Two-phase Heating in Flaring Loops
Chunming Zhu, Jiong Qiu, and Dana W. Longcope

Physics Department, Montana State University, Bozeman, MT 59717-3840, USA; chunming.zhu@montana.edu

Received 2017 December 7; revised 2018 January 31; accepted 2018 February 2; published 2018 March 21

Abstract
We analyze and model a C5.7 two-ribbon solar flare observed by the Solar Dynamics Observatory, Hinode, and GOES on 2011 December 26. The flare is made of many loops formed and heated successively over one and half hours, and their footpoints are brightened in the UV 1600 Å before enhanced soft X-ray and EUV missions are observed in flare loops. Assuming that anchored at each brightened UV pixel is a half flaring loop, we identify more than 6700 half flaring loops, and infer the heating rate of each loop from the UV light curve at the footpoint. In each half loop, the heating rate consists of two phases: intense impulsive heating followed by a low-rate heating that is persistent for more than 20 minutes. Using these heating rates, we simulate the evolution of their coronal temperatures and densities with the model of the “enthalpy-based thermal evolution of loops.” In the model, suppression of thermal conduction is also considered. This model successfully reproduces total soft X-ray and EUV light curves observed in 15 passbands by four instruments GOES, AIA, XRT, and EVE. In this flare, a total energy of $4.9 \times 10^{30}$ erg is required to heat the corona, around 40% of this energy is in the slow-heating phase. About two-fifths of the total energy used to heat the corona is radiated by the coronal plasmas, and the other three fifth transported to the lower atmosphere by thermal conduction.

Key words: magnetic reconnection – Sun: flares – Sun: UV radiation – Sun: X-rays, gamma rays

1. Introduction
Solar flares, observed as increased radiation across a broadband of electromagnetic spectrum, are generally accepted to be associated with a sudden release of free magnetic energy through the process of magnetic reconnection. During flares, the heated and accelerated particles travel along the newly formed coronal loops down toward the chromosphere, and deposit their energy at the loop footpoints, which usually form two evolving ribbons. The energy deposition there drives the chromospheric evaporation (Canfield et al. 1980; Fisher et al. 1984), which fills the coronal loops. The heated coronal plasmas then cool down gradually due to thermal conduction and radiation (Culhane et al. 1970; Antiochos & Sturrock 1978; Cargill et al. 1995).

The hydrodynamic evolution of the flaring plasmas has been investigated by many theoretical models. The properties and response of plasmas confined in coronal loops to some assumed heating mechanisms were studied by solving the one-dimensional (1D) hydrodynamic equations (e.g., McClymont & Canfield 1983; Nagai & Emslie 1984; Longcope et al. 2010; Bradshaw & Cargill 2013). However, the investigation of a wide range of parameters in various heating mechanisms (Mandrini et al. 2000) makes it very challenging for the computationally intensive 1D models. Thus the zero-dimensional (0D) models were developed to study the averaged values in each single loop/thread (e.g., Fisher & Hawley 1990; Kopp & Poletto 1993; Cargill 1994). Klimchuk et al. (2008) proposed an improved 0D model called “enthalpy-based thermal evolution of loops” (EBTEL), which gives an efficient way to calculate the average temperature and density in coronal loops/threads.

The response of the plasmas inside a coronal loop is governed by the energy input, or the heating rate. However, the physical mechanism of heating, and the amount of heating energy in flare loops, still remain largely unknown. Qiu et al. (2012) proposed an intuitive empirical method to infer the heating rates in flare loops that are continuously formed throughout the flare, utilizing spatially resolved UV emission in the lower atmosphere. They assume that anchored at each newly brightened UV pixel is a flare (half) loop, and the impulsive rise of the UV light curve at the pixel is scaled with the heating rate in the loop. This is the so-called UV Footpoint Calorimeter (UFC) method. With this method, hundreds to thousands of flare loops are identified in a flare even into the decay phase of the flare, when continuous energy release (and formation of new loops) still occur (e.g., Cargill & Priest 1983; Czaykowska et al. 1999, 2001; Reeves & Warren 2002). With the inferred heating rates, Qiu et al. (2012) and Liu et al. (2013) compute the evolution of flare loops and synthesize SXR and EUV emissions therein, which compare favorably with observed emissions during the rise of the flare. Subsequently, Qiu & Longcope (2016) studied a flare that exhibits a long-duration emission at 10 MK and slow cooling to lower temperatures. They found that superposition of many intense impulsive heating events, even into the decay phase of the flare, cannot reproduce the observed signatures at different temperatures. To improve the model-observation agreement, they needed to use a two-phase heating profile for each flare loop or thread: an intense impulsive heating, followed by a gradual slow heating. The two-phase profile may or may not coincide with a suppression of thermal conduction below its Spitzer value, in order to maintain the coronal plasma at high temperatures for a longer time (e.g., Jiang et al. 2006; Battaglia et al. 2009; Wang et al. 2015).

In this study, we analyze and model a two-ribbon flare with a modified UFC, and study the effects of two-phase heating as well as thermal conduction suppression (TCS) introduced in each flare loop. We find that the inclusion of both the persistent slow-heating and TCS in flare loops leads to the best agreement between model synthetic and observed SXR and EUV light curves in many passbands. In Section 2, we give an overview of the C5.7 flare observed on 2011 December 26. In Section 3, we model the flare evolution with EBTEL and compare the synthetic X-ray and EUV light curves to the observations from...
GOES, SDO/AIA, and EVE, and Hinode/XRT. The energetics and physical properties of flare loops are analyzed in Section 4. Conclusions and discussions are given in Section 5.

