EPISODIC FOOTPOINT HEATING OF CORONAL LOOPS: DOES IT WORK?

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ABSTRACT

Short answer: YES! And in more details.: Coronal loop temperatures are known to be of a few millions degrees but the nature of the energy source remains as a longstanding fundamental problem for solar and stellar physics. Observations of solar chromosphere-corona transition region plasma show evidence of small, short-lived dynamic phenomena called e.g., explosive events, blinkers, micro-flares and nano-flares. These events may serve as the basic building blocks of the heating mechanism(s) of the solar atmosphere. In this paper, we study the heating of the solar corona by numerous micro-scale randomly localized events representing the energy dissipation found by observations. It is found that these energy input distributions can maintain the plasma along the loop at typical coronal temperatures. We also found, that typical loop temperature structures seen by e.g. TRACE are recovered when the energy release occurs close to the foot points of the loop. Implications of these results upon the latest coronal loop observations are addressed.

Key words: Coronal heating; Coronal loops; Transition region; Hydrodynamics.

1. INTRODUCTION

EUV and X-ray observations have shown that the building blocks in the solar atmosphere are loop-like structures, which outline the coronal magnetic field in the form of magnetic flux tubes that confine the plasma. While the temperature of these structures are of the order of $\sim 10^6$ K, the nature of the energy source remains a longstanding fundamental problem for solar and stellar physics. Although it has been accepted that the Sun’s magnetic field plays a vital part neither theory nor observations have yet been able to unambiguously settle this argument. However, recent interest has centered on the idea that the solar atmosphere is heated by numerous small localized events (Parker 1988). When the response of the solar corona to an initial perturbation consists of slow motions on a time scale longer than the Alfvén travel time the mechanism is called direct current (DC) dissipation. Phenomena like explosive events, micro-flares, blinkers and nano-flares are believed to be manifestations of localized magnetic field reconnection where DC currents are dissipated.

High resolution satellites (SOHO and TRACE) have reported a kind of very small-scale activity at transition-region temperatures (Pérez et al. 1999; Erdélyi et al. 2001). Loop plasma modelling have been used to study the temperature evolution under the assumption of time-varying heating (Nagai 1980; Mariska et al. 1982; Peres et al. 1982; Sterling et al. 1993; Walsh & Galtier 2000). In particular, Sterling et al. (1993) have investigated the relationship between brightenings and chromospheric ejections by varying the spatial and temporal distributions of the energy source and placing the source at different heights in the middle and upper chromosphere. A spatial-temporal heating form has been considered to study impulsively heated solar flares (Mariska et al. 1989; Peres et al. 1987; Betta et al. 2001) and coronal loops maintained close to steady conditions (Reale et al. 1994; Betta et al. 1999). In the latter models, either random or periodic heat pulses were released at the loop apex. Additionally, a numerical study of the nature of explosive events and their contribution to the coronal heating mechanism was carried out by Sarro et al. (1999). The response of coronal plasma loop to a dynamic heat input generated by the flux braiding model was studied by Walsh and Galsgaard (2000). Recently, Spadaro et al. (2002) and Mendoza-Briceño et al. (2002) investigated the hydrodynamic behaviour of coronal loops undergoing transient heating.

In the present work, we attempt to investigate the response of the coronal plasma in a magnetic loop to microscale heating pulses at periodic and random injections close to the footpoint. In Sect. 2 we present the basic equations and briefly describe the loop models. The results of the model calculations are described in Sect. 3. Finally, Sect. 4 contains a discussion of the results along with the main conclusions.
2. BASIC EQUATIONS

The magnetic field plays an important role in the solar corona by producing complex networks of individual loop-like structures. The coronal plasma $\beta$ is much smaller than unity (with typical values of $\sim 10^{-2}$) and the velocities are less than the Alfvén speed. Therefore, it can be assumed that a strong magnetic field confines the plasma in such a way as to provide a loop geometry that channels both the mass flow and the heat flux. Thus, in a first approximation motion of the plasma along the confining magnetic field can be described by solving the mass, momentum and energy conservation laws in one space dimension along a semi-circular flux tube. If we define the spatial variable $s$ as the position along a loop of constant cross-sectional area, the energy conservation equation, including the effects of thermal conduction and radiative cooling and heating, reads

$$\frac{\partial (\rho v T)}{\partial t} + \frac{\partial (\rho v T)}{\partial s} = -\frac{\mu (\gamma - 1)}{R_g} \times$$

