HYDRO_DYNAMIC SIMULATION OF A NANOFLAKE-HEATED MULTISTRAND SOLAR ATMOSPHERIC LOOP

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ABSTRACT

There is a growing body of evidence that the plasma loops seen with current instrumentation (SOHO, TRACE, and Hinode) may consist of many subresolution elements or strands. Thus, the overall plasma evolution we observe in these features could be the cumulative result of numerous individual strands undergoing sporadic heating. This paper presents a short (10° cm 10 Mm) “global loop” as 125 individual strands, where each strand is modeled independently by a one-dimensional hydrodynamic simulation. The energy-release mechanism across the strands consists of localized, discrete heating events (nanoflares). The strands are “coupled” together through the frequency distribution of the total energy input to the loop, which follows a power-law distribution with index α. The location and lifetime of each energy event is random. Although a typical strand can go through a series of well-defined heating/cooling cycles, when the strands are combined, the overall quasi-static emission-measure-weighted thermal profile for the global loop reproduces a hot apex/cool base structure. Localized cool plasma blobs are seen to travel along individual strands, which could cause the loop to “disappear” from coronal emission and to appear in transition or chromospheric emission. As α increases (from 0 to 2.29 to 3.29), more weight is given to the smallest heating episodes. Consequently, the overall global loop apex temperature increases, while the variation of the temperature around that value decreases. Any further increase in α saturates the loop apex temperature variations at the current simulation resolution. The effect of increasing the number of strands and the loop length, as well as the implications of these results for possible future observing campaigns for TRACE and Hinode, are discussed.

Subject headings: hydrodynamics — methods: numerical — Sun: activity — Sun: corona

Online material: color figures

1. INTRODUCTION

The discovery that a significant proportion of the radiation emitted from the solar corona is concentrated along well-defined loops represented a major advance in our understanding of the Sun. These loops are the basic structural elements of the atmosphere, as has been revealed in unprecedented detail by the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE), and the Hinode missions. It is now universally believed that these features coincide with magnetic flux tubes and occur because plasma and thermal energy can flow along, but not easily across, the magnetic field. However, it must be noted that the phrase “loop” is an inclusive, general term. In particular, there has been some discussion as to whether an individual loop has yet to be resolved; that is, do even TRACE extreme-ultraviolet (EUV) loops further consist of a bundle of filamentary plasma strands at a range of temperatures that, when averaged over, give the appearance of uniformly bright structures (Lenz et al. 1999)? Using SOHO Coronal Diagnostic Spectrometer and Yohkoh soft X-ray observations for 13 positions along a given loop structure, Schmelz et al. (2001) argue that the resulting broad differential emission measure (DEM) is a strong indicator of a multithermal plasma. Since the heat transport across the magnetic field should be very small, the conclusion could be that the loop under investigation is multitthreaded in nature.

One-dimensional (1D) hydrodynamic modeling of a loop as plasma evolving along individual field lines has been popular since the late 1970s (Peres 2000; Walsh et al. 1995). However, it must be recognized that if the range of loop structures we can observe do consist of many “subresolution” elements, then these 1D models are really only applicable to an individual plasma element or strand. Thus, a “loop” is an amalgamation of these strands. They could operate in thermal isolation from one another, with a wide range of temperatures occurring across the structural elements.

Until now, several multistrand static models have been associated with specific observations. For example, Reale & Peres (2000) showed that their hydrostatic solution, which contains six strands, is in rough agreement with an isothermal loop observed by TRACE. Aschwanden et al. (2000) compare hydrostatic solutions with 41 TRACE EUV loops of different lengths, but mostly fall short of being able to reproduce the TRACE emission (the loops appear to be denser that those generated by static calculations). To explain the discrepancy, Winebarger et al. (2003) conclude that it is unlikely that the overdense loops can be reconciled with any static model.

