DIRECT OBSERVATIONS OF PLASMA UPFLOWS AND CONDENSATION IN A CATASTROPHICALLY COOLING SOLAR TRANSITION REGION LOOP

N. B. ORANGE, D. L. CHESNY, H. M. OLUSEYI, K. HESTERLY, M. Patel, and P. CHAMEPE
Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA

ABSTRACT

Minimal observational evidence exists for fast transition region (TR) upflows in the presence of cool loops. Observations of such occurrences challenge notions of standard solar atmospheric heating models as well as their description of bright TR emission. Using the EUV Imaging Spectrometer on board Hinode, we observe fast upflows ($v_{\parallel} \lesssim -10 \text{ km s}^{-1}$) over multiple TR temperatures ($5.8 \lesssim \log T \lesssim 6.0$) at the footpoint sites of a cool loop ($\log T \lesssim 6.0$). Prior to cool loop energizing, asymmetric flows of $+5 \text{ km s}^{-1}$ and $-60 \text{ km s}^{-1}$ are observed at footpoint sites. These flows, speeds, and patterns occur simultaneously with both magnetic flux cancellation (at the site of upflows only) derived from the Solar Dynamics Observatory’s Helioseismic Magnetic Imager’s line-of-sight magnetogram images, and a 30\% mass influx at coronal heights. The incurred non-equilibrium structure of the cool loop leads to a catastrophic cooling event, with subsequent plasma evaporation indicating that the TR is the heating site. From the magnetic flux evolution, we conclude that magnetic reconnection between the footpoint and background field is responsible for the observed fast TR plasma upflows.

Key words: Sun: atmosphere – Sun: corona – Sun: transition region – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Definitively solving the problem of how upper solar atmospheric structures (i.e., transition region (TR) and coronal) are heated and maintained (Tripathi et al. 2012) is a paramount challenge in solar physics that remains open. Studies of plasma loops, the primary components of each level of the solar atmosphere (Hanson et al. 1980; Walker et al. 1993a, 1993b; Golub et al. 1999; Oluseyi et al. 1999a, 1999b), have vastly improved and influenced our understanding of solar atmospheric heating, most notably that of the corona (Aschwanden & Nightingale 2005; Warren et al. 2008).

These basic building blocks of the solar corona, i.e., plasma loops, are commonly classified via their peak temperature (Chitta et al. 2013). Hot loops ($\log T > 6.0$) have been extensively studied and modeled (e.g., Mackay et al. 2010; Aschwanden & Schrijver 2002; Spadaro et al. 2006), while diffuse cool (TR) loops ($\log T \lesssim 6.0$) have been studied to a much lesser extent (e.g., Chitta et al. 2013; Tripathi et al. 2012; Müller et al. 2003, 2004; Oluseyi et al. 1999a, 1999b). Recent observational and theoretical advances on the heating of plasma confined within hot loop structures have revealed that both steady-state (e.g., Winebarger et al. 2011; Warren et al. 2010) and impulsive heating (e.g., Viall & Klimchuk 2012; Tripathi et al. 2010) processes are consistent with their observed temperature and intensity structures. Impulsive heating has been found to explain the properties of cool loops (e.g., Spadaro et al. 2003) that are not in equilibrium and constantly evolving (e.g., Ugarte-Urra et al. 2009). However, the role plasma condensation plays in such processes remains unknown (Chitta et al. 2013).

Impulsive heating events, bundles of nanoflare heated loop strands, occur at coronal heights and result in chromospheric evaporation (e.g., Klimchuk et al. 2008; Klimchuk 2009). Bright TR emission is widely considered to be a response to cooling coronal plasma which was impulsively heated. The pervasively observed TR redshifts (Hansteen et al. 1996) and observations that cool loops are characterized by plasma downflows, at footpoints and along the loop structures (e.g., Del Zanna 2008; Tripathi et al. 2009), have provided significant support to such models. However, observational evidence is emerging (to our knowledge, only those reported by Tripathi et al. 2012) that reveals the existence of fast TR upflows in the presence of cool loops. The significance of such results is the introduction of challenges to standard solar atmospheric heating models. In particular, these are their descriptions on the origin of bright TR emission and heights at which coronal heating occurs. Furthermore, emerging observational evidence for fast TR upflows, mainly associated with explosive events (Beckers 1968a, 1968b) and spicules (De Pontieu et al. 2007; Langangen et al. 2008), provide increasing support that atmospheric heating is not confined to the corona.

