Final Report

***Hydrodynamics by High-Energy-Density Plasma Flow
and
Hydrodynamics and Radiative Hydrodynamics with Astrophysical Application***

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Images:

Left– Radiograph, of Rayleigh Taylor experiment: 25 ns, iodine-doped tracer, backlit pinhole.
Right– Narrow dense layer in xenon due to collapsing radiative shock.

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I. SUMMARY

The fundamental motivation for our work is twofold. On the one hand, as a systematic scientific field of study high-energy-density physics is in its infancy. We can do fundamental work in this field, train students in the process, and by so doing support the national laboratories that require such knowledge and personnel. On the other hand, supernovae and other astrophysical phenomena are not well understood. Recent observations have clarified the depth of our ignorance, by producing observed phenomena that current theory and computer simulations cannot reproduce. Such theories and simulations involve, however, a number of physical mechanisms that have never been studied in isolation. We perform experiments, in compressible hydrodynamics and radiation hydrodynamics, relevant to supernovae and supernova remnants. These experiments produce phenomena in the laboratory that are believed to be important to astrophysics, but that have not been directly observed in either the laboratory or in an astrophysical system.

Our work is in two areas: compressible nonlinear hydrodynamics and radiative shocks. Compressible nonlinear hydrodynamics has been the most productive area to date in the emerging field of Experimental Astrophysics. This is a natural area of research for laser systems or z pinches built principally for inertial fusion applications. It also helps that one can do experiments that are in all respects well scaled from the laboratory to the astrophysical system. Experiments in this area to date have focused primarily on supernova (SN) explosion dynamics, supernova remnants, hydrodynamic jets, and the interaction of shocks and clumps. We have been involved in work on these problems using the Omega laser at Rochester and the Z machine at Sandia. In the following we summarize work done under this grant relating to coupled unstable interfaces, unstable diverging interfaces, multimode Rayleigh-Taylor instabilities, and Rayleigh-Taylor instabilities from 3 dimensional initial conditions that may lead to turbulence. In addition, we discuss our work with the interactions of shocks and clumpy media and in the design of experiments to probe astrophysical jets.

Radiative processes are essential to astrophysics, being important to emerging supernova shocks, accretion flows, supernova remnants, and other systems. Hot sources can launch diffusive radiation waves into nearby media. Radiative losses can cause certain regions to collapse spatially as they cool, greatly increasing their density. Radiation transport, often a fundamentally nonlocal process, can move energy through a system in complicated ways. Radiative-precursor shocks have been our initial entry into studies of radiation-hydrodynamic systems of relevance to astrophysics. They develop when the flux of forward-going ionizing photons from the shock-heated matter exceeds the flux of neutral atoms toward the shock. Such shocks develop for example during the emergence of a blast wave from a SN and during the propagation of a clump of dense matter up an astrophysical jet. Our proposed experiments will move us into the study of radiatively collapsing shocks. Astrophysical shocks, when they become cool enough, enter a radiatively collapsing phase in which their density can increase several orders of magnitude. All supernova remnants eventually pass through this phase. After such shocks enter this phase, they are believed to be unstable to the Vishniac instability. This instability may be responsible

Figure 1. Image of the Cygnus loop showing convoluted structures (H emission in green, S II in red, and O III in blue).

for the convoluted structures seen in the Cygnus loop, for example as shown in Figure 1. In addition, radiation can play an essential role in the early evolution of a SNR. In particular, when a red supergiant star, which produces a cold, dense stellar wind, explodes, the shocked ejecta is dense enough to immediately become radiative. This is believed to lead to radiative collapse and much stronger hydrodynamic instabilities.

We have assembled a collaborative team that includes a core group of experimenters and several theoretical groups. Our experiments follow a sequence. We identify promising ideas, we do design studies to understand their potential to produce worthwhile results, and we carry out the most promising experiments that have been well thought out. The analysis and related simulations that we perform during the detailed design phase lead us to increase our emphasis on some ideas and to drop others. The experiments themselves are followed by an initial phase of data reduction and analysis and a later phase of detailed comparison with astrophysical codes. Each theoretical group is typically involved with one or two of the experiments that are in the pipeline. In our use of Omega, we are typically doing active work on two experiments at a given time, with either wrap-up or scoping work on one or two others. Throughout this process, we make active use of Michigan students. We involve them as appropriate in various phases of the work, from design studies through data analysis. We also give them the experience of participating in the experiments. Further details of student involvement are discussed later in this report.

Our team includes leaders in astrophysics, nonlinear hydrodynamics, and ICF to attack these problems of fundamental interest to DOE, cast in the framework of experimental astrophysics. The participation of the ASCI Alliance Center at the University of Chicago allows us to move beyond the “simple” experiments of the past toward experiments that test computational models at an unprecedented level of detail and complexity. Progress made utilizing the SN codes at the University of Arizona, at Stony Brook, at Colorado, at Maryland, and at the Naval Research Laboratory, and utilizing the ASCI codes under development at the University of Chicago and in the

Figure 2. HED Laboratory Astrophysics and specifically our Omega experiments were discussed in the June, 2001 *Discover* cover article.

DOE labs, on our ICF-scale SN experiments should prove to be very useful for the DOE ICF program. The rigorous scaling under various conditions to be developed as part of this work will also find utility in scaling from current Omega experiments to ignition experiments being planned for NIF. Our proposal highlights the multi-use benefits of a major DOE facility for the pursuit of inertial confinement fusion (ICF), ASCI V&V, and basic science. Radiative shocks are important to astrophysics and to some ICF applications. We are just beginning to explore them. Deep nonlinear, compressible hydrodynamic mixing represents one of the key unsolved problems both in astrophysics and in ICF. We are excited at the prospects of making further progress in both of these areas.

Our work to date has had a broad impact, both within the refereed literature and beyond. The 25 refereed publications supported in whole or in part by this grant are listed in Section V. Our fourth conference on High-Energy-Density Laboratory Astrophysics was held in Ann Arbor and chaired by the PI. Our work has produced a steady string of invited talks at scientific conferences, including among others at the 2003 APS/DPP meeting, at the associated miniconference on Laboratory Astrophysics, at the IPELS meeting in 2003, and

at the APS spring meeting in Albuquerque in 2002. The P.I. was also selected as a Distinguished Lecturer in Plasma Physics by the Division of Plasma Physics of the American Physical Society, and presented a lecture at 7 universities. A complete list is in Sections VII and VIII. In addition, the PI was asked to speak the NRC panel entitled the Committee on the Physics of the Universe and was asked to speak to the Committee on High Energy Density Plasma Physics. In addition, Discover magazine (Figure 4) featured our work at Omega in its June, 2001 cover story “Star in a Jar” and it was earlier discussed in Sky & Telescope (“From swords to supernovae”), Smithsonian Air & Space (“Star in a bottle”), Scientific American (“Flea-sized supernovae” and New Scientist (“SuperNova”). Moreover, the BBC has been airing a documentary on the origin of the elements that includes a segment featuring the PI, shot at Omega in Dec. 2000.

The most enduring impact of our program may be felt through the involvement of students. Section VI lists the 2 post-doctoral fellows, 6 graduate students, and 8 undergraduate students who have participated in this work. All but one of them have traveled to Omega to participate in the experiments, where most of them have played an active role in carrying them out.