2. Overview of Observations

This C5.7 flare was positioned northeast of an active region NOAA 11384, and near the center of the solar disk. We focus on the X-ray and Extreme-Ultraviolet (EUV) observations provided by three spacecraft, including the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), Hinode (Kosugi et al. 2007), and GOES. SDO has three observing instruments onboard: the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) takes full-disk images of the Sun in 10 EUV/UV channels (log $T$ ranges 3.7–7.3) with roughly 0.56 pixel$^{-1}$ spatial resolution; the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) measures full-disk magnetograms with 1" spatial resolution and 45 s cadence; and the Extreme ultraviolet Variability Experiment (EVE) provides irradiance with high spectral resolution. The X-ray Telescope (XRT; Golub et al. 2007) on board Hinode observes this flare during its early phase in multiple bandpasses with a scale of ~1" pixel$^{-1}$. GOES has two X-ray sensors measuring the X-ray fluxes in the wavelength bands of 0.5–4 Å (short channel) and 1–8 Å (long channel).

The GOES soft X-ray in the long channel begins to increase at 11:23 UT and ends at 12:18 UT, with its peak appearing at 11:50 UT, as seen in Figure 1(a). Figure 1(b) gives the cooling process observed in the EUV channels from SDO/AIA: the peaks of the light curves appear progressively from the hotter to cooler channels (e.g., ~10 MK in 131 Å and 0.6 MK in 171 Å). Similar phenomena have been reported in previous studies (e.g., Ryan et al. 2013; Viall & Klimchuk 2013).

The flaring loops, when the total peak brightness is observed in AIA 211 Å (~2 MK), are shown in Figure 1(d). The overall shape of these loops are usually well described as semi-circular (e.g., Reale 2014). Six optically thin SDO/AIA EUV channels (except 304 Å) can be utilized to derive the emission measures at varying coronal temperatures. Figure 1(e) gives an example of the differential emission measures (DEMs) with log $T$ ranging from 6.65 to 6.75, calculated with the sparsity-based inversion method (Cheung et al. 2015). Similar DEM values appear along each loop in the flaring arcade, suggesting that the evolution of flare loops, though formed and heated at different times, is rather similar.

Two elongated ribbons observed in AIA 1600 Å are shown in Figure 1(f). They are located beside the polarity inversion line, and spread outward sequentially, as seen in Figure 1(g). The flare ribbons are composed of small kernels outlining the footpoints of flaring loops (Fletcher et al. 2004). The distance between the two ribbons increasing from 31 Mm at 11:27 UT to 42 Mm at 12:00 UT, indicating that loops anchored at newly brightened flare ribbons become longer, as magnetic reconnection forming these loops occurs at progressively higher altitudes (e.g., Gallagher et al. 2003). The reconnection rate (e.g., Forbes & Priest 1984; Qiu et al. 2004; Kazachenko et al. 2017), estimated by the amount of magnetic flux swept by the flaring ribbons at a given time, is shown with the blue curve in Figure 1(c), with the cumulative flux in red.

3. Modeling Plasma Evolution in Flaring Loops

We use the UFC method, with some modifications, to infer heating rates and model evolution of flare loops. The AIA 1600 Å images are processed using the standard routine aia_prep and then differentially rotated to a time just before the flare at 11:00 UT. The brightening pixels in 1600 Å are chosen with two criteria: (1) their values are larger than a threshold of ~200 DN/s, which corresponds to 2.5 times the median value of all pixels in the region of interest before the flaring, and (2) the brightening in each pixel lasts for at least 3
minutes. A few tests suggest that the outputs are not sensitive to the arbitrary values in both criteria. As a result, there are 6700 brightening pixels in total identified in AIA 1600 Å in this C5.7 flare. With each such pixel we assume that a half flaring loop of a constant cross-section (0.6 × 0.6) is rooted in it. Then we investigate the evolution of the plasma parameters of each half loop with EBTEL.

3.1. EBTEL Setup

The basics of setting up EBTEL can be found in Qiu et al. (2012) and Liu et al. (2013). The model solves two equations, an energy equation and a mass conservation equation, to compute the time evolution of the mean temperature and density of a flare loop, assuming that the corona and transition region evolve in equilibrium, i.e., uniform pressure. Energy input in the corona is required to run the model, and energy loss terms include radiations by the corona and transition region.

During the heating phase, energy is transferred, such as by thermal conduction, from the corona to the transition region, which in turn transports mass (and enthalpy flux) back to the corona.

To model the flare evolution, we first determine some loop properties from observations, the length of the loop and the heating rate in each loop. For this C-class flare without significant nonthermal emission above 20 keV, we do not consider heating by chromospheric evaporation driven by nonthermal particles that precipitate in the lower atmosphere; therefore, all corona heating is in situ. In this paper, we use ad-hoc coronal heating rates inferred from UV light curves and do not explore the mechanism for the in situ heating. Improved over the standard UFC method, we include TCS in the model, and also examine the effect of slow heating, following the impulsive heating in each loop.

