CP845, *Shock Compression of Condensed Matter - 2005,*
edited by M. D. Furnish, M. Elert, T. P. Russell, and C. T. White

CONTEXT AND THEORY FOR PLANAR RADIATIVE SHOCK EXPERIMENTS IN XENON

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Abstract. Our laboratory studies of radiative shocks include development of the semi-analytic theory that corresponds to various cases of interest to experiments, development of experiments, comparison of experiments and simulations, and drawing connections to astrophysics. Here we discuss theory and experiment of radiative shocks that are optically thin to thermal radiation in the upstream direction but optically thick in the downstream direction.

Keywords: Shock waves: profile, radiation: hydrodynamics.
PACS: 52.35.Tc, 95.30.Jx, 95.30.Lz.

INTRODUCTION

Laboratory studies of radiative shocks are motivated by the presence of such shocks in astrophysics [1], by the developing ability to perform radiation hydrodynamic experiments in the laboratory [2-7], and by the need for experiments to benchmark new generations of astrophysical radiation-hydrodynamic codes. In our ongoing work with collaborators [8, 9] we have developed experiments that can produce these shocks and have diagnosed them by radiography and other techniques. In the following we discuss how these specific experiments fit into the overall context of radiative shocks. Then we discuss the theory of such shocks, which is not much developed in the existing literature. Finally, we summarize the experiments and show some of the data.

THE RADIATIVE SHOCK CONTEXT

We work in the usual "shock frame", in which this matter enters a stationary shock from "upstream" and the shocked matter flows away from the shock "downstream". Radiative shocks are characterized by three key parameters, all of which are intuitively straightforward. The energy input to the dynamics is the kinetic energy flux, $\rho_o u_s^3/2$, of the material incident on the shock (of mass density ρ_o and of speed u_s). The first parameter is the ratio of the radiation flux at the characteristic post-shock temperature, T_s, to this energy. We evaluate T_s at the nominal density jump of a strong shock, $(\gamma+1)/(\gamma-1)$, $RT_s = 2(\gamma-1)u_s^2/(\gamma+1)^2$, where R is the gas constant and γ is the polytropic index of the medium. In fact, R may not be constant and the density jump may differ a great deal from the nominal value, and that while $\gamma = 5/3$ for single-particle gasses, it is typically smaller than this for ionizing and radiating matter and also may not be constant. These details do not alter the condition on the energy flux ratio

$$\frac{\sigma T_s^4}{\rho_o u_s^3/2} = Q\frac{16(\gamma-1)^4}{(\gamma+1)^8} > 1, \qquad (1)$$

in which the shock strength parameter Q is $2\sigma u_s^5/R^4\rho_o$ and Q must reach several thousand for radiative effects to be important. This defines a threshold velocity for radiative shocks, which is for example 60 km/s in Xe at 10 mg/cm^3 and is 200 km/s in CH at 10 mg/cm^3.

The other two key dimensionless parameters are the optical depths upstream of and downstream of the shock. Here the optical depth is the number of exponential absorption lengths in the medium, for radiation emitted by the heated post-shock material. The conceptual point is that it makes a difference whether the energy emitted in some direction is absorbed deep within the medium, escapes freely from it, or exhibits more complicated behavior. One conceptually simple limit is the case when both the upstream medium and the downstream medium are optically thin. This allows nearly all of the initial post-shock thermal energy to be radiated away. Many astrophysical shocks are in this limit, including for example shocks in supernova remnants in their "radiative" phase [10], and are easily observed as the radiation escapes. A second conceptually simple limit is that in which both the upstream medium and the downstream medium are optically thick. In this case the radiation is confined within the medium, as may happen for example in some supergiant variable stars [11]. The case of interest here is the hybrid case in which the upstream medium is optically thin while the downstream medium is optically thick. Astrophysical shocks emerging from optically thick objects such as stars or supernovae experience this phase [12].

THEORY FOR THICK-DOWNSTREAM, THIN-UPSTREAM CASE

The context for the needed theory is set by a number of properties of the experimental system. The density jump corresponds to heating of the ions by viscous effects, which occurs on a very small spatial scale. The ions then equilibrate with the electrons, which may involve further ionization. Under typical conditions, the distance over which this equilibration occurs is small compared to the radiation mean-free path [13]; here we will take it to be instantaneous. The heated matter then radiates, and some of the radiation penetrates upstream of the shock, producing a *radiative precursor*. This radiative emission cools the heated matter over some distance until a final state is reached in which there is no net

