Magnetic Loops above a Small Flux-emerging Region Observed by 
**IRIS, Hinode, and SDO**

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Abstract

I report on observations of a set of magnetic loops above a region with late-phase flux emergence taken by **IRIS**, **Hinode**, and **SDO**. The loop system consists of many transition-region loop threads that are $5''-12''$ in length and $\sim 0''5$ in width and coronal loops with similar length and $\sim 2''$ width. Although the loop system consists of threads with different temperatures, most individual loop threads have temperatures in a narrow range. In the middle of the loop system, there is a clear systematic blueshift of about $10$ km s$^{-1}$ in the transition region that is consistent with a flux-emerging picture, while a redshift of about $10$ km s$^{-1}$ in the corona is observed. The nonthermal velocity of the loop system is smaller than that of the surrounding region in the transition region but is comparable that in the corona. The electron densities of the coronal counterpart of the loop system range from $1 \times 10^{9}$ cm$^{-3}$ to $4 \times 10^{9}$ cm$^{-3}$. The electron density of a transition-region loop is also measured and found to be about $5 \times 10^{10}$ cm$^{-3}$, a magnitude larger than that in the coronal loops. In agreement with imaging data, the temperature profiles derived from the differential emission measurement technique confirm that some of the loops have been heated to corona level. Our observations indicate that the flux emergence in its late phase is much different from that at the early stage. While the observed transition region is dominated by emerging flux, these emerging loops could be heated to corona level, and the heating (if via nonthermal processes) most likely takes place only after they reach the transition region or lower corona.

**Key words:** Sun: atmosphere – Sun: corona – Sun: transition region

Supporting material: animations

1. Introduction

The ionized gas in the solar atmosphere can be highly structured by the magnetic field, forming a variety of loop features therein. These loop features, called magnetic loops, are one of the fundamental building blocks of the solar atmosphere. These loops are normally brighter than the background and can be easily traced in the remote-sensing data. Therefore, they are popular objects used to investigate the transport processes of magnetic flux and energy from the solar interior to the outer solar atmosphere.

The physical parameters, such as the velocity, density, and temperature of magnetic loops, are directly related to the pressure and emissivity, whose distribution along the loop length depends on the heating therein (e.g., Priest et al. 1998; Klimchuk 2006; Patsourakos et al. 2007; Klimchuk et al. 2008; Warren et al. 2008b; Viall & Klimchuk 2013; Reale 2014; Polito et al. 2018). Therefore, these parameters are crucial to understanding the mechanism and spatial distribution of heating in the loop. Measurements of those parameters have been achieved, but mostly for magnetic loops in the corona thanks to their relatively stable geometries (an overview of these observations of coronal loops can be found in Xie et al. 2017). However, it is challenging to obtain such measurements for cool transition-region loops, because this class of loops is highly dynamic on the timescale of minutes (Kjeldseth-Moe & Brekke 1998; Huang et al. 2015). In the **SOHO** era, magnetic loops with line-of-sight velocities from a few tens to a hundred kilometers per second have been reported in **CDS O V** ($2.5 \times 10^{5}$ K) observations (Brekke et al. 1997; Kjeldseth-Moe & Brekke 1998; Di Giorgio et al. 2003) and **SUMER O VI** ($3.2 \times 10^{5}$ K) data (Chae et al. 2000; Teriaca et al. 2004; Doyle et al. 2006). Since the **Interface Region Imaging Spectrograph (IRIS)**; De Pontieu et al. 2014) achieved its first light in 2013, the transition region has been observed with unprecedented spatial and temporal resolution. With **IRIS** observations, Huang et al. (2015) confirmed that this class of loops is diverse and dynamic, and they observed siphon flows of $10-20$ km s$^{-1}$ in a group of loops. Regarding density and temperature, accurate measurements for cool transition-region loops are rare because of the lack of suitable spectroscopic data.

Dynamic phenomena in cool transition-region loops could also provide insight for energy and mass transportation therein. It has been reported that interaction between cool transition-region loops could produce explosive events (Huang et al. 2015, 2017, 2018b), which are the signature of energy release in the solar transition region via magnetic reconnection (e.g., Dere et al. 1991; Innes et al. 1997; Huang et al. 2014; Li et al. 2018, etc.). It has also been observed that interaction between cool transition-region loops could result in heating and then forming hotter coronal loops (e.g., Alissandrakis et al. 2017; Chitta et al. 2018; Yan et al. 2018).

Here, I report on multiwavelength observations of a set of magnetic loops above a region with flux emergence at its late phase. Rather than an individual loop, I will focus on the global observational characteristics of these loops. I will investigate the dynamics of the loops and their thermal structure coupling from chromospheric to coronal temperatures. By analyzing the spectroscopic data, I will also determine the physical parameters of the loops, such as velocities, densities, and temperatures. Based on these observations, I will discuss the behavior of flux emergence at its late phase and the possible heating processes of these emerging loops. The study is
organized as follows: the data information is described in Section 2, the analysis results and discussion are given in Section 3, and the conclusion is given in Section 4.