Though observational evidence exists indicating that heating occurs in cooler regions of the solar atmosphere; the heights, timescales, and mechanisms responsible remain unclear (Tripathi et al. 2012). Moreover, a current topic of hot debate is whether fast TR upflows provide significant mass-influx to coronal heights, as well as the role they play in the generation of observed coronal phenomena (De Pontieu et al. 2009; Langangen et al. 2008; Klimchuk 2012). It is also emphasized that minimal investigations have been carried out on how plasma condensation relates to non-thermal equilibrium states of cool loops (Müller et al. 2003, 2004), while the role of the underlying magnetic field plays in such scenarios remains unquantified (Chitta et al. 2013).

In relation to the discussion above, we have a unique data set derived from observations taken with the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board Hinode that provides direct observational evidence of high-speed upflows at multiple TR temperatures occurring at the footpoint sites of a catastrophically cooling loop. We compliment these data with line-of-sight (LOS) magnetogram observations from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory to investigate the...
effects of magnetic flux evolution on both plasma upflows and the runaway cooling event.

The remainder of this paper is organized as follows. Observational data its processing and analysis are presented in the following section. Section 3 presents the measurement results, while a discussion of these results and our conclusions are provided in Sections 4 and 5, respectively.

2. OBSERVATIONS, PROCESSING, AND ANALYSIS

Observational data was obtained from EIS during the following time frame: 14:02:36 UT to 15:19:55 UT at ≈20 minute time intervals on 2011 October 18. The data consists of raster scans with a 2′′ slit width using 1″ steps resulting in a final field-of-view (FOV) of 100″ × 130″ (Figure 1). Nine emission lines providing temperature coverage from the chromosphere (log \( T \) ≈ 4.9) to the corona (log \( T \) ≈ 6.4) were used. In Table 1, we provide the emitting ions, their respective wavelengths, and peak formation temperatures.

Image pre-processing of EIS level-0 data was performed with standard Solar Software (SSW) to obtain flux calibrated data. Additional corrections were made for the spatial offset occurring between its short (171–212 Å) and long (250–290 Å) wavelength bands (Young & Gallagher 2008), instrument and orbital jitter variations (Shimizu et al. 2007), CCD spectrum drift (Mariska et al. 2007), and the tilt of the emission on the detector. The resultant EIS level-1 image data then possesses an absolute wavelength calibration of ±4.4 km s\(^{-1}\) (Kanjo et al. 2010).

The standard SSW routine eis_auto_fit.pro (Young 2010) was used to derive integrated spectral line intensities and their respective Doppler shifts, as well as build both intensity and LOS velocity images of the loop (Figures 1 and 2). This routine fits a single Gaussian to each pixel forming the raster scan with the well-known mpfit.pro algorithm and propagates uncertainties from \( \sigma \) fit uncertainties. However, we note that during this process multiple Gaussian fits were applied to both the He II 256.32 Å and O v 192.90 Å spectra due to their blending with coronal emission lines. In particular, He II 256.32 Å is blended with that of the Si x 256.37 Å and Fe x 256.41 Å lines, while O v 192.90 Å is blended with that of the Fe xi 192.83 Å line (Young et al. 2007b; Brown et al. 2008). Visual inspection of He II 256.32 Å fits were consistent with the report of Del Zanna (2013) that, in on-disk quiet Sun regions, it contributes over 80% of the observed intensity. Further support of this notion is found in a direct comparison of distinct bright network regions of the Fe x and He II intensity images in

| Ion       | Wavelength (Å) | \( \log T \) |
|-----------|----------------|-------------|
| He ii     | 256.32         | 4.9         |
| O v       | 192.90         | 5.4         |
| Fe viii   | 185.21         | 5.8         |
| Fe ix     | 197.86         | 5.9         |
| Fe x      | 184.54         | 6.0         |
| Fe xii    | 186.88         | 6.2         |
| Fe xii    | 195.12         | 6.2         |
| Fe xiv    | 274.20         | 6.3         |
| Fe xv     | 284.16         | 6.4         |

Note. Columns list ion, wavelength (Å), and logarithmic electron temperature, respectively.
cadence of \( \approx 45 \) s and corresponded to the approximately one hour of EIS observations. Magnetogram data was pre-processed using standard SSW techniques incorporating per-pixel noise subtraction (Brown et al. 2011) and then averaged over \( \approx 2.5 \) minute intervals to increase the signal-to-noise ratio with additional pointing corrections using the techniques of Orange et al. (2013a). Magnetograms were co-aligned to EIS scans, with observational time differences of \( \leq 3 \) minutes, using the SSW routine \texttt{dxot-map.pro}. A resultant alignment error of \( \leq 2'' \) was measured by cross-correlating visually bright coronal structures to strong magnetogram regions. We also note that the image’s vicinity to the solar disk center \(( \leq \pm 150'' \) in both the solar x and y directions) results in negligible projection effects.

