THERMODYNAMIC DECAY SCALING LAWS IN SOLAR LOOP FLARES

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Introduction

One-dimensional hydrodynamic models have shown a remarkable success in modeling the sequence of events characteristic of the thermal phase of solar or stellar flares and following the sudden switching of an impulsive heating mechanism (Peres *et al.*, 1987; Reale *et al.*, 1988). In this paper we use the results of numerical calculations, together with analytical considerations, as a guide to set up diagnostic tools for the flare decay phase in terms of the temperature-density (n-T)diagram.

The numerical model has been extensively described elsewhere (Peres and Serio, 1984). We model the decaying flaring loop as a hydrodynamic process in a rigid, semicircular tube in a vertical plane, with footpoints anchored in the photosphere. We assume that the magnetic field acts only to confine plasma motions and channel heat conduction along the loop, and therefore our problem is effectively 1-D.

If we limit our interest to the decay phases of the X-ray flare, the basic equations for the evolution along the tube coordinate s (reckoned from the tube footpoint) of plasma density n, velocity v, and internal energy density ϵ, neglecting viscosity, are written as follows:

$$\frac{dn}{dt} = -n\frac{\partial v}{\partial s} \tag{1}$$

$$nm_H\frac{dv}{dt} = -\frac{\partial p}{\partial s} + nm_H g_s \tag{2}$$

$$\frac{d\epsilon}{dt} + (p+\epsilon)\frac{\partial v}{\partial s} = E_H(s,t) - n^2P(T) + \frac{\partial}{\partial s}\left(\kappa_o T^{5/2}\frac{\partial T}{\partial s}\right) \quad , \tag{3}$$

where κ_o is Spitzer's (1962) thermal conductivity, and g_s is the gravitational acceleration along the loop.

To these equations we add the equation of state in corona $p = 2nkT$, and the relationship between internal energy density and pressure $\epsilon = 3/2\ p$, where k is Boltzman constant.

The term $E_H(s,t)$ in Eq. 3 describes a source term for coronal heating, both steady state and dynamic, and can, in principle, be specified according to different physical models. The function $P(T)$ describes radiation losses per unit emission measure.

Thermodynamics of the flare decay phase

The decay of the flare can actually be described in a somewhat simplified way when Eq. 3 is rewritten in terms of the entropy per particle $S = k\ \ln(T^{5/2}/p)$ (Serio *et al.*, 1991):

$$p\frac{d}{dt}S/k = E_H(s,t) - n^2P(T) - \frac{\partial}{\partial s}F_c \qquad . \qquad (4)$$

It is now easy to see that the sudden switching off of E_H at $t = 0$ will result in the switching on of the d/dt term in Eq. 4, so that, since the radiative and conductive terms will initially be balanced by E_H, the result is

$$p\ \frac{dS/k}{dt} = -E_H \qquad . \qquad (5)$$

Near the top of the loop, where we have $d/dt \sim \partial/\partial t$ being $v \sim 0$ for symmetry, Eq. 4 can be integrated to give

$$S \sim S_o - \frac{k\ t}{\tau} \qquad , \qquad (6)$$

$$\frac{T^{5/2}}{p} \sim \frac{T_o^{5/2}}{p_o}\ e^{-t/\tau} \qquad , \qquad (7)$$

where

$$\tau = \frac{p_o}{E_H} = \frac{3.7\cdot 10^{-4}\ L}{\sqrt{T_o}} \sim 120\frac{L_9}{\sqrt{T_7}} \qquad , \qquad (8)$$

and T_7 is the initial temperature at the top of the loop in units of 10^7 K, L_9 the length of the loop in units of 10^9 cm, and we have used the Rosner, Tucker and Vaiana (1978) scaling laws.

The validity of Eq. 6 can be verified by means of numerical calculations (using the complete set of equations including viscosity and chromosphere), and a typical result is given in Fig. 1, which shows the evolution of entropy and other thermodynamic variables. The details of such a comparison, for a a grid of model of solar loop flares, are discussed in Serio *et al.* (1991). The behavior of the entropy is initially linear in time, as predicted; such "linear phase" lasts generally, approximately 1.5 - 2 decay time scales.