2. Observations and Data Reductions

2.1. Data Description

The data were acquired during an observing campaign in coordination with the Goode Solar Telescope (GST; Goode et al. 2003, 2010; Cao et al. 2010) operated in the Big Bear Solar Observatory (BBSO; Zirin 1970), IRIS (De Pontieu et al. 2014), Hinode (Kosugi et al. 2007), and the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). On 2017 August 26, the region of interest was observed by a raster scan of the IRIS spectrograph from 18:00 UT to 19:27 UT, and also by Hinode instruments. During this period, the GST did not target this region because of the other arrangement.

Here, I analyzed the spectroscopic data obtained by the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board Hinode and IRIS, UV and EUV images taken with the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO and IRIS, soft X-ray images taken with the X-ray Telescope (XRT; Golub et al. 2007) on board Hinode, and line-of-sight magnetograms measured by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on board SDO.

IRIS was running in a 320-step dense raster mode, and the spectrograph obtained spectral data from a region of size $112'' \times 129''$ with a center at $(x = -3''3, y = 33''2)$. Hinode/EIS was scanning a region centered at $(x = -21''2, y = -26.6)$ in the short-wavelength (SW) band with a size of $120'' \times 512''$. The Hinode/XRT field of view has a size of $384'' \times 384''$ and was centered at $(x = -3''0, y = -0.5)$. A summary of the imaging data analyzed in this study is given in Table 1, and the spectral data are shown in Table 2.

All of the data were first prepared with standard procedures provided by the instrument teams. The coalignments of the data were obtained by cross-correlations of observations at wavelengths with the closest representative temperatures. In the present case, the reference coordinates are given by HMI magnetograms. The AIA 1700 Å images were used to align with the HMI magnetograms, and the rest AIA passbands were aligned with each other via cross-correlations. The IRIS 1330 Å data were then aligned to AIA 1700 Å images. The XRT Al-poly images were aligned to AIA 94 Å, and Hinode EIS Fe XII 195 Å raster images are then aligned to the soft X-ray.

The region of interest where a group of magnetic loops were observed and its context on the AIA 304 Å passband are shown in Figure 1. The region is part of the active region NOAA AR12672. By the beginning of the observations, the active region itself had been fully grown, and no large-scale magnetic flux emergence was observed in this period of time. In the region of interest, small-scale flux emergence was observed in the later phase was observed in the current data set (see details in Section 3.1). This small flux emergence formed a small loop system that is the main object of the present work. This is different from many previous studies on flux emergence, which focused on the emerging stage of the active regions themselves.

2.2. Analysis of Spectroscopic Data

IRIS data used in the present study are level 2 data that have been fully prepared by the instrument team, and no further calibration is applied. EIS data were downloaded as level 0. They were first reduced by the standard procedures packaged in eis_prep.pro, which also includes radiometric calibration. The details of the procedures can be found in the document eis_swnote_01 in the solarsoft directories.

To derive line parameters of the observed spectral lines, including peak intensity, line center, and line width, Gaussian fits are used. For those spectral lines used to derive Doppler velocities, nonthermal velocities, and electron density, blended lines should be carefully handled. Most of these lines could be well fitted by a single Gaussian function even...
though some are blended. In these cases, the blended lines could not be removed with multi-Gaussian fits, and their effects will be considered when evaluating the observational results. The only case where the blended line could be removed by double Gaussian fits is FeXIII 203.8 Å, which is blended with Fe XII 203.7 Å.

To obtain Doppler velocities, wavelength calibration is required. The wavelength calibration has been performed in IRIS level 2 data by the instrument team referencing neutral lines (see details in IRIS Technical Note 20). However, absolute wavelength calibrations for the EIS data are difficult. Alternatively, an averaging profile from a quiet-Sun region could be used as reference (Young et al. 2012). However, this quiet-Sun method cannot be used here because very few quiet-Sun regions are covered in the field of view. In the present study, a spectral profile averaging of the entire field of view was first obtained, and its line center was taken as the rest wavelength of that spectral line. In this case, the obtained Doppler velocities from EIS data should have an accuracy of about 4.4 km s\(^{-1}\) (Kamio et al. 2010). Compared to calibration with quiet-Sun regions, this wavelength calibration method could lead to an offset of 5.4 km s\(^{-1}\) toward redshifts in the corona (see discussion in Young et al. 2012), and this offset has been taken into account in the present study.

While constructing a map for Doppler velocities, thermal drifts and slit tilt should also be corrected. For EIS data, the thermal drifts can be obtained through a method proposed by Kamio et al. (2010), and the slit tilt can be obtained from specially designed observations. These corrections can be achieved by software provided in solarsoft by the instrument team, and they have been included for producing the Doppler velocity maps. For IRIS data, the basic corrections for thermal drifts and slit tilts have been applied by the data processing pipeline, and no further corrections are required in the present case.

To derive nonthermal velocities, the calculation steps given in Chae et al. (1998) are followed. The instrument broadenings given by the instrument team are used, which are 0.054 Å (FWHM) for EIS Fe XII 195.1 Å and Fe XII 202.0 Å and 0.032 Å (FWHM) for IRIS Si IV 1393.8 Å. The thermal temperature of a spectral line is assumed to be the formation temperature as listed in Table 2.

