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MASTER

A SIMPLE MODEL FOR THE STELLAR ANALOGY OF COMPACT SOLAR FLARES

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ABSTRACT We have developed a simple "point" model to describe the average thermodynamical properties of a compact flare loop as a function of time during the flare decay phase. The model includes thermal conduction, chromospheric evaporation, and radiative losses; moreover, it assumes lateral (gas + magnetic) pressure balance with the background corona at all times. For the case of a low-β plasma (rigid flux tube), detailed 1-D hydrodynamical simulations are available in the literature for comparison; we show that the temporal variation of average loop properties predicted by the point model are in good agreement with these numerical simulations for a loop with the same energy input.

INTRODUCTION

Solar flares are usually regarded as falling into one or the other of two generic classes: "ribbon flares" (RF), which represent the largest events and are characterized by a major rearrangement of the coronal magnetic field geometry; and "compact flares" (CF), which are much smaller (often spatially unresolved) and less energetic events that apparently involve the excitation of plasma on only a single coronal magnetic flux tube, with no obvious disruption of the large-scale magnetic geometry.

In this paper we present an abbreviated description of a simple physical model for the dynamical response of the plasma on a closed magnetic flux tube to the abrupt release of energy that takes place at the onset of a compact flare. The model concerns itself only with the time dependence of average properties of the loop plasma; i.e., it comprises a zero-dimensional, or "point", model. Containing only a few adjustable parameters, the model has potential application to the interpretation of stellar flare observations, for which spatial resolution is entirely lacking. A new feature of the model, yet to be incorporated in more detailed hydrodynamical simulations of flaring loops, is the inclusion of fluxtube dilatation during the heating process. This effect is expected to be important for CF's if the energy release occurs on a time scale as short as a few seconds, since without it the pressure of the rapidly heated flare plasma may exceed that of the confining magnetic field.

THE COMPACT FLARE MODEL

Our model of a compact flare loop is based on the idea that the loop, of fixed semi-length L, may be adequately described at any time t by the average properties of its plasma and magnetic field. In so doing we of course sacrifice detailed knowledge of the loops' spatial structure, but we gain simplicity in the overall mathematical description. We make the following assumptions:

1) Uniform plasma pressure, $P(t)$, along the loop;
2) Pressure equilibrium (gas + magnetic) with the ambient active-region corona;
3) Conductive heat loss, F_c, from loop footpoint to chromosphere $= \alpha K(T)T/L$ (where $\alpha \cong \frac{2}{7}$ is a constant and $K(T) = 6\ 10^{-7} T^{5/2}$ is the classical thermal conductivity), but not to exceed 0.1 x free-streaming electron thermal flux;
4) Upward enthalpy flux (evaporation) = conductive heat loss to chromosphere;
5) Optically thin radiative losses: $\nabla \cdot \mathbf{F}_{\mathbf{rad}} = \mathrm{a}\mathrm{T}^{\mathrm{n}}\mathrm{N}_{\mathrm{e}}^{2}$, where $a = 6.12\ 10^{-19}$ and $n = -0.6$ over the temperature range $2\ 10^5 < T < 10^8\ K$.

Spatially integrating the partial differential equations expressing conservation of mass and energy along a dilatable loop (subject to the symmetry conditions that the conductive flux and velocity vanish at the loop apex), and invoking the conditions of lateral pressure equilibrium ($P + B^2/8\pi \equiv \Pi_0 = const.$) and conservation of magnetic flux ($BA = const.$), we obtain the following coupled ordinary differential equations for the loop temperature and pressure:

$$\frac{dP}{dt} = -\frac{(\gamma - 1)}{2k^2} P a T^{n-2} \left\{ \frac{1}{P} + \frac{\gamma}{2(\Pi_0 - P)} \right\}$$

$$\frac{dT}{dt} = T \left\{ \frac{1}{P} + \frac{1}{2(\Pi_0 - P)} \right\} \frac{dP}{dt} - \frac{v}{L} ,$$

where γ is the specific heat ratio, k is Boltzmann's constant, and $v = [(\gamma - 1)/\gamma] F_c/P$ is the evaporation velocity. Numerical integration of these equations, starting from initial values of temperature and pressure of the loop plasma at the end of the flare heating phase, yields the plasma history during the decay (cooling) phase. The magnetic field and fluxtube area then follow from the algebraic relations $B(t) = [8\pi(\Pi_0 - P(t))]^{1/2}$ and $A(t) = B_0 A_0 / B(t)$, where subscript '0' denotes ambient coronal values.

