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CAN *TRACE* EXTREME-ULTRAVIOLET OBSERVATIONS OF COOLING CORONAL LOOPS BE USED TO DETERMINE THE HEATING PARAMETERS?

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ABSTRACT

Recent analysis of relatively cool (∼1 MK) active region loops observed with *TRACE* has suggested that these loops have been heated impulsively and are cooling through the *TRACE* bandpasses. In this Letter we explore the evolution of cooling loops to determine if the *TRACE* EUV observations can be used to determine the magnitude, duration, and location of the energy release. We find that the evolution of the apex density and temperature in an impulsively heated cooling loop depends only on the total energy deposited (not the magnitude, duration, or location of the energy deposition) after the loop cools past an "equilibrium point," where the conductive and radiative cooling times are comparable. Hence, observations must be made early in the evolution of a loop to determine the heating parameters. Typical *TRACE* observations of cooling loops do not provide adequate information to discriminate between different heating scenarios.

Subject heading: Sun: corona

1. INTRODUCTION

One of the central goals in observing the solar corona is to determine the coronal heating mechanism. An important first step is to understand the magnitude, duration, and location of heating along a coronal loop. Priest et al. (2000), for example, demonstrated that the shape of the temperature profile along a steadily heated loop was sensitive to the location of the heating. For instance, in a loop where the heating is highly confined to the loop footpoints, the temperature profile along the loop would be flatter than in a loop where the heating is uniformly distributed. Hence, Priest et al. (2000) suggested that the location and magnitude of the steady heating could be determined by simply comparing information derived from coronal structures (the temperature and density along a heated coronal loop, for instance) to theoretical models. This method has been applied to several X-ray loop observations (e.g., Porter & Klimchuk 1995; Kano & Tsuneta 1996; Priest et al. (2000).

Several recent studies with the *Transition Region and Coronal Explorer* (*TRACE*) have discovered a class of bright long-lived active region loops that have a flat 195/171 Å filter ratio along their lengths (Lenz et al. 1999a, 1999b; Aschwanden et al. 2000). Because their flat filter ratios indicate a near-uniform temperature along the loops, Aschwanden et al. (2001) concluded that the heating is most probably constrained to the loop footpoints. Winebarger et al. (2003a), however, found that the observed intensities could not be explained with the density associated with steady footpoint heated solutions. Furthermore, Winebarger et al. (2003b) followed the temporal evolution of five well-isolated loops and determined that (1) they appear in the hotter *TRACE* 195 or 284 Å filter before appearing in the cooler *TRACE* 171 Å filter and (2) the lifetime of the loops was longer than expected for a single cooling loop. One possible explanation for the large intensities, flat filter ratios, and temporal evolution is that the loops are a bundle of filaments, each heated impulsively and sequentially (Warren et al. 2002, 2003).

Using the delay time (the difference in the time it takes for a loop to appear in subsequent *TRACE* filters) and assuming that this delay is due to the first heated filament cooling through both bandpasses, Warren et al. (2003) were able to determine some limits on the magnitude and duration of the heating of the first filament. Namely, they found that any dynamic solution with the same total energy deposited resulted in the same delay. This led to a family of possible heating magnitudes and durations that could reproduce the observations. They did not attempt to discriminate among the solutions further, nor did they consider the effects of different heating locations.

The goals of this Letter are threefold: (1) to determine under what conditions the properties of cooling loops with the same total energy deposition, but different heating parameters, are similar and under what conditions they are different, (2) to determine if observing a loop cooling through *TRACE* EUV filters can provide enough information to distinguish between different heating parameters, and (3) to hypothesize on the observations necessary to make these distinctions.

We investigate the evolution of a hypothetical set of cooling loops using density-temperature diagrams (Jakimiec et al. 1992). We demonstrate that families of solutions with the same total energy deposition, but with different magnitude, durations, and locations of heating, share the same "equilibrium point"—a time in the evolution of the cooling loop when the temperature and density of the loop is consistent with that of a steady, uniformly heated loop. This point occurs when the conductive and radiative cooling times are comparable. Before this time, the evolution of the loop density and temperature depend on the details of the heating, while after this time, the evolution of the loop density and temperature is independent of the heating parameters. Hence, the information on the magnitude, duration, and location of heating is unrecoverable if observations of the loops occur only after they cool past the equilibrium point. Because most *TRACE* EUV loop observations indicate that the loops are overdense, a condition that occurs only after the loop cools past the equilibrium temperature, the EUV observations cannot be used to determine the location, magnitude, or duration of heating. In the discussion section, we discuss the types of observations necessary to discriminate between different heating parameters.

