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MASTER

A SEMI-ANALYTICAL MODEL OF STELLAR FLARES

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ABSTRACT We present a simplified "point" model to describe the hydrodynamic response of coronal loop plasma to the sudden release of energy which occurs at the time of a flare. Our simplification allows the full set of partial differential equations for energy, momentum, and mass conservation to be replaced by a corresponding set of ordinary differential equations for the plasma properties *averaged over the loop volume*. The temporal profiles of plasma temperature, density, and velocity are calculated over a time interval long enough to ensure that pre-flare conditions are re-established. The model is used for the interpretation of stellar flare data. In particular, we derive a set of representative loop geometries and flare energy inputs which allows us to reproduce the high emission measures typically inferred from observations of stellar flares.

INTRODUCTION

Observations of stellar flares in X-rays have been made extensively only in the last few years, by the *Einstein* and *EXOSAT* observatories. However, the limited number of observed events and the lack of spatial resolution in the data have not stimulated a thorough analysis of stellar flares, which consequently remain poorly understood phenomena. The hydrodynamics of the flaring coronal loop plasma, for instance, has been studied by only a few authors. The work of Reale et al. (1988), who applied the numerical hydro-code calculations previously used in solar flare studies to analyze a flare on Prox Cen, represents, so far, nearly the only attempt to extend methods used in solar physics to stellar flare research. On the other hand, the lack of any information on the spatial characteristics of stellar events suggests dropping such sophisticated numerical schemes in favor of a simplified technique capable of predicting the time dependence of the only observable quantities, namely, the spatially averaged plasma properties.

In the following we propose a simple "point" model which includes thermal conduction, chromospheric evaporation, radiative losses, and gravitational loop draining, and which gives the temporal evolution of temperature, density, and velocity averaged over the flaring loop. The model allows a rapid survey to be made of flare loop parameter space: we show that the high flare emission measures (EM) can be interpreted within the framework of the model, although it is not possible to evaluate uniquely the physical parameters of the flaring region.

THE FLARE MODEL

Our model hypothesizes a sudden energy release in a rigid flux tube and describes the successive behavior of the loop plasma. By integrating the partial differential equations for mass and energy conservation along a loop, whose pressure is assumed to be spatially uniform, and equating the downward conductive flux to the upward enthalpy flux at the loop base, we get a set of ordinary differential equations for the average loop pressure, $P(t)$, and density, $\rho(t)$:

$$\frac{dP}{dt} = \frac{(\gamma P v)}{L} + \frac{(\gamma - 1)}{L}[(F_c - F_{c0}) + (F_r - F_{r0})]$$
$$\frac{d\rho}{dt} = \frac{\rho v}{L},$$

where γ is the specific heat ratio, $v = [(\gamma - 1)/\gamma](F_c - F_{c0})/P - v_{ff}$ is the evaporation velocity minus the gravitational free-fall velocity, and L is the loop semi-length; F_c, F_r, and F_{c0}, F_{r0} represent the conductive and radiative fluxes at times t and $t = 0$ (pre-flare atmosphere), respectively.

The adequacy of the model to reproduce realistically the flaring loop plasma behavior has been tested by comparing its predictions against those from full hydro-code calculations, commonly adopted in solar flare modeling. In order to make this comparison we have selected the "standard model" of Pallavicini et al. (1983). Results from the "point" model agree quite closely with the results of Pallavicini et al. throughout the decay phase of the flare, for a loop with identical boundary and initial conditions (Kopp and Poletto, 1990).

APPLICATION TO STELLAR FLARES AND CONCLUSIONS

Stellar flares cover a broad range of X-ray energies and emission measures. On M dwarf stars EM's are about 10^3 times larger than solar flare EM's, ranging from $\approx 10^{51}$ to a few times 10^{53} cm^{-3} (Pallavicini et al., 1990). Our point model has the capability of determining values for the flare parameters which are compatible with these high emission measures. To this end we evaluated the pressure and density profiles resulting from different energy inputs, for loops with an aspect ratio of 0.1 and semi-lengths $L = .5, 1,$ and $2 \times 10^{10} cm$. Observational results suggest that initial conditions may vary from "low" values of $T = 3 \times 10^6$ K, $N = 1.2 \times 10^{10} cm^{-3}$ to "high" values of $T = 1 \times 10^7 K$, $N = 1.2 \times 10^{11} cm^{-3}$. A check on the influence of initial conditions on the results shows, however, that the subsequent flare-plasma temperature and density values vary by less than a factor of 2 over this range of initial conditions. In all our simulations the preflare state was eventually re-established.

Figure 1 gives the maximum EM as a function of the flare energy input, for the three loop semi lengths. These results show that:

1) EM values between 10^{51} and $10^{53} cm^{-3}$ can be easily explained by our choice of initial conditions and loop geometries;

2) the flare energy input is, for the largest flares, a few hundred times larger than in typical solar flares - see Pallavicini et al.'s (1983) "standard model";
3) large flares can originate only in large loops, because a large energy input in a small loop results in a catastrophic loop disappearance driven by large radiative losses. "Intermediate" flares, however, can be explained by a variety of parameter values. Observations of flare electron densities, via the density-sensitive line ratio technique, may help solve this ambiguity.

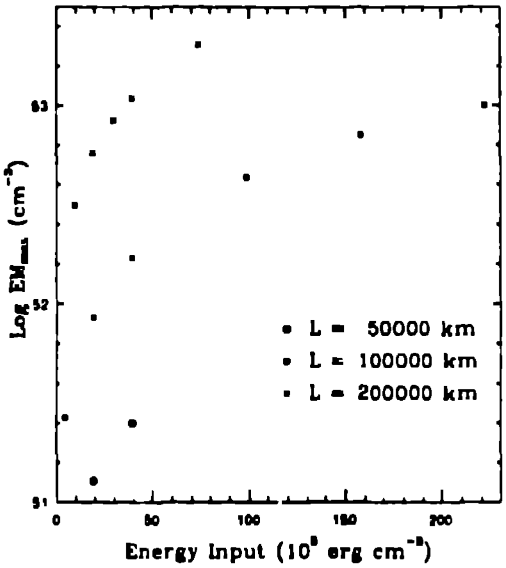

Fig. 1 Maximum emission measure versus energy input for different loop semi-lengths L. Gravity is assumed equal to $2g_\odot$.

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