II. ASTROPHYSICAL MOTIVATION

There is tremendous intellectual excitement associated with the emerging field of Experimental Astrophysics. High-Energy-Density (HED) laboratory tools can produce velocities, temperatures, and pressures that are directly relevant to issues in astrophysics. This offers the potential to add an experimental component to the problem of understanding the universe – to use controlled experiments to probe the physics that powers nature’s grandest displays. The challenge of using laboratory tools to explore such issues has proven very attractive to students. The opportunity to seek common intellectual ground across a vast range of scales has proven attractive to both astrophysicists and laboratory scientists. This was most evident when 80 researchers, many of them quite senior, traveled to Ann Arbor in February 2002 to attend the 4th International Conference on High-Energy-Density Laboratory Astrophysics, chaired by the PI of this proposal.

As one example of an astrophysical application, consider supernova 1987A. On February 23, 1987 at 0735 UT, the blue supergiant Sanduleak -69° 202 located in the Large Magellanic Cloud (LMC), a dwarf galaxy at a distance of 50 kpc from earth, exploded as a core-collapse Type II supernova (SN) with a fiery release of 1.5×10^{51} ergs of gravitational energy. This event was marked by a prodigious outburst of neutrinos followed ~3 hr later by the UV flash as the shock broke through the surface of the star. Thus began an epic saga that will occupy the careers of astrophysicists who are not yet born. SN 1987A today is a (very) young supernova remnant (SNR). The astrophysics community has been studying SN1987A for 13 years; our understanding has progressed enormously. One example is the consensus within the community that strong hydrodynamic mixing of the heavier core elements outwards into the lower density envelope is needed to explain a wide range of observables. Despite considerable effort worldwide, however, simulations still predict that the mixing front progresses nearly a factor of two more slowly than required by the observations. Three dimensional modeling has barely begun, and the extent overall to which 3D modeling and radiative effects will refine or modify our understanding of SNe is virtually unknown. We have added a new component to the supernova research community. Combining carefully designed high-power laser experiments on the Omega laser with high-power computing capabilities including those of ASCI, we have created an experimental testbed for SN research at Omega, and have been using it to explore unresolved issues relating to SN and SNR hydrodynamics.

SN 1987A is now poised to present us with one of the most spectacular SNR events ever observed: the fiery collision of the high-speed explosion ejecta with the surrounding dense circumstellar ring nebula. This collision has, in fact, already commenced. There are several “hot spots”, clearly seen in Figure 3 (from the Hubble Space Telescope WFPC2 camera). Interpreting data from this collision to reveal the true nature of the ring, however, is fraught with uncertainties. The observed behavior of the shock waves inside the ring differs strongly from the predictions of simulations. The collision itself will be strongly 3D in nature, and almost surely radiative. Without tested 3D hydrodynamics codes, and without tested, coupled radiative-hydrodynamic shock models, the extent to which this strong-shock collision can be quantitatively used to reveal the true nature of the ring is suspect. In our research, we are seeking to remove several key fundamental uncertainties in the physics of this spectacular extragalactic event. We have been working to develop, carry out, and model strong-shock hydrodynamics “bench-test” experiments, and radiative-shock hydrodynamics experiments, to help develop the tools needed to interpret this event and other SNRs.

Figure 3. SNR 1987A showing five hotspots where the ring-ejecta collision is beginning.

III. EXPERIMENTS IN COMPRESSIBLE NONLINEAR HYDRODYNAMICS

We have developed a standard configuration for the Omega experiments addressing issues in supernova explosions. As a consequence, we do not need to waste shots testing a new drive and backlighting setup for each new experiment. This maximizes our productivity. In this section, we first review this approach. The next section discusses the experiments.

Figure 4. The standard target irradiation and backlighting scheme used for all our experiments

Figure 4 illustrates the standard target irradiation, and backlighting scheme used for all of our experiments. There are drive laser beams, which produce the desired pressure pulse to initiate the experiment, and backlighter beams, which produce the x-rays needed for diagnostics. Some axis, such as the one passing through the center of port H14 and the center of the target chamber defines the reference “drive axis” for the experiment. The inner 6 drive beams are arrayed about this axis in a symmetric hexagon. Up to 4 more drive beams, which are the next closest beams on the chamber, may also be used. The drive beams strike a target surface, usually plastic or a plastic overcoat, to initiate the experiment. Shielding around the drive beam spot prevents the laser beams from otherwise affecting the evolution of the target or the diagnostics. The drive beams launch a shock wave into the first layer of material in the target. The choice of that material and its geometry, and those of the subsequent target components, determines the nature of the experiment. The primary diagnostic technique is x-ray backlighting. One adjusts the backlighting material, and the number, timing, and focusing of the backlighter beams, to obtain good x-ray absorption in a given

target. Backlighting is useful either through the side of the target, perpendicular to the drive axis, or along the axis of the target. Additional shields, calibration grids, and alignment features are added to the target as necessary for each experiment. This system provides a standard experimental environment within which we can address a very wide range of physical questions, as is illustrated by the experiments discussed below.

A. Coupled interface experiments

We have completed and published results from an experiment to produce and observe interface coupling, in which the preimposed perturbations at a first interface introduce structure in a transmitted shock wave, causing the development of structure at an initially flat second interface. A paper describing these experiments and modeling of them has been published in *Physical Review E*. A second paper that includes a comparison of these data with results of the ASCI FLASH code at Chicago has been published in *The Astrophysical Journal*. Figure 5 shows an exploded view of the target used for this experiment. The first interface, at the Cu/plastic boundary, is rippled. The plastic material contains a localized layer of brominated plastic, allowing the x-ray backlighter to detect the structure deep within the target at the second, plastic/foam, interface. (Thus, edge effects do not complicate the data.) The target is driven by 10 beams of the Omega laser, in a 1 ns pulse at an average irradiance of $5.7 \times 10^{14} \text{ W/cm}^2$. We have

Figure 5. Exploded view of the target: a) 10 μm CH ablator, b) 85 μm Cu layer with $\lambda = 200 \mu\text{m}$, $a_{p/v} = 40 \mu\text{m}$ ripple, c) 150 μm polyimide layer, d) embedded CH (4.3%Br) tracer layer, e.) 800 μm diameter CRF foam cylinder, and f) Be shock tube.

Figure 6. Data from the interface coupling experiment on Omega. Perturbations at a Cu/plastic interface grew enough to produce structure at an outer plastic/foam interface.

used similar targets, but without the copper layer and with the structured interface at the plastic-foam boundary, for our other deep nonlinear hydrodynamic experiments.

Figure 6 shows an image obtained during these experiments, at a time of 65 ns. The Cu is completely opaque, and one can see the very extended spikes of Cu material that develop through long-term RM and RT growth combined with the rarefaction of the Cu. One can also see the darker feature produced by the brominated plastic. This shows that the plastic-foam interface, which was initially flat, has developed a complicated structure, and that we can see this structure very well in the experiment. We have compared these results with those of simulations using the astrophysical code PROMETHEUS, and have begun modeling them with the ASCI code, FLASH, developed at Chicago. Figure 7 shows results from the PROMETHEUS simulation at

65 ns, which compare quite well with the data. Figure 8 shows, at full resolution, the results of the simulations using the the ASCI FLASH code at Chicago. FLASH is a modular, adaptive, parallel simulation code capable of handling general compressible flow problems. The simulations begin with 1D initial conditions from a HYADES simulation.

Work is in progress to simulate this experiment using HYADES is a one-dimensional Lagrangian hydrodynamics code with multi-group radiation transport and a tabular equation of state, which includes the necessary laser and radiation physics to model the development of the shock in the initial layer of Cu. Two-dimensional initial conditions are produced by taking the 1D simulation results at an appropriate time and adding the 2D structure that is present in the target (and is as yet unperturbed). In Figure 8, the shock is near the right edge.

