau = 52 \text{ s}$ at $\log T = 6.1$. Once the temperature falls below this, it enters a phase of catastrophic cooling (Cargill & Priest 1982). In this phase, the pressure balance can no longer be maintained along the loop and the cooling plasma can be expected to fall downward under gravity, giving rise to a free-fall acceleration of the plasma.

5. SYNTHETIC SPECTRA

The structure of Doppler shifts within the bullet, shown in Figure 3(c), indicates that the plasma within the flare loops, seen in Figure 1(c), is flowing down the loops on either side from the loop tops toward the footpoints. This is in contrast to a siphon flow, which would presumably display blueshifts along one side of the loops. From Figures 3 and 5, we observe that the flare loops, visible in 171 and 1400 Å, cross the slit at an angle of 20° – 30° (on the plane-of-sky, not relative to the solar surface normal), and thus technically the Doppler shifts we observe along the north–south axis are from different loops. However, the close spacing and similar visible geometries of the loops means that we are sampling the Doppler shift for each loop at sequential positions along the loop geometry, supported by the smooth transition from stationary to redshifted spectral lines moving north and south from loop center. Finally, in Section 4.5, we found that the densities within the bullet, and hence across each of the sampled loops, are clustered around a density of 10^{11} cm^{-3} , supporting the idea that the loops are relatively similar in their evolution.

We therefore consider a simplified model in which the observed Doppler shifts are treated as resulting from flows along a single flare loop, which is then sampled at various positions along the SG slit. We will assume that the flare loop geometry may be approximated by a static ellipse with

Figure 7. Model loops and synthetic spectra as described in Section 5. (a) Two possible loop geometries, with eccentricities $e = 0.0$ (dashed line) and $e = 0.8$ (solid line). (b) Free-fall velocity (dashed line) and Doppler component (solid line) for the $e = 0.0$ loop. (c) Free-fall velocity (dashed line) and Doppler component (solid line) for the $e = 0.8$ loop. (d) Synthetic spectra for the $e = 0.0$ loop and constant NTB model. (e) Synthetic spectra for the $e = 0.8$ loop and constant NTB model. (f) Synthetic spectra for the $e = 0.8$ loop and variable NTB model. (g) Si IV 1402.772 Å spectral data from 12:03:16 UT displaying “C”-shaped redshifts (reprinted from Row 4 of Figure 2).

eccentricity $e = \sqrt{1 - 4h^2/d^2}$, where h is the maximum loop height and d is the footpoint separation. From Section 4.5, we recall that the footpoint separation was ~ 15.8 Mm. In panel (a) of Figure 7, we show the height profiles for two loops with eccentricities $e = 0.0$ (circle, dashed line) and $e = 0.8$ (ellipse,

solid line), which have maximum loop heights of ~ 7.9 Mm and ~ 4.8 Mm, respectively. These are side-on views of the loops, with the north–south footpoint separation (in Mm) on the y-axis (with solar north as indicated) and the height above solar surface (in Mm) on the x-axis; in this view, *IRIS* is located to

the right with the LOS as indicated. We emphasize that we are *not* suggesting that these two loops exist together as shown; although that might indeed be the case, we are simply considering two possible loop geometries separately.

We will further make the assumption that the flows we are observing represent plasma that begins at rest near the loop top and subsequently falls freely under the force of gravity down the sides of the loop toward the loop footpoints. This model is generally supported by our observation of the initial Fe XXI emission at the loop tops, which does not display any significant Doppler shift, which is followed later by the “C”-shaped redshifts in Si IV and O IV. In panels (b) and (c) in Figure 7 we show the velocity profiles for the total velocity (dashed lines) and Doppler velocity component (solid line), for each of the two loops $e = 0.0$ (panel (b)) and $e = 0.8$ (panel (c)). Velocity (in km s^{-1}) is along the x -axes, with the y -axes coincident to the y -axis in panel (a). We also note that, at this stage, the Doppler component of the velocity for both loops is significantly more “C”-shaped than the total velocity, a direct result of the elliptical loop shape on the angle of the flow velocity to the LOS.