Warren et al. (2002) outline a multistrand loop model by choosing 10 randomly selected time periods from their single hydrodynamic loop simulation, synthesize TRACE 171 and 195 Å intensities, and average the resulting emission over the threads. They obtain a flat 171/195 filter ratio along the loop, resulting in much larger coronal intensities than those estimated by static heating. Ugarth-Urra et al. (2006) employ impulsive and quasi-static heat input to a hydrodynamic loop model to examine the subsequent evolution in X-ray and EUV, but find that compared to observed loops, the simulated EUV response lifetime for a single cooling loop is much shorter than those observed from TRACE. Warren (2006) employs a series of multiple (50) strand loop simulations to reproduce the high-temperature evolution of a solar flare; the numerical results suggest that an individual strand has an optimum heating timescale of a few hundred seconds.

Thus, this leads to another important question of how the million-degree plasma within loops is heated in the first place. One of several possible theoretical heating mechanisms is the concept
that the plasma is energized by the cumulative effect of numerous, small-scale ($\sim 10^{24}$ erg per event), localized, time-dependent energy bursts, or nanoflares (Parker 1988). It has already been observed that the frequency of occurrence $f$ of larger solar flares has a dependence on their energy content ($E$), and that it follows the power law

$$df/dE = E_0 E^{-\alpha},$$

with an index of $\alpha \sim 1.8$. Hudson (1991) pointed out that for the corona to be heated predominantly by nanoflares, a steeper slope ($\alpha > 2$) would be required. Several authors claim to have observed this steeper distribution from observed brightenings in both EUV and X-rays (e.g., Pauluhn & Solanki 2007; Krucker & Benz 1998; Parnell & Jupp 2000).

Thus, if nanoflare heating is taking place within loops, then multiple subresolution strand modeling with a heat input that is episodic in nature should be important. One approach to simulating this scenario is to use a zero-dimensional (0D) hydrodynamic calculation, as introduced by Cargill (1994) and later modified by Cargill & Klimchuk (1997, 2004) and Klimchuk & Cargill (2001). These authors devised a semianalytic, multistrand model in which it is assumed that each strand can be represented by a single temperature and density only. Each strand experiences “impulsive” nanoflare heating in the sense that the heat deposition occurs on timescales much shorter than any plasma cooling time. The heated plasma cools initially by conduction and then later by radiation. Subsequently, a “global loop” was constructed of many (say, 500–5000) strands, and observables (e.g., emission measure) were calculated. The results show that increasing the number of strands in the global loop leads to a slight increase in overall average temperature, but that the emission measure remains almost unaffected. The model also explains the overdensity of warm coronal loops (Cargill & Klimchuk 2004).

Following on from this model, Cargill & Klimchuk (1997) compared the radiative signature of their 0D loop with Yohkoh Soft X-ray Telescope (SXT) observations. Observed loop dimensions and radiative losses were used as multistrand nanoflare model inputs, and observables such as temperature, emission measure, and filling factors were derived. Their results show that the model agrees fairly well with very hot loops ($T > 4 \times 10^6$ K) but not with cooler loops ($T \sim 2 \times 10^6$ K). Subsequently in Cargill & Klimchuk (2004), the authors studied the effect of altering the power-law index in their nanoflare energy distributions. Their results show that steeper power-law indices (e.g., $\alpha = 4$) considerably change the emission-measure profiles and the value of the filling factor compared to the flat ($\alpha = 0$) distribution.

In that regard, Patsourakos & Klimchuk (2005) generate synthetic line intensities from a nanoflare-heated hydrodynamic loop simulation. They localize the spatial distribution of the nanoflare events, finding that the resulting TRACE and Yohkoh SXT emission was only weakly affected by the various dominant heat deposition locations. Patsourakos & Klimchuk (2006) further stress the importance of predicting line profiles for their nanoflare-heated loop model, indicating that the profile for a hot line (in this case, Fe xvi at $\sim 5$ MK) should be seen to undergo strong broadening with distinctive enhancements in the line wings.