Figure 1. (a) An area near the center of the solar disk viewed in the AIA 304 Å passband at 18:09 UT on 2017 August 26, in which the region of interest with cool transition-region loops studied in the present work is enclosed by dotted lines. (b)–(d) The IRIS SJ 1400 Å image (b), the HMI magnetogram (c), and the AIA 171 Å image (d) of the region of interest, on which the white and blue contour curves represent the magnetic flux density measured at 18:09 UT with levels of −800 Mx cm\(^{-2}\) and 800 Mx cm\(^{-2}\), respectively. The HMI magnetogram is artificially saturated at −1000 Mx cm\(^{-2}\) (black) and 1000 Mx cm\(^{-2}\) (white). The positive and negative polarities that are connected by the magnetic loops are marked in the magnetogram as “P” and “N,” respectively.

3. Results and Discussion

In this section, I show the observational analysis of the magnetic loops using multiwavelength imaging and spectroscopic data.

3.1. Evolution of the Magnetic Features

In Figure 1, one can see that the magnetic loops are rooted in a large patch of positive polarity in the south (marked as “P” in Figure 1(c)) and a patch of negative polarity in the north (marked as “N” in Figure 1(c)). The positive polarity corresponds to a set of small sunspots that were part of the trailing sunspot group of the active region. The evolution of magnetic features in the region is shown in Figure 2 with the associated animation. We can see that the negative polarity clearly shows an emerging process from 10:00 UT to 20:00 UT. The total negative flux in the region increases about 25 times from about 10\(^{19}\) Mx, which gives a flux-emerging rate of $\sim$7 × 10\(^{15}\) Mx s\(^{-1}\) on average. During the emerging process, small magnetic features with negative polarity appeared at the edge of the major positive polarity (“P” in Figure 1(c)) and then moved northward and merged with each other to form the large patch seen in Figure 1(c).
(denoted as “N”). Since the positive polarity is predominant in the region, its emergence was not as clear as that of the negative one in the observations.

As seen in the variation of the negative flux (right panel of Figure 2), the IRIS and Hinode observations were taken at the late phase of the emergence, when many magnetic loops have already formed between the two major polarities. During this period of observing time (18:00 UT–19:27 UT), many small negative polarities were still appearing at the edge of the major positive polarity and moving toward the major negative one. Meanwhile, we could also see many small positive polarities moving into the region between the positive and negative polarities. These small positive polarities might have appeared at the edge of the major negative polarity or split from the major positive polarity. Most of these small polarities (both positive and negative) could not reach the major ones. They might simply disappear halfway, or they might also meet and cancel each other out. The emerging, splitting, and canceling of small polarities can be clearly traced by the small dynamic brightenings in AIA 1700 Å images (see the animation associated with Figure 3).

### 3.2. Imaging of the Magnetic Loop System

In Figure 3 and the associated animation, I show the evolution of the magnetic loop system viewed in multiple passbands of the imagers. The details of the loop system can be clearly seen in the IRIS SJ 1330 and 1400 Å images. While many loops were connecting the two major polarities, we can also see that some others were connecting the major polarities and the weaker ones. The loop system was very dynamic and evolved (appearing and disappearing) very quickly in a timescale comparable to the cadences of the observations. Brightenings frequently occurred in the footpoint regions and led to flaring of many loop threads. However, there are also some flaring loop threads that do not show bright footpoints in the IRIS SJ 1330 and 1400 Å images. In general, the loop system shows a clear response in images of IRIS SJ passbands, AIA EUV channels, and the XRT Al-Poly filter. However, the structures viewed in AIA and XRT are much more fuzzy than that in IRIS SJ passbands. One of the possible reasons is the lower spatial resolution of the AIA and XRT images, and another reason could be that the counterparts of nearby loop threads at higher temperatures cannot be separated from each other.

The higher resolution images from IRIS SJ 1330 and 1400 Å (Figures 3(c) and (d)) show many fine threads of loops with a cross section ≤0.5″ (FWHM) and ~12″ separation between the two footpoints. Besides these loops connecting the two major polarities, we also see smaller ones with length of about 5″ that are connecting a major polarity with minor ones in between (see the animation associated with Figure 3). For comparison, the cross sections of the loop threads determined from the AIA 171 Å and XRT images are around 2″ (Figures 3 and 4). The widths of the hot threads are consistent with those measured in TRACE filter images (Aschwanden & Nightingale 2005). Such hot threads seen in AIA data might contain multiple finer threads, as reported in Hi-C data (Brooks et al. 2013), and this could be the case in the present loop system, although we do not have higher resolution images at hot temperatures.

We also notice that not all loop threads at lower temperatures have visible counterparts at higher temperatures. Figure 4 shows light curves taken along a slit across the loop system seen at around 18:43:30 UT (shown as the white solid line in Figure 3(c)). A peak in these curves is representative of a loop thread seen in the corresponding channel. Many loop threads seen in the IRIS SJ 1330 and 1400 Å passbands do not have distinguishable counterparts in the images taken in passbands with hotter representative temperatures (see Figures 3 and 4), a phenomenon that is consistent with previous studies (e.g., Fludra et al. 1997; Spadaro et al. 2000). In Figure 3, I highlight a loop thread (outlined by the cyan dotted lines) that is clearly seen in X-ray and AIA 94 Å images but almost invisible in the other passbands. (This can also be seen in Figure 4, where the peaks in the light curves are denoted by the cyan dashed line.) In contrast, two loop threads (outlined by yellow dotted lines in Figure 3) are clearly visible in AIA 304 and 171 Å but almost invisible in X-ray. (This can also be seen in Figure 4, where the peaks in the light curves are denoted by yellow dashed lines.) This suggests that these loop threads have counterparts only in a narrow temperature range, and this is consistent with that reported by Warren et al. (2008a).