The loop plus minimal background emission was defined by using a semi-supervised tracing algorithm applied at each observational time step to O \( \nu 192.9 \) Å (log \( T \approx 5.4 \)) intensity images (Figure 1). The resultant region was then used to isolate the loop in all other EUV images. We assigned the loop a set coordinates \( s \), corresponding to pixels along its spine, and segmented them into three distinct regions of the core and the north and south footpoints (NFP and SFP, respectively; Figure 1). Segmentation was performed using loop footpoint regions identified in Fe \( \text{viii} \) 185.2 Å (log \( T \approx 5.8 \)) intensity images at each time step. Note that the footpoint regions were visually verified in corresponding He \( \text{ii} \) 256.3 Å (log \( T \approx 4.9 \)).

Prior to measuring radiative flux \(( F_x; \text{arbitrary units}) \) as a function of loop length \( x \), we apply a rigorous background subtraction method. In this method, solar background/foreground emission is removed from the loop structure by applying custom written software to image thumbnails with the loop at the center and background/foreground emission surrounding it. The technique obtains a background estimate by first applying a low-pass filter to remove high-frequency noise such as bad pixels. Next, a histogram of the image flux is used to isolate the lowest 10%. Finally, a weighted average is applied to the lowest 98% of the isolated flux. Note that care is taken to reduce background overestimation (i.e., generation of negative pixel values) since previous studies have shown that coronal intensities of loop structures are \( \approx 10\% - 20\% \) higher than background/foreground emission (e.g., Viall & Klimchuk 2012; Del Zanna & Mason 2003). The result is a background subtracted image where pixel values are reduced by \( \approx 10\% \). We then measure \( F_x(s) \) by averaging over cross sections of loop width at each point along its spine. Light curves are generated from the total radiative flux for each respective region (i.e., loop core, NFP, and SFP) by integrating their 3\( \sigma \) brightest fluxes.

Resultant spectral intensities of the Fe \( \text{xii} \) emission lines (Table 1) were used to generate electron density images of the loop (Figure 2) via the techniques discussed by Young (2011). Note that although each Fe \( \text{xii} \) emission line is blended, previous studies have suggested, for densities \(< 10^{10} \) cm\(^{-3} \), that blending effects to the Fe \( \text{xii} \) 195 Å line are not important, consistent with results herein (Dere 2008). Moreover, Dere et al. (2007) have suggested a root-mean-square error of \( \approx 1.6 \) for the determination of densities in the quiet Sun when this line ratio is utilized in the aforementioned conditions. Then, LOS velocities \(( v_x; \text{km s}^{-1} \) \) and electron density \(( N_e; \text{cm}^{-3} \) \) are measured as a function of loop length by the techniques described above. Light curves of these parameters as a function of loop region are obtained by smoothing over the core and footpoint regions as function of time.

The loop’s footpoint regions are used to aggregate magnetic field data at each time step (Figure 1). These magnetogram data cubes are used to measure the magnetic flux density, i.e., the number of positive and negative polarity elements above and below a threshold value of 20 G, respectively. This threshold value is consistent with the average FOV strength of our magnetic field imagery. Note that analyzing magnetic field imagery in this manner provides information on flux likely contributing to reconnection events given the notion that stronger flux (i.e., > threshold) reconnects while weaker flux (i.e., < threshold) is “scattered” (Sakai et al. 1997; D. L. Chesnys, 2013, private communication).

To examine the temperature structure as a function of the loop region, we use the aforementioned measurements of the total radiative flux to execute an emission measure (EM) loci analysis via the techniques discussed by Orange et al. (2013b). We employ the physical assumptions used by Orange et al. (2013b), with exception of \( N_e \), which is derived from our measurements discussed above. Note that loci curves represent the EM as it originates from isothermal plasma at a given temperature, thereby revealing isothermal plasmas where all curves meet (Kamio et al. 2011).

3. RESULTS

Shown in the top row of Figure 3 and corresponding to the 14:20:40 UT, temperatures \( \leq 1 \) MK are characterized by visually
Figure 3. EIS intensity images (erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$) covering electron temperatures in the range of log $T \approx 4.9$–6.2 (left to right, respectively), observed on 2011 October 18 from 14:20:40 UT to 15:19:55 UT (top to bottom, respectively) showing both the cool (log $T \leq 6.0$) and hot loop (log $T > 6.0$) flux evolution. Note that an arrow identifies the filled cool loop corresponding to the time of peak emission in the core region.