To construct our synthetic *IRIS* spectra, we first construct a synthetic Si IV 1402.772 Å spectral line for every point along the loop of the form

$$I(\lambda) = \exp \left[- \left(\frac{\lambda - 1402.772 - \Delta\lambda}{\sigma_{\text{th}}^2 + \sigma_{\text{inst}}^2 + \sigma_{\text{nt}}^2} \right)^2 \right], \quad (8)$$

where $\Delta\lambda = 1403.772 \cdot v_{\text{dop}}/c$ is the Doppler shift and where $\sigma_{\text{th}} = 6.86 \text{ km s}^{-1}$ and $\sigma_{\text{inst}} = 3.9 \text{ km s}^{-1}$ (De Pontieu et al. 2015). We use two different models for the NTB. The first is a constant NTB given by $\sigma_{\text{nt}} = 12.0 \text{ km s}^{-1}$ (chosen to match the NTB of the central pixels in the bullet), and the second is a scaled NTB given by

$$\sigma_{\text{nt}} = 12.0 + 48.0 \frac{v}{\max(v)}, \quad (9)$$

which scales as the total flow velocity along the loop and yields a maximum NTB of 60 km s^{-1} near the footpoints. We next construct synthetic *IRIS* pixels by first dividing the loop into 35 equal-sized bins (in Solar- Y , i.e., along the x -axis in panel (a) of Figure 7), corresponding to the ~ 35 *IRIS* pixels wherein we observe the “C” shape. We weight each synthetic spectral line by the appropriate emission measure $EM = n_e^2 \cdot dz$, where dz is the size of each segment of the loop (which is larger near the ends due to the projection of the uniform grid in Y onto the elliptical loop) and $n_e = 10^{11} \text{ cm}^{-3}$ is the uniform loop density inferred above. Finally, we sum the weighted spectral lines over each of the 35 bins and normalize the result across all bins to a maximum intensity of 300 DN s^{-1} , corresponding roughly to the maximum intensities that we observe in the *IRIS* spectra for the “C” shape.

The resulting synthetic spectra are shown in panels (d)–(f) in Figure 7. In all three plots, the x -axis is the Doppler shift in km s^{-1} , the y -axis is Solar- Y in arcsec, and the vertical dashed line represents stationary Doppler shift (exactly as for the spectra displayed in Figure 2). For comparison, we have also plotted in panel (g) the Si IV 1402.772 Å spectral data from Row 4 in Figure 2 to show the characteristic “C”-shaped redshift pattern on the same spatial and spectral scale as panels (d)–(f). In panel (d), we show the synthetic spectra for

the $e = 0.0$ loop (dashed line in panel (a)) with the constant NTB model. We note that something like the “C” in the observed spectra does indeed appear; however, we also note that the maximum Doppler redshift, at $-160''$ and $-170''$, is somewhat too high ($>50 \text{ km s}^{-1}$ rather than the observed $40\text{--}50 \text{ km s}^{-1}$, which is not surprising given the free-fall flow speeds in panel (b)), and that the broadening near the ends of the “C” is too narrow compared with the observations. Next, in panel (e), we have plotted the synthetic spectra for the $e = 0.8$ loop (solid line in panel (a)), also with the constant NTB model. Here, we note the sight reduction in the maximum Doppler shift down to $\sim 40 \text{ km s}^{-1}$, as we would expect from the reduced maximum free-fall flow speed seen in panel (c). Once again, though, we note that the broadening at the endpoints is too narrow.

