The high densities, long lifetimes, and narrow emission measure distributions observed in coronal loops with apex temperatures near 1 MK are difficult to reconcile with physical models of the solar atmosphere. It has been proposed that the observed loops are actually composed of sub-resolution “threads” that have been heated impulsively and are cooling. We apply this heating scenario to nearly simultaneous observations of an evolving post-flare loop arcade observed with EUVI/STEREO, EIS/Hinode, XRT/Hinode, and TRACE. We find that it is possible to reproduce the extended loop lifetime, high electron density, and the narrow differential emission measure with a multi-thread hydrodynamic model provided that the timescale for the energy release is sufficiently short. The model, however, does not reproduce the evolution of the very high temperature emission observed with XRT. In XRT the emission appears diffuse and it may be that this discrepancy is simply due to the difficulty of isolating individual loops at these temperatures. This discrepancy may also reflect fundamental problems with our understanding of post-reconnection dynamics during the conductive cooling phase of loop evolution.

Key words: Sun: corona

Online-only material: color figures, animation

1. INTRODUCTION

One of the principal problems in solar physics is understanding how the Sun’s corona is heated to very high temperatures. Recent work on coronal loops indicates that they have physical properties that are difficult to reconcile with theoretical models. Coronal loops with temperatures near 1 MK are observed to persist longer than a characteristic cooling time, suggesting steady or quasi-steady heating (e.g., Lenz et al. 1999; Aschwanden et al. 2000). Steady heating models, however, cannot reproduce the high electron densities observed in these loops (Winebarger et al. 2003). Multi-thread, impulsive heating models have been proposed as a possible heating scenario (e.g., Cargill & Klimchuk 1997; Warren et al. 2003; Patsourakos & Klimchuk 2008). Such models are motivated by our understanding of the energy release during magnetic reconnection in flares (e.g., Parker 1983). In these models, impulsive heating leads to high densities and multiple, sub-resolution “threads” lead to long lifetimes relative to the cooling time for an individual loop. These models are severely constrained by the relatively narrow distributions of temperatures that are often observed in loops with apex temperatures near 1 MK (e.g., Del Zanna & Mason 2003; Aschwanden & Nightingale 2005; Curtain et al. 2007; Warren et al. 2008). A narrow distribution of temperatures suggests that the loop can contain only a few independent threads.

One difficulty with fully testing coronal heating scenarios such as these with hydrodynamic models has been the sparseness of data. Previous work on loop evolution has generally focused on measurements imaging instruments (e.g., Winebarger et al. 2003; Aschwanden & Nightingale 2005; Ugarte-Urra et al. 2006), which have limited diagnostic capabilities. Current solar observatories, however, allow for coronal loops to be observed in unprecedented detail. The EUV Imaging Spectrometer (EIS) on the Hinode mission provides high spatial and spectral resolution observations over a very wide range of coronal temperatures. EIS plasma diagnostics yield important constraints on the physical properties of coronal loops. The X-ray Telescope (XRT) on Hinode complements these observations with high spatial and temporal resolution observations of the high temperature corona. The multiple viewpoints of the twin Solar Terrestrial Relations Observatory (STEREO) spacecraft allow for loop geometry, a critical parameter in the modeling, to be measured using the EUV Imagers (EUVIs). The Transition Region and Coronal Explorer (TRACE) currently provides the highest spatial resolution images of the solar corona.

In this paper, we use STEREO, Hinode, and TRACE observations of an evolving loop in a post-flare loop arcade to make quantitative comparisons between a multi-thread, impulsive heating model and measured densities, temperatures, intensities, and loop lifetimes. An important component of this work is the development of methods for integrating the different observations into hydrodynamic simulations of the loop. We find that it is possible to reproduce the extended loop lifetime, the high electron density, and the narrow differential emission measure (DEM) with a multi-thread model provided the timescale for the energy release is sufficiently short. The model, however, does not reproduce the evolution of the high-temperature emission observed with XRT.

One goal of investigating the heating on individual loops is to motivate the modeling of entire active regions or even the full Sun (e.g., Schrijver et al. 2004; Warren & Winebarger 2006; Mok et al. 2005; Lundquist et al. 2008). It is possible, however, that there is not a single coronal heating mechanism that can be applied to all coronal loops. For example, it may be that steady heating is the dominant heating scenario on some fraction of coronal loops (e.g., Martens 2008; Antiochos et al.
For EIS the times of the \textit{STEREO} images are shown below the \textit{STEREO} images. There are gaps in the \textit{STEREO} data due to orbital eclipses. There is also a gap in the \textit{STEREO} data.