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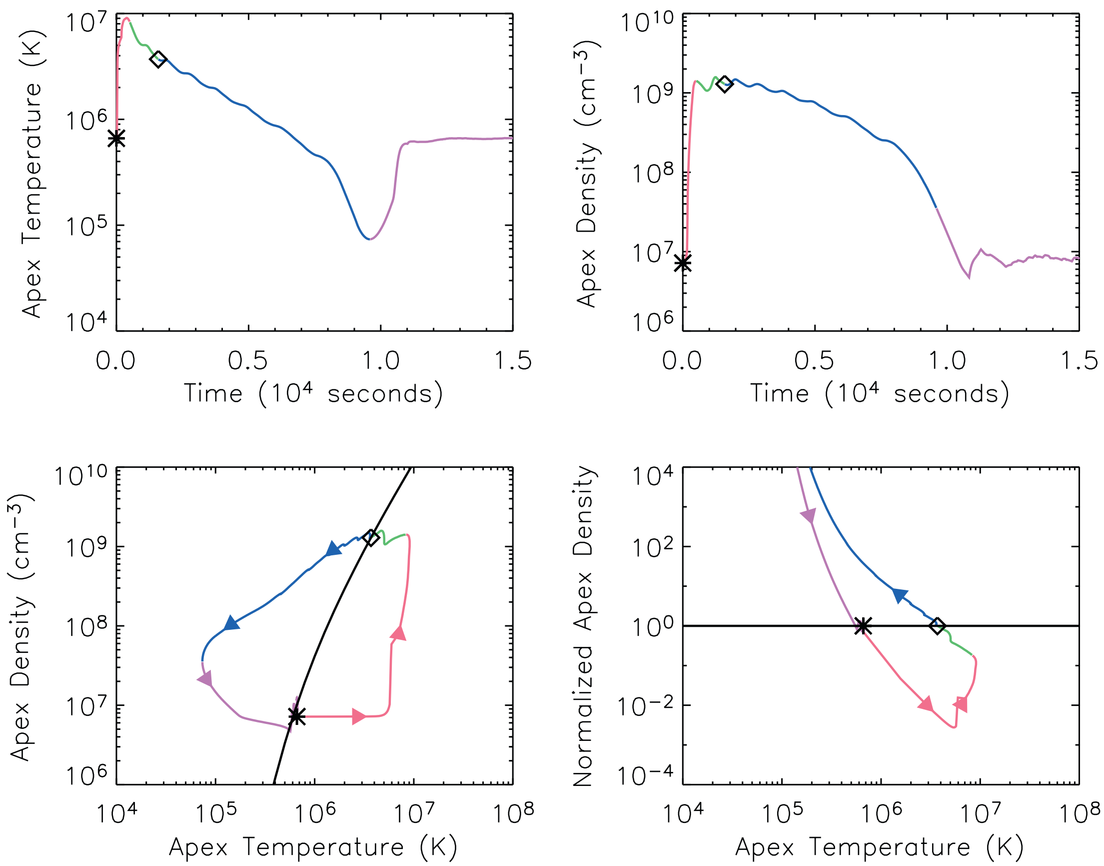

FIG. 1.—*Top*: Apex temperature and density of an impulsively heated loop as a function of time. *Bottom left*: Apex density as a function of temperature. The thick black line shows the relationship of apex density to temperature for a loop of the same length heated steadily and uniformly. *Bottom right*: Apex density divided by the corresponding RTVS density as a function of temperature. The evolution of the density and temperature is shown with arrows. When the impulsive heating is turned on, the evolution is shown with a red line. When conduction dominates, the evolution is shown with a green line. When radiation dominates, the evolution is shown with a blue line. When the loop is returning to an equilibrium consistent with its background heating, the evolution is shown with a purple line. The asterisk marks the time that the loop is in its initial equilibrium condition; the diamond marks the equilibrium point of the loop.