Finally, in panel (f), we show the synthetic spectra for the $e = 0.8$ loop with the scaled NTB model described above. The most striking difference between this plot and panels (d) and (e) is the significantly enhanced broadening at the ends of the “C.” Since it results from the same flow velocity as panel (e), the peak Doppler shifts at the north and south ends is again $\sim 40 \text{ km s}^{-1}$. If we compare panel (f) to the Si IV 1402.772 Å spectra shown in Row 4 of Figure 2 (reprinted for comparison in panel (g)), we see that the synthetic spectra qualitatively matches the observed data quite well in many respects. There is, however, one important exception; namely that the observed data has the highest intensity in the “C” near the center, as opposed to the synthetic data which has higher intensity at the north and south. In the synthetic data, this is because the EM weighting we applied is greater near the ends, as the segment length dz becomes longer. We will speculate on possible reasons for the discrepancy with the observed data in the discussion below.

6. DISCUSSION

In this paper, we have presented the results of our analysis of an on-disk spectroscopic observation of flare loops using the *IRIS* instrument. We found that the fortuitous positioning of the SG over the flare loops provides coverage of three important phases in the evolution of the loops during the flare: the filling of the loop with hot plasma via chromospheric evaporation (which we did not investigate in significant detail); the subsequent cooling of the flare loop plasma back into chromospheric lines; and, finally, the loop draining as revealed in the “C”-shaped pattern of redshifts in the spectra. Although previous studies have investigated all three of these phases of flare loop evolution individually (Brekke et al. 1997; Czakowska et al. 1999; Schrijver 2001; Winebarger et al. 2001, 2002), many of those studies were limited by observational techniques (e.g., off-limb loops or feature-tracking in imaging observations), and no study was able to capture all three phases from a single observation. Additionally, no study has attempted to construct a complete flow profile for a flare loop during draining; Figure 1 in Czakowska et al. (1999) shows redshifts interior to the ribbons in the arcade region, but the authors did not explore these loop flows in depth or attempt to model them. To the best of our knowledge, therefore, our work represents the first time the spectral evolution of on-disk flare loops from evaporation to draining has been observed and interpreted by using a flow model to generate synthetic spectra.

We will briefly summarize our results. We used time–distance stack plots of the Fe XXI 1354.067 Å and Si IV 1402.772 Å spectral lines to find an ~ 11 minute delay between the appearance of the hot, initially blueshifted, Fe XXI line signifying evaporation and the cooler Si IV line that was seen to be redshifted along the loop, and to identify a bullet-shaped region of interest using the Si IV intensity. After noting that the Si IV 1402.772 Å spectral line displays inconsistent components and significant redshifted wings, we opted to use a moment-based analysis to determine the Doppler shift and the NTB of the Si IV 1402.772 Å line. As expected from the spectra, we determined that the Si IV 1402.772 Å line displays $\sim 40 \text{ km s}^{-1}$ redshifts near the loop footpoints and is stationary near the loop tops. We noted significant NTB in the Si IV 1402.772 Å line, varying from $\sim 12 \text{ km s}^{-1}$ near the loop tops up to $\sim 60 \text{ km s}^{-1}$ to the north and south near the footpoints. We used the density-sensitive O IV line pair to determine the densities for pixels located within the bullet, finding a roughly uniform and constant density in the loops of $n_e \approx 10^{11} \text{ cm}^{-3}$ for those pixels, and we used this density to estimate the cooling time within the loops to be ~ 6.6 minutes. Finally, we developed a simple model, assuming free-falling plasma along the loop and using the observed Doppler shifts and NTB to constrain parameters, to create a synthetic spectra that is remarkably similar to the appearance of the observed spectra.

In Section 4.5, we estimated that the cooling time for an 11 MK plasma at the density we calculated to cool to $\sim 80,000 \text{ K}$ (~ 6.6 minutes) was approximately 40% shorter than the time delay we observed for the Fe XXI 1354.067 Å emission to fade and reappear in the Si IV 1402.772 Å and O IV 1401.157 Å spectral lines (~ 11 minutes). Generally speaking, however, it is not uncommon for flare emission to persist much longer than would be expected for a single heating event followed by simple loss mechanisms, such as conduction and radiation; we point the reader to Reeves & Warren (2002) and Qiu & Longcope (2016) for fuller discussions of this effect and possible resolutions. Certainly, our estimate is not significantly too short and is well within the correct order of magnitude. Additionally, we recall that in Section 4.2, we made note of two particular emission brightening events that do indeed appear to transition from Fe XXI 1354.067 Å to the Si IV 1402.772 Å with a ~ 6 minute delay (evident from the intensity stack plots), indicating that our estimate may in fact be accurate for at least some portions of the loops.