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

bright footpoints and diffuse partially to unfilled loops. The cool loop can then be seen beginning to fill from the SFP to the NFP at log $T \approx 5.8$ and 14:41:17 UT (i.e., second row from top of Figure 3). The loop is completely filled (log $T \leq 6.0$), with a typical length $\approx 40$ Mm, by 14:59:21 UT (i.e., the third row from the top of Figure 3 and identified by an arrow on the Fe viii 185.2, Å image). In the last observation time, 15:19:55 UT, the loop returns to equilibrium and has cooled sufficiently given that the observed decreases in visually bright plasma. We also point out that the blending of O v 192.90 Å (log $T = 5.4$) with that of the Fe xi 192.83 Å line (log $T = 6.1$) is clearly observed in Figure 3.

In Figure 4, we have provided the light curves of the NFP, core, and SFP. In the NFP, the flux decreases until the cool loop begins to fill (14:41 UT) and increases thereafter, with the exception of log $T \geq 6.2$, which continually decreases. The core region of the loop experiences similar trends in flux evolution, as function of temperature, as that of the NFP, with the
exception $\log T \geq 6.2$, which exhibits a triangular shape. SFP light curves for temperatures over $5.8 \leq \log T \leq 6.0$ peak in irradiance at 14:41 UT, while both cooler and hotter regimes peak $\approx 20$ minutes later (14:59 UT).

In relation to the cool loop, $\log T \leq 6.0$, irradiance peaks are consistent with the structural evolution, observed in Figure 3 (i.e., consistent with previous results that the loop fills from the SFP to the NFP). In terms of temporal evolution, these flux peaks occur as follows: first the SFP at 14:41 UT, then the core at 14:59 UT, and finally the NFP at 15:19 UT. Inspection of Figure 4 indicates that the cool loop is not a result of cooling coronal material based on comparisons between peak TR and coronal fluxes at the SFP site where TR flux peaks precede those of hotter temperatures. Furthermore, the SFP peak in TR EUV flux transverses the loop back to the NFP while hotter regions peak in the NFP and progress toward the SFP site.

At the NFP prior to the appearance of the cool loop (14:20 UT; $\approx 40$ minutes), temperatures over $5.8 \leq \log T \leq 6.2$ were characterized by plasma upflow speeds of $\approx 8.0–40$ km s$^{-1}$ (Figure 5) with plasma falling at hotter and cooler temperatures. In the NFP at 14:41 UT and $\log T \approx 5.9$, the plasma upflow speed peaked at $\approx -60$ km s$^{-1}$, with upflowing plasma still occurring over a temperature range of $5.8 \leq \log T \leq 6.2$. However, at the SFP site and this same temperature range, plasma fell at a typical rate of $\lesssim 5$ km s$^{-1}$ (Figure 5). Once the cool loop was completely filled, (i.e., 14:59 UT) the plasma flow directions versus temperature returned to their typical forms, that is, upflowing plasma in the upper TR and lower corona ($5.8 \leq \log T \leq 6.2$) with falling plasma at cooler and hotter temperatures. Note that maximized NFP plasma upflows, particularly over $5.8 \leq \log T \leq 6.0$ temperatures, corresponded with the transition from upflows to downflows at similar temperatures in the SFP region.

The coronal ($\log T \approx 6.2$) electron density evolution in the NFP was roughly constant over the time frame studied here (Figure 6). However, in the SFP region, significant density fluctuations occurred and are described as follows (Figure 6). During the first $\approx 20$ minutes (14:20 UT–14:41 UT) a mass in-flow of $\approx 30\%$ is found. Next, mass-loss of $\approx 40\%$ is witnessed over the next $\approx 20$ minutes (14:41 UT–14:59 UT). Finally, during the time in which the loop cooled completely

Figure 4. Flux $F_{\lambda}$ (arbitrary units) vs. time (14:02 UT–15:19 UT) of the loop’s NFP, core, and SFP regions (left to right, respectively) displayed from top to bottom as a function of increasing temperature for the emission lines of Table 1, respectively. (A color version of this figure is available in the online journal.)
Figure 5. LOS velocity (km s$^{-1}$) vs. electron temperature (log $T$) for the NFP (asterisks) and SFP (pluses) regions derived from observational data on 2011 October 18 at the observational times of 14:20:40 UT–14:59:21 UT (top to bottom, respectively). Note that $v_\lambda < 0$ and $> 0$ indicate upflows and downflows, respectively, while $v_\lambda = 0$ is denoted by the dashed line.

(14:59 UT–15:19 UT), it continued to lose mass with a total loss of $\approx 30\%$.