As the flare progresses, two ribbons separate, indicating larger lengths of newly formed loops. We approximate the lateral expansion of the ribbons by a linear increase with time. The half-loop length of the flaring arcade also grows linearly from 24 Mm at 11:27 UT to 33 Mm at 12:00 UT, described by L = 24 + 0.27(t − t0) Mm, where t0 is the time of flare onset at 11:27 UT, and t is the time of the peak UV brightening at the foot of the half loop expressed in minutes. We assume that the length of a particular half-loop does not change during its subsequent evolution. Before t0 of 11:27 and after 12:00 UT, the lengths are fixed at 24 and 33 Mm, respectively.

Under the flaring conditions, the thermal conduction can sometimes be suppressed (e.g., Jiang et al. 2006; Battaglia et al. 2009; Wang et al. 2015). In this study, we consider the TCS given by Rosner et al. (1985), i.e., when the ratio of the mean-free path for thermal electrons \( l_{\text{mfp}} \) is larger than 0.015 of the temperature scale length \( L_{\text{th}} \) (here using the loop half length), a reduction factor of 0.11\( (l_{\text{mfp}}/l_{\text{th}})^{−0.36} \) is applied to the classical thermal conduction (Spitzer 1962) until it is further saturated (Luciani et al. 1983; Karpen & Devore 1987). Here we choose \( l_{\text{mfp}} = 1.4 \times 10^7 (T/10^6 \text{K})^{n}(n/10^5 \text{ cm}^{-3})^{-1} \) cm, where \( T \) and \( n \) are the average temperature and density in each loop, respectively. We adopt the same expressions of the classical and saturated thermal conductions as shown in Equations (18)–22 in Klimchuk et al. (2008).

The heating rates are derived from the light curves of the associated flaring pixels in AIA 1600 Å. The light curve of such a pixel is shown in Figure 2(a). The standard UFC method fits the rise of the UV light curve with a half-Gaussian and assumes that the impulsive heating flux is proportional to the full Gaussian, as indicated by the dashed line in the figure. The observed UV light curve typically decays much slower than its rise, with a gradually attenuated tail following the Gaussian fitting. The slow decay of the UV light curve may be partly due to continuous heating of the transition region by thermal conduction from the corona without more energy deposit into the corona; however, it is also likely that during this slow decay, additional heating also takes place in the corona. To understand the effect of slow heating during the decay, in this study, we model and compare flare loop evolution with two types of heating rates, impulsive heating and two-phase heating. Following Qiu et al. (2012), the impulsive heating rate \( H_{\text{imp}} \) is chosen to be proportional to the Gaussian fitting of the light curve with a scalar factor \( \lambda_0 \) in units of erg cm\(^{-2}\) DN\(^{-1}\), which converts the UV count rates \( I_{\text{imp}} \) to the impulsive heating flux by \( H_{\text{imp}} = \lambda_0 I_{\text{imp}} \). The two-phase heating contains an extra gradual heating \( H_{\text{grad}} \), which in this study is assumed to be proportional to the slow tail of the UV light curve \( (I_{\text{tail}}) \) by another scaling factor \( \lambda_1 \), having the same units as \( \lambda_0 \), i.e., \( H_{\text{grad}} = \lambda_1 I_{\text{tail}} \). Such reconstructed heating functions are displayed in Figure 2(b). The same values of \( \lambda_0 \) and \( \lambda_1 \) are used for all loops. They are determined by comparing model synthetic SXR emission with that observed by GOES.

The radiative loss from the transition region is also specified in the model as scaled with the mean pressure of the corona by a scaling constant \( \eta \), which is the same for all loops. This parameter is chosen by comparing the model synthetic EUV emission at the low temperature (1–2 MK) with observations (Qiu & Longcope 2016).

Given the heating functions and the half length of the flaring loop, its evolution can be modeled with EBTEL. We considered three scenarios: (I) impulsive heating, (II) impulsive heating with TCS, and (III) two-phase heating with TCS. Figures 2(c)–(e) show the temperature, density, and pressure of one flare loop, with \( \lambda_0 = 6.3 \times 10^{5} \text{erg cm}^{-2} \text{ DN}^{-1} \), \( \lambda_1 = 3.2 \times 10^{5} \text{erg cm}^{-2} \text{ DN}^{-1} \), and \( L = 27.3 \text{Mm} \), modeled in these three cases. It is notable that (1) TCS helps retain more energy in the corona and thus leads to a higher temperature (the suppressed conduction drives less chromospheric evaporation; therefore, the peak density is lower, and the resulting effect leads to comparable pressures) and (2) the slow tail in the two-phase heating continues heating the loop and thus keeps it warmer longer, and the density is also slightly higher in the decay phase.

3.2. Synthetic GOES and AIA Light Curves

With the evolution of each flaring loop modeled by EBTEL, the light curves of the whole flaring region are derived by convolving the DEM calculated from multiple loops with the response functions of various channels from different instruments (e.g., Qiu et al. 2012; Liu et al. 2013; Zeng et al. 2014; Qiu & Longcope 2016). Figure 3 gives the comparison of the synthetic light curves with the observations from GOES soft X-ray and SDO EUV channels, under those three heating scenarios, respectively.