Another point in our estimation of the cooling time that is worth noting is that we implicitly assumed that the plasma was stationary in the loop. In the presence of bulk plasma flows, which certainly is the case in this observation, there exists an *enthalpy* flux along the loop that can add to or subtract from the total heat energy of the plasma (Bradshaw & Cargill 2010). In the case of siphon flows, this means that energy can flow from one footpoint to the other, possibly maintaining the plasma temperature against the losses described above. In our observation, however, the flows are always directed away from the loop top and toward the footpoints, meaning that any energy transport by enthalpy flux will only contribute to the total losses and potentially decrease the cooling time from what we found above. However, as noted in Section 4.3, throughout the majority of the loop volume, the Si IV 1402.772 Å redshifts indicate plasma flows that are subsonic at the line formation temperature ($< 50 \text{ km s}^{-1}$ at 80,000 K), although the velocity may approach the sound speed near the footpoints. Subsonic

flow velocities are too slow to contribute significantly to the total energy losses, and thus the flows do not likely affect the cooling timescale in our case.

We note two significant open questions regarding our synthetic spectral model. The first concerns the scaled NTB model we developed to replicate the excess NTB near the footpoints in the observed Si IV spectra. At face value, we have no particular reason to choose the NTB model that we did, other than that it makes the synthetic and observed spectra more similar. Nonetheless, the observed spectra do indeed show additional NTB nearer to the footpoints, and we are left to speculate why this may be occurring. One reason we might expect the NTB to increase as the flow velocity increases is that there is more energy available to cascade down into turbulence, resulting in a greater NTB. Another possibility is that, as noted above, the flow velocity in Si IV near the loop ends does approach the sound speed. This implies that shocks may be forming near the footpoints, and that the observed excess NTB is due to the sharp velocity gradients across the shocks. The fact that the excess NTB appears to smoothly increase from loop top to footpoints, however, would seem to contradict that scenario.

The other open question (mentioned in Section 5) is the apparent discrepancy between the observed and synthetic spectral intensity structure. Recall that the intensity of the observed spectra are greater near the loop tops than at the footpoints, whereas our synthetic spectrum displays the opposite behavior. We noted that the synthetic spectral intensity is greater to the north and south due to the nature of the EM weighting we applied. We speculate two possible explanations for the discrepancy. First, we expect from mass conservation that plasma flows will reduce the plasma density near the footpoints, resulting in reduced emission. When we calculated the densities in the loops in Section 4.4, however, we noted that the density profile running north–south was relatively uniform, and did not show significant gradients near the ends, although even a slight reduction in the density n_e would result in a more substantial decrease in the emission measure $EM \sim n_e^2$. The other possibility is that the plasma is more optically thick near the footpoints closer to the ribbon. Unfortunately, this *IRIS* observation only recorded the Si IV 1402.772 Å spectral window and did not record the Si IV 1393.757 Å spectral window, meaning that checking the optical thickness using those lines is not possible.

Throughout this paper, we have been assuming that the loop plasma is in ionization equilibrium continuously during the entire process. This is the simplest assumption, as the physics of spectral line formation for plasma in ionization equilibrium is well understood. However, it is an *a priori* assumption, and we have neither shown it to be true nor have any reason to expect it to be. The topic of *non-equilibrium ionization* (NEI) is far too complex to discuss in any detail in this paper; we refer the reader to Bradshaw & Klimchuk (2011) for an in depth discussion of NEI effects on cooling loop models. However, we do note several effects of NEI that may affect our results. First, Olluri et al. (2013) and Martínez-Sykora et al. (2016) demonstrate that the formation temperatures of Si IV and O IV lines are significantly extended toward hotter temperatures (indeed, up to 1 MK for O IV) if NEI models are incorporated. A higher formation temperature would offer another possible explanation for the enhanced NTB we observe. Second, NEI could also account for the observed reduced footpoint emission