In Figure 7, we have provided EM loci curves for both footpoints as a function of observation time. It is observed that a distinctive isothermal component at log $T$ $\approx 6.2$ (i.e., NFP and SFP; Figure 7). We note that, though not shown here, these results are indicative of the loop core’s EM loci analysis as well. The isothermal component is expected, given the hot loop’s consistent visually bright nature both throughout our observational sequence and emission lines with such formation temperatures (Figure 3). Furthermore, the EM loci analysis indicates that the cool loop and its footpoints, peak formation temperatures $\leq 1.0$ MK, were non-isothermal during our analysis given its broad distribution of loci curves. These results, as well as the approximately constant TR EM distribution, are suggestive of an unresolved structure (Brooks et al. 2012) and are expected given the varying visual nature observed in emission lines formed at these temperatures (Figure 3).

The EM loci analysis also indicates that the SFP is the site of condensation based on observed differences between EMs of the two footpoint regions (log $T$’s $\leq 6.0$; Figure 7). This notion is expected when a single footpoint acts as the dominant energization site (Craig & McClymont 1986; McClymont & Craig 1987). These results are further consistent with previous observations that the cool loop is filling from the SFP to the NFP. Moreover, they are consistent with both the evolution of flux and velocity observed in each of the loop regions as a function of temperature.

The evolution of the normalized magnetic flux density at both footpoint sites is shown in Figure 8. We note that the NFP and SFP sites corresponded to the positive and negative polarity magnetic flux, respectively. The positive magnetic flux density evolution, for intensities $> 20$ G, is described in detail as follows (i.e., NFP). The flux density decreased at a rate of $\approx 1\%$ minute$^{-1}$ during 14:41 UT–14:59 UT, thus correlating with the complete filling of the cool loop. While the cool loop drained and returned to equilibrium the magnetic flux density again decreased at $\approx 1\%$ minute$^{-1}$. For the SFP site, the magnetic flux density, intensities $< -20$ G, were approximately constant with minimal fluctuations, $\approx \pm 5\%$, during the observation time frame studied (Figure 8). In Figure 8, a magnetogram sequence centered on the NFP has been provided to show the major flux elements contributed to magnetic flux density measurements are contained and do not drift out of the FOV.

4. DISCUSSION

We have presented observations of a cool loop (log $T \approx 6.0$) directly below a thermally isolated hot coronal loop (log $T \approx 6.2$) recorded on 2011 October 18 by EIS near solar center ($\leq 100''$ in both the solar $x$ and $y$ directions). Our study, to the best of our knowledge, provides the first observational evidence of plasma upflows in the presence of cool loops in quiet Sun regions. HMI LOS magnetic field observations were utilized to investigate the relationship between EUV flux evolutions and plasma motion compared to that of the underlying magnetic field. The intensity and velocity structure of the cool loop showed characteristics similar to those published by Tripathi et al. (2012) for active region loops, and contrast those most typically found in the presence of such structures, e.g., redshifts along and at the footpoints of these structures (e.g., Del Zanna 2008; Tripathi et al. 2009). Both footpoints
Figure 7. EM loci curves (blue and green represent emission lines with peak formation temperatures in the TR and corona, respectively) for observation times of 14:20:40 UT–14:59:21 UT (top to bottom, respectively) of the NFP and SFP regions, left and right columns, respectively, derived from EIS emission line intensities (Table 1).
(A color version of this figure is available in the online journal.)

Figure 8. Right: evolution of the normalized magnetic surface flux density ($\rho_\Phi$; arbitrary units) for the NFP (asterisks; $\Phi^+ > 20$ G) and SFP (triangles; $\Phi^- < 20$ G) regions over the observational time frame studied herein. Left: magnetogram temporal evolution of NFP region over the observational time frame of 14:20 UT–15:19 UT from top right to bottom right in clockwise fashion, respectively.
(A color version of this figure is available in the online journal.)

were predominately blueshifted throughout the upper TR and lower corona ($5.8 \leq \log T \leq 6.2$) during the cool loop’s lifetime, except when filling began (14:41 UT). At that time, a symmetrical flow was observed that corresponded with maximal upflow speeds in the NFP region ($v_\lambda \approx 60$ km s$^{-1}$) peaking at $\log T \approx 5.9$ and decreased with increasing temperature.