With only impulsive heating and classical thermal conduction rate (see Figure 3(a)), the synthetic emission at high temperature \( \gtrsim 10 \text{ MK} \) decays faster than observed, and the emission at 1 MK rises 20 minutes earlier than observed. This indicates that the plasmas cool down faster in the simulation. In the impulsive heating with the TCS scenario (Figure 3(b)), the
cooling is delayed by \( \sim 5 \) minutes, yet the difference between the model and observation is still remarkable. With only impulsive heating, the model cannot produce sufficient emissions at high temperatures after the peak of the flare, even though new heating events are still identified (Figures 1(c) and (g)).

With the inclusion of an extra slow tail in the heating function, i.e., the two-phase heating with TCS displayed in Figure 3(c), the total flare emission at \( \geq 10 \) MK persists for a longer time with the lower temperature emission significantly delayed thereby agreeing with observations. This scenario produces sufficient emission in both the rise and decay phases of the flare, with the parameter set \( \lambda_0 = 6.3 \times 10^5 \) erg cm\(^{-2}\) DN\(^{-1}\), \( \lambda_1 = 3.2 \times 10^5 \) erg cm\(^{-2}\) DN\(^{-1}\), \( \eta = 2.4 \times 10^6 \) cm s\(^{-1}\). In Section 4.2, we discuss the rationale for the different choices of the scaling constant during the impulsive and gradual phases.

To quantitatively evaluate the outputs of the three heating scenarios, the linear Pearson correlation coefficient in each channel (after comparable amplitudes obtained as shown in Figure 3) is calculated. The average values of those coefficients in each scenario, given in the lower-left corners (Figure 3), are 0.64, 0.80, and 0.96, respectively. This also suggests that the

Figure 2. Heating and the resultant response of the plasma in one flaring loop. (a) Light curve of a single pixel in AIA 1600 Å and its Gaussian fitting. The tail part is indicated. (b) Construction of the heating rates with two heating mechanisms: impulsive heating and two-phase heating. The impulsive heating function is based on the Gaussian fitting, while the two-phase heating has an additional slow tail that is proportional to the tail of the light curve, which is denoted in (a). (c)–(e) Evolution of temperature (\( T \)), density (\( n \)), and pressure (\( P \)) of this individual flaring loop given by EBTEL in three scenarios: impulsive heating (dashed), impulsive heating with thermal conduction suppression (TCS, dashed–dotted), and two-phase heating with TCS (solid), respectively.

Figure 3. Comparison of the observed (black) and simulated (colored) light curves of the whole flaring region in two GOES channels and six SDO/AIA passbands. The background values are subtracted. Each flux is multiplied by the denoted factor and is offset by 1 from top to bottom. The three panels correspond to the results under three heating scenarios: impulsive heating (left), impulsive heating with TCS (middle), and two-phase heating with TCS (right). The average value of the correlation coefficients in each scenario is displayed at the lower-left corner in the corresponding panel.
third scenario gives the best agreement to the observations. Overall, the comparisons indicate that the flare might be involved with both TCS and two-phase heating.

### 3.3. XRT and EVE Light Curves

The two-phase heating model with TCS produces the synthetic X-ray and EUV light curves in reasonable agreement with the GOES and AIA observations; therefore, we use this model and make further comparisons of the synthetic light curves to the observed X-ray flux from *Hinode/XRT* and EUV lines from *SDO/EVE*, as displayed in Figure 4.

Figures 4(a) and (b) give the *Hinode/XRT* coverage of this flare between 11:27 and 11:51 UT, roughly corresponding to the early phase until the flaring peak. Three XRT channels are listed in Figure 4(b), including Be-thick, Al-med, and Be-thin. As there is no data covering this region before the flare, the background level in each channel is estimated with the average value of pixels outside the flaring region. Then the total background contribution is subtracted from the original light curves. The results in Figure 4(b) suggest that the two-phase heating gives good agreement with the observations in those three channels.

Figure 4(c) shows the observed and synthetic EVE curves during the flare. They also display good agreement in the listed typical emission lines, including Fe XX/XXIII (log T ~ 6.97), Fe XVIII (log T ~ 6.81), Fe XVI (log T ~ 6.43), and Fe XIV (log T ~ 6.27), with both comparable peaking values and decay time. Though the observed cooler Fe XIV line has complicated profiles possibly due to other contributions such as the emissions from the transition region.

### 3.4. DEMs

The distributions of the DEMs covering the whole flaring region are inverted from the *SDO/AIA* observation and are also synthesized from the EBTEL simulation, as shown in Figures 5(a) and (b), respectively. The sparsity-based inversion method for the DEMs by Cheung et al. (2015) is used for this inversion. Figure 5(b) gives the synthetic DEMs under the scenario of two-phase heating with TCS. For both DEM maps, the averaged values from 11:00 to 11:15 UT are chosen as the background levels and thus get subtracted from the original DEM values. Both maps display a downward trend before ~12:30 UT and stays roughly flat thereafter, and both give higher peaking DEM values during 11:45–12:30 UT. A clear difference is that the DEMs inverted from the observation have broader distributions than the simulation, and the former has more contribution from plasma hotter than ~12 MK.