Even if impulsive heating of the kind discussed here is only a minor contributor to the heating of the solar corona, this study provides important insights into the energy release during magnetic reconnection, a fundamental process in astrophysical and laboratory plasmas.

2. OBSERVATIONS

In this section, we provide an overview of the instruments and observations used in this study. A summary of the observations is shown in Figure 1. The loop considered here is a post-flare loop from a very small event (\textit{GOES} class B2.5) that peaked around 19:00 UT on 2007 May 2.

The EIS instrument on \textit{Hinode} produces stigmatic spectra in two wavelength ranges (171–212 Å and 245–291 Å) with a spectral resolution of 0.0223 Å. There are 1" and 2" slits as well as 40" and 266" slits available. The slit–slot mechanism is 1024" long but a maximum of 512 pixels on the CCD can be read out at one time. Solar images can be made using one of the slots or by stepping one of the slits over a region of the Sun. Telemetry constraints generally limit the spatial and spectral coverage of an observation. See Culhane et al. (2007) and Korendyke et al. (2006) for more details on the EIS instrument.

For these observations the 1" slit was stepped over the active region and 15 s exposures were taken at each position. An area of 256" × 256" was imaged in about 71 minutes. A total of 20 spectral windows were read out of the CCD and included in the telemetry stream. The raw data were processed using \texttt{eis$_{-}$prep} to remove dark current, warm pixels, and other instrumental effects using standard software. During the processing the observed count rates are converted to physical units. Intensities from the processed data are computed by fitting the observed line profiles with Gaussians. The EIS rasters are co-aligned to account for any spatial offsets (see Young et al. 2009 for a discussion). Spacecraft jitter during the raster has not been accounted for. The \textit{Hinode} housekeeping logs suggest relatively small displacements (less than 1 pixel) for the narrow field of view of interest here. For larger structures spacecraft jitter can be important. EIS rasters in a number of different emission lines are shown in Figure 2 and show post-flare loops at various temperatures in the lower part of the active region. These rasters also indicate a brief data gap due to orbital eclipse.

One limitation of these EIS data is the lack of temporal information. Better information on the temporal evolution of these loops is provided by the imaging instruments, such as the EUVI (Howard et al. 2008) on the \textit{STEREO} mission. The EUVI is a normal incidence, multilayer telescope which can observe the Sun in four wavelength bands centered at 284, 195, 171, and 304 Å. EUVI observes the full Sun and therefore has reduced spatial resolution (1" pixels) relative to the other observations that we consider here. There are two \textit{STEREO} spacecraft with identical instrument packages. The twin \textit{STEREO} spacecraft drift away from the Earth at about 23° per year. On 2007 May 2 the separation between the spacecraft was small, about 6°.

The EUVI images taken around the time of the EIS raster are indicated in Figure 1. Because of telemetry constraints the image cadence is limited. For these observations 171 Å images were taken at a relatively high cadence (∼ 150 s) while the images at the other wavelengths were taken at lower cadences (∼ 600–1200 s). The raw data are processed using \texttt{euvi$_{-}$prep} to produce calibrated, co-aligned images. Images of the active region and flare from \textit{STEREO} B EUVI are shown in Figure 3.

The XRT on \textit{Hinode} is a high cadence, high spatial resolution (approximately 1" pixels) grazing incidence telescope that images the Sun in the soft X-ray and extreme ultraviolet wavelength ranges. Temperature discrimination is achieved through the use of focal plane filters. Because XRT can observe the Sun at short wavelengths, XRT images measure the emission from high temperature solar plasma very efficiently. The thinner XRT filters allow longer wavelength EUV emission to be imaged and extend the XRT response to lower temperatures. Further details on XRT are given in Golub et al. (2007).

As indicated in Figure 1, the principal XRT images taken during this time period were in three filters, Ti-Poly, Al-Thick, and Be-Thick, at a variable cadence. Unfortunately, the exposure times on the Be-Thick images are too short for the images to be used for analyzing active region loops. The standard processing routine \texttt{xrt$_{-}$prep} is used to remove the CCD bias, dark current,
Figure 2. EIS rasters of active region 10953 in 10 different emission lines. These images were constructed by stepping the 1" slit from west (right) to east (left) over the region between 20:27 and 21:38 on 2007 May 2. The field of view is 256" × 256". Each exposure is 15 s in duration. Note that the Fe x1 192.813 Å raster shows both Fe x and Ca xvii 192.858 Å emission. The dark vertical band is from a Hinode orbital eclipse. For comparison with the imaging data a vertical line has been drawn on the rasters corresponding to data taken 20:58:34 UT. In the online version of the manuscript a combined EIS/TRACE movie is available. In the movie the static EIS Fe x 184.536 Å raster is shown in the green channel and the TRACE 171 Å frames are shown in the red channel. Features that are common to both instruments appear in yellow. The movie also shows the position of the EIS slit for each TRACE frame.