As discussed in Section 1, cool loops have often been considered to be a result of cooling and condensing coronal
material that was heated impulsively over many strands at coronal heights. However, like the suggestions of Tripathi et al. (2012), our observations of plasma motions do not support models that predict upper TR and lower coronal emission lines that are dominated by redshifted emission. Our EM loci analysis indicates the presence of an unresolved structure and non-isothermal plasma throughout the cooler layers of the atmosphere (log $T \lesssim 6.0$; Figure 7). This result is expected in the presence of impulsive heating type events (Brooks et al. 2012). We explain these results by first noting that at the cool loop onset (i.e., initial filling) non-steady symmetrical flows indicate an asymmetric loop structure (Mariska et al. 1982; Craig & McClymont 1986; McClymont & Craig 1987), while plasma condensation is simultaneously occurring at the SFP site (Figure 7). The runaway cooling observed $\approx 20$ minutes later, 14:59 UT, in the lower coronal and upper TR EUV images is then indicative of the movement of the condensation region to the less heated footpoint (i.e., NFP). Craig & McClymont (1986) noted that the temperature gradient of a condensing loop leg (i.e., our SFP region) is shallower than that of the evaporating leg (i.e., our NFP region), and as such is characterized by larger EMs. Therefore, using the minima of our footpoint EM distributions, over log $T = 5.8$–6.0 (Figure 7), a heating rate asymmetry of $\approx 2\%$ existed between the NFP and SFP regions. We point out that Müller et al. (2003) reported that a 1% energy asymmetry between loop legs dictates the draining direction, which supports our observations that the condensation is driven from the SFP to the NFP. These results provide significant evidence that the catastrophic cooling event occurred from the loop’s nonequilibrium state. Moreover, the non-equilibrium state formed when plasma condensation began in a single footpoint. Below, we hypothesize on the mechanism responsible for initiating the condensation event.

Heggland et al. (2009) suggest that observations of solar atmospheric bi-directional jets are useful tools for probing the heights in which magnetic energy is converted to thermal energy. As such, bi-directional jets provide unique diagnostic tools for constraining the heights of atmospheric heating. Inspecting our velocity versus temperature profiles prior to and at the onset of loop filling (Figure 5), a bi-directional jet occurs between log $T \approx 5.4$–5.8 at the NFP site. Combining these observations with significant drops in magnetic surface flux density (Figure 8) occurring simultaneously both spatially with the NFP and temporally with peak plasma upflows, we find support that impulsive magnetic reconnection events between the photospheric footpoint and surrounding background field are the source of the jet. Consistencies between our observational reports and Heggland et al.’s (2009) TR simulated reconnection lead us to suggest that the reconnection event propelled a cool dense blob of plasma upward along the field lines to the region of the SFP. Thereby, the SFP’s sudden density enhancement (Figure 6), and most likely the conversion of magnetic wave energy to heat (Hollweg & Yang 1988; Poedts & de Groof 2004), initiated plasma condensation. However, it cannot be ruled out that a dip in the magnetic field topology, at or very near the SFP, was responsible for the initiation of plasma condensation (Müller et al. 2003).

The previous discussion points to the fact that the cool loop was heated in a single footpoint (i.e., SFP), which lead to a runaway cooling based on the nonequilibrium structure of the loop. The SFP heating event is considered to be low frequency in nature (e.g., nanoflare; Chitta et al. 2013), as this explains our EM loci results (Figure 7), while remaining consistent with previous notions of cool loops (Ugarte-Urra et al. 2009; Spadaro et al. 2003). Our pervasive blueshifts immediately after catastrophic cooling are indicative of plasma evaporation (Tripathi et al. 2012) and suggest that the origin of the nanoflare storm was cooler regions of the solar atmosphere, particularly the upper TR. Moreover, these notions support footpoint heating scenarios, possibly at higher temperatures than typically considered (Tripathi et al. 2012; Aschwanden et al. 2007). Finally, our results also point to the fact that this whole process can be considered to be a direct result of TR magnetic reconnection in the opposing loop leg. Therefore, we have presented strong evidence supporting notions that coronal heating is not confined only to coronal temperatures while tracing the origin of its magnetic energy conversion source.

It is worth noting that, for log $T \gtrsim 6.2$, light curves indicate footpoint heating of the hot loop in the NFP region, which peaked at $\approx 14:20$ UT (Figure 4). Coronal EM loci provide evidence of condensation simultaneously occurring in time and spatial regions (Figure 7). Using the techniques discussed previously, a heating asymmetry of $\sim 5\%$ was measured between the footpoints for temperatures of log $T \approx 6.2$–6.4 (Figure 7). These results further support our suggestion of footpoint heating for the hot loop (i.e., NFP region), as well as the reports of Tripathi et al. (2012) and Aschwanden et al. (2007). Finally, symmetrical flows in the hot loop at log $T \approx 6.2$ and 14:20 UT (Figure 5) provide evidence that the heating event occurred at coronal heights with high enough frequency to maintain its visually and isothermally stable nature (Figures 3 and 7, respectively).