The DEMs at six times, as indicated between Figures 5(a) and (b) by (c1)–(c6), are shown in Figures 5(c1)–(c6) accordingly. Before ~12:00 UT, including (c1) and (c2), the peaks of the simulated DEMs are higher and shift to hotter temperatures by a few MK than the observationally inverted ones. After that, the peaks of those DEMs are comparable in the magnitude and also the associated temperatures. Besides, larger inverted DEMs at very hot temperatures (>12 MK) are also noticeable in those profiles.

These comparisons indicate that the EBTEL well reveals the general evolution of the DEM during this flare, especially in its decay phase. Though little emission from a temperature larger than 12 MK is present in the result of EBTEL, which might be due to the 0D nature of EBTEL based on the average values of the loops.
4. Energetics of the Flare

4.1. Energy Partition

The evolutions of the total heating rate and the cumulative heating energy are estimated and displayed in Figure 6. The peak of the heating rate is $1.7 \times 10^{27}$ erg s$^{-1}$ at 11:35 UT. With the increased temperatures of the flaring loops due to the impulsive heating, the thermal conduction increases accordingly and peaks at 11:37 UT with $\sim 1.2 \times 10^{27}$ erg s$^{-1}$. Because the temperature tends to increase earlier than the density, as is evident from Figures 2(c) and (d), the peak of the transition region radiation ($R_{\text{tr}} \propto n$) appears earlier than coronal radiation ($R_{\text{c}} \propto n^2$). The peaking values of $R_{\text{tr}}$ are $7.7 \times 10^{26}$ erg s$^{-1}$ at 11:46 UT, around 1.6 times the peaking $R_{\text{c}}$ of $4.8 \times 10^{26}$ erg s$^{-1}$ at 11:58 UT.

To study the energy partitions during the flare, the cumulative energies are tracked and shown in Figure 6(b). By 13:10 UT, the total heat input is around $4.9 \times 10^{30}$ erg, roughly balanced by the total radiation energy, which is composed of $R_{\text{tot}}$ of $3.0 \times 10^{30}$ erg and $R_{\text{c}}$ of $1.9 \times 10^{30}$ erg. The coronal radiation can also be estimated from the GOES soft X-ray data (Cox & Tucker 1969; Emslie et al. 2005). It gives a value of $2.2 \times 10^{30}$ erg, roughly agrees with $R_{\text{c}}$ from our simulation. The total thermal conduction loss is roughly at $3.1 \times 10^{30}$ erg, which is radiated through the transition region.

4.2. Energetics in the Two Phases

Assuming that a half flare loop is anchored at each UV brightened AIA pixel, we have identified and modeled over 6700 half loops, each with a different heating rate and length as constrained by observations. In this study, each flare loop is heated “impulsively” and then gradually, as demonstrated by the two-phase UV light curve at the footpoint. We explore the different roles of the heating in the two phases.

Figure 7(a) shows the distribution of the rise times of the UV light curves. The rise times primarily range between 2 and
6 minutes. The timescale of thermal conduction \( \tau_{\text{cond}} \) using the Spitzer thermal conductivity at temperature \( T \sim 10 \) MK and density \( n \sim 10^9 \) cm\(^{-3}\) is no longer than 1 minute, and the reaction of the transition region to energy deposition is of the order of a few seconds. Therefore, the observed rise time of the UV light curves is substantially longer than the timescale of thermal conduction, indicating that the observed rise time is characteristic of the heating timescale. We also note that for the coronal plasma at temperature \( T \sim 10 \) MK and the length of the coronal loop at \( L = 30 \) Mm, the characteristic acoustic time is \( 1-3 \) minute, which is a fraction of the heating timescale. If the AIA instrument, at a resolution of \( 0''6 \), nearly resolves individual flare loops, then flare loops would mostly evolve in quasi-equilibrium even during the “impulsive” phase. If an AIA-identified flare loop consists of substructures like threads, the heating time of each thread could be shorter (Graham & Cauzzi 2015).

The next three panels in Figure 7 show the distributions of the time lags of the peak temperature, pressure, and density of a loop relative to the time of the peak heating rate \( \tau_1 = t_{\text{max}} - t_{H_{\text{max}}} \), \( \tau_2 = t_{P_{\text{max}}} - t_{H_{\text{max}}} \) and \( \tau_3 = t_{n_{\text{max}}} - t_{H_{\text{max}}} \) respectively. It is seen that the temperature of the corona peaks shortly after the peak heating rate, whereas the pressure peaks a few minutes later, when the impulsive heating has nearly finished. These results indicate that the impulsive heating raises the thermal energy of the coronal loop, so that the thermal energy density \( \epsilon \) is roughly proportional to the time integral of the volumetric heating rate \( Q \). \( \epsilon_{\text{max}} = (3/2)P_{\text{max}} \sim \int Q_{\text{imp}} dt \). Figure 8 further corroborates this point. Figure 8(a) shows the scatter plot of \( \epsilon_{\text{max}} \) versus \( E_{\text{imp}} \). Their power-law relation is indicated by the solid line in red, with a fitting shown in the top left corner. The dashed line indicates positions along \( y = x \). (b) The histogram of \( \epsilon_{\text{max}} / E_{\text{imp}} \).

Figure 7. Distributions of the rise times of the heating rates (a), and the delays of the peak values of the temperature \( (T_{\text{max}}) \) in (b), pressure \( (P_{\text{max}}) \) in (c), and density \( (n_{\text{max}}) \) in (d) with regard to the peak heating rate \( H_{\text{max}} \) in each loop.