(A color version and an animation of this figure are available in the online journal.)

Figure 3. EUVI/STEREO B 284, 195, and 171 Å images of active region 10953 from approximately 20 to 22 UT on 2007 May 2. The field of view is approximately 216" × 168".

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

and calibrate the images. Images are also “dejittered” using Hinode spacecraft housekeeping data so that the images are co-aligned with respect to each other. Hinode tracks solar rotation so there is no need to account for it in the images. Example Ti-Poly images are shown in Figure 4. These images have a field of view of 512" × 512".

The TRACE instrument is a high-resolution normal incidence telescope. The primary and secondary mirrors are divided into quadrants and a rotating shutter is used to select which quadrant is illuminated. Three of the quadrants are coated with multilayers for imaging at EUV wavelengths. The multilayer coatings have peak sensitivities at approximately 171, 195, and 284 Å. The fourth quadrant is coated with aluminum and magnesium fluoride for imaging very broad wavelength ranges near 1216, 1550, 1600, and 1700 Å. Images in all of the wavelengths are projected onto a single detector, a 1024 × 1024 CCD. Each CCD pixel represents a solar area approximately 0.3′′ on a side. The instrument is described in detail by Handy et al. (1999). The initial in-flight performance is reviewed by Golub et al. (1999) and Schrijver et al. (1999).

During this period TRACE observed mainly in the 171 Å channel at a cadence of about 60 s with occasional 1600 Å and white light context images. All of the images have a 512" × 512" field of view. As shown in Figure 1, there are periodic data
gaps in the TRACE data due to orbital eclipses. All of the TRACE images are processed using a standard application of trace_prep. Additionally, the images are despiked and co-aligned with respect to each other to account for solar rotation and drifts in the pointing. A simple cross-correlation method is used for this purpose. The TRACE 171 Å images are very similar in appearance to the EUVI 171 Å images.

3. ANALYSIS

The primary goal of this study is to compare multi-threaded, hydrodynamic simulations with the emission observed in an evolving coronal loop. As we will discuss in more detail later in the paper, hydrodynamic simulations involve solving the equations for the conservation of mass, momentum, and energy in the loop given some input heating rate. Relating the heating rate to physical observables is a critical element of the modeling. Our strategy is to measure the electron density with EIS and use a family of hydrodynamic simulations to infer the required heating rate for this density. Previous numerical simulations suggest that for a fixed loop length there is a power-law relationship between the peak electron density and the input energy (Warren & Antiochos 2004). Since we want the loop length to be fixed, the other critical element of this modeling is an accurate measurement of the loop geometry, including the inclination. Observations from the twin EUVI instruments allow the loop geometry to be measured, and we use the STEREO software package developed for this purpose (Aschwanden et al. 2008a).

Once the density and loop geometry have been determined we can perform hydrodynamic simulations and synthesize the expected emission during the entire evolution of the loop. The simulation results can then be compared with light curves determined from TRACE and XRT, and in this section we discuss how these light curves are calculated. The distribution of temperatures in the loops is an important constraint on the modelings, and in this section we also discuss the calculation of the DEM distribution with the EIS spectra.

3.1. EIS

Our analysis requires the identification of loops observed simultaneously with both EIS and TRACE. To facilitate this, we wrote routines to co-register EIS rasters with TRACE images and to display 24 bit color images using an EIS raster for one color channel and a TRACE image for another color channel. An animation of these images allowed us to quickly identify times when the EIS slit was cospatial with a loop observed with TRACE (see the animation associated with Figure 2 in the electronic version of this paper). To optimize the co-alignment between EIS and TRACE we had to allow for a small roll angle between the images. This is in addition to the usual spatial shifts between the pointing information contained in the data headers. Since the TRACE data were taken in the Fe xix/x 171 Å channel we used the EIS Fe x 184.536 Å raster for co-alignment.

EIS's relatively small field of view, TRACE's frequent data gaps due to orbital eclipse, and the complexity of the solar atmosphere make finding good data sets more difficult than anticipated. While there appear to be many good candidates for analysis in these data we have found only a single-loop segment whose evolution is completely captured by TRACE and is sufficiently isolated in EIS to allow for background subtracted intensities to be measured. This segment is not at the loop apex, but the temperature and density gradients in the solutions to the hydrodynamic loop equations are generally very weak in the corona.