5. CONCLUSION

This work has presented step by step the life cycle of a cool loop and emphasized the importance of the TR as the site of coronal heating. Our results have provided significant insight on the relationship between non-equilibrium structuring and condensation in cool plasma loops. It has also provided the first observational evidence, to the best of our knowledge, of plasma upflows in the presence of cool loops in quiet Sun regions while supporting the findings of Tripathi et al. (2012) for cool active region loops. We have built upon the work of Tripathi et al. (2012) by including complimentary LOS magnetogram data and coronal density evolution. We conclude from the evolution of the underlying magnetic flux that observed TR upflows are an indication of magnetic reconnection at similar atmospheric heights.

We recognize that more observations are required to provide conclusive statements about the specifics of cool loop heating and the shared relationship between their continuous evolution and plasma condensation, which are planned for a forthcoming paper. Moreover, these are required to better understand the cool loop’s non-equilibrium nature as it relates to both asymmetrical and symmetrical flow patterns. Finally, plasma upflows in cool loops require further observational evidence to be used as constraints on the models proposed by Müller et al. (2003, 2004) to determine their validity. Last, we have not made suggestions on whether any heating connection exists between the cool and hot loop. However, significant coronal mass-influx peaking simultaneously with TR plasma upflows suggest that such a connection exists. These notions give rise to questions of the mass and energy coupling relationship shared between these two loop structures, the TR and corona in general, and whether the high frequency heating events of the hot loop are a direct
result of the conversion of magnetic to thermal energy at TR heights.

The authors greatly appreciate the reviewer’s constructive comments on the manuscript. This research was supported by National Aeronautics and Space Administration (NASA) grant NNX-07AT01G and National Science Foundation (NSF) grant AST-0736479. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF or NASA. N. B. Orange was also supported by the Florida Space Grant Consortium, a NASA sponsored program administered by the University of Central Florida, grant NNX-10AM01H.