Figure 8. Relationship of the peak thermal energy density \( \epsilon_{\text{max}} \) in each loop to its total impulsive volumetric heating \( E_{\text{imp}} \). (a) Their power-law relation is indicated by the solid line in red. (b) The histogram of \( \epsilon_{\text{max}} / E_{\text{imp}} \).
That the coronal pressure $P$, or thermal energy density $e = (3/2) P$, reaches the maximum at the end of the impulsive heating, suggests that in the gradual phase, the heating energy is at most used to balance the radiative loss and does not continue to increase the thermal energy of the flare loop. In this phase, the coronal radiation becomes important, whereas the coronal pressure varies slowly. Therefore, in this phase, the energy equation is approximately $Q \approx (|R_i| + |R_u|)/L$. In our empirical model, we infer heating rates of flare loops from (transition region) UV radiation by a scaling factor $\lambda_0$ during the impulsive heating phase and $\lambda_1$ during the slow-heating phase. Different governing physics during these two phases specifies different relations between the heating rate and transition region radiation, which may explain why $\lambda_0$ is different from $\lambda_1$.

4.3. Properties of the Flare Loops

We also examine the distribution of physical parameters of these 6700 half loops. Figure 9 shows the histograms of the magnetic field strength, peak temperature, peak density, peak heating flux, and the total heating energy of these loops. The magnetic field strengths at the loop footpoints have a power-law distribution, with an index of $-1.52$. The peak temperature ranges from ~8 to 18 MK. In this flare, the peak heating flux ranges from $10^{8-9}$ erg cm$^{-2}$ s$^{-1}$. Heating flux of this order usually does not generate a strong chromosphere evaporation (Fisher et al. 1985; Reep et al. 2015); as a result, the peak density of this flare is of the order of $(1-3) \times 10^{10}$ cm$^{-3}$.

The total heating energy in the flare loop ranges between $10^{26-27}$ erg, or each flare loop is equivalent to a microflare (Hannah et al. 2011). In this flare, the distribution of the total energy released in each flare loop can be fitted to a log-normal distribution (Figure 9(e)). The center $\mu$ and width $\sigma$ of this fitting are $-0.68$ and $0.57$, respectively. Here the total energies follow a log-normal distribution, possibly related to the similar distribution of the magnetic flux concentrations (Abramenko & Longcope 2005).

4.4. Properties of the Flux Concentrations

We look into the relationships of the total heatings with magnetic energies and fluxes in the flaring flux concentrations, as seen in Figure 10. The flaring regions are partitioned into flux concentrations using the method presented by Abramenko & Longcope (2005). Here the flaring locations with magnetic field strength larger than a threshold of 25 Gauss are considered. This accounts for 71% of the 6700 flaring pixels. There are 206 flux concentrations identified and outlined in Figure 10(a).

Figure 10(b) shows the scaling of the total heating $E_h$ with the magnetic energy $E_{mag}$ in the magnetic flux concentrations. $E_{mag}$ is estimated to be $\sum_i (1/8\pi) B_i^2 L_i S$, where $B_i$ and $L_i$ are the footpoint field strength and the length of loop $i$ in a chosen concentration, respectively, and $S$ is the area of one pixel. In this event, $E_h$ and $E_{mag}$ can be scaled with a power law, i.e., $E_h = 7.7E_{mag}^{0.67}$. Overall, the amount of the heating energy is 12% of the magnetic energy calculated in flaring pixels.

A similar procedure is applied to check the relationship of $E_h$ and the magnetic flux $\Phi$, giving an equation of $E_h = 3.0 \times 10^9 \Phi^{0.97}$, with $E_h$ in units of erg and $\Phi$ in Mx, as shown in
The nearly linear relationship between the heating energy and magnetic flux suggests that the two physical quantities are scaled by the mean electric current in the current sheets $I \approx 3 \times 10^{10}$ Amp. The distribution of this current $I = E_h/\Phi$ in the current sheet(s) associated with each flux concentration is shown in Figure 10(d). It is on the order of $10^{10}$ Amps, consistent with previous studies (e.g., Longcope et al. 2007, 2010; Qiu 2009).

### Figure 10

(a) The magnetic concentrations in the flaring regions. Their boundaries are outlined by black/white curves around positive/negative magnetic fields. (b) The total heatings $E_h$ vs. the total magnetic energies $E_{mag}$ in the flux concentrations. A power law is indicated by a solid line, with the relationship given at the top left. (c) $E_h$ vs. the magnetic flux ($\Phi$) in the concentrations. The denotation is similar to (b). (d) The histogram of the estimated strengths of the electric currents in the current sheets that are associated with the concentrations during the flare.

Figure 10(c). The nearly linear relationship between the flare heating energy and magnetic flux suggests that the two physical quantities are scaled by the mean electric current in the current sheets $I \approx 3 \times 10^{10}$ Amp. The distribution of this current $I = E_h/\Phi$ in the current sheet(s) associated with each flux concentration is shown in Figure 10(d). It is on the order of $10^{10}$ Amps, consistent with previous studies (e.g., Longcope et al. 2007, 2010; Qiu 2009).