The EIS intensities for the loop of interest are summarized in Figure 5. Once the region of interest was identified we manually selected spatial positions along the loop in the EIS Fe xii 195.119 Å raster. These points are used as spline knots to define the loop coordinate system (s, t), with s along the loop and t perpendicular to it (see Aschwanden et al. 2008a, Figure 3). Since these loop coordinates are not necessarily aligned to the CCD we have interpolated to determine the intensities along the selected segment. The loop segments displayed in Figure 5 are interpolated to 0.2 per pixel. Using the loop coordinate system it is a simple matter to compute the intensity averaged along the loop segment. The coordinate system derived from Fe xii 195.119 Å is used for all of the EIS rasters.

To further isolate the intensity of the loop we identify two background points and fit a single Gaussian with a linear background to the selected region. Background subtraction is essential to separating the intensity in the loop from the contribution of the ambient corona, but there is no unique method for computing it. Analysis of EUVI data, which has the advantage of providing two different lines of sight for a single loop, suggests that the background subtracted intensities can be computed consistently, although there can be considerable uncertainties for individual measurements (Aschwanden et al. 2008a).

Since we are interested in emission that is cospatial, we extract the same region from all of the EIS rasters. The resulting
Intensities are shown in Figure 5. To test how cospatial the emission is at various temperatures, we have calculated a simple correlation coefficient between the background subtracted intensity in each line and Fe XII 195.119 Å, which represents a middle ground between the highest and lowest temperature emission that is observed. For this loop well-correlated, cospatial emission is observed for Fe XIII and below. For the emission at higher temperatures (Fe XIV–XVI) the correlation is poor.

It is clear from the images shown in Figures 2 and 5 that the combination of high spatial resolution and good temperature discrimination allows EIS to probe the interrelationship of emission at different temperatures. The loop intensities suggest that the emission at different temperatures is generally not cospatial and that the DEM in the loop of interest should be relatively narrow. This is shown more clearly in the “multicolor” image of this region presented in Figure 6. This image, which is a 24 bit image formed from rasters in three different emission lines, would be white in regions where the DEM is broad and the emission is strong in all three lines. There are some composite regions that are cyan (green + blue), but the post-flare loop arcade is generally dominated by emission in the primary colors suggesting relatively narrow distributions of temperature in each loop.

To investigate the temperature structure of this loop more quantitatively we compute the DEM using the background subtracted loop intensities for the loop segment. The intensities are related to the DEM by the usual expression

\[ I_\lambda = \frac{1}{4\pi} \int \epsilon_\lambda(n_e, T) \xi(T) dT, \]  

where \( \epsilon_\lambda(n_e, T) \) is the plasma emissivity and \( \xi(T) \) is the DEM.
distribution. We consider a Gaussian DEM model

$$\xi(T) = \frac{EM_0}{\sigma_T \sqrt{2\pi}} \exp\left[-\frac{(T - T_0)^2}{2\sigma_T^2}\right].$$

which allows for a dispersion in the temperature distribution. Since the density is an important parameter in determining the emissivities of many of these lines, we leave it as a free parameter. To determine the best-fit parameters (EM$_0$, $T_0$, $\sigma_T$, $n_e$), we use a Levenberg–Marquardt technique implemented in the MPFIT package. The CHIANTI 5.2 atomic physics database (e.g., Landi et al. 2006) is used to calculate the emissivities. The abundances of Feldman et al. (1992) and the low-density ionization fractions of Mazzotta et al. (1998) are assumed.

There are several subtleties to computing the emission measure parameters. One is the statistical uncertainty associated with each intensity. Because the intensities are averaged over a significant area the statistical uncertainties are generally small. The systematic errors introduced by the background subtraction and the atomic data, however, are large, but difficult to estimate. We simply assume that the relative error is 20% of the measured intensity. Another question is how to deal with the emission from lines such as Fe xvi 262.984 Å, that do not show evidence for the loop and have no measured intensity. For these lines the background-subtracted intensity is zero. Observations of these lines provide important constraints on the high-temperature component of the DEM and must be included. To account for possible errors in computing the background-subtracted intensities for these lines we assume that the uncertainty in the intensity is 20% of the background instead of 20% of the loop intensity. Since the background can be large this represents a substantial enhancement of the uncertainty.

