STABILITY OF RADIATIVE SHOCKS WITH TIME-DEPENDENT COOLING

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Abstract: The stability of a radiative shock subject to nonequilibrium cooling is investigated. It is found that high velocity shocks (> 140 km/s) are subject to oscillational and condensational instabilities.

Introduction: Although steady radiative shock models have proven useful in the interpretation of spectra from supernova remnants (e.g. the models of Cox 1972, Raymond 1979, Shull and McKee 1979), it is becoming apparent that steady shock models are not able to explain the combined optical and UV data (Benvenuti *et al* 1980, Raymond *et al* 1980, 1981, Fesen *et al* 1982), The likely cause for the spectral discrepancies is the presence of unsteady shocks (Raymond 1984, and references therein.) Radiative shocks cooling via power-law cooling functions are subject to an oscillatory instability (in which the shock position relative to the driving "piston" varies with time) if the power-law exponent is sufficiently small or negative. The instability was demonstrated analytically in the linear regime (Chevalier and Imamura 1982) and computationally in the nonlinear regime (Langer *et al* 1981; Imamura *et al* 1984).

In an interstellar shock, the assumption of a power-law cooling function is not adequate. The recombination timescales for important species can be comparable to the radiative cooling timescale, and the cooling function becomes history-dependent for temperatures below $\sim 3\times10^6$ K. In this work we combine an accurate numerical gasdynamics code (based on the PPM method of Colella and Woodward 1984) with a detailed treatment of the time-dependent ionization evolution and radiative cooling problem.

The Models: We examine the evolution of a nonlinear perturbation by starting with a uniform flow hitting a stationary "wall" and following the evolution until the shock damps to a steady state or a limit cycle is reached. The gas upstream of the shock front is assumed to be preionized; we use the results of Shull and McKee (1979) for shocks with velocities below 130 km/s. For higher velocity shocks we estimate the precursor conditions by using a steady state ion equilibrium for a temperature roughly 0.4 times the postshock temperature (obtained by extrapolating the trends of Shull and McKee 1979). The ionization equilibrium downstream of the shock is allowed to relax according to the local thermodynamic conditions until the gas reaches 10^4 K, at which point we "turn off" the cooling. The precursor density is 9.4 nuclei cm^{-3}. The atomic rates are extracted from the Raymond and Smith (1977, 1984) code, and the abundances are from Ross

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and Aller (1976). We examined nonlinear perturbations for 130, 150, and 200 km/s shocks.

The 200 km/s shock is strongly unstable in the fundamental mode and the shock structure oscillates periodically (figure 1). The time development of the temperature profile through one cycle is shown in figure 2. During the expansion phase (curve a) the shock temperature is higher than that for a steady shock. The cooling length increases rapidly with temperature, and the resulting overpressure drives the shock far beyond the steady-state position. As the shock reaches its maximum position, the cooling in the interior robs the shock of its pressure support (curve b). A secondary shock forms where the flow hits the cold gas.

As the shock falls in and weakens, the shock temperature falls. A cooling instability occurs behind the shock as an overdense region undergoes runaway cooling and collapse (curves c, d). When the gas in the cooling clump gets cold (10^4 K in these models), the clump repressurizes and weak shocks are driven into the adjacent material. In curve d we see hot gas in the primary and secondary shocks separated by cold gas. The pressure in the cold gas is not sufficient to halt the collapse of the structure. In curve e the two hot regions are about to collide; this repressurizes the gas and drives a strong shock back out (curve a again), completing the cycle. The qualitative features of the evolution can be seen in a model with power-law cooling ($\propto \rho^2 T^{-1/2}$) and in a model using an isobaric (but time-independent) cooling function. The models with simplified cooling functions did not exhibit the condensational instability in the collapse phase, however.

Innes *et al* (1987) examine the collision of a steady 200 km/s shock with a sinusoidal density perturbation; their figures show features similar to those in figure 2 above. Innes *et al* argue that the evolution becomes aperiodic. The discrepencies between these results likely arise from the different means of exciting the perturbation together with the short time Innes *et al* were able to run the model. The sinusoidal density perturbation may be more effective in exciting transients which would confuse the interpretation of the initial part of the cycle. In addition, their model may not have been carried far enough to show the cyclic behavior.