REFERENCES

Aschwanden, M. J., & Nightingale, R. W. 2005, ApJ, 633, 499
Aschwanden, M. J., & Schrijver, C. J. 2002, ApJS, 142, 269
Aschwanden, M. J., Winebarger, A., Tsiklauri, D., & Peter, H. 2007, ApJ, 659, 1673
Beckers, J. M. 1968a, SoPh, 3, 367
Beckers, J. M. 1968b, SoPh, 3, 367
Brooks, D. H., Warren, H. P., & Ugart-Urra, I. 2012, ApJL, 755, L33
Brown, C. M., Feldman, U., Seely, J. F., Korendyke, C. M., & Harra, H. 2008, ApJS, 176, 511
Brown, D., Regnier, S., Marsh, M., & Bewsher, D. 2011, STFC Advanced Summer School 2010: Working with Data from the Solar Dynamics Observatory, http://helio.cfa.harvard.edu/trace/SSXG/ynsu/I/sdo_primer_V1.1.pdf
Chitta, L., Kariyappa, R., van Ballegooijen, A. A., et al. 2013, ApJ, 768, 32
Craig, I. J. D., & McClymont, A. N. 1986, ApJ, 307, 367
Culhane, J. L., Harra, L. K., James, A. M., et al. 2007, SoPh, 243, 19
Del Zanna, G. 2003, A&A, 406, 1089
Del Zanna, G., & Mason, H. E. 2002, ApJS, 142, 269
De Pontieu, B., McIntosh, S. W., Hansteen, V. H., & Schrijver, C. J. 2009, ApJL, 701, L1
De Pontieu, B., McIntosh, S., Hansteen, V. H., et al. 2007, PASJ, 59, 655
Dere, K. P. 2008, A&A, 491, 561
Dere, K. P., Doschek, G. A., Mariska, J. T., et al. 2007, PASI, 59, 721
Golub, L., Bookbinder, J., Deluca, E., et al. 1999, PhPl, 6, 2205
Hanson, J. M., Roelof, E. C., & Gold, R. E. 1980, NASA STI/Recon Technical Report N 81 (Pt. Belvoir, VA: Ft. Belvoir Defense Tech. Info. Center), 28032
Hansteen, V., Malathy, P., & Malagoli, A. 1996, in ASP Conf. Ser. 111, Magnetic Reconnection in the Solar Atmosphere, ed. R. D. Bentley & J. T. Mariska (San Francisco, CA: ASP), 116
Heggland, L., De Pontieu, B., & Hansteen, V. H. 2009, ApJ, 702, 1
Hollaegg, J., & Yang, G. 1988, JGR, 93, 5423
Kamio, S., Curtid, W., Teriaca, L., & Innes, D. E. 2011, A&A, 529, A21
Kamio, S., Hara, H., Watanabe, T., Fredvik, T., & Hansteen, V. H. 2010, SoPh, 266, 209
Klimchuk, J. A. 2009, in ASP Conf. Ser. 415, The Second Hinode Science Meeting: Beyond Discovery—Toward Understanding, ed. B. Lites, M. Cheung, T. Magara, J. Mariska, & K. Reeves (San Francisco, CA: ASP), 221
Klimchuk, J. A. 2012, IGRF, 117, 12102
Klimchuk, J. A., Patsourakos, S., & Cargill, P. J. 2008, ApJ, 682, 1351
Langangen, O., De Pontieu, B., Carlsson, M., et al. 2008, ApJL, 679, L167
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 333
Mariska, J. T., Doschek, G. A., Boris, J. P., Oran, E. S., & Young, T. R., Jr. 1982, ApJ, 255, 783
Mariska, J. T., Warren, H. P., Ugart-Urra, I., et al. 2007, PASJ, 59, 713
McClymont, A. N., & Craig, I. J. D. 1987, ApJ, 317, 402
Müller, D. A. N., Hansteen, V. H., & Peter, H. 2003, A&A, 411, 605
Müller, D. A. N., Peter, H., & Hansteen, V. H. 2004, A&A, 424, 289
Oluseyi, H. M., Walker, A. B. C., II, Porter, J., Hoover, R. B., & Barbee, T. W., Jr. 1999a, ApJ, 524, 1105
Oluseyi, H. M., Walker, A. B. C., II, Santiago, D. I., Hoover, R. B., & Barbee, T. W., Jr. 1999b, ApJ, 527, 992
Orange, N. B., Oluseyi, H. M., Chesney, D. L., et al. 2013a, SoPh
Orange, N. B., Oluseyi, H. M., Chesney, D. L., et al. 2013b, SoPh
Poedts, S., & de Groof, A. 2004, in Proc. SOHO 15 Workshop: Coronal Heating, ed. R. W. Walsh, J. Ireland, D. Danesy, & B. Fleck (Paris: ESA), 62
Sakai, J. I., Ryutova, M., Schrijver, K., et al. 1997, BAAS, 29, 904
Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, SoPh, 275, 229
Shimizu, T., Katsukawa, Y., Matsuzaki, K., et al. 2007, PASJ, 59, 845
Spadaro, D., Lanza, A. F., Karpen, J. T., & Antiochos, S. K. 2006, ApJ, 642, 579
Spadaro, D., Lanza, A. F., Lanzafame, A. C., et al. 2003, ApJ, 582, 486
Tripathi, D., Mason, H. E., Del Zanna, G., & Bradshaw, S. 2012, ApJL, 754, L4
Tripathi, D., Mason, H. E., Dwivedi, B. N., del Zanna, G., & Young, P. R. 2009, ApJ, 694, 1256
Tripathi, D., Mason, H. E., & Klimchuk, J. A. 2010, ApJ, 723, 713
Ugart-Urra, I., Warren, H. P., & Brooks, D. H. 2009, ApJ, 695, 642
Viall, N. M., & Klimchuk, J. A. 2012, SoPh, 275, 35
Walker, A. B. C., Jr., Hoover, R. B., & Barbee, T. W., Jr. 1993a, Proc. SPIE, 1742, 515
Walker, A. B. C., Jr., Hoover, R. B., & Barbee, T. W., Jr. 1993b, Proc. SPIE, 1742, 500
Warren, H. P., Ugart-Urra, I., Doschek, G. A., Brooks, D. H., & Williams, D. R. 2008, ApJL, 686, L131
Warren, H. P., Winebarger, A. R., & Brooks, D. H. 2010, ApJ, 711, 228
Winebarger, A. R., Schmelz, J. T., Warren, H. P., Saar, S. H., & Kashyap, V. L. 2011, ApJ, 740, 2
Young, C. A., & Gallagher, P. T. 2008, SoPh, 248, 457
Young, P. 2010, SSW software for automatically fitting Hinode/EIS spectra, http://msslxr.mssl.ucl.ac.uk:8080/Wiki.jsp?page=eis_auto_fit.pro
Young, P. 2011, Deriving Densities, Column Depths, and Filling Factors from Hinode/EIS data, eS Software Note No. 15, Version 2.3, http://msslxr.mssl.ucl.ac.uk:8080/Wiki.jsp?
Young, P. R., Del Zanna, G., Mason, H. E., et al. 2007a, PASJ, 59, 727
Young, P. R., Del Zanna, G., Mason, H. E., et al. 2007b, PASJ, 59, 857