The resulting DEM for this loop segment is shown in Figure 7. The observed and computed intensities are given in Table 1. From this analysis we obtain an electron density of log $n_e = 9.7$. For this work, we use the Fe xiii 203.826/202.044 Å lines to provide the bulk of the density sensitivity. Recently, Young et al. (2009) have noted systematic discrepancies between the various density-sensitive line ratios from Fe xii and Fe xiii. In light of this, we compared the densities inferred from Fe xiii 203.826/202.044 Å and Fe xii 186.880/195.119 Å with those from Si x 258.375/261.058 Å in a series of other active region and quiet Sun observations. The Si x lines, which were not included in this study, are relatively weak and not sensitive over as large a range as the Fe xii and Fe xiii lines. However, the atomic data for Si x are potentially more reliable than the atomic data available for the complex Fe ions. We find that the densities derived from the Si x and Fe xiii ratios are in excellent agreement and emphasize the Fe xiii ratio here. The densities inferred from Fe xii 186.880/195.119 Å are as much as a factor of 3 higher. Details of this analysis are presented in Warren et al. (2010).

The dispersion in the temperature is found to be log $\sigma_T = 5.5$, which is comparable to other active region loop observations with EIS (Warren et al. 2008). These lines observed in the quiet corona above the limb indicate much narrower temperature distributions (log $\sigma_T \lesssim 5.0$; Warren & Brooks 2009). Here, we find a dispersion in temperature that is several times greater, indicating that this loop is not strictly isothermal. The relatively intense, cospatial emission observed from both Si vii and Fe xiii provides the best direct evidence for a distribution of temperatures in this loop. These lines have peak temperatures of formation that are about 1 MK apart. The application of a delta function emission measure to Equation (1) confirms that a single temperature model cannot adequately reproduce the intensities observed in these emission lines.
3.2. TRACE

In searching for coronal loops observed with both EIS and TRACE we co-aligned the EIS rasters with the TRACE images for this period. Thus, to compute the TRACE intensities we use the same coordinate system and apply it to all of the TRACE images taken during the time of interest. Since the co-alignment between EIS and TRACE is not perfect, the spline knots selected in the EIS raster are modified slightly to better align with the loop. Background subtracted intensities are computed for each of the available TRACE images taken during this time using the same procedure that was used on the EIS data. For each image the region defined by the spline knots was extracted, straightened, and averaged along the loop coordinate to produce the intensity as a function of the perpendicular coordinate. The intensity at each time refers to the background subtracted intensity integrated over the loop.

The TRACE light curve is shown in Figure 8. For most of this period the background subtracted loop intensities are in the noise and the evolution of this loop can be seen clearly. We have manually selected the region around the peak in the light curve and fit it with a single Gaussian. This fitting yields a Gaussian width of about 294 s.

3.3. EUVI

To extract the three-dimensional geometry of this loop we use the software package developed by Markus Aschwanden and the STEREO team for this purpose. An application of this software is discussed in detail in Aschwanden et al. (2008a, 2008b). The initial processing co-registers images from STEREO A and B to account for differences in spacecraft roll angle and spatial resolution. The next step is to outline the loop in the STEREO A image. The selected coordinates are projected onto the corresponding B image. Since geometry of the loop has not yet been determined this projection yields a range of possible coordinates in the B image and the user selects the position of the loop within this range. Once the coordinates of the loop have been selected in both images the geometry of the loop is determined from simple trigonometric relationships.

Due to the gap in the A data, an image pair at 21:16 UT, after the peak emission observed in this loop, is used so there is some ambiguity in the loop identification. The selections of nearby structures in the loop arcade generally yield very similar results. The projection of the extracted loop geometry onto the EUVI B image available at the peak of the loop emission (20:59 UT) also outlines the observed loop very well. Thus, it does not appear that the calculation of the loop geometry is significantly impacted by the data gap. The selected loop and the projection of this loop in various planes are shown in Figure 9.

3.4. XRT

Images taken with the XRT provide information on the evolution of the loop at high temperatures. We have computed an XRT light curve similar to that computed for TRACE. To use the loop coordinates derived from EIS we first co-align the XRT images with the EIS Fe xvi 262.98 Å raster, which shares some common features. We then compute the background subtracted intensities by selecting two background points and doing a linear
fit. The emission seen earlier in the event is much broader than what is observed with TRACE and so we select a wider area to compute the intensities. The resulting XRT light curve is shown in Figure 10.

As is indicated by the light curve, the XRT images clearly show strong emission in the region that is eventually occupied by the loops observed with EIS and TRACE. It is also clear, however, that XRT does not show any individual loops that are as narrow as those that are seen at cooler temperatures. Consistent with this, the loop cross section measured with XRT is systematically wider than what is measured with EIS and TRACE. To illustrate these differences we have constructed multicolor images from XRT and TRACE. These images, which are presented in Figure 11, use different color channels to display the XRT and TRACE data in the same picture. To illustrate the differences in morphology as the plasma cools we have offset the times of the selected images by 1 hr. We show examples of the loop cross sections in Figure 12. This difference between high-temperature and low-temperature emission in flares and active regions is well documented (e.g., Tripathi et al. 2009; Patsourakos et al. 2002; Warren 2000) and may be further evidence for fine scale structure in the solar corona. We will discuss this point in more detail later in the paper.