The dense Cu has formed a well-developed spike at the Cu/plastic interface, which is the dominant feature near the center of the image. A low-density bubble of foam is rising toward this spike from the right. Thus, the spikes of plastic are out of phase with those of Cu, as observed. Note that the adaptive refinement of the grid allows improved resolution of the structures at the interfaces. This simulation used a polytropic equation of state, with $\gamma = 2$ for the Cu and plastic and $\gamma = 1.3$ for the foam. The interface-coupling experiments have thus provided direct observation of interface coupling and are now providing a good test case for astrophysical simulations.

Figure 7. Simulated radiograph, by PROMETHEUS, for the interface coupling experiment. The resolution in this image is better than the experimental resolution. Out-of-phase growth at the second interface is clearly visible here and in the data. (Simulation by J. Kane, LLNL)

Figure 8. The density produced in FLASH simulations of the interface coupling experiment, at 65 ns. (Simulation by A. Calder, Chicago)

B. Spherically Diverging Experiments

Figure 9.
Experimental
radiograph.

Figure 9 shows a radiograph of a section of the perturbed capsule at $t = 13$ ns in experiment 20620, in which the initial capsule ID and thickness were $443 \mu\text{m}$ and $109 \mu\text{m}$, respectively. The initial perturbation wavelength and amplitude were $70 \mu\text{m}$ and $10 \mu\text{m}$, respectively. The dimensions of the wire grid in the image are $62.5 \mu\text{m}$ from wire center to wire center. These and other data show that we succeeded in producing a (very nearly) spherically divergent system. The spherical divergence was sufficient to increase the wavelength of the perturbation more than threefold during the experiment. We examined two density ratios across the

Figure 11. Data and simulations from the spherically diverging experiment.

hydrodynamic models to this system can begin at 2 ns. We mapped the CALE output into FronTier at 2 ns, after the 1 ns laser pulse but before the shock exited the capsule. Figure 10 shows a density profile calculated by FronTier at 26 ns. One can see the highly developed, dense tips of

We completed and published results from the first experiments to produce a spherically diverging, hydrodynamically unstable system that can provide a well-scaled test of computer models of supernova explosion hydrodynamics. The system involved using a strong, laser-generated shock to produce a brief, outward acceleration of a hemispherical layer of material, against a thick layer of less-dense material, followed by an extended period of deceleration. The spatial structure near the interface between the two materials is similar to that produced (according to simulations) at the H / He interface in SN 1987A. In both the experiment and the SN, the interface is hydrodynamically unstable. In the experiment, the instability was seeded by an initial perturbation at this interface.

Figure 9 shows a radiograph of a section of the perturbed capsule at $t = 13$ ns in experiment 20620, in

Figure 10. Density profile from FronTier.

interface, two perturbation geometries, and two capsule thicknesses. We were able to follow the growth of the perturbations until they broke up the capsule.

We numerically simulated these experiments with 2D CALE (run by Omar Hurricane at Livermore) and FronTier (run by Yongmin Zhang and James Glimm at SUNY Stony Brook). The CALE model included the detailed laser plasma and radiation physics necessary to model both the radiation-hydrodynamics of the first 2 ns of the experiment as well as the long-term, purely hydrodynamic evolution of the system. The application of astrophysical or other

the spikes. Figure 11 shows the resulting growth of the perturbations. (Later versions of CALE did better at calculating the growth of peak-to-valley amplitude.) A paper describing this work has been published in *The Astrophysical Journal*.

Figure 12. Structures developed at 26 ns from a 2-mode perturbation.

C. Multimode perturbations

We have extended our study of the RT instability at an embedded interface, like that in the exploding star, to examine the growth of multimode, 2D initial perturbations. The targets are like those just described. They used 100 mg/cc foam and the multimode perturbation was imposed on the plastic surface adjacent to the foam. We have obtained data showing the time evolution of the structures produced from initial conditions including 1 mode, 2 modes, and 8 modes. The

Figure 13. Structures developed at 26 ns from an 8-mode perturbation.

perturbations were designed to keep the global peak-to-valley amplitude constant at $5\ \mu\text{m}$ as the number of modes changed. Figure 12 shows some data we obtained using a 2-mode perturbation and Figure 13 shows some data using an 8-mode perturbation. At earlier times, the multimode data show articulated spikes, as can be seen on the front cover. Later, as in these figures, they show the emergence of large-scale features. A student from the University of Maryland and collaborators at Livermore have analyzed these experiments using CALE, with results submitted for publication.

D. 2D vs. 3D Rayleigh Taylor and the Transition to Turbulence

This topic is difficult yet exciting to describe, as both experiment and theory (described later) are leading us in new directions with very large potential impact. We began trying to address what the astrophysical community believes to be one of the major issues in the evolution of supernovae: whether three-dimensional effects can resolve the differences between reality and simulations, nearly all of which are in two dimensions (or even one dimension). A few 3D simulations, not yet benchmarked, suggest that 3D effects are not sufficient to resolve these differences. Our initial goal has been to provide the benchmarking. This led us to address the long-term evolution of turbulence from 2D vs. 3D initial conditions. The targets are similar to that shown in Fig. 6, except that there is no Cu layer and it is the surface of the plastic adjacent to the foam that is rippled. They include a two-layer package composed of plastic, of density $1.41 \pm 0.01\ \text{g/cc}$, and carbon resorcinol foam, of density 100 mg/cc. The plastic layer is $150\ \mu\text{m}$ thick, and the foam is nominally 1.5 mm long. The plastic is composed of polyimide, with an embedded strip of CH doped with 4.3% Br, which has the same density. This provides an x-ray absorptive strip at the center of the line of sight of the diagnostic. For the 2D case, the initial imposed perturbation, on the rear surface of the plastic, is of $50\ \mu\text{m}$ wavelength. For the 3D case, the initial imposed perturbation is an “eggcrate” pattern in two directions x and y . It has wavenumbers in x and y , k_x and k_y , respectively, equal to $2\pi/70\ \mu\text{m}$, which would give the 2D and 3D cases the same linear growth rate in the small amplitude limit. Both perturbations have an initial amplitude of $5\ \mu\text{m}$. This makes them weakly nonlinear at first.

In the course of these experiments, and while developing and testing methods of producing and diagnosing systems with 3D initial perturbations, we obtained extensive data regarding the long-term evolution of a RT-unstable system with 2D initial conditions. Figure 14 shows an example of these data, in comparison with recent CALE simulations by Univ. of Maryland grad student Aaron Miles working with John Edwards of LLNL. Here the laser was originally incident from the right and the

Figure 14. A comparison of the data obtained using a 2D initial perturbation with the results of simulations using the CALE code.

shock is propagating to the left. Darker colors represent weaker x-ray intensity, corresponding to higher-opacity material. One can see that there is overall consistency between the data and the simulation. Quantitative analysis is needed to establish the agreement or disagreement on the details. A paper connecting these 2D results with theories of turbulence has been published in *Physics of Plasmas*. Comparisons with the CALE simulations will also be written up and submitted for publication.