through altering the optical thickness of the plasma for the Si IV line. We do not expect that our results for the Doppler shifts would be affected, given that we see very similar shifts in every Si IV and O IV line in the SG window. Our density analysis in Section 4.4 does depend on assuming ionization equilibrium, and NEI would presumably affect the calculated densities. If, however, we trust that the plasma density in the loops is at least 10^9 cm^{-3} , then Bradshaw & Klimchuk (2011) suggests that any NEI effects on the plasma would be small.

In closing, we repeat our statement from the introduction that *IRIS* provides a unique platform for performing observations of on-disk flare loops during the evaporation–cooling–draining process. Our analysis of this observation has revealed one particular possibility for describing for this process, and we believe this to be this first study to use such a model to interpret observed flare loop spectra during the draining phase. However, we have left open significant questions regarding both the plasma cooling process and the NTB of chromospheric lines. Resolving these issues will likely require additional imaging and spectroscopic observations with *IRIS*, perhaps in coordination with other instruments such as *Hinode/EIS*. In particular, we suggest high-cadence sit-and-stare observations similar to the one we have discussed, at similar slit orientations relative to the flare loops and preferably including the Si IV 1393.757 Å spectral window. Additionally, we suggest that a set of radiative hydrodynamic simulations brought to bear on this observation may reveal additional insights into the evolution of the *IRIS* spectra in this event, specifically whether the free-fall assumption holds up in a more physically realistic model.

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 ESA and the Norwegian Space Centre. The author wishes to thank the anonymous referee who provided constructive comments that greatly improved the quality of this paper. The author would like to especially thank Prof. Dana Longcope for his role as a graduate adviser during this research, and for his feedback on the manuscript. The author would also like to acknowledge Prof. Charles Kankelborg, Dr. Sarah Jaeggli, Prof. David McKenzie, and Bryan Joseph for helpful and productive discussions concerning this work. This work was supported by contract 8100002702 from Lockheed Martin to Montana State University.