4. HYDRODYNAMIC MODELING

One of the primary paradoxes of coronal loops with temperatures near 1 MK is the disparity between the rapid cooling suggested by the high electron densities and the relatively long observed lifetimes. EIS density diagnostics allow us to make more rigorous comparisons between these timescales. Densities inferred from observed intensities require an accurate determination of the DEM, the absolute instrumental calibration, and the loop geometry. Such a measurement also represents a lower bound on the density. The density inferred from density sensitive line ratios circumvents many of these problems.

If we assume that the loop is cooling only through radiation the energy balance is simply

$$\frac{\partial E}{\partial t} \approx -n T^2 \Lambda(T),$$  \hspace{1cm} (3)

where $\Lambda(T)$ is the radiative loss function for an optically thin plasma. In the limit of no flows the energy is $E = \frac{1}{2} P$. The plasma pressure given by $P = \frac{n e k_B T_e}{\Lambda(T)},$ where $k_B$ is the Boltzmann constant. The radiative cooling time is defined as

$$\frac{1}{\tau_R} = \frac{1}{E} \frac{\partial E}{\partial t} = \frac{1}{P} \frac{\partial P}{\partial t},$$  \hspace{1cm} (4)

and is given by

$$\tau_R = \frac{3 k_B T_e}{n_e \Lambda(T_e)}.\hspace{1cm} (5)$$

Using the temperature and density derived from the EIS DEM analysis (log $n_e \sim 9.7$ and log $T_e \sim 6.11$) and a radiative loss rate of $3.2 \times 10^{-22}$ erg cm$^3$ s$^{-1}$ (Brooks & Warren 2006) we obtain a radiative cooling time of 341 s.

The radiative cooling time is not directly comparable to the loop lifetime that we have measured with TRACE. If we make the additional assumptions that $T_e(t) = T_0 \exp(-t/\tau_T)$ and $T_e(t) \sim n_T^2(t)$ we can relate the radiative cooling time ($\tau_R$) to the timescale for changes in the temperature ($\tau_T$):

$$\tau_T = \frac{1 + \alpha}{\alpha} \tau_R. \hspace{1cm} (6)$$

Numerical simulations suggest that $\alpha \approx 2$ (Jakimiec et al. 1992). Finally, to compare with the observed loop lifetime we must incorporate the temperature changes into the TRACE temperature response curve. This yields

$$I_\lambda(t) \sim \exp \left[ -\frac{T_\lambda^2 (t - t_0)^2}{\sigma_\lambda^2 / 2 \tau_T^2} \right],$$ \hspace{1cm} (7)

where $T_\lambda$ is the peak temperature of the TRACE response and $\sigma_\lambda$ is the Gaussian width of the TRACE response (see Warren...
et al. 2003, Equation (9)). This yields

$$\sigma_t = \frac{\sigma_{171}}{T_{171}} T_R = \frac{\sigma_\lambda}{\alpha} \frac{1 + \alpha}{\alpha} T_R.$$  (8)

With $T_{171} = 0.96$ MK and $\sigma_{171} = 0.25$ MK (Warren et al. 2003) we obtain $\sigma_t = 141$ s, which is smaller than the observed Gaussian width of 294 s.

This mismatch between the predicted and observed loop lifetime is one of the key motivations for the multi-thread modeling of coronal loops. By assuming that the observed emission comes from a series of loops that are heated at different times it is clear that we can create a composite loop with the required lifetime. The challenge is to also match the relatively narrow DEM and the lifetime of the loop as it is observed with XRT.

To simulate the evolution of this loop we consider numerical solutions to the full hydrodynamic loop equations using the NRL Solar Flux Tube Model (SOLFTM). We adopt many of the same parameters and assumptions that were used in previous simulations with this code and we refer the reader to the earlier papers for additional details on the numerical model (e.g., Mariska 1987; Mariska et al. 1989). For example, we assume that the loop is symmetric and only simulate the evolution over half of the loop length. We also assume that each loop has a constant cross section.
For this work, we consider a heating function for each thread that is a simple spatially uniform heating rate:

\[ E_i(t) = E_0 + g(t)E_F^i, \] (9)

where \( g(t) \) is a triangular envelope that peaks at time \( t_i \) and has width \( \delta \), which we set to be 100 s, and \( E_F^i \) is the peak energy input into the thread. The parameter \( E_0 \) is a small background heating rate that provides the initial loop equilibrium. As we mentioned earlier, our strategy for inferring the heating rates from the observations is to use the density determined from EIS and the results from systematic hydrodynamic simulations. This will determine the peak heating rate for the ensemble of threads. The heating rate for the other threads will be determined by assuming a Gaussian envelope for the heating function.