Studies of turbulence in fluids have a long history, during which a fundamental understanding of the transition to turbulence has proven difficult to achieve. Even the determination that a system is “turbulent” is not necessarily clear. It may mean that its properties are independent of its initial conditions, or that the spectrum of fluctuations includes an inertial range, or, in more practical terms, that the rate of material diffusion between (and chemical interaction of) two fluids has greatly increased. These circumstances may overlap, and may be causally connected, but such connections have not been fundamentally clear. In addition, whether or not such a transition will occur in the same way in plasmas is an open, and interesting, question. The reason is that plasmas in principle contain energy dissipation mechanisms that are not present in fluids. To whatever extent the motions of the medium produce internal electric and magnetic fields, these interact with the particles to provide additional dissipation. This has the potential to alter the transition to turbulence in any plasma system. Thus, an additional reason to explore the transition to turbulence in plasma systems is to identify the similarities and differences in comparison with ordinary fluids. In the following discussion, we show that our experiments can improve the understanding of the transition to turbulence in plasmas, and that this is profoundly important for astrophysics.

An important paper by Dimotakis⁸⁰ surveys and analyzes the experimental literature regarding the transition to turbulence in steady-state systems, reaching two conclusions. First, the transition to a strongly mixed state occurs at a Reynolds number, R , just above 10,000. Figure 15 shows a relevant example from laboratory jets. Second, this transition also corresponds to the inferred development of an inertial range in the fluid. The inertial range develops as a physical consequence of the growth of diffusive, laminar boundary layers in local shear regions. It occurs when their thickness becomes large compared to the spatial scale at which dissipation takes place (the “Kolmogorov” scale). We have submitted a follow-on paper⁶⁸ by Robey *et al.* that extends this analysis to time-dependent systems, motivated by the fact that our (time-dependent) experiments, described above, achieved $R > 10,000$ yet did not appear to be turbulent. This paper considers the growth of laminar boundary layers in time, identifying a time at which turbulence would be expected to appear. It also concluded that our previous experiments probably would not have evolved into a turbulent state but were not far away. It is also important to note that the transition to turbulence may in addition be affected by the initial conditions, because these may accelerate or delay the appearance of the local shear regions discussed by Dimotakis.

At this point our experimental circumstances became dynamic, confusing, and exciting. We had performed some experiments to compare the growth of RT instabilities from 3D as opposed to 2D initial conditions. Our initial experiments, which used targets made entirely of CHBr (which absorbs our backlighting x-rays), with very smooth, molded modulations, showed faster spike growth in 3D but no other dynamics. Our next experiments employed a CHBr tracer strip with a much rougher surface, produced by the machining that created the modulations. These experiments yielded tantalizing data suggestive of a turbulent transition, shown in Figure 16, and roughly coincident with the theoretical analysis just described. Analysis of the initial data led us to lower the density of the foam from 100 mg/cc to 50 mg/cc, so that the shock would pull further ahead of the spikes. We were able to produce circumstances for which the analysis of Robey *et al.* predicts that the transition to turbulence will occur. The further data were obtained in subsequent experiments is still being analyzed as of the end of this grant.

Figure 15. The left image shows a laser induced fluorescence visualization of Dimotakis, Lye, & Papantoniou, at $R = 2,300$. The right image shows a shadowgraph visualization of Landis and Shapiro at $R = 30,000$. Both are from Van Dyke, *An album of Fluid Motion*, Parabolic Press (1982).

The implications for astrophysics of this work may be substantial. Hydrodynamically unstable systems that endure sufficiently will produce far more mixing than one would infer from an analytic evaluation of instability growth or from a computer simulation (discussed next). In addition, the transition to turbulence is likely to affect the evolution of the global scale of the mix layer. Some examples of the impact of these effects are as follows. The rate of fuel burning in Type Ia supernovae could substantially increase. The extent of mixing in Type II supernovae could also increase. The global evolution of the mix layer in such objects could also change, although it is an unresolved question whether it would become faster and larger or slower and smaller, involving the interplay of the spherical, diverging geometry and the contributions of the turbulence in the evolution of the modes. The mix layer in supernova remnants and

Figure 16. Development of the perturbations in targets with 3D initial perturbations. At 13 ns about half the mixing layer appears to include finer-scale structures, which might possibly represent the initial stages of the onset of turbulence. At 26 ns the shock and the grid are still clearly seen, but any structure due to the unstable modulations is no longer resolved.

shock-cloud interactions could become more uniform and more extensive. The degree of mixing near astrophysical jets could increase. Other astrophysical systems would also be affected. In addition, this work could potentially improve our understanding of astrophysical systems that are known to be turbulent, including for example the MHD fluctuations in interplanetary and interstellar space and the convective mixing zones in stars.

E. Other Hydrodynamic Experiments

1. Shocks in clumpy media

We collaborated with researchers at the Sandia National Laboratories and in Astronomy at the University of Rochester to devise an experiment to explore the propagation of a shock wave through a clumpy medium.

Several goals for an experiment that is to explore the propagation of shocks through clumpy media can be identified. 1) The fraction of the volume occupied by the clumps should be realistic; we chose 5%. 2) The ratio of density in the clumps to density in the interclump medium should be realistic. Our choice was 40 to 1. This is on the low end of observed values; we chose it to maximize the heating of the clumps and for other reasons discussed below. 3) The shock wave in the clump region should be reasonably steady and enduring. Specifically, it should be sustained long enough so that it interacts with many clumps without any substantial change in the properties of the shock or the post-shock flow. 4) The experiment should allow comparison of the clumpy case with alternative cases, in which the shock wave propagates through media having either a density equal to the average density of the clumpy medium or a density equal to the interclump density. 5) The shock wave should be as strong as possible, in order to maximize the heating of the clumps. Ideally, the clumps should be ionized so that they can be accurately treated by an ideal-gas equation-of-state with a polytropic index $\gamma = 5/3$. 6) The experiment should be diagnosable using available techniques.

In seeking to meet these goals, we have developed the experimental design shown in Figure 17. The energy source for these experiments is a pulse power device known as a Z pinch, specifically the “Z Machine” operated by Sandia National Laboratories (Matzen 1997). A Z pinch can implode an array of W wires at high velocity, so that an intense x-ray pulse is produced when the wires collide and their kinetic energy is thermalized. Among existing high-energy-density research facilities, Z can deliver the most energy to a target. This is essential for an experiment that requires a

Figure 17. A drawing of the package designed for the experiment in which a shock wave will penetrate a clumpy medium.

(comparatively) large volume; the present experiment involving many clumps is a good example. Through the use of a surrounding, high-Z container (a hohlraum) to help contain the x-rays, it is feasible to irradiate up to 4 targets per implosion with an x-ray pulse whose spectrum is reasonably approximated as a blackbody spectrum with a temperature of 140 eV. The full-width half-maximum (FWHM) of this x-ray pulse is 8 ns. The radiation-hydrodynamic computer code HYADES (Larsen & Lane 1994) was used to evaluate our design options. HYADES is a single-fluid, Lagrangian code in which the material composition can be different from cell to cell and in which the electron and ion temperatures evolve independently. The electron heat transport is by flux-limited diffusion, but this was not important here. The version of the code used here employs a single-temperature (“greybody”) radiation field with flux-limited, diffusive radiation transport. This was only

important in the initial delivery of energy to the target. The code was run with SESAME equation-of-state tables. For our purposes here, what mattered in the radiation hydrodynamics was to deliver the correct amount of energy to the initial layer in the target. Accordingly, we adjusted the radiation temperature to obtain the correct ablation pressure for the measured radiation temperature, based on well-confirmed scaling relations (Lindl 1998). We also compared the behavior of targets simulated using a measured radiation pulse, which includes an extended, low-temperature foot at the start of the pulse, with the behavior using an approximate pulse of constant temperature and 8 ns duration. These were very similar (the energy coupling is dominant). Therefore, a simpler 8 ns pulse was used for our scaling studies that developed the specific target properties.