REFERENCES

- Antiochos, S. K. 1980, *ApJ*, **220**, 1137
- Antiochos, S. K., & Sturrock, P. A. 1978, *ApJ*, **241**, 385
- Antolin, P., Vissers, G., Pereira, T. M. D., et al. 2015, *ApJ*, **806**, 81
- Aschwanden, M. J. 2005, *Physics of the Solar Corona* (Berlin: Springer)
- Bradshaw, S. J., & Cargill, P. J. 2010, *ApJ*, **717**, 163
- Bradshaw, S. J., & Klimchuk, J. A. 2011, *ApJS*, **194**, 26
- Brannon, S. R., Longcope, D. W., & Qiu, J. 2015, *ApJ*, **810**, 4
- Brekke, P., Kjeldseth-Moe, O., Brynildsen, N., et al. 1997, *SoPh*, **170**, 163
- Brosius, J. W., & Daw, A. N. 2015, *ApJ*, **810**, 45
- Brown, J. C. 1973, *SoPh*, **31**, 143
- Brueckner, P. K. 1981, in *Solar Active Regions: A monograph from Skylab Solar Workshop III*, ed. F. Q. Orrall (Boulder, CO: Colorado Associated Univ. Press), 113
- Cargill, P. J., Mariska, J. T., & Antiochos, S. K. 1995, *ApJ*, **439**, 1034
- Cargill, P. J., & Priest, E. R. 1982, *GAPFD*, **20**, 227
- Carmichael, H. 1964, in *Proc. AAS-NASA Symp., The Physics of Solar Flares*, ed. W. N. Hess (Washington, DC: NASA), 451
- Craig, I. J. D., & McClymont, A. N. 1976, *SoPh*, **50**, 133
- Culhane, J. L., Phillips, A. T., Inda-Koide, M., et al. 1994, *SoPh*, **153**, 307
- Czaykowska, A., DePontieu, B., Alexander, D., et al. 1999, *ApJL*, **521**, L75
- De Pontieu, B., McIntosh, S., Martínez-Sykora, J., et al. 2015, *ApJL*, **799**, L12
- De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, *SoPh*, **289**, 2733
- Del Zanna, G., Dere, K. P., Young, P. R., et al. 2015, *A&A*, **582**, A56
- Dere, K. P., Landi, E., Mason, H. E., et al. 1997, *A&AS*, **125**, 149
- Flower, D. R., & Nussbaumer, H. 1975, *A&A*, **45**, 145
- Forbes, T. G., Malherbe, J. M., & Priest, E. R. 1989, *SoPh*, **120**, 285
- Foukal, P. V. 1978, *ApJ*, **223**, 1046
- Foukal, P. V. 1987, in *NASA-Goddard Space Flight Center, Theoretical Problems in High Resolution Solar Physics II* (Washington, DC: NASA), 15
- Freeland, S. L., & Handy, B. N. 1998, *SoPh*, **182**, 497
- Handy, B. N., Acton, L. W., Kankelborg, C. C., et al. 1999, *SoPh*, **187**, 229
- Harrison, R. A., Sawyer, E. C., Carter, M. K., et al. 1995, *SoPh*, **162**, 233
- Hirayama, T. 1974, *SoPh*, **34**, 323
- Keenan, F. P., Crockett, P. J., Aggarwal, K. M., et al. 2009, *A&A*, **495**, 359
- Kopp, R. A., & Pneuman, G. W. 1976, *SoPh*, **50**, 85
- Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, *SoPh*, **275**, 17
- Liang, H., Zhan, L., Xiang, F., et al. 2004, *NewA*, **10**, 121
- Longcope, D. W., Guidoni, S. E., & Linton, M. G. 2009, *ApJL*, **690**, L18
- Malherbe, J.-M., Tarbell, T., Wiik, J. E., et al. 1997, *ApJ*, **482**, 535
- Martínez-Sykora, J., De Pontieu, B., Hansteen, V. H., & Gudiksen, B. 2016, *ApJ*, **817**, 46
- Milligan, R. O. 2011, *ApJ*, **740**, 70
- Olluri, K., Gudiksen, B. V., & Hansteen, V. H. 2013, *ApJ*, **767**, 43
- Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, *SoPh*, **275**, 3
- Qiu, J., & Longcope, D. W. 2016, *ApJ*, **820**, 14
- Reeves, K. K., & Warren, H. P. 2002, *ApJ*, **578**, 590
- Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, *SoPh*, **275**, 207
- Schrijver, C. J. 2001a, *SoPh*, **198**, 325
- Scullion, E., Rouppe van der Voort, L., Wedemeyer, S., et al. 2014, *ApJ*, **797**, 36
- Semenov, V. S., Volkonskaya, N. N., & Biernat, H. K. 1998, *PhPl*, **5**, 3242
- Sturrock, P. A. 1966, *Natur*, **211**, 695
- Sturrock, P. A. 1973, in *NASA Spec. Publ., Vol. 342*, ed. R. Stone & R. Ramaty (Greenbelt, MD: NASA), 3
- Tian, H., Wuelser, J. P., Boerner, P., et al. 2014, *IRIS Tech. Note 20: Wavelength Calibration*
- Wiik, J. E., Schmieder, B., Heinzel, P., et al. 1996, *SoPh*, **166**, 89
- Wilhelm, K., Curdt, W., Marsch, E., et al. 1995, *SoPh*, **162**, 189
- Winebarger, A. R., DeLuca, E. E., & Golub, L. 2001, *ApJL*, **553**, L811
- Winebarger, A. R., Warren, H., Van Ballegooijen, A., et al. 2002, *ApJL*, **567**, L89