To determine the relationship between the input heating rate and the densities and temperatures observed during the cooling phase of the loop evolution, we have performed 21 simulations with \( E_F \) varying between \( 10^{-3} \) and \( 10^2 \) erg cm\(^{-3}\) s\(^{-1}\). Using the parameters derived from the EUVI observations, the loop length is fixed at 135 Mm and the loop inclination is fixed at 68.5°. For each simulation, we average over the loop apex to determine a representative density and temperature. The simulation results are summarized in Figure 13. We find that the apex density at 1.3 MK, which is the peak temperature in the DEM, essentially scales as \( n_e \sim \sqrt{E_F} \). This implies that for a fixed loop length the observed intensity is linearly proportional to the input energy. The relationship shown in Figure 13 indicates that a heating rate of 0.8 erg cm\(^{-3}\) s\(^{-1}\) is required to reproduce an apex density of \( \log n_e \approx 9.7 \).

The density-heating rate relationship is valid for a single loop. For a multi-thread simulation, we assume the heating rate for each thread is related to this peak heating rate by

\[ E_F^i = E_F^{\text{peak}} \exp \left[ -\frac{(t_i - t_0)^2}{2\sigma_H^2} \right], \] (10)

where \( \sigma_H \) determines the duration of the heating envelope. The parameter \( t_0 \) is chosen so that all of the times are positive. The heating events are spaced so that as the heating in the previous loop ends the heating in the next loop begins. This heating scenario is illustrated in Figure 14 for \( \sigma_H = 100, 200, \) and 300 s.

Once the individual hydrodynamic simulations are run, we average over the loop apex at each time step to compute a representative temperature and density. These densities and temperatures are then used as inputs to the TRACE temperature response to calculate the expected count rates in the TRACE 171, 195, and 284 Å channels as function of time. The simulation times are shifted so that the peak in the 171 Å emission corresponds to the observed peak. Since we are not interested in resolving the differences in absolute calibration among the various instruments, we also introduce a scaling factor so that the peak-simulated emission matches what is observed. The simulation results are shown in Figure 15 and indicate that \( \sigma_H = 200 \) s simulation, which yields a simulated loop lifetime of \( \sigma_t = 286 \) s, best matches the observations.

We also use the simulated densities and temperatures as a function of time to compute the expected intensities in many of the emission lines that can be observed with EIS. Light curves from selected emission lines are shown in Figure 16. Since the absolute time for the simulation has been established through the comparisons with TRACE, we select the simulated EIS intensities that correspond to the time of the EIS observations and use them as inputs to the same DEM code that was used to produce Figure 5. The resulting simulated DEM is shown in Figure 16. The simulated intensities are given in Table 1.

The agreement between the observed and simulated DEMs is relatively good. The simulation captures the salient features of the observations, a relatively high density and a narrow DEM. For these simulated intensities, we do obtain a somewhat lower electron density (\( \log n_e = 9.5 \) for the simulation and 9.7 for the observation) and peak temperature (\( \log T_e = 6.04 \) for the simulation and 6.11 for the observation). The dispersion in the DEM also does not match the observation exactly (\( \log \sigma_T = 5.24 \) and 5.48). Given the approximate nature of the simulations we consider these discrepancies to be small. The difference in the density comes about because we have inferred the heating rate from a family of single-loop hydrodynamic simulations but the emission is actually a composite from several threads. It is likely that iterating on this solution would yield better agreement with the observations, but this is unlikely to yield addition physical insights.

Finally, we have simulated the expected XRT emission for the Open/Ti-Poly filter combination using the standard XRT
Figure 13. Family of hydrodynamic simulations for the loop geometry inferred from STEREO. The top panels show the apex densities and temperatures as a function of time. For each simulation, we have determined the density as the loop cools through 1.3 MK. The bottom panel shows the relationship between the input heating rate and the density at 1.3 MK.

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

Figure 14. Assumed heating rate for multi-thread simulations of the loop. The Gaussian curve represents the heating rate envelope. The triangles represent the heating rate for each thread.

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

software routine xrt_t_resp. The simulated and observed light curves are shown in Figure 17. This comparison presents the greatest challenge to the modeling. The modeled composite intensities, which have been scaled to match the observations at 20:00 UT, clearly do not extend back in time enough to cover the entire evolution of the emission in this region. The peak observed emission in this loop occurs at approximately 19:30 UT, before the simulation has even begun.