The current paper greatly extends the above by examining a fully 1D hydrodynamic simulation of a small (10 Mm) loop consisting of 125 individual strand elements. Each strand operates independently of the plasma response along the structure; however, the strands are connected through the frequency distribution of the energy input via small-scale heating episodes that follow a power law with a predefined index. The paper is arranged as follows. In §2, the numerical model for a single strand is outlined, as well as the plasma response to the sudden deposition of a nanoflare-sized energy burst. Section 3 constructs a “global loop” consisting of multiple (125) strands, where each strand is subjected to several successive impulsive energy bursts. Subsequently, the effect of varying the power-law index $\alpha$ is investigated. Finally, §4 presents a discussion and an outline of future work (both through further simulation and possible observations).

2. SINGLE-STRAND MODEL

Consider a loop $10^9$ cm = 10 Mm in length, with a cross-sectional radius of $\sim 1.1 \times 10^9$ cm = 1.1 Mm. Let us assume that this loop consists of 125 individual plasma strands that fill the loop volume (that is, the radius of each strand is $9.6 \times 10^6$ cm = 0.098 Mm). These strands are thermally independent, i.e., the dynamics of one strand cannot affect any other. The evolution of an individual strand in response to a designated heat input is outlined in the following sections.

2.1. Numerical Model of a Strand

Since the solar corona is a highly conducting low-$\beta$ medium, the magnetic field confines the plasma along flux tubes, and the plasma can be described with 1D hydrodynamics. A Lagrange remap 1D hydrodynamic code (adapted from Arber et al. 2001) is employed for the purpose of solving the following time-dependent 1D differential equations of mass, momentum, and energy conservation:

$$\frac{D\rho}{Dt} + \rho \frac{\partial v}{\partial s} = 0,$$

$$\rho \frac{Dv}{Dt} = - \frac{\partial p}{\partial s} + \rho g + \rho \frac{n^2}{\gamma - 1},$$

$$\frac{\rho'}{\gamma - 1} \frac{D}{Dt} \left( \frac{1}{\rho'} \right) = \frac{\partial}{\partial s} \left( \frac{nT}{\gamma - 1} \right) - n^2 Q(T) + H(s, t),$$

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + v \frac{\partial}{\partial s},$$

where $\rho$, $p$, $n$, $v$, and $T$ respectively represent the mass density, pressure, particle density, velocity, and temperature of the plasma. Here, $s$ is the spatial coordinate along the strand ($-L < s < L$, where in this case $L = 5$ Mm), which is assumed to be semi-circular. In equation (3), $g$ represents the component of the gravity along the semicircular loop; because we are considering a small loop, we assume $g$ to be a constant with a value equal to the surface value ($2.74 \times 10^4$ cm s$^{-2}$) for all points along the loop. The term $\gamma$ represents the adiabatic index of the medium, which we consider to be 5/3, and $\kappa$ is the conductivity of the plasma in the direction of $s$ ($=9.2 \times 10^{-7} T^{-2/3}$ erg s$^{-1}$ cm$^{-1}$ K$^{-1}$). Here, $R$ is the molecular gas constant (8.3 $\times 10^7$ erg mol$^{-1}$ K$^{-1}$), and $\bar{u}$ is the mean molecular weight, with $\bar{u} = 0.6$ mol$^{-1}$. The coefficient of kinematic viscosity $\nu$ is assumed to be uniform throughout the plasma. For $Q(T)$, the optically thin radiative loss function, we adopt a piecewise continuous function with the general form $Q(T) = \chi T^\gamma$, which is based on the work by Rosner et al. (1978). Finally, $H(s, t)$ is our prescribed spatially and temporally dependent coronal heating term. The coronal loop is assumed to be symmetrical, and initially