There are also some loop threads having clear counterparts in all of the passbands. We can see that two peaks indicated in Figure 4 by black dashed lines correspond to two loop threads identified on the images of all AIA EUV channels and XRT Al-Poly filter. By taking into account the spatial resolution of the instruments, we can also consider that these two loop threads also correspond to peaks in the IRIS SJ 1330 and 1400 Å light curves (see Figure 4).

### 3.3. IRIS and EIS Spectroscopic Observations

This region was scanned by the IRIS slit from 18:25 UT to 18:56 UT, and repetitively by the EIS slit from 18:00 UT to 23:59 UT. Because IRIS and EIS were scanning the region of interest at different times, the analysis here focuses on the global characteristics of the loop system rather than any individual loop thread. Figure 5 shows the IRIS and EIS raster images of the region in a few spectral lines. With the high-resolution data, IRIS could clearly distinguish many loop threads in the raster images (Figure 5(a) and (b)). Even though the loop system in the EIS data is fuzzy and one cannot distinguish any single loop threads, we can also see that the region occupied by the loops is brighter than the background (especially in He II, Fe XI–Fe XVI). Using the imaging data as guidance, I believe that some of the loop threads (for example, see the fuzzy bright structure denoted by the arrow in Figure 5(k)) have been heated to more than 2 × 10⁶ K (i.e., formation temperatures of Fe XV and Fe XVI). These hot loops are seemingly not visible in the raster images of Fe VIII–Fe X (Figures 5(d)–(f)). This again confirms that most of the loop threads have a narrow range of temperatures.

In C II and Si IV radiance maps (Figures 5(a) and (b)), the footpoints of the loop system appear to be dark regions that suggest lower emission than the background (see the blue and purple contours in the figure). The north footpoint (purple contour) is most clearly seen in the He II, Fe X, and Fe XI images (Figures 5(c), (f), (g)), though its southwest portion is clearly seen in the other EIS spectral lines. While He II 256.3 Å is blended with Si X and Fe X, it suggests that the temperature of the north footpoint is in the range of 1.1 × 10⁶ to 1.4 × 10⁶ K (i.e., between formation temperatures of Fe X and Fe XI). The south footpoint (blue contour) is most clearly seen in Fe XI (Figure 5(g)), suggesting its temperature is about 1.4 × 10⁶ K. This suggests that heating was concentrated in the
footpoints of the loop system. To further understand these loops, I exploit the spectroscopic data to deduce their physical parameters, as show in the following sections.

### 3.3.1. Doppler Velocities

To derive the Doppler velocities, a spectral profile averaging of the entire field of view was first obtained, and its line center was taken as the rest wavelength of that spectral line. Figure 6 displays the Doppler maps of the region measured with different spectral lines by IRIS and EIS. In IRIS Si IV 1393.8 Å (transition-region temperature), the loop system shows a systematic blueshift (∼10 km s⁻¹) in the middle of the loops, while their footpoints are redshifted (Figure 6(a)). The blueshifts in the middle of the loops are in line with the picture of flux emergence. Because the blueshifted pattern is systematic in the
loop region, it indicates that the loop system should keep emerging during the period of the \textit{IRIS} raster (~25 minutes). This should not be the case for any particular loop thread, otherwise it would move upward for about 20", and this should be observed in the imaging data (unless they are all moving along the line of sight). The systematic blueshifts could be understood if there are many loop threads continuously moving upward in the transition region. Because no clear upward motion was observed in the imaging data, these loop threads should not move very far while they have transition-region temperatures. The absence of downflows (redshifts) could be due to heating in the loops that leads to disappearance of the loop threads at the transition-region temperature. This understanding is supported by the extremely dynamic nature (frequent appearance and disappearance) of the loops seen in the \textit{IRIS} SJ 1330 and 1400 Å images (see Section 3.2). Because these loop threads have a relatively small range of temperatures, the continuing emergence could be observed as the frequent appearance of the loop threads in these passbands, and heating of the loop threads could lead to their disappearance. Therefore, the downflows could only be seen at higher temperatures, and these are observed in EIS Fe VIII–Fe XV (Figures 6(b)–(f)).

With EIS data, Doppler maps are derived from Fe VIII 185.2 Å (Figure 6(b)), Fe X 184.5 Å (Figure 6(c)), Fe XII 195.1 Å (Figure 6(d)), Fe XIII 202.0 Å (Figure 6(e)), and Fe XV 284.1 Å (Figure 6(f)), with temperatures ranging from 4.5 × 10⁵ K to 2.2 × 10⁶ K. In the Doppler maps of Fe VIII to Fe XIII, it is clear that redshifts are predominant in the middle of the loops. The Doppler map of Fe XV (Figure 6(f)) also shows a clear redshifted pattern at places around \((X = -3", Y = 55")\) where the loop structure appears (see Figure 5(k)). From Fe X to Fe XV, the Doppler velocities in the middle of the loops show a trend from large \((\gtrsim10\;\text{km s}^{-1})\) to small \((<5\;\text{km s}^{-1})\), which is close to the accuracy of the measurement. This might imply that the loop plasmas become more stationary while they are heated to higher temperatures.

