RADIATIVE HYDRODYNAMICS OF FLARES: PRELIMINARY RESULTS AND NUMERICAL TREATMENT OF THE TRANSITION REGION

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We report on a comprehensive numerical simulation of flare dynamics, encompassing the corona, transition region and chromosphere. A coronal loop geometry, whose magnetic pressure dominates gas pressure, is assumed. These preliminary results assume optically thin radiation; we are currently incorporating optically thick radiative transfer in the chromosphere. We discuss difficulties in modelling the transition region under flare conditions, and suggest tentative solutions.

The hydrodynamic equations, incorporating the effects of thermal conduction, viscosity and radiation, are described by Craig and McClymont (1976) while the probabilistic method for radiative transfer is discussed by Canfield and Ricchiazzi (1979). We write the continuity, momentum and energy equations in Lagrangian form using column mass as the independent variable and consider the atomic rate equations for the fractional populations rather than absolute number densities. Thus we eliminate all convective terms. The equations are then written in fully implicit finite difference form and are solved by simultaneous iteration at each timestep.

We have carried out preliminary calculations neglecting radiative transfer effects. The simple model atmosphere used is not claimed to be a faithful replica of a loop in the solar atmosphere, rather it is intended to illustrate global features. Figure 1 shows the velocity response of a loop to the impulsive injection of energy at its apex, raising the coronal temperature from 1.6×10^6K to 5×10^6K. Coronal material is driven down the legs of the loop and collides with the dense transition region after 1 minute. The chromosphere is then compressed downwards while coronal material is reflected upwards again. Thereafter the atmosphere undergoes oscillations, heavily damped by conduction and radiation, of period ~ 4 minutes. Global oscillations of this type (and of greater amplitude for stronger flare heating) appear in all our calculations but, as far as we know, have not been reported observationally. Figure 2 shows the results of injecting the same amount of energy at a height of 1000 km in the chromosphere; in this case a surge-like ejection

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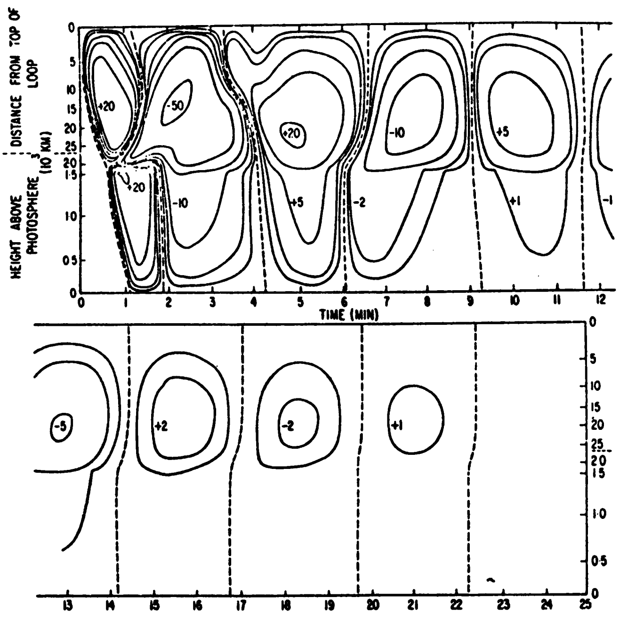

Fig. 1. Velocity as a function of height and time following the injection of impulse of energy at the top of the loop. Contours are labelled in units of km s^{-1} (positive velocities downward). Note that the vertical axis is a Lagrangian coordinate, heights and distances correspond to the initial position of gas elements. The scale is distorted non-linearly to show both the corona and chromosphere, which extends to a height of ∿ 2000 km.

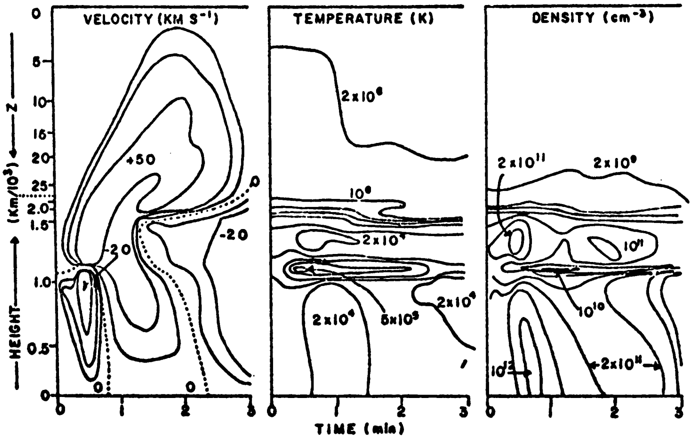

Fig. 2. Velocity (positive upwards), temperature and density as a function of column mass and time in a model surge. Note cool dense core of surge material above 1000 km, the initial energy release height. See Figure 1 caption regarding non-linear vertical axis.

of chromospheric material into the corona occurs. The Lagrangian vertical axis in Figure 2 does not explicitly show the motion, but integration of the velocity over time shows that this small surge reaches a height of only 5000 km. The most interesting feature of the calculation is the lack of heating of the surge material by the energy release; in fact the material is compressed as it is driven upwards and cools rapidly through the enhanced radiative loss rate. Thus we have a possible explanation for the appearance of cool, dense surges in the corona.