$$\times \left[ \rho \frac{\partial v}{\partial s} + \rho^2 Q(T) - H(s,t) \frac{\partial}{\partial s} \left( \kappa \frac{\partial T}{\partial s} \right) \right], \tag{1}$$

where $\rho$ is the (mass) density, $v$ is the fluid velocity along a fixed magnetic field line, $T$ is the temperature, $p$ is the gas pressure, $\gamma = 5/3$ is the ratio of specific heats, $Q(T)$ is the optically thin radiation loss function (Hildner 1974; Rosner et al. 1978), $H(s,t)$ is the heating and $\kappa = \kappa_0 \approx 10^{-11} T^{5/2}$ W m$^{-1}$ K$^{-1}$ is the coefficient of thermal conductivity parallel to the magnetic field (Braginskii 1965). The set of governing differential equations is closed by assuming an equation of state of the form $p = R_g \rho T/\mu$, where $\mu$ denotes the mean molecular weight and $R_g$ is the gas constant.

The term $H(s,t)$ is the unknown coronal heating function. Here, this function is assumed to have the form

$$H(s,t) = h_0 + H_0 \phi(s) \psi(t), \tag{2}$$

where $h_0 = 3.6 \times 10^{-5}$ J m$^{-3}$ s$^{-1}$ is the uniform and constant background heating needed to maintain the initial atmosphere and the second term on the right-hand side represents the spatially and temporally varying impulsive heating. This term may be due to current dissipation. The parameter $H_0$ represents the amplitude of the impulsive heating.

The initial conditions are specified by setting the density, velocity and temperature profiles at $s = 0$, i.e.,

$$\rho_i = \rho(s,0); \quad v_i = v(s,0); \quad T_i = T(s,0), \tag{3}$$

with $v(s,0)$ usually taken to be zero. In all cases, the boundary conditions are defined by specifying the density and temperature at the base of the loop. Here we restrict ourselves to study only symmetrical loops in which the location of the summit is held fixed in space and time.

The basic equations are solved using a one-dimensional, finite-difference hydrodynamics code based on a second-order accurate, Lagrangian-remap technique. A detailed description of the code is given in Sigalotti & Mendoza-Briceño (2002).

3. NUMERICAL RESULTS

In the present models, we assume that the impulsive heating energy is deposited just below the transition region. Specifically, we localize the energy in a Gaussian spatial distribution

$$\phi(s) = \exp\left( -(s-s_0)^2/\beta^2 \right) \tag{4}$$

centered at $s_0$. The amplitude of the disturbance is assumed to decay exponentially in time according to

$$\psi(t) = \exp(-\alpha t), \tag{5}$$

where $\alpha = \ln 0.1/\Delta t$. This means that 90% of the total energy is deposited at a time $t = \Delta t$, where $\Delta t$ is taken to be 150 s for the calculations of this paper. In particular, we study the dynamical response of a loop model to both periodical and random energy inputs of total energy $E_{tot} \sim 10^{18}$ J, injected at a location close to the footprint in contrast to previous works (Reale et al. 1994; Betta et al. 1999). In all cases, the amplitude of the impulsive heating is $H_0 = 3$ J m$^{-3}$ s$^{-1}$.

3.1. Periodical energy input

We first consider the effects of releasing periodic energy pulses at a fixed position $s_0$ near the loop footpoint. We vary the number of input pulses from 1 to 10, with all of them being centered at the same position $s_0 = 4.9 \times 10^6$ m (the half length is $L = 5 \times 10^6$ m). Figure 1 shows the evolution of the loop temperature for the case in which ten periodic heating pulses were released. For the sake of clarity, we only show the computed solution at intervals of 10 s each. The time interval between successive pulses is of 60 s, with the first pulse being injected at $t = 0$ s. It is observed that the pulse produces an increase of temperature at its location, and thereafter the evolution proceeds with a cold dense plasmoid travelling along the loop towards the apex. The overall temperature of the

![Figure 1. Evolution of temperature along half a loop for ten pulses. Note that the origin in space has been rotated and made to coincide with loop footpoint.](image-url)
loop reaches values of $\sim 1 - 1.2 \times 10^8$ K, and these are kept for a longer period of time compared to the models with a less number of injected pulses. After $t = 650$ s, when the impulsive heating has decreased to about 1/3 of its maximum value, the corona starts to cool. The evolution have been followed for many minutes after the end of the last heating pulse by which time the loop has cooled down reaching typical chromospheric values ($\sim 10^4$ K). After about 1000 s the overall loop temperature increases again because of the constant heating $h_0$ implied by Eq. (2). By about 1650 s, the loop reaches its stationary initial equilibrium which is then maintained until the end of the calculation ($\sim 2000$ s).