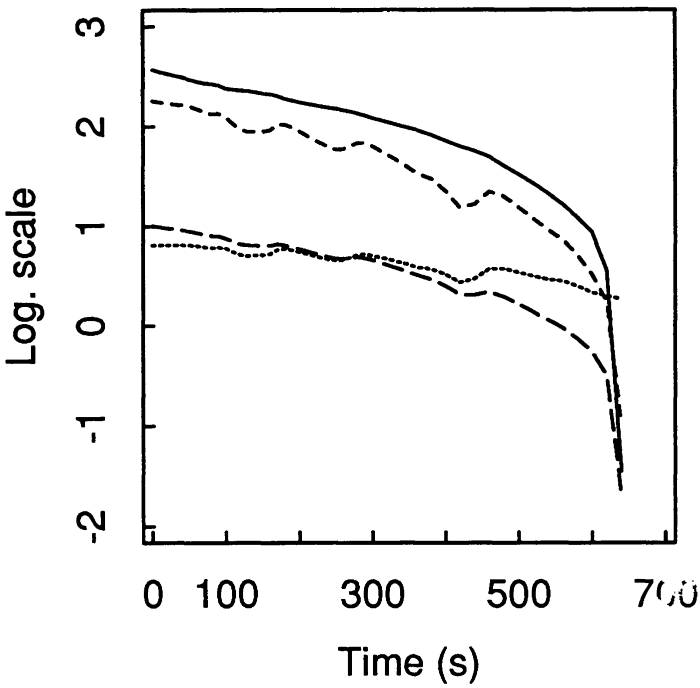

Figure 1: Decay curves for temperature [long dashes - log(T) in units of 10^6 K], density [dots - log(n), 10^{10} cm^{-3}], pressure [short dashes - log(p), dyne cm^{-2}] and entropy [solid line - 0.5 $(S/k - 30)$, c.g.s. units] at the top of a typical flaring loop model (loop semilength 2×10^9 cm, temperature at the top 10^7 K, pressure at the base 185 dyne cm^{-2}).

We notice that during the linear phase temperature, density and pressure show, on the average, an exponential decay with time scales τ_T, τ_n, τ_p, respectively. We obtain from best fits the following empirical relationships:

$$\tau_T \sim \frac{1}{2}\,\tau_n \sim \frac{3}{2}\,\tau_p \sim \tau \qquad (9)$$

The temperature-density diagram

It is interesting to see that the factor of 2 difference in the decay times of density and temperature will force a $T \propto n^2$ relationship during the decay phase. Since spectrally resolved observations can be used to monitor the decay of T and n, this relationship can be used for diagnostic purposes.

We show in Fig. 2, as an example, that indeed the trajectory on the n-T plane has a slope ~ 2 for a wide set of peak model flare conditions.

A complete description of these results will appear elsewhere (Jakimiec *et al.*, 1991), and a detailed analysis of SMM solar flares to show the diagnostic value of the n-T diagram on actual data is being completed.

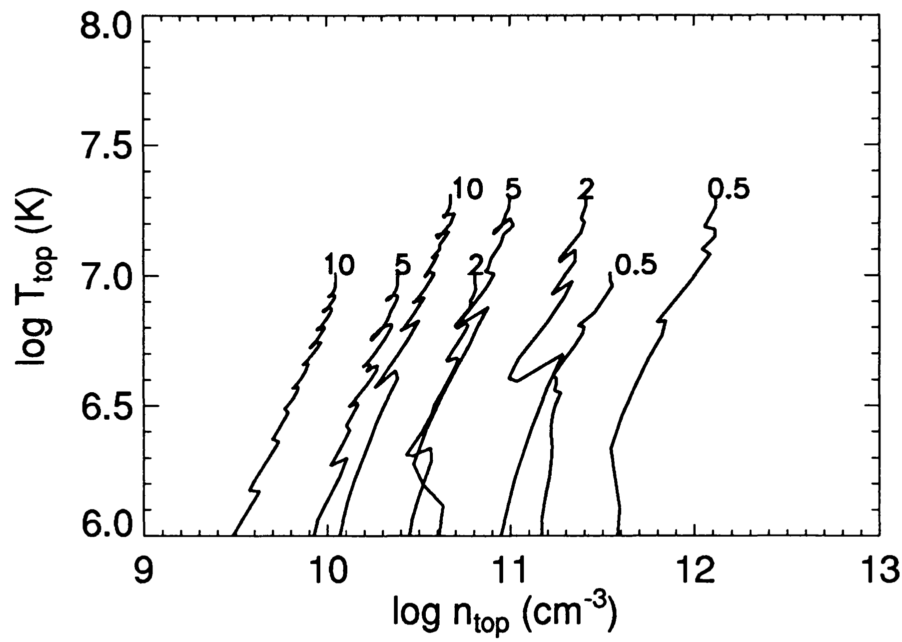

Figure 2: Density-temperature diagram (at the top of the loop) for decay phase models of flaring loops with various semilengths (labelled in units of 10^9 cm) for two different initial temperatures at the top (10^7 K and 2×10^7 K).

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