$$\frac{\partial T}{\partial s} - \frac{\partial p}{\partial s} = 0.$$
Fig. 1.— Successive snapshots of strand evolution in temperature (left) and velocity (right) in response to $1.049 \times 10^{24}$ erg of energy being deposited 2.8 Mm to the right of the strand apex (at $s = 0$).
at the loop apex ($s = 0$). The boundary conditions follow as

$$T(-L, t) = T(L, t) = T_{ch} = 10^4 \text{ K}$$

and

$$p(-L, t) = p(L, t) = p_{ch} = 0.314 \text{ Pa}$$

at the loop footpoints deep in the chromosphere (where $T_{ch}$ and $p_{ch}$ are the chromospheric temperature and pressure, respectively). The chromosphere has a depth of 0.4 Mm at each loop leg. At the beginning of the simulation, the temperature along the strand is kept at the chromospheric temperature, i.e., $10^4 \text{ K}$, and the velocity along the strand is kept fixed at zero. Both the pressure and the density are decreased exponentially toward the strand apex; subsequently, the plasma is gravitationally stratified, and higher density plasma at the chromosphere is available for chromospheric evaporation during the simulation. As we shall see in these simulations, the sudden release of localized energy bursts will create traveling shock fronts throughout the strand plasma. The Lagrange remap code has been shown to deal very well with resolving this type of front (Arber et al. 2001). Thus, an average grid spacing of 0.037 Mm was employed at the central coronal part of the loop; this optimizes the simulation in terms of both the resolution required to track the dynamic features in the strand and a reasonable simulation run time.

2.2. Strand Plasma Response to a Nanoflare

Using the above strand model, let us examine the response of the plasma within the initially cool, evacuated strand to a rapid deposition of localized energy, i.e., a nanoflare. Consider the evolution of the plasma temperature and velocity along the strand, as shown in Figure 1. Here, the total energy contained within the heating burst is $1.049 \times 10^{24} \text{ erg}$. The heating is localized at 2.8 Mm to the right of the strand apex (at $s = 0$) and occurs over a length scale of 0.2 Mm. The event lifetime is 50 s (starting at 57.5 s after the simulation begins).

After an initial localized raising of the temperature where the energy is deposited, the extra heat is carried away from this site by conduction; eventually, the overall strand temperature rises to over 4 MK. From the velocity snapshots (at 58.46 and 65.05 s) it is clear that, due to sudden heating, a shock front develops that propagates along the strand with a velocity up to $>140 \text{ km s}^{-1}$. As expected from basic acoustic shock front physics, the propagation of the front is also observed in a slight local increase in the temperature. At time $107.5 \text{ s}$, the heating burst is switched off. Sound waves continue to bounce back and forth along the strand (reflecting off the high-density chromospheric boundary), and eventually the overall temperature begins to decrease, the shock front decays, and the plasma velocity declines (to $30 \text{ km s}^{-1}$ at $239.63 \text{ s}$).

The main feature of this 0D model is that initially it allows a strand to cool solely by conduction until the ratio of the conduction timescale to the radiation timescale becomes unity. Thereafter, radiative losses take over. In contrast, the present model keeps both processes active, with the dominant cooling mechanism determined automatically when solving the set of hydrodynamic equations. In addition, the present model is capable of transporting localized extra heat by means of mass flow via enthalpy flux. Thus, consider Figure 2, where the strand apex temperature (Fig. 2a) and density (Fig. 2b) are seen to evolve after the nanoflare burst. The density evolution clearly shows that chromospheric evaporation continues to take place up to around 300 s, after which the density drops as the plasma condenses back to the chromosphere. In contrast to Figures 1 and 2 in Cargill (1994), there is no sudden switch between cooling timescales. Also, there are some smaller scale structures due to the flow of material along the loop as the plasma cools; the spatial evolution of this plasma flow is shown in Figure 1.