2. THE EVOLUTION OF IMPULSIVELY HEATED LOOPS

In this section, we discuss the evolution of a family of hypothetical loops that have been heated impulsively and allowed to cool with only minimal residual background heating. The same total energy is deposited into each loop, but with different magnitudes, durations, and locations of the impulsive heating.

To solve the hydrodynamic loop equations, we use the Naval Research Laboratory solar flux tube model. We adopt many of the same parameters and assumptions that were used in previous simulations with this code, and we refer the reader to the earlier papers for additional details on the numerical model (e.g., Mariska 1987; Mariska et al. 1989). In all of our simulations, we assume that the loop is semicircular and oriented perpendicular to the solar surface. We parameterize the spatial and temporal dependence of the energy deposition as

$$E_H(s,t) = E_0 + g(t)E_F \exp\left[\frac{(s-s_0)^2}{2\sigma_s^2}\right], \qquad (1)$$

where s_0 designates the location of the impulsive heating, σ_s is the spatial width of the heating, and E_F is a constant that determines the maximum amplitude of the heating. The function g is chosen to be a simple triangular pulse,

$$g(t) = \begin{cases} t/\delta, & 0 < t \leq \delta, \\ (2\delta - t)/\delta, & \delta < t \leq 2\delta, \end{cases} \qquad (2)$$

where 2δ is the duration of the impulsive heating. The background heating, E_0, is always applied, and the loop will eventually return to the equilibrium solution associated with this heating rate.

For the simulations in this Letter we choose a loop half-length (including the model chromosphere) of 110 Mm, which is a typical length for *TRACE* loops (e.g., Aschwanden et al. 2000). We always begin with an initial equilibrium atmosphere that is cool (≈0.66 MK) and tenuous, and we choose the background volumetric heating rate to be consistent with this atmosphere, i.e., $E_0 = 1.5 \times 10^{-6}$ ergs cm^{-3} s^{-1}. In these simulations the loop is assumed to be symmetric, and only the evolution of half of the loop is calculated. All simulations presented in this Letter are initialized the same way and have the same background heating applied. The only variations in the simulations are the location (s_0, σ_s), magnitude (E_F), and duration (2δ) of the impulsive heating.

The top panels in Figure 1 illustrate an example of the evolution of the apex temperature and density for a loop with a heating

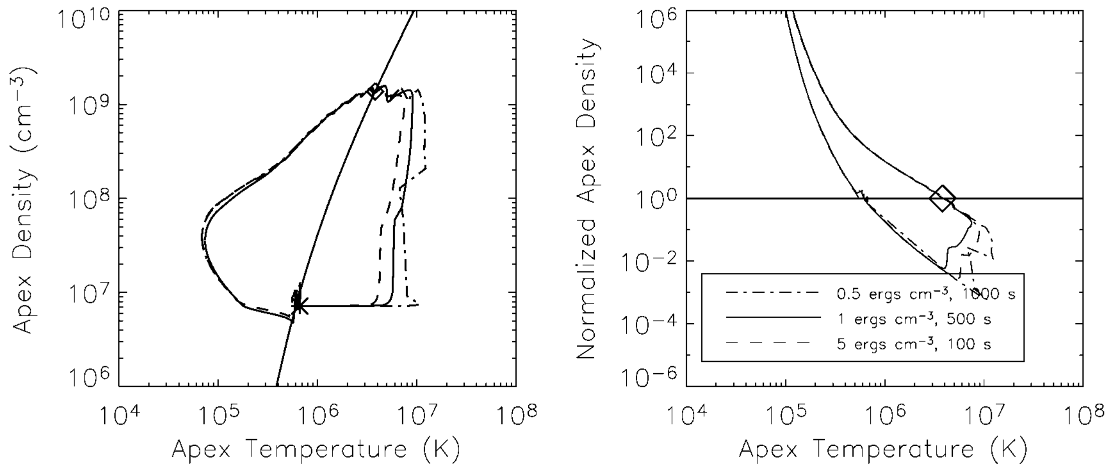

Fig. 2.—Apex density and normalized apex density as a function of temperature for three hydrodynamic simulations. The three solutions shown were all heated with the same total energy and at the same location but with different magnitudes and durations.