The 150 km/s shock is unstable, but to a lesser degree than the 200 km/s shock, and the collapse phase is less violent. The clump formed in the condensational instability cools roughly isobarically so that additional shocks are not produced by the clump formation. The 130 km/s shock is stable; the oscillations die away with time. There are early indications of an overtone mode, but the decaying fundamental mode dominates at late times.

It would appear that the transition to instability lies between 130 and 150 km/s. This is roughly in line with expectations based

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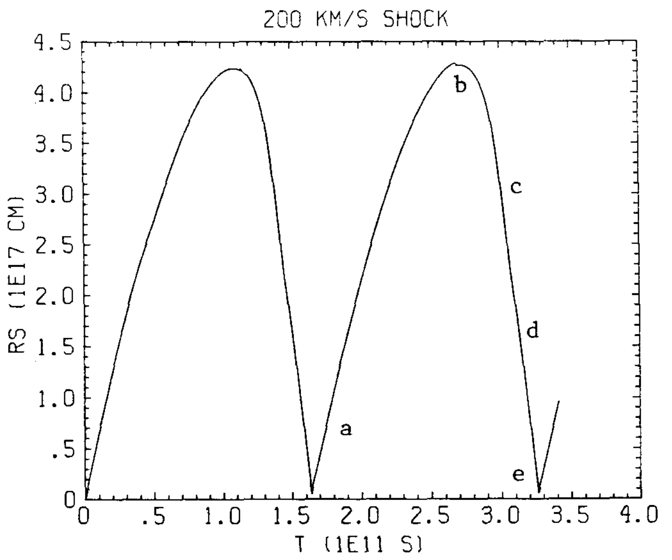

Figure 1. Shock radius (measured from the location of the cold gas) versus time. The piston velocity is 200 km/s. The flow is unstable to the fundamental mode.

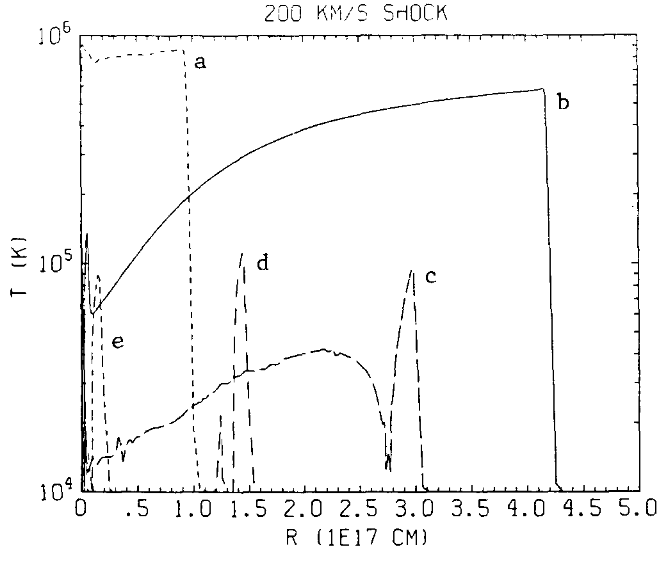

Figure 2. Temperature versus distance from the location of the cold gas. The piston velocity is 200 km/s.

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upon examination of the effective cooling function versus temperature behind a steady shock. The shocked gas spends most of its time with temperature comparable to the shock temperature. It is expected that the stability of small perturbations is determined by the slope of the effective cooling function near the shock temperature just below the ionization zone. (Because of the high emissivity in the ionization zone, the gas cools rapidly through the ionization zone; this zone usually covers a narrow temperature range, however.) For large perturbations one must take into account that the slope of the cooling function behind a steady shock is a function of shock temperature. Since the slope decreases with increasing shock temperature above 10^5 K (neglecting the high-emissivity ionization zone), there will be a tendency for large perturbations to be less stable than small perturbations.

Conclusions: Radiative shocks with velocities above about 140 km/s are subject to the oscillational instability found earlier in models cooling by power-law cooling curves. The precise stability limit may depend on the amplitude of the perturbation. A condensational instability arises in the collapse phase of the oscillation cycle. Steady shock models are not an adequate description of high-velocity radiative shocks.

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