The available x-ray pulse cannot be used to directly drive the desired shock wave. It is too brief, and one needs to absorb it by solid-density matter before driving the shock through a lower density material. The initial challenge in the design is thus to transform the x-ray energy into hydrodynamic energy, which eventually will be used to drive the desired steady shock. The most efficient way to extract energy from a radiation source is to allow it to accelerate a thin layer of material over some distance, while ablating some fraction of the initial layer (Ripin *et al.* 1980). The initial layer must be massive enough to provide the necessary momentum to the additional mass encountered later during the experiment. It also must be thick enough that instabilities at the ablation surface do not disrupt it. Scaling studies showed that a 125 μ m thick layer of polystyrene, at a density of 1 g/cc, worked well for this purpose. The range of optimum thickness is not narrow; one would obtain comparable results from thinner or thicker layers. The initial layer is accelerated across a 500 μ m vacuum gap. The size of the gap was optimized so that the plastic layer collides with the next layer in the target (the C foam) just at the end of the 8 ns drive pulse. At this time, it has been accelerated to a velocity of about 70 km/s.

The second design challenge is to convert the energy initially delivered by the 8 ns x-ray pulse into a form that can drive a shock for tens of ns, which turns out to be necessary for reasons discussed below. To accomplish this, we let the accelerated plastic layer impact a C foam layer of density 200 mg/cc and thickness 1.5 mm. Our goal here is to let a blast wave develop in the C foam, in which an abrupt shock is followed by a gradual deceleration over a significant distance. The areal mass

density of the C foam is several times that of the plastic that remains when the foam is impacted, so that this blast-wave becomes approximately a (planar) Sedov-Taylor wave, decelerating slowly, accumulating mass, and growing spatially. Our goal is to use the rarefaction of the leading edge of this blast wave into the clumpy medium, to drive the enduring shock that we intend to produce. Here again, we used scaling studies to set the foam density and thickness. The C foam must be dense enough that its leading edge can drive the shock we require through the clumpy medium, yet not so dense that the shocked foam becomes too cool and the rarefaction becomes too slow. The changes in behavior were seen to be gradual, so that the specific parameters of the target represent specific conditions within a broad range of reasonable choices.

Figure 18. Evolution of the density as the blast wave penetrates the interclump medium.

Figure 18 shows the evolution of the blast wave as it reaches the end of the C foam. By these times the initial plastic layer, seen as the dense feature on the left, has decelerated nearly to rest. The local modulations in density and velocity are acoustic and are artifacts of the zoning used in the simulation. The first profile shows the blast wave near the end of the C foam. One sees the characteristic abrupt shock and gradual deceleration. One can also see that the structure of the blast wave extends over several hundreds of m. This enables it to deliver its energy for several tens of ns, with characteristic velocities of tens of km/s. When the blast wave reaches the interclump medium, its velocity is 33 km s⁻¹. At that time, as seen in the other profiles, a rarefaction wave forms. This drives a faster, reasonably steady shock into the interclump medium, as is expected for a centered rarefaction (Zeldovich & Raizer 1966)⁶. The rarefaction propagates backward into the C foam as well. However, no subsequent reflected shock is produced during the experiment because there are no density structures in the blast wave.

The properties of the clumpy medium were chosen based on several considerations. The interclump medium must be low in density to allow the rarefaction of the blast wave to expand at a high velocity and to allow diagnostic x-rays to penetrate distances of several mm for radiography. Subject to these constraints, higher values of this density produce larger ram pressures and more heating of the clumps. We chose 25 mg/cc divinyl benzene (DVB) foam for this material. This produced the minimum realistic ratio of 40 to 1 between the interclump medium and the plastic clumps at 1 g/cc. The value of 1 g/cc was the lowest density for clumps that could be implemented, leading to the maximum clump heating. The clumps were chosen to be two-dimensional rods since, on one hand, this was easier to diagnose and simpler to model and, on the other, since an approach to the manufacturing method of such a system could be identified. The choice of a 5% volume fraction for the clumps implied a relation between the radius of the clumps and the clump density. The choice of a clump size was subject to the competition between the goals of being able to make them and to diagnose them, which favored large clumps, and the goals of maximizing their temperature and of having many clumps in the experiment, which favored small clumps. The size of the clumps was chosen to be 50 μ m, corresponding to an average interclump spacing of 200 μ m, a clump density of 25 per square mm, with a total of 200 clumps in a 4 mm wide, 2 mm thick clumpy layer. The location of the clumps in the clumpy medium was chosen to be random, as is the case in

actual clouds. This was accomplished by using an algorithm that employed a random number generator to specify these locations.

By using a divinylbenzene (DVB) foam with a density of 73 mg/cc in place of the clumpy medium, one could observe the propagation of the shock wave through a medium of uniform density (at least on scales larger than the m-cell size within the foam material). By using 25 mg/cc DVB foam without clumps, one could observe the propagation through the uniform interclump medium. Beyond the clumpy medium, additional components are placed that allow the emergence of the shock to be detected and ideally also the subsequent velocity of the interface at the end of the clumpy medium to be measured. One approach is to place a quartz window, coated with a thin (1 m) Al layer, at the end of the foam and to diagnose the motion of the Aluminum layer interferometrically.

The specific targets described here did not prove to be buildable. A modified design was built and awaits experimental shots.

2. Jet experiments

We are also involved in collaborative experiments, both at Omega and at Z, to produce and study hydrodynamic jets of astrophysical relevance. A number of these experiments are based on the initial design work described in the following. This work is ongoing, and has not yet led to publications.

We developed an approach to jet-driven explosion experiments and assessed, with 1D simulations, the feasibility of producing the jet. The challenge is to provide an enduring supersonic jet. It must endure long enough that the bow shock it produces can blow apart a block of material whose size far exceeds the jet diameter. We have identified an approach to this that works in 1D, this formed the basis for further and more detailed 2D simulations by Alexei Khokhlov, Bernie Wilde, and Paula Rosen.

Basic approach:

Figure 19 illustrates the basic approach. Laser beams irradiate a 1-mm-diameter, 800- μm -thick layer of plastic (of density 1 g/cc). This drives a shock wave into the plastic, which is the source of energy for the subsequent evolution. The shock wave traverses the plastic, after which the ejecta from the back of the plastic expand and cool across a 1 mm deep hole in a gold washer. This produces a collimated, quasi-one-dimensional, high-Mach-number flow of material. This material flows out of the hole in the gold washer and into low-density foam (at ~ 10 mg/cc). This jet of flowing material drives a bow shock in the foam. When this bow shock reaches the gold washer (which is 2000 times the foam

Figure 19. Schematic of experiment.

density), it will reflect, establishing the Mach stem seen in the astrophysical calculations.

Issues and Calculations:

The basic approach here, to the problem of producing an enduring, high-Mach-number, plasma flow is similar to that we developed for supernova-remnant experiments using the Nova laser. The new issues here in 1D were:

1. Whether one could avoid the emergence of subsonic, higher pressure material into the foam. (Such material would expand laterally, spoiling the dynamics.)
2. Whether one could produce a source for a jet that would endure long enough for the head of the jet to move a distance of many times the jet diameter.
3. Whether the jet could supply enough momentum to sustain a shock wave in a material of reasonable density over long distances.

We simulated a range of conditions, to determine how thick the plastic layer could be and how much space there should be between the plastic and the foam, before settling on the dimensions described above. We found that the response of the system is not very sensitive to either of these distances. As one increases the thickness of the plastic layer, the distance over which the jet can push increases while the velocity decreases. We also had to deal with some computational issues, such as the fact that the EOS table for solid CH is not appropriate to describe the behavior of cooling plasma that was produced by ionizing CH.