Note that the Doppler shifts measured with Fe XII 195.1 Å are significantly larger than that with Fe XII 202.0 Å, and this bias might be brought in by the blending of Fe XII 195.2 Å in the red wing of the Fe XII 195.1 Å lines. While randomly checking tens of locations selected from the region, in agreement with Young et al. (2009), I found that the contribution of Fe XII 195.2 Å is more significant in the brighter region than that found on average (see a few examples in Figure 7). However, the blending cannot be easily removed in most of the positions of the region because their profiles are well fitted by single Gaussian functions (see examples in Figures 7(c) and (d)). Although the blending might be removed by double Gaussian fits with assumptions of a few parameters of the blending component (see, e.g., Testa et al. 2016), it could easily bring in additional artificial effects, and also the fittings cannot converge in many cases. Nevertheless, the Fe XII 195.1 Å Doppler map still gives a good indication of velocity at the corresponding temperature, while we have the Fe XII 202.0 Å one for reference.

\subsection*{3.3.2. Nonthermal Velocities}

We measured the nonthermal velocities of the region by assuming the thermal temperature to be the formation temperature (listed in Table 2). Figure 8 displays the nonthermal velocities of the region measured with \textit{IRIS} Si IV 1393.8 Å and with EIS Fe XII 195.1 Å and Fe XIII 202.0 Å.

In \textit{IRIS} Si IV 1393.8 Å, a few locations where flaring loops exist have nonthermal velocities of \(\sim30\;\text{km s}^{-1}\), which is significantly larger than that of the surrounding background. Apart from those locations, the nonthermal velocities of the loop region are less than 10 km s\(^{-1}\), much smaller than that of the surrounding region. This suggests that most of the emerged loop plasma was less disturbed by nonthermal processes in the transition region before flaring up. The small nonthermal velocity is dominant in the loops, suggesting that most of the emerging loops have not been heated (by nonthermal processes) before reaching the transition region.

Using EIS data, nonthermal velocities from Fe XII 195.1 Å and Fe XIII 202.0 Å are derived (Figures 8(b) and (c)). In the loop region, the nonthermal velocities derived from Fe XII 195.1 Å are in the range of 40–50 km s\(^{-1}\), which are overall larger than that from Fe XIII 202.0 Å (30–40 km s\(^{-1}\)). This discrepancy is again due to the blending of Fe XII 195.2 Å at the red wing of Fe XII 195.1 Å. Please note that radiation calibration has been applied on the present data, which might overestimate the values by 10%–20% (Brooks & Warren 2016; Testa et al. 2016). Taking into account this effect, the nonthermal velocities measured here are still larger than that in normal active regions (~20 km s\(^{-1}\); see,
e.g., Brooks & Warren 2016; Testa et al. 2016). Since these loops are active and have a size similar to coronal bright points, the nonthermal velocities of these loops in corona are consistent with that of active-region bright points (Imada et al. 2009).

Nevertheless, both nonthermal velocity maps from EIS data indicate that the entire loop region has nonthermal velocities similar to that of the surrounding quiet corona. From the point of nonthermal velocity, this indicates that the emerged loop plasma is not much different from the normal coronal plasma. If the emerging loops have been heated by any nonthermal processes, it should have occurred before reaching these temperatures.

3.3.3. Electron Density Measured with Coronal Lines

Using EIS spectroscopic data, I produce electron-density maps (Figure 9) of the loop region using the intensity ratios of the line pairs Fe XII λ186.9/195.1 and Fe XIII λ202.0/203.8 (both are recommended for density diagnostics; see Young et al. 2007, 2009) and version 8.0.7 of the CHIANTI atomic database (Dere et al. 1997; Del Zanna et al. 2015). We can see that the electron density derived from Fe XII λ186.9/195.1 is larger than that from Fe XIII λ202.0/203.8, by a factor of ~2. This discrepancy between the two line pairs has been discussed in detail by Young et al. (2009). The discrepancy should be much less because the new model is used in this version of the CHIANTI database (Del Zanna et al. 2015). However, this discrepancy has been found to be worse in the EIS data obtained in recent years and cannot be corrected by the new atomic database alone (G. Del Zanna 2018, private communications). The discrepancy appears to be a result of a combination of many factors that have yet to be fully understood. The electron density in the loop region is in the range 2~8 \times 10^9 \text{ cm}^{-3} measured with Fe XII λ186.9/195.1 and in the range 1~4 \times 10^9 \text{ cm}^{-3} with Fe XIII λ202.0/203.8. These values are significantly larger than that found in the background corona (where the density is about 0.6 \times 10^9 \text{ cm}^{-3}). This indicates that these loops have not only been heated to coronal temperature, but also have been filled in with denser plasma. Furthermore, the electron density of the north footpoint is larger than that of the south, by a factor of ~2.
3.3.4. Electron Density along a Cool Loop