3. MULTISTRAND MODEL

Consider now a loop as consisting of 125 individual strands, where these strands are related through the distribution of the localized energy input across the elements. The localized heat input $H(s, t)$ arising from the deposition of a given amount of energy $E$ over an event lifetime $\tau$ is chosen randomly in time, with constraints $10^{23} \text{ erg} \leq E \leq 5 \times 10^{24} \text{ erg}$ and $50 \text{ s} \leq \tau \leq 150 \text{ s}$.

The energy bursts are released within a fixed volume element, where the element length is 0.2 Mm. The heating episode location ($S_h$) can be anywhere along the strand within the range of $-4.5 \text{ Mm} \leq S_h \leq 4.5 \text{ Mm}$, so as to avoid the chromospheric part of the structure.

The overall energy-release profile follows the power law given in equation (1). The larger the value of $\alpha$, the steeper the slope of the frequency distribution, and hence the more weight given to the smallest heating episodes. The total energy input to the global loop remains the same for the following three simulations, namely, $4 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$ for a total run time of $1.725 \times 10^4 \text{ s}$. 

![Figure 2](image_url)

**Figure 2.**— Evolution of strand apex (a) temperature and (b) density, after a localized energy burst.
First, consider a flat frequency distribution ($\alpha = 0$), where 175 heating events with energy distributed randomly between $10^{23}$ and $5 \times 10^{24}$ erg provide the amount of total heat input indicated above. Each strand experiences an average of 14 energy bursts during the simulation. Figure 3 displays a histogram of the size of an event versus the number of times it occurs during the simulation across all strands; generally, there is no preferred weighting toward any heating scale.

Let us examine the evolution of a single strand undergoing multiple heating bursts. The temperature and density evolution at the strand apex of a typical element (the 55th) is shown in Figure 4; several maxima are observed in response to the recurring sudden energy release. As examined in §2, after an initial heating burst, the localized heat is distributed by conduction, and the strand plasma dissipates the excess heat through radiation unless it is heated by another energy event.

However, what Figure 4 does not portray is the effect of the spatial localization of the heating. Thus, the temperature evolution along a strand is displayed as an image plot in Figure 5. Each individual heating event can be identified easily, as the temperature along the strand increases dramatically (sometimes up to ~9 MK); at other times, the strand plasma is much cooler. Note that the maximum value of the temperature along the strand might not be at the strand apex.

Figure 5 (bottom) concentrates on a narrower time range (4800 – 7400 s) and displays three specific heat deposition episodes; these are also marked in Figure 4. At episode (1), an energy release (of $6.88 \times 10^{23}$ erg for the duration of 77.39 s starting at 4985.25 s) occurs 0.05 Mm away from the strand apex. In contrast to episode (1), episode (2) occurs ~3 Mm away from the apex and is larger ($2.3 \times 10^{24}$ erg released over 83.5 s). At episode (3), two heating events have occurred close together in time. The first event ($4.8 \times 10^{24}$ erg over 133.5 s at ~1 Mm) occurs at 7032.25 s, while the second ($1.26 \times 10^{24}$ erg over 51.2 s, at 2.8 Mm) is initiated at 7176 s. The evolution of the strand temperature is clear in Figure 5 (bottom right), as the plasma is heated to a maximum of ~9 MK. The plasma is still hot (maximum ~6 MK) when the second event occurs, which therefore does significantly raise the temperature once again.

Now consider combining all 125 strands to form a “global loop.” As individual strands are unresolved, the observed temperature has to be affected by the composite emission of all the strands together. Therefore, we derive the emission-measure-weighted temperature ($T_{EM}$) as

$$T_{EM} = \frac{\sum_{i=1}^{125} n_i^2(s, t) d(l) T_i(s, t)}{\sum_{i=1}^{125} n_i^2(s, t) d(l)},$$

where $dl(s)$ is the grid resolution.