We used a laser irradiance of 5×10^{14} W/cm² for 1 ns, because this is a sensible upper limit for experiments on the Omega laser. This will not matter for the 2D simulations, however, since we will provide an initial condition at a later time, when laser and radiation effects are no longer present. This produced the initial behavior that is illustrated in Figure 20. The laser drives a shock wave into the plastic layer, which evolves into a blast wave after the laser turns off. The blast wave breaks out of this layer at about 20 ns. The shocked ejecta then expand and cool, across the 1 mm gap. This produces a jet-like, high-Mach-number flow. This flow then impacts the low density foam, shocking it and heating it. For a plastic layer thickness of ≥ 200 μ m, the motion of the bulk plastic is slow enough to avoid launching a slug of dense plasma.

Figure 21 shows the longer-term behavior, on a timescale of 100 to 800 ns. The emerging jet encounters the reverse shock at a velocity of about 20 km/s, where the Mach number of the jet is about 40. The layer of shocked jet and foam material is at a temperature of about 10 eV and a pressure in the range of 50 kbar (5×10^{10} dynes/cm²). The density of the jet material gradually decreases, but it remains above the unshocked foam density through 800 ns. The bow shock, moving at about 30 km/s, has a very large upstream Mach number because the foam is at room temperature.

This completes the definition of a physically viable experiment that is well matched to the “natural” 1 mm Omega spot. This would be a good case for which to do 2D calculations to assess the behavior. For an actual experiment, one might choose to scale the system down somewhat in size, for reasons discussed next.

Figure 20. The early behavior of the 800 μm thick target. Profiles are shown at 15, 30, 45, 60, and 75 ns. The blast wave that was launched by the laser emerges from the plastic layer, producing ejecta that cool and accelerate across the vacuum gap, where they begin to drive a shock wave through the low-density foam.

Figure 21. The long-term behavior of the target with the 800 μm thick plastic layer, from a 1D calculation. Profiles are shown at 100, 275, 450, 625, and 800 ns. The expanding, cool, high-Mach-number ejecta drive a shock wave forward through the foam.

Experimental issues:

Diagnosis of such an experiment needs to be addressed, since beyond about 100 ns our standard backlighting measurements become unfeasible. We will need to think about this. One possibility is to use aerogel foam, which is transparent, combined with shadowgraphy or Schlieren to see the shock front.

References

- Drake, R.P., J.J. Carroll, K. Estabrook, S.G. Glendinning, B.A. Remington, and R. McCray, Development of a laboratory environment to test models of supernova remnant formation, *Ap. J. Lett.*, 500 (June 20), L157-L161, 1998a.
- Drake, R.P., S.G. Glendinning, K. Estabrook, B.A. Remington, R. McCray, R. Wallace, L.J. Suter, T.B. Smith, R. London, and E. Liang, Observation of forward shocks and stagnated ejecta driven by high-energy-density plasma flow, *Phys. Rev. Lett.*, 81 (10), 2068-2071, 1998b.
- Drake, R.P., J.J.C. III, T.B. Smith, P. Keiter, S.G. Glendinning, O. Hurricane, K. Estabrook, D.D. Ryutov, B.A. Remington, R.J.W. (LLNL), E. Michael, and R. McCray, Laboratory Experiments to Simulate Supernova Remnants, *Phys. Plasmas*, 7 (May), 2142, 2000a.
- Drake, R.P., T. Smith, J.J.C. III, Y. Yan, S.G. Glendinning, K. Estabrook, D.D. Ryutov, B.A. Remington, R.W. (LLNL), and R. McCray, Progress Toward the Laboratory Simulation of Young Supernova Remnants, *Ap. J. Suppl.*, in press, 2000b.

IV. EXPERIMENTS IN RADIATIVE HYDRODYNAMICS

A. Radiative Precursor Shocks

We designed and performed radiative-precursor shock experiments, also using the Omega laser, that are relevant to astrophysical modeling. Figure 22 shows a sketch of the experiments and Figure 23 shows a photograph of one of the targets. Laser irradiation shocked and accelerated a $60\text{ }\mu\text{m}$ thick plastic layer, which crossed a $160\text{ }\mu\text{m}$ vacuum gap to impact low-density SiO_2 foam, usually of density 0.01 g/cm^3 , then drove a shock wave through foam at $\sim 30\text{ km/s}$, which was fast enough to produce a radiative precursor. The cover shows a picture of the target used for these experiments. One can see the gold structure, used to support the

Figure 23. The radiative precursor target.

foam, and the plastic structures, which include both the layer of driven material (CH) and several shields of Pb-doped CH. The slot in the gold is present for diagnostic access. The cylindrical rod extending to the left holds the backlighter and pinhole assembly. The target stalk comes down from above. Alignment fibers are also visible. This is an elegant target. It is functional, easy to build, and easy to align.

The structure of the precursor was diagnosed using absorption spectroscopy. The foam material allows us to use absorption spectroscopy of the Si ions to determine the electron temperature. We use a backlit pinhole to illuminate the target with x-rays from a short-pulse (100 ps to 200 ps) thulium backlighter. The target is imaged, by this illumination, through a crystal and onto an x-ray CCD detector or film. This is a variation of point projection spectroscopy, which gives spatial imaging in one direction and both spatial imaging and spectral dispersion in the other. The diagnostic as implemented provides a $500\text{ }\mu\text{m}$ square field of view with 43x magnification. By measuring the 1s-2p and also the 1s-3p absorption lines of Si, we are able to determine the temperature. Hoarty et al. have demonstrated this technique using Cl lines. Absorption lines were detected from up to 6 different ionization states (see Figure 24). The lines from higher ionization states appear at higher temperatures. This allows one, with the help of the OPAL atomic code, to determine the temperature profile in the precursor. These experiments, in which a radiative-precursor shock evolves from

Figure 22. A sketch of the target for the radiative precursor experiments.

Figure 24. Absorption spectrum. The dark horizontal features are absorption lines. The dark vertical stripes are from a reference grid.

Figure 25. A comparison of the observed radiative precursor with that predicted by simulations.

a hydrodynamic intermediate state, should prove able to provide quality benchmark cases for astrophysical modeling. In recent experiments that are not yet fully analyzed, we have scaled the drive intensity and observed a variation in the length of the precursor.

To date, however, simulations of this experiment, using standard diffusive radiation models, disagree with the data. An example, from the HYADES radiation-hydrodynamic code is shown in Figure 25. HYADES is a one-dimensional Lagrangian hydrodynamics code with diffusive greybody or multi-group radiation transport and a tabular equation of state. It includes the necessary laser and radiation physics to model the development of the shock in irradiated materials. (Fig. 25 shows results from

a greybody calculation.) A similar disagreement has been obtained in preliminary modeling with LASNEX. We plan to explore and resolve these discrepancies in our continuing work, described below. A paper describing our present results has been published in *Physical Review Letters*.

B. Collapsing Radiative Shocks

Our work with radiative-precursor shocks in foams has represented a first step into radiative hydrodynamics. With the adoption of gas targets, however, we can produce shocks that radiatively collapse on Omega. Such experiments will be an exciting next step in our radiative hydrodynamic work. These experiments will also complement experiments being done on a much smaller scale, making them more difficult to diagnose and simulate, by two of our Co-Investigators in France (Serge Bouquet and Michel Koenig).