magnitude, E_F, of 1 erg cm^{-3} and a duration, 2δ, of 500 s. The central location of the energy deposition, s_0, is 25 Mm away from the chromospheric footpoint with a Gaussian width, σ_s, of 0.6 Mm. Another way of looking at the evolution of the loop is to examine the density-temperature diagram shown in the bottom left panel of Figure 1. The evolution begins at the asterisk, and time proceeds in the direction of the arrows. The solid black line shows the relationship between the apex temperature and density for a loop of the same coronal length that is heated uniformly and steadily. This relationship is derived from the Rosner, Tucker, Vaiana, and Serio (RTVS) scaling laws given in Serio et al. (1981); i.e.,

$$T \approx 1.4 \times 10^3 (p_0 L)^{0.33} \exp\left[-0.04L(2/s_H + 1/s_p)\right], \quad (3)$$

where T is the apex temperature in kelvins, p_0 is the base pressure in units of dyne cm^{-2}, L is the loop half-length in centimeters, s_H is the heating scale height (assumed to be ∞), and s_p is the pressure scale height ($\approx$47 Mm MK^{-1}). To find the apex density of the static solution from the scaling laws, we assume

$$n_{\rm apex} = \frac{p_0}{kT} \exp - \frac{s_p \pi}{2L}, \quad (4)$$

where k is Boltzmann's constant. The curve in the bottom right panel of Figure 1 shows the same density-temperature evolution, but in this plot the density at every point is divided by its corresponding RTVS density. Hence, at times when the evolution of the normalized density is less than 1, the loop is underdense relative to static equilibrium, while at times when the normalized density is greater than 1, the loop is overdense relative to static equilibrium.

There are three times in an impulsively heated loop's evolution that its apex density and temperature match that of the density and temperature of a loop in static equilibrium. The loop begins in static equilibrium; the beginning point on the temperature and density curves is marked with an asterisk. The loop's temperature then increases, and the density begins to increase as the model chromosphere is being evaporated into the loop while the loop is being heated; this stage of evolution is indicated with a red line. The temperature continues to increase while the energy is turned on, but as soon as the impulsive heating is turned off, the loop begins to cool. The cooling of the loop is initially dominated by conductive flux through the loop's footpoints; this stage of the loop's evolution is shown with a green line. At some point during the cooling, the temperature and density will again match that of a loop in static equilibrium. This point, which we refer to as the "equilibrium point," is marked with a diamond in the density-temperature plots. The loop's density at all times before the loop crosses the equilibrium point is less than the density of a loop with the same apex temperature and length in static equilibrium; hence the loop in this initial phase is underdense when compared to static equilibrium. The energetics of the loop before it crosses the equilibrium point are dominated by the initial heating and the conductive cooling. After the loop crosses the equilibrium point, the density is always larger than the density associated with static equilibrium. The cooling during this phase of the loop's evolution, shown with a blue line, is dominated by radiation. The loop will continue to cool and drain. If a background heating is applied (as it was in this simulation), the density and temperature of the loop will eventually return to the initial atmosphere. This return to equilibrium is shown with a purple line.

In the absence of strong residual heating or repetitive events, all dynamically heated loops will follow this cycle. The dominant terms in the energy equation as the loop travels through this cycle are impulsive heating, conductive cooling, radiative cooling, and background heating. The question then becomes, how do the magnitude, duration, and location of the impulsive heating event affect this cycle? Figure 2 shows the density-temperature and normalized density-temperature plots for three impulsively heated loops. The spatial profiles of the heating in all three simulations are the same, but the magnitude and duration of the heating are varied while keeping the total energy deposited in the loop a constant. Note that the solutions are different only in the initial heating and conductive cooling phase of the loop's evolution while the loop is underdense relative to static equilibrium. The three solutions all have the same equilibrium point and identical evolutions in temperature and density after the plasma passes through the equilibrium point.