For comparison, the models with less than 10 pulses at the same location ($s_0 = 4.9 \times 10^6$ m) have produced a similar evolution to that shown in Fig. 1; the main difference being that the duration time of the loop temperature plasma at $\sim 10^8$ K was seen to decrease. Thus, the higher the number of injected pulses, the longer the time during which the coronal loop can stay at temperatures over a million K.

3.2. Random energy input

We now describe the results when the energy pulses are injected randomly, which is also physically more realistic. In particular, we consider 10 randomly distributed pulses along a loop segment of length 0.1L from the footpoint of the loop and with elapsed times of 60 s. Figure 2 depicts the resulting temperature evolution. We see that the overall temperature of the loop experiences an increase from $5 \times 10^8$ to $\sim 2.5 \times 10^8$ K. For this case, the impulsive heating decreases to about 1/3 of its maximum value after 650 s as in the model with 10 periodic pulses (see Fig. 1). Thereafter, the coronal temperature decreases and from 800 to 1000 s, the loop reaches a configuration close to its initial stationary equilibrium.

Compared to the periodic cases, we note the complete absence of a cool dense gas plug travelling along the loop towards the apex. This occurs because the first randomly distributed injection is at a greater height compared to the periodic energy input case, where the pulse injections were always at a fixed location close to the footpoint. This was further confirmed by loop model calculations with periodical energy releases at different locations from the footpoint, finding that the gas plug is no longer observed when the periodical pulses are injected at heights greater than was done for the models of Sect. 3.1.

4. DISCUSSION AND CONCLUSIONS

The above models show the response of the plasma to periodic and random energy inputs. The energy input was introduced as an additional heating term in the energy equation by perturbing the initial equilibrium profile. In particular, when the number of pulses is increased, the plasma in the loop remains at temperatures of $\sim 10^8$ K for a longer time. As long as the energy pulses cease the plasma evolves towards its initial equilibrium profile as expected. For random injections, the top temperature reaches values higher than those seen in the models with periodic inputs. This is expected because in the former models the energy was distributed along a finite loop segment near the footpoint. In contrast, for the periodic models the energy was always injected at the same location. Figure 3 shows three temperature profiles resulting from averaging in time the temperature evolution for two distinct random energy distributions within 0.1L from the footpoint (solid and dotted lines) and for a periodic impulsive heating (fixed at $s_0$), all integrated over the first 540 s of the corresponding evolutions and for ten injected thermal pulses. The random temperature profiles show a higher summit temperature compared to the periodic one. This is also seen in Fig. 4, which depicts the evolution of the summit temperature for the same models of Fig. 3. We may clearly see how the top temperature increases over its initial value ($5.5 \times 10^8$ K) when the pulses are injected both periodically and randomly. On average, summit temperatures around 1.5 MK are maintained during the first 540 s of the evolution. Thereafter, when the pulses cease, the summit temperature drops and reaches its initial value by about 1000 s due to the background heating supplied to the system. From Fig. 3, we may also note that farther away from the footpoint the three curves reproduce a quasi-isothermal profile along the loop, suggesting a footpoint exponential decay heating as discussed by Aschwanden et al. (2001) and Mackay et al. (2000; see their Fig. 5b). In particular, Aschwanden et al. (2001) measured the thermal structure of EUV loops and deduced that they are mostly isothermal along their length. They further concluded that the footpoint heating dominates and that optically thin radiation rather that thermal conduction is the prevailing energy sink.

In connection to these observations, it is very important to outline that the results described in this paper have not been produced by imposing a spatial exponential decay heating but by just providing pulses with a certain periodicity in a small region near the footpoint. The spatio-temporal dependence of the injected heating in the present models (with periods of 60 s each) repro-
duces qualitatively well the observations, implying that the heating must not be only dynamic but also localized to reach agreement with the salient features deduced by observations.

In summary, the novelty of the present paper is that we have investigated the heating of coronal loops by randomly deposited energy pulses at the footpoint of the loop. We found that by dynamically injecting energy (e.g. as a result of nano-scale magnetic reconnection predicted by Parker 1988) coronal loops can stay at temperatures over a million K as observed. The integrated temperature profiles in Fig. 3 should be compared with observations in order to validate the predictions of the present calculations.

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