Radiation plays an important role in many astrophysical shock waves. The shock wave emerging from a supernova passes through regimes in which the shocked layer first radiates strongly enough to produce a radiative precursor and then collapses in space because of radiative energy losses. Similar dynamics can occur at the reverse shock in a supernova remnant formed from a star with a dense stellar wind. There is more generally a radiative cooling zone behind most astrophysical shocks. Collapse of the shocked layer can occur in some cases, as for example in aging supernova remnants in which the shocked layer is no longer driven. The production and study of laboratory shock waves in which radiation matters is relatively new. In this letter we report the production and observation of a radiative collapsing shock in planar geometry.

The thin, dense layers that are produced when shocked material collapses are subject to hydrodynamic instabilities like those discussed by Vishniac and Ryu. These instabilities produce convolutions in the dense layer, observed in simulations and believed to be responsible, for example, for the convoluted structure of the Cygnus Loop. The experimental system described here produces an isolated, dense layer that may permit the observation of the early phases of such instabilities in well-understood conditions.

One can organize the prior work on radiating shock waves by the strength of the radiative effects that were present. Two experiments have produced radiative effects at velocities low enough that radiation produced in consequence of shock heating is not the dominant effect. The experiments of Grun *et al.* appear to have produced the Vishniac instability, by driving a blast wave through xenon gas under conditions that produce strong radiation from low ionization states of xenon during the

shock transition. In the experiments discussed by Edwards *et al.*, radiation from a shocked layer that was further heated by electron heat conduction affected the medium upstream of the shock. The threshold for the formation of a radiative precursor, through the action of the shock itself, is reached when the number of ionizing photons radiated by the shock exceeds the number of atoms approaching the shock. Radiative precursors have been observed in experiments by Bozier *et al.*, Keiter *et al.*, and Koenig *et al.*

The present experiment is one of the first to exceed the threshold for radiative collapse through the formation of a post-shock cooling layer, and to detect the material that has been shocked and cooled. A post shock cooling layer must form when the thermal radiative losses from the shocked material exceeds the energy flux entering the shocked material. This threshold can be expressed as $R_r > 1$, where

$$R_r = \frac{\sigma T_s^4}{\rho_o c_v T_s u_s} = \frac{\sigma T_s^{5/2} \sqrt{2}}{\rho_o c_v^{3/2} (\gamma + 1)} = \frac{8\sigma}{\rho_o c_v^4 (\gamma + 1)^6} u_s^5, \quad (1)$$

in which u_s is the shock velocity, s is the Stefan-Boltzmann constant, ρ_o is the mass density of the unshocked, upstream material, c_v is the specific heat at constant volume of the post-shock material, γ is the polytropic index appropriate to the shock transition. The initial post-shock temperature is T_s , which assumes that the ions and electrons rapidly equilibrate behind the shock, as is the case in the laboratory experiments. Note that c_v and γ both should include the effects of ionization, especially in a material like xenon. The corresponding threshold velocity, {Drake,Reighard,Blackburn, in prep} in xenon at 10 mg/cm³, is about 50 km/s.

In a laboratory shock the cooling and the associated density increase will occur near the shock front. In most astrophysical shocks the entire, optically thin shocked layer may participate in the cooling. To apply Eq. 1 to astrophysical conditions one should replace s by es , where e is the “emissivity” of the shocked layer, meant to include both the effects of finite optical depth and of electron-ion equilibration.

EXPERIMENT

We attempt to drive a planar, radiative shock through a xenon-filled target, and observe the formation and evolution of a collapsed layer. Gas filled targets (see Figure 26) were constructed mainly from beryllium, with the cylindrical main target body .6 mm ID, .9 mm OD, and 3 mm long. These targets were filled with xenon via a fill tube at the end of the target, and held approximately 1.1 ATM ($\rho = 6$ mg/cc) of xenon at the time of the experiment. 10 drive lasers at $\lambda = .35 \mu\text{m}$ focused to a 820 μm diameter (FWHM) spot on a 50 μm thick, 2.5 mm diameter beryllium disk in a square, 1-ns pulse. This experiment was conducted at two drive energies: 225 J/beam (2250 J total energy, corresponding to an intensity of 2.8×10^{14} W/cm² on target) and 400 J/beam (4000 J total energy, corresponding to an intensity of 5×10^{14} W/cm² on target). Ablation pressure launched a shock through the beryllium pusher, into the xenon. A lead-doped plastic washer delayed the material which was accelerated outside of the main target body to help protect diagnostics. A tin area backlighter, 1.5 mm by 2.5 mm in area, 5 μm thick, was irradiated with 7 beams in a 1 ns-square pulse at 400 J/beam to provide the necessary illumination for radiography using x-ray framing cameras. A gold grid was placed on the target as a spatial indicator for radiography. Squares on the gold grid are 63 μm center to center, which allows not only position measurements, but places a spatial scale on each image. Beryllium arms distanced quartz windows from the

plasma, and provided a path through the gas perpendicular to the shock propagation direction for the VISAR (Velocity Interferometer System for Any Reflector) diagnostic. These arms were located away from the drive end of the target, and protected from high-energy electrons with gold foil. The quartz component closest to the interferometer laser was clear quartz, while the opposite component had one side coated with 1000 Å aluminum, to provide the reflection of the interferometer beam back onto itself.

Figure 26: Target diagram. In this view backlighter plate would sit directly behind target, in the plane of the figure.

One can gain some insight into the impact of radiation on the experiment through simulations. Here we discuss the results of simulations of this system using the 1D, Lagrangian code HYADES. HYADES was run using multigroup, diffusive radiation transport with 90 photon groups, adjusted to resolve the edges in the xenon opacity at up to 6 keV. The equation of state of xenon was the SESAME table. In the regime of this experiment, the polytropic index (g) inferred from the table is in the range of 1.2 to 1.3, as is appropriate for an ionizing medium that is dense enough that collisional recombination is dominant. {Drake, in prep} It is worth noting that the effective g of xenon can be significantly smaller in lower-density media in (more or less) coronal equilibrium, which is the case for the experiments with blast waves in gases. The xenon was modeled using an average-atom, LTE description, which one would expect to be only qualitatively accurate for xenon. The laser intensity used in such 1D simulations must be reduced to give accurate results, for well-known reasons. Here it was adjusted by the factor required to match the behavior of hydrodynamic experiments at a similar laser intensity.

Figure 27: Comparison of simulation results. The solid line shows the result for multigroup, diffusive radiation transport, while the dotted line shows the result for a non-radiative system. When radiation is suppressed (dotted line), a collapsed layer does not form.

The solid curve in Figure 27 shows the above-mentioned radiative simulation results, while the dashed curve shows results of a simulation in which radiation is artificially suppressed. One sees the shock wave to the right. It is moving to the right into unshocked matter. The layer of relatively constant-density, shocked xenon is to the left of the more-structured layer of beryllium material. The radiation has two effects. First, it produces post-shock cooling that rapidly increases the density by a factor of 3 above its immediate post-shock value. This narrows the shocked xenon layer, which is the primary effect one can detect using radiography. Second, it heats the beryllium that is driving the shock and causes the xenon layer to separate from the more dense beryllium material. As the layer radiates, radiation-driven ablation creates a distinct, low density region between the dense driver material and the dense collapsed layer. This produces conditions favorable to the Vishniac instability discussed above.

RESULTS

Radiography of the shock in xenon shows clear indications of a thin, dense shock (see Figure 28). Lineouts of radiography images at the lower drive intensity ($2.3 \times 10^{14} \text{ W/cm}^2$) taken at 18 ns after the drive beams shut off show a thin, dense layer at approximately $1700 \mu\text{m}$ from the drive disk. Given that the shock takes approximately 1 ns to break out of the beryllium and enter the xenon, the approximate velocity of this shock is 100 km/sec. The thickness of this layer as measured from the lineout is $80 \mu\text{m}$.