Figure 6 (top left) displays $T_{EM}$ at the loop apex. Neglecting for the moment the larger drops in $T_{EM}$ and the initial few hundred seconds as the simulation begins, the overall $T_{EM}$ fluctuates around 1.6 MK, with an amplitude ~ 0.4 MK. The very low values of $T_{EM}$ are a result of how this weighted temperature is being calculated. We can see that if the density in any given strand increases dramatically, then from equation (9), $T_{EM}$ will be dominated by the temperature of that strand. Subsequently, Figure 6 (top right) displays the average apex density evolution over the 125 strands; there is a high correlation between the sharp increases in density and the sudden changes in $T_{EM}$. Figure 6 (bottom) shows an image plot of $T_{EM}$ along the loop, together with an enlarged time window around 5000 s, which concentrates on the propagation of a particular $T_{EM}$ dip.

To better understand these sharp drops in the calculated $T_{EM}$, let us concentrate on a typical dip at around 5000 s. A reasonably sized heating event takes place in strand 11 of the simulation. This strand has had enough time to relax to a cool (~$10^4$ K), evacuated (~$10^9$ cm$^{-2}$) structure after a previous heating burst, which occurred in the strand at ~3000 s. It is heated again at 4904.75 s with an energy burst that lasts 113.5 s, contains $1.414 \times 10^{24}$ erg of energy, and is located 3.75 Mm to the right of the strand.

The detailed dynamic evolution that arises from this event can be seen in Figure 7. It is very clear that soon after the episodic heating event, a traveling front develops rapidly from the energy-release site. The reason for this drop in the $T_{EM}$ at the loop apex...
Fig. 5.— Temperature evolution of strand 55. Top: Complete evolution for the simulation. Bottom: Close-up of 4800–7400 s, displaying the thermal response to a number of distinct heating events. [See the electronic edition of the Journal for a color version of this figure.]
is due to a low-temperature “blob” traveling along the structure, as shown in Figure 7 (bottom right).

The local temperature rises up to 3 MK, with plasma being compressed ahead of the wave front. This localized cool plasma blob journeys along the strand just ahead of the corresponding increased temperature front. Subsequently, 125 s after the initial heating burst, the dense plasma front reaches the apex of the strand, while at that particular instant the local temperature is still chromospheric. Thus, for this short time (~10 s), the calculated $T_{EM}$ will produce a rapid dip. After the front passes the apex, the temperature at that location rises to coronal values. Eventually, the plasma blob travels down the other strand leg, assisted by gravity.

Similar phenomena can be observed in other strands. It appears that the development of such traveling cool plasma blobs depends on the density structure along the strand prior to the energy release, as well as the location and energy content of the event itself. For example, if a heating burst is initiated when the plasma is already hot and less dense, these plasma blobs do not form. Note that these events are identical to the formation and propagation of cold plasma blobs observed in the simulation by Mendoza-Briceño et al. (2005), who call their events “microspicules.”
Fig. 7.—Spatio-temporal description of the plasma blob evolution along strand 11. *Top left:* Temperature contour before and after the dramatic event. *Top right:* Density contour for the same time period. *Bottom left:* Temperature profile at three different snapshots. *Bottom right:* Density profile for the same snapshots. [See the electronic edition of the Journal for a color version of this figure.]
Interestingly, these sudden dips in $T_{\text{EM}}$ at a particular location in the loop could have observational implications. It could be the case that a loop could disappear from coronal emission and appear in transition or chromospheric emission (Schrijver 2001; O’Shea et al. 2007). However, it must be noted that although this phenomenon consists of a flow of cold plasma along a strand, it cannot be termed as classical catastrophic cooling, as analyzed theoretically by, e.g., Karpen et al. (2001) and Müller et al. (2003).

3.2. Case B: $\alpha = 2.29$

After investigating case A, where the occurrence rate for all heating events has equal weighting, consider case B, where the power-law index from equation (1) is $\alpha = 2.29$ (an energy event histogram similar to Fig. 3 is displayed in Fig. 8a). Since we are requiring that the same total amount of energy be deposited during this simulation as in case A, the total number of individual events occurring will increase: 7125 heating episodes take place, with each strand experiencing on average 57 events.