In some cases (normally in flaring events), the density-sensitive line pair O IV λ1399.8 Å/1401.2 Å is strong enough in IRIS observations and thus can provide an accurate diagnostic of electron density in the solar transition region with unprecedentedly high resolution (see Young 2015; Young et al. 2018a). Here, I found that the line pair of O IV has a good signal-to-noise ratio at some locations of a flaring transition-region loop (see Figure 10). It gives us an opportunity to measure electron density along this transition-region loop. Figure 10 shows O IV line profiles of a few locations along the flaring loop. The length of the loop is about 12″. It is apparently

![Figure 6: Dopplergrams of the magnetic loop system measured with IRIS Si IV 1393.8 Å and EIS Fe VIII 185.2 Å, Fe X 184.5 Å, Fe XII 195.1 Å, Fe XIII 202.0 Å, and Fe XV 284.1 Å. The observing time was the same as that given in Figure 5. The purple contour lines indicate the magnetic flux density at −800 Mx cm⁻², and the black ones are representative of that at 800 Mx cm⁻². The black dotted lines trace a few loop threads identified in the Si IV radiance image as shown in Figure 5 and can be used as references to compare different images.]

![Figure 7: Samples of Fe XII 195.1 Å profiles from the region of interest observed by EIS. The observed profiles are shown as black solid lines, and the single Gaussian fits to the observed profiles are shown as red dashed lines.]

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**Figure 6.** Dopplergrams of the magnetic loop system measured with IRIS Si IV 1393.8 Å and EIS Fe VIII 185.2 Å, Fe X 184.5 Å, Fe XII 195.1 Å, Fe XIII 202.0 Å, and Fe XV 284.1 Å. The observing time was the same as that given in Figure 5. The purple contour lines indicate the magnetic flux density at −800 Mx cm⁻², and the black ones are representative of that at 800 Mx cm⁻². The black dotted lines trace a few loop threads identified in the Si IV radiance image as shown in Figure 5 and can be used as references to compare different images.

**Figure 7.** Samples of Fe XII 195.1 Å profiles from the region of interest observed by EIS. The observed profiles are shown as black solid lines, and the single Gaussian fits to the observed profiles are shown as red dashed lines.
flaring at its north portion, and the length of the flaring section is about 8″. The flaring portion of the loop shows about a 10 km s\(^{-1}\) blueshift in the Doppler map and about 25 km s\(^{-1}\) nonthermal velocity in Si IV 1393.8 Å. In Figure 10, we can see that the O IV 1399.8 Å line of a few locations in the middle of the loop have relatively good signal-to-noise ratio (Figures 10(b)–(d)) and allow density diagnostics using the O IV line pair. The electron densities measured in these three locations are given as \(5.0 \times 10^{10} \text{ cm}^{-3}\) (b), \(7.9 \times 10^{10} \text{ cm}^{-3}\) (c), and \(1.6 \times 10^{10} \text{ cm}^{-3}\) (d). These values are consistent with that measured in active-region loops by Polito et al. (2016).

Due to very weak O IV lines in IRIS data, the line ratios of Si IV 1402.8 Å to O IV 1401.2 Å are also frequently used for density diagnostics (see details in Young et al. 2018a). Using the theoretical model based on a quiet-Sun DEM (see Table 2 of Young et al. 2018a), the electron densities derived from the line ratios of Si IV 1402.8 Å to O IV 1401.2 Å at the three locations are given as \(1.0 \times 10^{11} \text{ cm}^{-3}\) (b), \(7.9 \times 10^{10} \text{ cm}^{-3}\) (c), and \(6.3 \times 10^{10} \text{ cm}^{-3}\) (d). Even though the line ratios here fall in the range where the line ratios are not very sensitive to the electron densities (see Figure 2 of Young et al. 2018a), I am confident that the electron density measured with the line ratio of Si IV 1402.8 Å to O IV 1401.2 Å is above \(5 \times 10^{10} \text{ cm}^{-3}\), which is in the same magnitude as that from the O IV line pair. This suggests that using the line ratios of Si IV 1402.8 Å to O IV 1401.2 Å is an acceptable approach to estimating electron density. Because the dependence of the line ratios of Si IV 1402.8 Å to O IV 1401.2 Å on electron density could significantly vary in different theoretical models, the loops here are better fitted in the quiet-Sun DEM model than the log-linear DEM model (see Young et al. 2018a for details).

The electron density measured with transition-region lines is a magnitude larger than that with coronal lines. It suggests that the loop threads with coronal temperatures are not spatially identical to those with transition-region temperatures. This is in agreement with the imaging data, in which most of the loop threads appear to have a narrow range of temperatures.

3.3.5. Estimation of Temperatures

The spectroscopic data provide us with observations of multiple spectral lines at various temperatures. This gives us an opportunity to investigate the temperature profiles of the region using the differential emission measurement technique (see, e.g., Brooks et al. 2009, 2011; Hannah & Kontar 2012; Cheung et al. 2015; Su et al. 2018, and references therein). Here, I used the DEM procedure packaged with CHIANTI (chianti_dem.pro), in which the XRT_DEM package was called to calculate the DEM profiles. In order to reduce the error brought in by the radiometry calibrations of different instruments, I used the spectral lines from EIS only. Additionally, I used only the spectral lines from the element iron to avoid the uncertainty brought in by the abundance. The spectral lines used for DEM analysis are denoted in Table 2, and most of them have been used in previous studies (e.g., Brooks et al. 2009, 2011). The spectral lines used in the DEM analysis are formed in temperatures between \(4.5 \times 10^{5}\) and \(2.8 \times 10^{6} \text{ K}\) (i.e., \(\log T/K = 5.65–6.45\)); therefore, the derived DEM profiles are constrained by the observations only in this temperature range.