COMPARISON WITH NUMERICAL SIMULATIONS

One way to check the adequacy of the various physical assumptions underlying our CF model, is to compare its predictions against those of full hydro-code calculations for similar conditions of loop geometry, energy input, etc. Several such calculations exist in the literature. Without exception, however, these refer to a rigid flux tube ($\beta = 0$). We can recover this special case by setting the field strength, B_0, of the flaring region equal to a large value. For our comparison, we have chosen the simulation published by Pallavicini et al. (1983) and referred to as their "Standard Model" (cf. their Figure 9 and accompanying text). For this simulation the flux tube was chosen to have a semi-length $L = 20{,}000$ km, a pre-flare temperature at the loop apex of $3.2\ 10^6\ K$ (which we identify with the temperature, T_0, of the surrounding active region corona, since prior to the flare our model CF flux tube is indistinguishable from adjacent coronal flux tubes), and a "base pressure" of 6 dyne cm^{-2} (which, likewise, we equate to the ambient coronal pressure, P_0). The flare energy input adopted by these authors corresponds, if it were all added to the loop at $t = 0^+$, to an initial temperature and pressure of 1.114 10^8 K and 209 $dyne\ cm^{-2}$, respectively.

Figure 1 compares the temperature and pressure histories predicted by the CF flare model with the temporal profiles of average loop temperature and pressure from the full numerical simulation. One sees that, throughout most of the decay phase, these separate calculations agree quite closely. Obvious exceptions to this statement occur, however, at both early ($t < 100\ s$) and late ($t > 600\ s$) times. The early-time difference may be attributed directly to the fact that, in our "point" model, it was assumed that all of the flare energy is deposited instantaneously on the loop at $t = 0^+$, whereas in the simulation of Pallavicini et al. (1983) this energy was deposited at a constant rate over the first 100 s of the calculation. Late in the flare event, on the other hand, the differences are almost certainly due to the fact that the numerical simulation contained a "steady state" heating function, to ensure that the loop plasma returned directly to its pre-flare state (this, however, is only one of many possible scenarios). The CF loop model, lacking such steady heat input, simply continues to cool until one or the other of its physical assumptions becomes invalidated (e.g., the radiative loss expression at low temperatures).

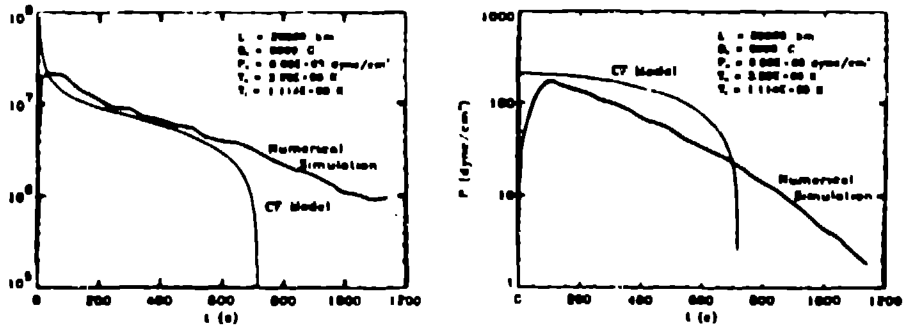

Fig. 1 Temporal evolution of T and P for a compact flare loop, as predicted by the CF model of this paper and compared with a numerical simulation.

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