There are a number of aspects to note. First, there are fewer low-$T_{\text{EM}}$ dips in Figure 8b than in Figure 6 (top left); the corresponding density evolution is also shown in Figure 8c. Second, the mean $T_{\text{EM}}$ over time has increased to $\sim 2.2$ MK, with a reduced fluctuation ($\sim 0.1$ MK) around this value. To explain this behavior compared to case A, consider once again the response of an individual strand to more numerous but less energetic bursts; this is shown for the apex temperature of a typical strand in Figure 9. We can clearly see that the strand plasma is rarely provided with the opportunity to cool sufficiently before another heating burst arrives. Thus, the condition for producing the cool plasma blobs is also rare (and hence the number of $T_{\text{EM}}$ dips at the apex is also greatly reduced). For the same reason, the average strand temperature is increased throughout the simulation, and subsequently the loop temperature $T_{\text{EM}}$ from the amalgamation of all strands also rises.

3.3. Case C: $\alpha = 3.29$

It is instructive to investigate the effect of further increasing the value of $\alpha$. Figure 10a displays the energy event histogram for $\alpha = 3.29$. In this case, approximately 21,500 events occur, with an average of 172 heating episodes per strand.

Once again, Figure 10b plots the loop apex $T_{\text{EM}}$; the mean value has increased slightly to $\sim 2.3$ MK compared to case B. The bigger fluctuations in $T_{\text{EM}}$ and density (Fig. 10c) have disappeared completely. The same arguments for the absence of $T_{\text{EM}}$ dips and for this increase in $T_{\text{EM}}$ can be employed as outlined in § 3.2. In particular, the strand plasma does not have adequate time to cool significantly before another heating event takes place. However, given that the energy event sizes are generally much smaller...
than in cases A and B, the impact of each event on the change in temperature is reduced. Increasing $\alpha$ further effectively “saturates” the temperature increase and further suppresses the fluctuations within the spatial resolution of the current simulation.

In order to obtain some idea of the quasi-static thermal profile along the loop, a simple average $T_{EM}$ profile of 125 strands is derived, and the cumulative effect of combining the plasma strands over a typical 5000 s period (from 5000 to 10,000 s) is shown for the left-hand side of the loop in Figure 10d. The usual overall thermal structure for a hot apex, cool footpoint loop is recovered. Figure 10d also compares this profile with two static equilibrium thermal profiles (referred to below as profiles 1 and 2) produced by the model outlined in Aschwanden & Schrijver (2002). For that particular calculation, we use a loop length of 10 Mm and employ the apex temperature of the nanoflare-heated thermal profile as a model input parameter. Note that the Aschwanden & Schrijver (2002) model has a heat input that is constant in time, and that we choose to have a heating scale length that is much longer than the overall loop length, i.e., the heat input is virtually spatially uniform. In static loop profile 1, a chromosphere of length 0.4 Mm is used; this matches the same chromosphere initially employed in the nanoflare model. In static loop profile 2, a chromosphere of length 0.9 Mm is chosen, as at this location the

![Fig. 9. Case B. Apex temperature evolution of a single strand when the power-law slope is $-2.29$.](image_url)