Background and foreground subtractions are another important issue that has to be considered in the DEM analysis (see, e.g., Del Zanna & Mason 2003; Aschwanden & Nightingale 2005). A region that is representative of the background and foreground is normally selected as close to the analyzed region as possible, and it should not contain any active features (e.g., other loop threads) in any spectral lines used for DEM analysis. The background and

Figure 8. Nonthermal velocities of the region measured with IRIS Si IV 1393.8 Å (a), EIS Fe XII (b), and Fe XIII (c). The purple and black contour lines outline the magnetic polarities, and the black dotted lines trace a few loop threads identified in the Si IV radiance image as shown in Figure 5.
foreground subtractions become difficult because the region of interest contains many loop threads, and they cannot be distinguished in the EIS data. Here, I performed the DEM analysis on five subregions of the loop system (see Figure 5(h)), including three from the footpoints ("A," "B," and "E") and two taken from the middle of the loops ("C" and "D"). I first selected a large region that includes all of the analyzed regions (denoted as "BK" in Figure 5(h)). While all of the pixels in the "BK" region are sorted in order from low to high intensity, the background and foreground emission is taken by averaging 10% of all the pixels counting from the lowest intensity one.

The DEM profiles of the analyzed regions are shown in Figure 11. The Monte Carlo simulations appear to prefer peak temperatures at around log\(T/K\) = 6.1–6.2 (i.e., 1.3–1.6 \(\times\) 10^6 K). However, we can see that these DEM profiles are not Gaussian, with either no clear peak or flat peaks; this does not allow us to quantitatively evaluate the temperature distributions (see, e.g., Warren et al. 2008a; Warren & Brooks 2009). Such flat peaks in the DEM profiles could be indications of multithermal components in the analyzed regions, where loop threads with different temperatures are included.

Figure 9. Electron-density maps of the loop region measured with EIS line pairs Fe XII \(\lambda\lambda 186.9/195.1\) and Fe XIII \(\lambda\lambda 202.0/203.8\). The contours and the dotted lines are the same as those shown in Figures 5–8.

Figure 10. Electron density derived in a few regions along a bright transition-region loop using IRIS spectroscopic data. For each region, the O IV 1399.8 Å and 1401.2 Å and Si IV 1402.8 Å (normalized) profiles are displayed. The labels following "U" give the normalized scale for each profile. In panels (b)–(e), the labels following "R1" give the line ratio of O IV 1399.8 Å to O IV 1401.2 Å, and the electron density (in log\(n_e\)) derived from this line ratio is shown as the numbers following the labels "Ne1." The labels following "R2" show the line ratio of Si IV 1402.8 Å to O IV 1401.2 Å, and the electron density (in log\(n_e\)) derived from this line ratio is shown as the numbers following the labels "Ne2." These values of electron density are derived with the theoretical model based on the quiet-Sun differential emission measurement (DEM), as shown in Table 2 of Young et al. (2018a).
3.4. Discussions

3.4.1. Flux Emergence at Its Late Phase

While the magnetic flux tube that hosts loop plasma is emerging from the solar convective zone, it experiences a dramatic change of plasma environment in the lower solar atmosphere, where the plasma ionization turns from partial to full and the plasma beta changes from greater than one to less than one. This might lead to a serpentine geometry for a flux tube observed in the lower solar atmosphere (Fan 2001; Cheung et al. 2007, 2008; Archontis et al. 2009; Cheung & Isobe 2014; Huang et al. 2018a), and this could lead to a variety of energetic events such as Ellerman bombs and UV bursts (see, e.g., Pariat et al. 2004, 2009; Peter et al. 2014; Innes et al. 2015; Nelson et al. 2015, 2016; Vissers et al. 2015; Tian et al. 2016; Hong et al. 2017; Zhao et al. 2017; Ni et al. 2018; Young et al. 2018b).

By analyzing observations of a flux-emerging region at its early stage, Toriumi et al. (2017) reported two types of local heating events that could result from magnetic reconnection in the bald patches (magnetic dips) of the emerging flux and shocks or strong compression caused by fast downflows along the overlying magnetic system. Similarly, Tian et al. (2018) observed IRIS bombs with spatially resolved bidirectional jets at the earliest stage of a flux-emerging region, and they found that the bombs are associated with bald patches and are located in regions with a large squashing factor at height of about 1 Mm, which strongly suggested magnetic reconnection in the lower solar atmosphere. Moreover, Guglielmino et al. (2018) reported observations of long-lasting UV bursts occurring at the late phase of flux emergence while emerging flux tubes are interacting with ambient fields. Therefore, activities in magnetic loops above the flux-emerging region could provide observational hints about how a magnetic flux is emerging through and affecting the ambient field in the solar atmosphere.