### 5. Discussion and Conclusions

We modeled a typical two-ribbon flare of C5.7 class on 2011 December 26 observed by SDO, Hinode, and GOES to determine the heating rates in $\sim 6700$ half flaring loops. Three heating scenarios are tested with the 0D EBTEL model, including impulsive heating, impulsive heating with TCS, and two-phase heating with TCS, among which the latter gives the best agreement with the observed X-ray and EUV light curves.

The peak temperatures and densities of the flaring loops are around 12 MK and $1.5 \times 10^{10}$ cm$^{-3}$ (Figure 9), respectively, which imply that the thermal flux can be locally limited (e.g., Battaglia et al. 2009). In this study, the minimum values of the TCS reduction factors for each half loop are among 0.07–0.13. The TCS results in a higher coronal temperature (Figure 2(c)), so that the simulation better agrees with observations at hot channels (Figures 3 and 4). However, our study suggests that the impulsive heating with TCS cannot reproduce the observed slow cooling process in this flare (Figure 3), and an additional persistent low-rate heating is necessary to agree with observations. This result is consistent with the recent study by Bian et al. (2018), which suggests that both the extended duration of magnetic energy release and the suppression of heat conduction are needed to explain the inferred physical properties from flare observations.

Under the two-phase heating scenario, the total input energy is composed of impulsive and gradual heating with amounts of $2.8 \times 10^{30}$ and $2.1 \times 10^{30}$ erg, respectively, i.e., the impulsive and slow heating components account for 60% and 40%, respectively, of the total heating during this flare. The timescale of the impulsive heating, as inferred from the observed UV light curves, ranges between 2 and 6 minutes, and that of the
ensuing slow heating is typically over 20 minutes, considering the decay timescale of the light curves (e.g., Qiu et al. 2010; Cheng et al. 2011; Liu et al. 2013). The peak heating flux in the impulsive phase reaches a few times $10^7$ erg cm$^{-2}$ s$^{-1}$, and during this phase, the heating energy is mostly used to raise the thermal energy of the coronal loop. The slow heating at a lower rate, of a few times $10^5$ erg cm$^{-2}$ s$^{-1}$, does not increase the thermal energy of the loop, and nearly balances the radiative losses in the corona as well as the transition region, allowing the loop to cool more gradually than otherwise. The observed slow decay of the UV light curve at the footpoint of a flare loop is a reflection of the slowly evolving corona, which keeps heating the transition region by thermal conduction. Previously, Liu et al. (2013) modeled the flare loop evolution using only an impulsive heating, and calculated the footpoint UV radiation caused by thermal conduction of the corona without additional heating during the decay phase. They found that the synthetic flux of C IV, which is dominating in the 1600 Å emission during flares, can roughly account for around half of the observed values in this channel during the long decay. In this paper, we illustrate the need for additional heating in the decay phase of a flare loop, such as the observed shrinkage affecting its length (e.g., Savage & McKenzie 2011; Zhu et al. 2016), usually last for a few minutes or less, which is small compared to the whole flaring timescale. Thus EBTEL is expected to provide a good approximation at least in the long gradual phase of the flare. Other effects, e.g., how the spatial and temporal changes of the cross section (Klimchuk 2001; Mikić et al. 2013) and the plasma composition (Phillips 2004; Barnes & Longcope 2016) affect the hydrodynamic evolution of a loop/thread should be evaluated in a future study.

For future work, we will look further into the role of the slow heating in solar flares to answer some related questions, such as whether it is ubiquitous in the flares, how much it varies with different magnitudes of flares, and what the mechanisms for impulsive and slow heatings are in a flare. We will also investigate the heating process for more flares with complex configurations and see how it may vary with the evolving magnetic structures.

The authors thank the referee for several constructive comments. This work is supported by the NASA grant NNX14AC06G, the NSF SHINE collaborative grant AGS-1460059, and the ISSI/ISSI-BJ team “Diagnosing Heating Mechanisms in Solar Flares.” We thank Sarah Pearce for the preliminary study.

Facilities: SDO, Hinode/XRT, GOES.