Figure 3 shows similar density-temperature and normalized density-temperature plots for three different impulsively heated loops. In these simulations, the magnitude and duration of the heating are identical, but the loops are heated at different lo-

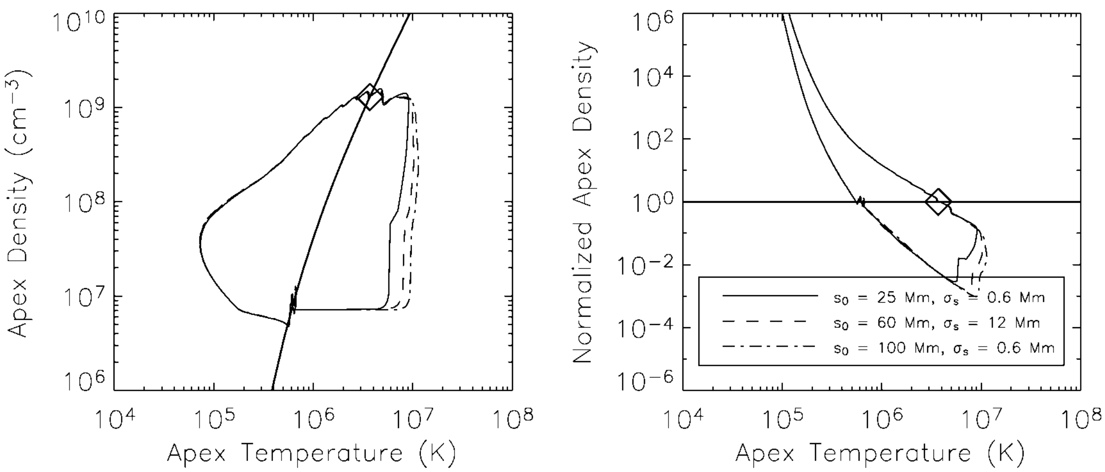

FIG. 3.—Apex density and normalized apex density as a function of temperature for three hydrodynamic simulations. The three solutions shown were all heated with the same total energy, magnitude, and duration but at different locations.

cations, again keeping the total energy deposited in the loop a constant. Again, the differences in the three solutions all occur in the initial heating and conduction phase of the plasma's evolution while the plasma is underdense. The three solutions all have the same equilibrium point and identical evolutions in temperature and density after the plasma passes through the equilibrium point.

3. DISCUSSION

We have discussed the cycle that an impulsively heated loop goes through in the absence of multiple heating events or strong residual heating. We have demonstrated that the temperature and density of loops heated with the same total energy, but different magnitudes, locations, and durations, differ in only the initial heating and conductive cooling phase of the loop's evolution. Loops heated with the same total energy will share the same "equilibrium point," where the radiative and conductive cooling times are comparable. After the loops cool past the equilibrium point, the evolution of the apex density and temperature is identical.

The implication of this result is that observations of a loop in its radiative cooling phase (or after the loop has cooled through the equilibrium point) cannot be used to determine magnitude, duration, or location of the heating. In fact, it would be impossible to conclusively say that the loop was impulsively heated at all. The loop could have been heated at the rate corresponding to its equilibrium point for an indefinite time, then for whatever reason, the heating removed. In a sense, the equilibrium point is the "event horizon" in the evolution of a loop. The loop's evolution before it has crossed the equilibrium point cannot be determined by observations at any time after the loop has cooled through the equilibrium points. Because the *TRACE* loops are generally overdense (Aschwanden et al. 2001), we are observing them after they have cooled through their equilibrium point. Hence *TRACE* observations of the loops cannot give us any specific information on the heating parameters. Indeed, all the simulations shown in this Letter would produce the same apex intensities as a function of time in the three *TRACE* EUV filter images.

The question, then, is what observations are necessary to determine the heating parameters of an impulsively heated loop? There are several avenues that could provide useful discriminatory information in future observations. As shown in Figures 2 and 3, the solutions with different magnitudes, durations, and locations differ while the loop is in its initial underdense phase. One approach is to follow the evolution of a loop as it cools from the soft X-ray telescope, where it is likely to be underdense, to *TRACE*. Spectroscopic observations of high-temperature density-sensitive line ratios would constrain the heating parameters. Since the timescale for each solution is different, they all reach the equilibrium point at different times. Thus spectroscopic measurements of velocities along the loop should also constrain the heating parameters.

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