At the late phase of this flux emergence, very few energetic UV bursts were observed. This is different from the behavior of the flux emergence in the early phase. Besides many loops with multiple temperatures that had been formed between the two major polarities, we could also see smaller loops connecting the major polarities and the smaller ones. These smaller loops could be formed by (1) a newly emerging flux that is observed as small magnetic features with opposite polarity appearing at the side of and moving away from the major ones, and (2) preexisting loops that are dragged downward and observed as small magnetic features with the same polarity splitting and moving away from the major ones. While the total magnetic flux is still increasing and the loops show systematic blueshifts in the transition-region Doppler map, it indicates that the emerging flux should still be dominated at this stage. These smaller loops might move toward and interact with each other, which leads to magnetic cancellation between small magnetic features. A question is whether such interactions among the smaller loops could result in energy release heating the loops. In the present observations, only brightenings in AIA 1700 Å are seen, and no energetic event (such as UV bursts) has been detected in the IRIS Si IV spectral data. This question remains open, and we will make a further investigation in a follow-up work using IRIS sit-and-stare data that were taken after the raster data reported here.

Figure 11. DEM curves for the five regions (“A” to “E”) marked in Figure 5(b). The gray curves are the solutions given by Monte Carlo simulations, and the best solution is given by the black line.
3.4.2. Heating of the Loops

We found that the nonthermal velocities of the loop system are generally smaller than the background in the transition region, but comparable in the corona. This suggests that most of the emerging loops should be heated only after they reach the transition region. Because the footpoints of the loop system have higher temperatures and the flaring transition-region loops show bright footpoints prior, it suggests that the heating processes should take place in the footpoints.

The parameters (such as loop width, electron density, and temperature profiles) of these loops measured with EIS data are similar to those in larger loops (see, e.g., Aschwanden & Nightingale 2005; Warren et al. 2008a; Tripathi et al. 2009; Warren & Brooks 2009). Actually, some larger loop systems studied previously also contain loop threads at temperatures from transition region to coronal (Warren et al. 2008a; Tripathi et al. 2009). Although those loop systems might be experiencing flux-emerging processes similar to the current one, the loop system observed here is much smaller (in length), and the heating therein could be much different.

Not like many hot loops in the corona, the cool loops observed here show a very dynamic evolution. It suggests that they should be heated in an impulsive way. We also observed that some flaring cool loops did not have any bright footpoints in the spectroscopic data. This is consistent with recent one-dimensional simulations of loops with apex density more than $10^9$ cm$^{-3}$ that were assumed to be heated by nanoflares occurring at the apex with heating either in an electron beam model with energy cutoff up to 15 keV or in a thermal conduction model (Polito et al. 2018). However, the loops observed here are systematically emerging and evolving, and also they are much shorter than that modeled in Polito et al. (2018). Because the heating mechanism also depends on loop length, determining whether the loops observed here were heated in the same way needs further modeling constrained by the present observations. The follow-up work using sit-and-stare data will also shed more light on this problem.

The size of these loops is comparable to coronal bright points (see Madjarska 2018 for a review of this topic), which also have a multithermal nature (see, e.g., Madjarska et al. 2012). One of the heating mechanisms of coronal bright points is believed to be magnetic reconnection among converging magnetic loops (e.g., Priest et al. 1994; Mou et al. 2016). Could such loop systems as observed here be formed and heated in a similar way? This question is worth investigating further using higher-cadence IRIS data, and it will also help us understand the possible heating mechanisms of coronal bright points.

A set of loops had been formed between the two major polarities at the beginning of our observations. Some of the loop threads are connecting the two major polarities, and some others are connecting one major and one smaller polarity. The cross section of the loop threads is about 0.5$^\circ$ measured with IRIS SJ images. We found that they consist of loop threads with temperatures from $2.5 \times 10^4$ K (low transition region) to $2.8 \times 10^5$ K (corona). Most of the loop threads with different temperatures are not identical in space, suggesting that the loop threads appear to have temperatures in a small range.

In the middle of the loop system, the Doppler maps show an upward velocity of $\sim 10$ km s$^{-1}$ in the transition region (Si IV) and a downward velocity of $\sim 10$ km s$^{-1}$ in the corona (Fe XII). In the transition region, the nonthermal velocities of most of the loops are found to be less than 10 km s$^{-1}$ and are much smaller than the surrounding region, while in the corona, they are not different from the surrounding region. The electron densities of the loop system measured in coronal temperature are found to be in the range of $1$–$4 \times 10^9$ cm$^{-3}$, with larger values in the footpoints. Using the IRIS O IV line pair, we are also able to measure the electron density of a flaring loop thread in the transition region, which is found to be in the range $2$–$8 \times 10^{10}$ cm$^{-3}$ with an average of $\sim 5 \times 10^{10}$ cm$^{-3}$. The DEM profiles derived with EIS iron lines in a few locations of the loop system imply that these locations should contain loop threads with different temperatures.

Our observations indicate that the flux emergence in its late phase is much different from that at the early stage. It might consist of a magnetic reconnection between a newly emerging flux and a preexisting flux, but it does not produce any UV bursts that are signatures of magnetic reconnection in the lower solar atmosphere. Most of the emerging loops at this stage are likely to be heated after they reach the transition region or above because most of them have a small nonthermal velocity in Si IV. The dynamics of these loops suggests that they are heated impulsively, and how it actually works requires further investigation. In a following study, we will exploit an IRIS sit-and-stare data set to investigate the evolution of this loop system, which will shed more light on their physics.

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