![Fig. 10. (a) Energy histogram fitted with a straight line to show that the power-law slope has a value of $\alpha = 3.29$. (b) Corresponding loop apex temperature evolution. (c) Corresponding loop apex density evolution. (d) Comparison between the nanoflare-heated quasi-static half-loop temperature ($T_{EM}$) profile and the static equilibrium temperature profile (Aschwanden & Schrijver 2002).](image_url)
nanoflare model thermal profile begins to level off at 10^4 K. Static loop profile 1 follows the nanoflare thermal structure in the “coronal part” of the loop well; however, after ~2.7 Mm, its temperature values are higher than those of the nanoflare model. Static profile 2 is not a good fit to the nanoflare model; from the common apex temperature, profile 2 deviates quickly from the nanoflare case, giving lower temperature values to ~3.8 Mm and higher values in the leg. However, it is to be noted that the overall difference between the nanoflare-heated quasi-static loop profile and static loop profile 2 would be indistinguishable from the current observational standpoint. Similarly, although static loop profile 1 shows a significant difference from the quasi-static profile over the ~1 Mm segment at the footpoint of the loop, considering the ambiguity of observing the loop footpoints, this difference as well could go unnoticed at the present instrumental resolution.

4. DISCUSSION AND FUTURE WORK

This paper has outlined a multistrand hydrodynamic model of a short (10 Mm) plasma loop undergoing sporadic, localized heating. During the simulations undertaken, the total energy deposited in the loop is constant, while the distribution of this energy throughout the 125 individual strands follows a power law, as outlined in equation (1). The results show that even though any given strand can evolve through a series of many heating and cooling cycles, the resultant “global loop” thermal profile can appear relatively uniform (e.g., Figs. 6 [top left], 8b, and 10b). Increasing the value of the power-law index $\alpha$ in equation (1) (from 0 to 2.29 to 3.29) increases the subsequent mean loop apex temperature, although at the current simulation resolution, this temperature value saturates if $\alpha$ is increased further.

Note that for computational expediency, these investigations have considered a short 10 Mm loop with the limited filamentation of $N_s = 125$ strands. If the number of strands were increased further ($N_s > 125$), the total volume occupied per strand would decrease. Concentrating on case B ($\alpha = 2.29$), if the total energy deposition into the loop throughout the simulation remains fixed, and the lower energy range cutoff ($E_{\text{low}}$) does not change (from 10^23 erg, as in Fig. 3), then the number of events per strand will decrease, but the energy density per event per strand will increase. That is, although there would be fewer events occurring per strand throughout the simulation time, the impact on the temperature evolution would be greater due to the reduced individual strand volume. Cargill (1994) found that for the 0D model, increasing $N_s$ leads to a slight overall increase in average loop temperature.

Further investigations are underway to quantify fully the effect of altering $N_s$ in this hydrodynamic model.

In addition, if the overall global loop is lengthened, longer strands will subsequently have longer conductive cooling times. However, the total energy deposited within the complete simulation time frame would need to increase accordingly (approximately tenfold for a 100 Mm loop) to be able to raise the temperature of the longer strands to values comparable to the current simulation. Considering case B once again, this could be achieved with this specific power-law index by either (1) keeping fixed the original energy range (10^23 – 5 × 10^24 erg) over which the events can occur, but allowing an increased number of each event size to take place, or (2) widening the event range so that many, much smaller events (<10^23 erg) and a few much larger events (>5 × 10^24 erg) can happen. It is difficult to estimate fully the impact of each of these different “energy scenarios” on the overall plasma evolution. For the first, it could be envisaged that the resulting thermal evolution, average apex temperature, and apex temperature variation would be quite similar to those already outlined in case B. For the second, the extension to much smaller, more numerous energy events would mean that the plasma reacts in a manner similar to that of case C (with a slightly raised apex temperature compared to the first case and a reduced apex temperature variation). Once again, simulations are being undertaken to examine the consequences on longer loop structures.

It would also be useful to forward-fold the plasma parameters through the instrument response functions of say, TRACE and Hinode XRT. In particular, the high temperature of individual strands that should be observable in the XRT lines could lead to an important distinguishing factor for coronal heating diagnostics; in contrast, TRACE EUV emission could come mainly from plasma that is cooling into the passbands. This is where this multistrand modeling approach has a distinct advantage over the 0D models, as the current simulations can be compared directly to the observed dynamics/signatures along individual loop structures. These aspects will be tackled thoroughly in a future paper.

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