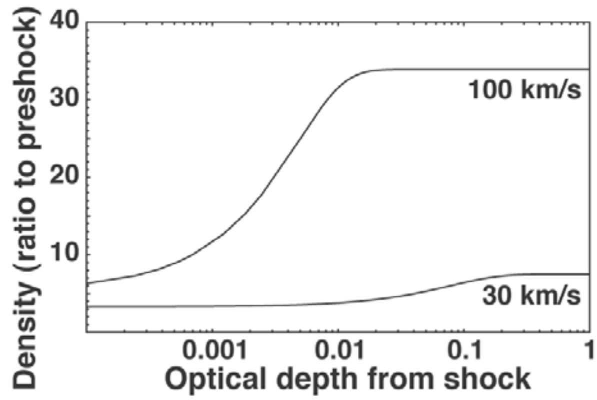

Figure 1. Density profile for a simplified xenon model. The immediate post-shock density is shown on the left, and within one optical depth the final density has been reached. From Drake [13].

downstream radiative flux. This layer where radiative cooling occurs can be labeled a *cooling layer*. For the case of interest here, there remains a steady upstream flux of radiation that escapes the system. The optically thin precursor is heated by this radiation, but does not contribute significantly to the energy dynamics of the system.

In typical regimes of current interest, the radiative fluxes are large (Eq. 1 is satisfied) but the radiation pressure and energy density are negligible, so we will ignore these. Under these conditions the differential equation for energy balance for a steady shock becomes

$$\nabla \bullet \left[\rho \mathbf{u} \left(\varepsilon + \frac{u^2}{2} \right) + p\mathbf{u} \right] = -\nabla \bullet \mathbf{F}_R , \qquad (2)$$

in which the specific internal energy is ε, the pressure is p, the velocity is $\mathbf{u}$, and the radiation energy flux is $\mathbf{F}_R$. Combining this with the equations for mass and momentum balance, for a one-dimensional shock, one has

$$RT = (1-\rho_o/\rho)\,\rho_o/\rho \text{, and} \qquad (3)$$

$$\frac{\rho_o u_s^3}{2}\frac{\partial}{\partial z}\left[\frac{-2\gamma}{(\gamma-1)}\left(\frac{\rho_o}{\rho}\right) + \frac{(\gamma+1)}{(\gamma-1)}\left(\frac{\rho_o}{\rho}\right)^2 \right] = -\frac{\partial F_R}{\partial z} . \quad (4)$$

Because the cooling layer is optically thin, it proves useful to describe the radiation using the zeroth moment of the radiation transfer equation, which in steady state gives $-\partial F_R/\partial z = 4\pi\kappa(B - J_R)$, where $B = \sigma T^4/\pi$, $J_R = \int_{4\pi} I_R d\Omega/(4\pi)$, with I_R being the radiation intensity (energy flux per sr), and κ is the Planck mean opacity, assumed as usual to be accurate for J_R in addition to B. Here J_R does not change as one traverses the optically thin cooling layer (the flux emitted from a thin sublayer being equal in both directions) and matching the cooling layer to the final state requires $J_R = B_f = \sigma T_f^4/\pi$. The boundary conditions are found from the energy balance [13] to be

$$\rho_o/\rho_f = \sqrt{\sqrt{1+8Q}-1}\Big/\sqrt{4Q}\text{, and} \tag{5}$$

$$F_{Rs} = 2\sigma T_f^4, \tag{6}$$

where F_{Rs} is the radiation flux at (and continuous across) the density jump. With these, one can integrate Eq. 4 to find the profiles of density and other parameters in the cooling layer.

Figure 1 shows qualitatively typical profiles of the post-shock density. Here a simplified model is used for xenon at a density of 1 mg/cm^3, in which κ is assumed to scale as $T^{-4/3}$ and $\gamma = 4/3$, which is reasonable for the ionizing xenon of our experiments. More complex models for κ are possible [14]. As the shock velocity increases, the post-shock temperature and radiative fluxes increase, causing a larger fraction of the energy to be radiated and a larger total increase in density.

THE EXPERIMENT DESIGN

The experiment uses the Omega Laser [15] to ablatively accelerate a planar "drive disk" of material, launching it down a shock tube where it drives a shock through xenon gas like a piston. Approximate 4 kJ of energy at a wavelength of 0.35 μm, in a 1 ns pulse, irradiates the slab, which is typically of Be and is nominally 10 μm, 20 μm, or 40 μm thick. The laser spot is ~ 800 μm while the polyimide shock tube is ~ 600 μm in diameter. The ablation pressure of ~ 50 Mbars (5 TPascal) first shocks and then accelerates the Be slab, which reaches a velocity of 100 km/s to 250 km/s. As the piston moves down the tube, the shocked Xenon is heated sufficiently to radiate strongly, leading to radiative preheat of the material ahead of the shock and to a density increase of the shocked Xe.