While investigating the dynamic formation of an atmosphere with a corona-transition-zone-chromosphere structure from an initially uniform plasma, Craig and McClymont (1979) found that incorrect results were obtained for high conductive fluxes through the transition region. It is now clear that only fluxes for which the scale height of temperature variation is greater than the finite difference grid spacing can be reproduced accurately. That is, the flux F is limited to $p\kappa(T)/(k\ \Delta N)$, where p is pressure, $\kappa(T)$ is the conductivity, k is Boltzmann's constant and ΔN is the Lagrangian grid spacing. With the grid spacing typically used in numerical modelling of this type (e.g. Kostyuk and Pikel'ner, 1975; Kostyuk, 1976; Somov et al., 1978; Craig and McClymont, 1979) this criterion is marginally satisfied in the quiet solar atmosphere but grossly violated under flare conditions. Under dynamic flare conditions there is an "evaporative" conduction front moving through the plasma at a "velocity" u $(cm^{-2}\ s^{-1})$. In order to reproduce the temporal behavior of the atmosphere satisfactorily, conditions at a grid point must change slowly compared to the timestep Δt, i.e. we require $u\ \Delta T << L(T) = p\kappa/(2\ kF)$, where L(T) is the characteristic scale of T variation, $[(T)(dT/dN)]^{-1}$. Under flare conditions this is very severe restriction on the timestep; we must depart from conventional finite difference techniques to handle the transition region. We suggest the following methods, none of which have been investigated in detail:

(1) Within the transition zone, formulate the equations for a set of grid points which convect through the plasma with the conduction front.

(2) Introduce a "pseudo-conductivity" term in analogy with the pseudo-viscosity term, with suitable modification of the energy equation.

(3) Approximate the transition region as a thin interface between an upper temperature T_1 in the corona and a lower temperature T_2 in the chromosphere.

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DISCUSSION

Uchida: (Comment) I would like to mention that a similar and elaborated calculation was done recently by Dr. Nagai, one of our graduate students. He obtained solutions which explain many of the observed properties of hot loop formation nicely. The oscillatory response which you found was also shown to occur if the heat input has a short duration.

Kahler: Do you expect to get an oscillation of the chromospheric material for an arbitrary energy release profile in the corona or is it limited to an impulsive input?

McClymont: For the results shown, energy is injected during the first minute. Any timescale of energy injection shorter than the oscillation period should result in oscillations. With a more realistic initial atmosphere, the oscillation probably won't penetrate so deeply-at present the density of our lower chromosphere is too low.

Emslie: (1) About the Canfield and Ricciazzi (Ap. J., submitted) radiative losses you use in your calculations. Although I agree, it results in much shorter computation times. It is important to realize the effort of Lα backwarming on the chromospheric energy budget, which is not included in the Canfield and Ricciazzi calculations (c.f., the large discrepancy between the Canfield and Ricciazzi and Canfield and Athay (1974) curve at Lα temperatures). This backwarming has been shown by Machado and Emslie (1979, Ap. J., *232*) and Machado *et al.* (1980, Ap. J., submitted) to be a strong source of energy to the flare chromosphere, and it therefore may have a significant effect on your results.

(2) With regard to the steep temperature gradient you encounter in the transition zone, it is worth remembering that for very high energy inputs the collision non-free path might well be greater than the characteristic transition zone thickness, so that Spitzer (1962) conductivity is no longer valid (c.f., Spicer, 1979, *Solar Phys., 62*). Are there possible deviations from Spitzer conductivity considered in your calculations?

McClymont: We realize that backwarming is the major source of error in the probabalistic calculations done so far. The error is very acceptable in view of the fact that the probabalistic method makes dynamical calculations with radiative transfer possible on a routine basis. We don't know yet how significant the error will be under all circumstances.

We expect that classical conductivity will break down under some flare conditions due to both the mean free path and flux saturation. For these preliminary results we assumed the Spitzer conductivity. We are currently investigating the whole problem of thermal conduction in the transition region.