Given the diffuse nature of the XRT emission and the difficulty of isolating individual loops at high temperatures perhaps the simplest explanation may be that the XRT light curve includes the contributions of many loops in addition to the loop we isolated using the EIS and TRACE data. The identification of individual loops at very high temperatures with XRT is likely to be hampered by the slow evolution of plasma during the conductive cooling phase. This is evident by the slow evolution of the threads in the simulation. In Figures 16 and 17, for example, we see that the threads last for approximately 1 hr at high temperatures. At the lower temperatures, when radiative losses are much higher, the cooling is dominated by radiation and the evolution is much faster. In these simulations, the threads last only for about 10 minutes in the TRACE 171 Å bandpass. This difference suggests that the differentiated loops seen at lower temperatures, such as those illustrated in Figure 6, would appear as a single structure in XRT. These differences are also related to the broad temperature response of XRT. The relatively narrow-line emission imaged with EIS and TRACE emphasizes small differences in temperature.

Alternatively, the inability of the model to reproduce the observed XRT emission may reflect inadequacies with the hydrodynamic simulations during the conductive phase of the cooling. It may be that the heating is not as impulsive as we
Figure 15. Simulated and observed TRACE light curves for $\sigma_H = 100$, 200 and 300 s. The simulation times have been adjusted so that the peak emission in 171 Å matches what is observed. The magnitude of the simulated emission has also been scaled to match the observations. The lifetime of the loop is calculated from a Gaussian fit to the composite light curve. The $\sigma_H = 200$ s simulation most closely matches to observed loop lifetime.

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

Figure 16. Top panel: the apex temperature as a function of time for each thread. The vertical line represents the approximate time of the EIS observations. Middle panel: simulated EIS light curves for selected emission lines. Only the composite light curves are shown. Bottom panel: the DEM inferred from the simulated EIS emission.

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

have assumed. Many previous studies have suggested a gradual decay in the heating (e.g., Reale et al. 2004). These differences in the assumed heating may be related to the changes in the topology of the magnetic field during the evolution of the event. Observations of post-flare loop arcades have shown that newly reconnect field lines relax from cusp-shaped to approximately semi-circular during the early phases of the cooling (Svestka et al. 1987; Forbes & Acton 1996; Sheeley et al. 2004; Reeves et al. 2008). The comparisons between the hot and cool emission shown in Figure 11 clearly suggest that field line shrinkage is occurring in this event. The cool post-flare loops observed with TRACE are generally observed at the lowest heights of the arcade and do not overlap with the high temperature XRT emission seen at the top of the arcade. The implications of field line shrinkage on hydrodynamic simulations have not been investigated. In general, the conversion of magnetic energy into thermal energy through the process of magnetic reconnection is not well understood (see, e.g., Longcope et al. 2009). More detailed analysis of MHD simulations is needed to better understand the evolution of coronal loops after reconnection (e.g., Linton & Longcope 2006).

5. SUMMARY AND DISCUSSION

In this paper, we have made use of the unprecedented opportunity to observe evolving coronal loops in detail. We have used STEREO, EIS, TRACE, and XRT data to constrain a multi-
thread model of coronal heating and compare with observations. These comparisons indicate that it is possible to reproduce the high densities, long lifetimes, and relatively narrow emission measure distributions inferred from the data so long as the heating envelope of the heating is sufficiently narrow.

The most challenging comparisons are with XRT, where the model fails to reproduce the extended lifetime of the emission at high temperatures. It is not clear if this is due to our inability to isolate narrow loops at high temperatures or to problems with the assumed envelope on the heating. Recent analysis of the EIS spectral range has identified Ca xiv, xv, xvi, and xvii emission lines that can be used in the analysis of high temperature plasma (Warren et al. 2008; Del Zanna 2008; Watanabe et al. 2007). These lines will provide additional information on plasma evolution during the conductive phase and have been incorporated into the latest EIS observing sequences. New active region observations should be available during the rise of the next solar cycle.

Ultimately our goal is to apply the multi-thread modeling described here to non-flaring active region loops. It is encouraging that the simulated EIS DEM curve derived here is similar to those derived for lower density active region loops (Warren et al. 2008). It remains to be seen, however, that this model can also reproduce the loop evolution observed in TRACE and XRT. The launch of the Atmospheric Imaging Assembly on the Solar Dynamics Observatory, which will combine full disk imaging, TRACE-like spatial resolution, 10 s cadences, and multiple filters, will greatly expand the number of useful active region observations that combine EIS plasma diagnostics and loop evolution.

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![Figure 17](image_url)

Figure 17. Simulated and observed light curves for the XRT Open/Ti-poly filter combination.

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

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