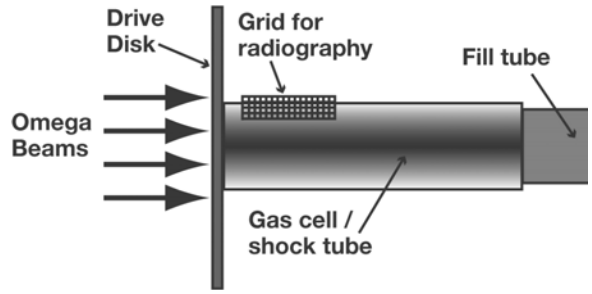

Figure 2. Sketch of experiment to produce radiative shocks. The tube is filled with Xe at 6 mg/cm^3. The xray source for radiography is below the page, and the detector is above the page.

We assess the evolution of this system, for experiment design and for comparison with data, using the HYADES simulation code [16]. This is a Lagrangian code treating the plasma as a single fluid but separately evaluating the energy of the ions, electrons, and radiation. It models the heat flow diffusively, using a multigroup model of the radiation and a single-group model of the electrons, both flux-limited. The code finds a narrow region at the shock where the ions are heated to many hundreds of eV, followed by equilibration with the electrons and the associated ionization, much like that reported previously [2]. Radiative cooling then creates an increase of density, leading to the thin dense layers of Xe shown in Fig. 3. The radiation

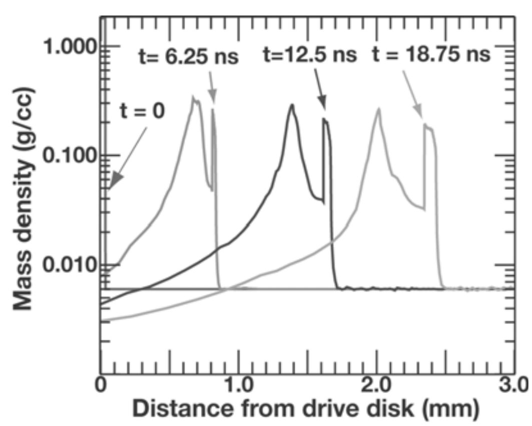

Figure 3. The density profile at several times, from a simulation using HYADES for a 40 μm Be drive disk. The thin dense layer to the right is the shocked Xe, while the peaked structure to the left is the drifting Be.

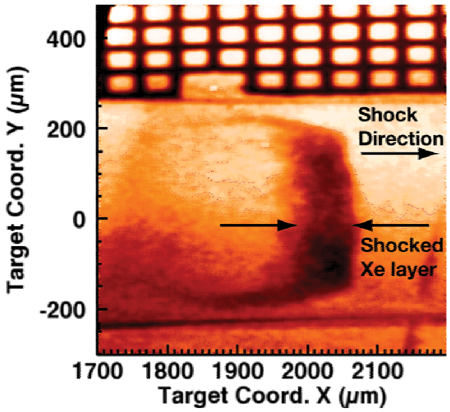

Figure 4. Radiographic data, at 14.6 ns after the initiation of an experiment using a 20 μm Be drive disk. The image is stretched for clarity, the grid cells are squares spaced 63 μm from center to center.

from the Xe also ablates the dense Be, producing a separation of the Be density peak from the Xe density peak, as the figure also shows. In addition, the shocked Xe over time develops an extended layer of relatively constant density. This layer is optically thick and so corresponds a quasi-steady final state like that described above.

We have at this writing obtained a large number of radiographic images of this system, in addition to limited data from other diagnostics. Figure 4 shows an example. The radiographs show the shock tube, the calibration grid, and a thin layer of Xe. The Xe layer appears to be relatively uniform and to become thicker as the shock propagates, which is as expected from this type of radiative shock. There is some structure on the surfaces of the Xe layer, which remains to be explored. There is also a thin sheet of Xe that is left behind along the edges of the cylinder. This is consistent with two-dimensional simulations.

CONCLUSIONS

The work discussed here is at its beginning. We have developed a semi-analytic theory that is useful for understanding radiative shocks that are optically thick downstream and optically thin upstream. We have also developed an experimental system that permits the study of such shocks, and have begun the process of diagnosing their properties. Future work includes iterating the semi-analytic model to be more aligned with the experiments, developing a range of diagnostics of the experimental properties, and comparing the experimental results with emerging astrophysical codes.

ACKNOWLEDGEMENTS

We acknowledge useful discussions of the theoretical context with Dmitri Ryutov and John Edwards, Bruce Remington, Ted Perry, Gail Glendinning. Freddy Hansen and work on the experiments with the Omega NLUF Experimental Astrophysics Team, and financial support from the National Nuclear Security Administration under the Stewardship Science Academic Alliances program through DOE Research Grant DE-FG52-03NA00064 and DE FG53 2005 NA26014.

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