References

Abramenko, V., & Longcope, D. 2005, ApJ, 619, 1160
Antiochos, S., & Sturrock, P. 1978, ApJ, 220, 1137
Barnes, W. T., Cargill, P. J., & Bradshaw, S. J. 2016, ApJ, 829, 31
Battaglia, M., Fletcher, L., & Benz, A. O. 2009, ApJ, 698, 891
Bian, N., Emslie, A. G., Horne, D., & Kontar, E. P. 2018, ApJ, 852, 127
Bradshaw, S. J., & Cargill, P. J. 2013, ApJ, 770, 12
Canfield, R., Brown, J., Craig, I., et al. 1980, in Skylab Solar Workshop II, ed. P. A. Sturrock (Boulder, CO: Colorado Associated Univ. Press), 231
Cargill, P., & Priest, E. R. 1983, ApJ, 266, 383
Cargill, P. J. 1994, ApJ, 422, 381
Cargill, P. J., Marsika, J. T., & Antiochos, S. K. 1995, ApJ, 439, 1034
Cheng, J., Kerr, G., & Qiu, J. 2011, ApJ, 744, 48
Cheung, M. C., Boerner, P., Schrijver, C., et al. 2015, ApJ, 807, 143
Cox, D. P., & Tucker, W. H. 1969, ApJ, 157, 1157
Culhane, J., Vesecky, J., & Phillips, K. 1970, SoPh, 15, 394
Czaykowska, A., Alexander, D., & De Pontieu, B. 2001, ApJ, 552, 849
Czaykowska, A., De Pontieu, B., Alexander, D., & Rank, G. 1999, ApJL, 521, L75
Emslie, A. G., Dennis, B. R., Holman, G. D., & Hudson, H. S. 2005, JGRA, 110, A11103
Fisher, G., Canfield, R., & McCoylont, A. 1984, ApJL, 281, L79
Fisher, G. H., Canfield, R. C., &McClymont, A. N. 1985, ApJ, 289, 414
Fisher, G. H., & Hawley, S. L. 1990, ApJ, 357, 243
Fletcher, L., Pollock, J. A., &Potts, H. E. 2004, SoPh, 222, 279
Forbes, T., & Priest, E. 1984, SoPh, 94, 315
Gallagher, P. T., Dennis, B. R., Krucker, S., Schwartz, R. A., & Tolbert, A. K. 2003, in The Reuven Ramaty High-Energy Solar Spectroscopic Imager, ed. R. P. Lin, B. R. Dennis, & A. O. Zen (Berlin: Springer), 341
Golub, L., DeLuca, E., Austin, G., et al. 2007, SoPh, 243, 63
Graham, D., & Cauzzi, G. 2015, ApJL, 807, L22
Hannah, I., Hudson, H., Battaglia, M., et al. 2011, SSRV, 159, 263
Jiang, Y. W., Liu, S., Liu, W., & Petrosian, V. 2006, ApJ, 638, 1140
Jiang, Y. W., Liu, S., Liu, W., & Petrosian, V. 2006, ApJ, 638, 1140
Jiang, Y. W., Liu, S., Liu, W., & Petrosian, V. 2006, ApJ, 638, 1140
Jiang, Y. W., Liu, S., Liu, W., & Petrosian, V. 2006, ApJ, 638, 1140
Karp, J. T., & Deove, C. R. 1987, ApJ, 320, 904
Kazachenko, M. D., Lynch, B. J., Welsch, B. T., & Sun, X. 2017, ApJ, 845, 49
Klimchuk, J. 2001, in Physics of the Solar Corona and Transition Region, ed. O. Engvold et al. (Berlin: Springer), 53
Klimchuk, J., Patsourakos, S., & Cargill, P. 2008, ApJ, 682, 1351
Kopp, R. A., & Poletto, G. 1993, ApJ, 418, 496
Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, SoPh, 243, 3
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Liu, W.-J., Qiu, J., Longcope, D. W., & Caspi, A. 2013, ApJ, 770, 111
Longcope, D., Beveridge, C., Qiu, J., et al. 2007, SoPh, 244, 45
Longcope, D., Des Jardins, A., Carranza-Fulmer, T., & Qiu, J. 2010, SoPh, 267, 107
Luciani, J., Mora, P., & Virmont, J. 1983, PhBrL, 51, 1664
Mandrini, C. H., Demoulin, P., & Klimchuk, J. A. 2000, ApJ, 530, 999
McClymont, A., & Canfield, R. 1983, ApJ, 265, 483
Mikić, Z., Lionello, R., Mok, Y., Linker, J. A., & Winebarger, A. R. 2013, ApJ, 773, 94
Nagai, F., & Emslie, A. G. 1984, ApJ, 279, 896
Pesnell, W. D., Thompson, B., & Chamberlin, P. 2012, SoPh, 275, 3
Phillips, K. 2004, ApJ, 605, 921
Qiu, J. 2009, ApJ, 692, 1197
Qiu, J., Liu, W., Hill, N., & Kazachenko, M. 2010, ApJ, 725, 319
Qiu, J., Liu, W.-J., & Longcope, D. W. 2012, ApJ, 752, 124
Qiu, J., & Longcope, D. W. 2016, ApJ, 820, 14
Qiu, J., Wang, H., Cheng, C., & Gary, D. E. 2004, ApJ, 604, 900
Reale, F. 2014, LRSP, 11, 4
Ree, J. W., Bradshaw, S. J., & Alexander, D. 2015, ApJ, 808, 177
Reeves, K. K., & Warren, H. P. 2002, ApJ, 578, 590

1 https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2011_12/univ2011_12.html
Rosner, R., Low, B., & Holzer, T. 1985, in Physics of the Sun, ed. P. A. Sturrock et al. (Berlin: Springer), 135
Ryan, D. F., Chamberlin, P. C., Milligan, R. O., & Gallagher, P. T. 2013, ApJ, 778, 68
Savage, S. L., & McKenzie, D. E. 2011, ApJ, 730, 98
Schou, J., Scherrer, P., Bush, R., et al. 2012, SoPh, 275, 229
Spitzer, L. 1962, Physics of Fully Ionized Gases (New York: Interscience)
Viall, N. M., & Klimchuk, J. A. 2013, ApJ, 771, 115
Wang, T., Ofman, L., Sun, X., Provornikova, E., & Davila, J. M. 2015, ApJL, 811, L13
Zeng, Z., Qiu, J., Cao, W., & Judge, P. G. 2014, ApJ, 793, 87
Zhu, C., Liu, R., Alexander, D., & McAteer, R. J. 2016, ApJL, 821, L29