Lineouts of radiography images at the higher drive intensity ($5 \times 10^{14} \text{ W/cm}^2$) taken 11 ns after the drive beams shut off also resolve a

Figure 28: Radiography image plus averaged intensity lineout. The thin layer of denser material is approximately $80 \mu\text{m}$ thick and has a shock velocity of 100 km/sec.

thin, dense layer at approximately $1800\text{ }\mu\text{m}$ from the drive disk, corresponding to a velocity of approximately 140 km/sec . The thickness of this layer as measured from the lineout is also approximately $80\text{ }\mu\text{m}$.

We had hoped that the VISAR diagnostic, which is a frequency-sensitive variation on interferometry, might show the density evolution in the precursor plasma, produced by radiative heating ahead of the shock. This density evolution in a similar, but smaller and less planar, system has been measured using interferometry in France, so this was plausible. Preliminary calculations did show that absorption of the probe beam in the precursor plasma was a risk, however, and indeed we lost the VISAR signal soon after the laser turned on, as one can see in Figure 29. We did gain useful data from the VISAR measurements, as we did see a signal for a brief period at about 15 ns , which we attribute to reflection from the edge of the dense shocked layer. Thus, the VISAR confirmed the detection of the shock by radiography. During the next year we will make a first attempt at Thomson scattering from the shocked material, with the goal of determining the density and temperature.

Figure 29. The VISAR data showed fringes until soon after the laser pulse began, and then showed a brief signal when the dense shocked layer passed through the observed

CONCLUSIONS

Measurements of the thickness of the collapsed layer are an upper limit on the true thickness of the layer, as the orientation of the layer in space is not well known. If the shock is tilted with respect to the target axis, images may not be directly edge on, making the layer seem thicker than it really is. Even with this caveat, comparison of the data to simulation supports the conclusion that the dense layer seen is radiatively collapsed.

V. REFEREED PUBLICATIONS

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- J. Kane, R.P. Drake, B.A. Remington, "An evaluation of the Richtmeyer-Meshkov instability in supernova remnant formation", *Astrophysical J.*, **511**, 335-340 (1999).
- J. Kane, D. Arnett, B.A. Remington, S.B. Glendinning, G. Bazan, R.P. Drake, B.A. Fryxell, R. Teyssier, K. Moore, "Scaling supernova hydrodynamics to the laboratory", *Phys. Plasmas* **6**, 2065-2071, (1999)
- R.P. Drake, "Laboratory experiments to simulate the hydrodynamics of supernova remnants and supernovae", *J. Geophys. Res.* **104**, 14,505-14,515 (1999)
- D.D. Ryutov, R.P. Drake, J. Kane, E. Liang, B.A. Remington, M. Wood-Vasey, "Similarity Criteria for the Laboratory Simulation of Supernova Hydrodynamics," *Astrophysical J.*, **518**, 821 (1999).
- B.A. Remington, D. Arnett, R.P. Drake, H. Takabe, "Modeling astrophysical phenomena in the laboratory with intense lasers," *Science* **284**, 1488-1493 (1999).
- R.P. Drake, J.J. Carroll III, T.B. Smith, P. Keiter, S. Gail Glendinning, Omar Hurricane, Kent Estabrook, D.D. Ryutov, B.A. Remington, R.J. Wallace, Eli Michael, R. McCray, "Laboratory Experiments to Simulate Supernova Remnants, *Phys. Plasmas* **7**, 2142 (2000).
- B.A. Remington, R.P. Drake, H. Takabe, D. Arnett, "A review of astrophysics experiments on intense lasers", *Phys. Plasmas* **7**, 1641 (2000).
- R.P. Drake, T. Smith, J.J. Carroll III, Y. Yan, S.G. Glendinning, K. Estabrook, D.D. Ryutov, B.A. Remington, R. Wallace, R. McCray, "Progress Toward the Laboratory Simulation of Young Supernova Remnants," *Astrophysical J. Suppl.* **127**, 305-310 (2000).
- J. Kane, D. Arnett, B.A. Remington, S.G. Glendinning, G. Bazan, R.P. Drake, and B.A. Fryxell, "Supernova experiments on the Nova laser," *Astrophysical J. Suppl.* **127**, 365-369 (2000)
- D. Ryutov, R.P. Drake, and B.A. Remington, "Criteria for scaled laboratory simulations of astrophysical MHD phenomena," *Astrophysical J. Suppl.* **127**, 465-468 (2000).
- S.G. Glendinning, K.S. Budil, D. Farley, D.H. Kalantar, J. Kane, M.M. Marinak, B.A. Remington, D. Ryutov, R.J. Wallace, S.V. Weber, C. Cherfils, A. Richard, R.P. Drake, and J. Stone, "Experimental measurements of hydrodynamic instabilities on Nova of relevance to astrophysics," *Astrophysical J. Suppl.* **127**, 325-331 (2000).
- R.P. Drake, "The design of laboratory experiments to produce collisionless shocks of cosmic relevance," *Phys. Plasmas* **7**, 4690-4698 (2000).

- D.D. Ryutov, B.A. Remington, H.F. Robey, R.P. Drake, "Magnetohydrodynamic scaling: from astrophysics to the laboratory", *Phys. Plasmas* **8**, 1804-1816, (2001)
- H.F. Robey, J.O. Kane, B.A. Remington, R.P. Drake, O.A. Hurricane, H. Louis, R.J. Wallace, J. Knauer, P. Keiter, D. Arnett, D.D. Ryutov, "An experimental testbed for the study of hydrodynamic issues in supernovae", *Phys. Plasmas* **8**, 2446-2453, (2001)
- J.O. Kane, H.F. Robey, B.A. Remington, R.P. Drake, J. Knauer, D.D. Ryutov, H. Louis, R. Teyssier, O. Hurricane, D. Arnett, R. Rosner, A. Calder, "Interface imprinting by a rippled shock using an intense laser" *Phys. Rev. E* **63**, 055401R (2001).
- O.A. Hurricane, S.G. Glendinning, B.A. Remington, R.P. Drake, K.K. Dannenberg, "Late-Time Hohlraum Pressure Dynamics in Supernova Remnant Experiments", *Phys. Plasmas* **8**, 2609-2612 (2001)
- R. P. Drake, H. F. Robey, O. A. Hurricane, B. A. Remington, J. Knauer, D. Arnett, D.D. Ryutov, J.O. Kane, K.S. Budil, J. Grove, "Experiments to produce a hydrodynamically unstable, spherically diverging system of relevance to instabilities in supernovae," *Astrophys. J.* **564**, 896-908, (2002).
- R.P. Drake and P.A. Keiter, "Rayleigh Taylor Growth at Decelerating Interfaces", *Phys. Plasmas* **9**, 267-274 (2002).
- R.P. Drake, "Design of flyer-plate-driven compressible turbulent mix experiments using Z", *Phys. Plasmas* **9**, 3545 (2002)
- P. A. Keiter, R. P. Drake, T. S. Perry, H. Robey, B. A. Remington, C. A. Iglesias, R. J. Wallace, J. Knauer, "Observation of a Hydrodynamically-Driven, Radiative-Precursor Shock", *Phys. Rev. Lett.* **89**, 165003/1-4 (2002)
- A.C. Calder, B. Fryxell, T. Plewa, R. Rosner, T. Dupont, H.F. Robey, J.O. Kane, B.A. Remington, R.P. Drake, G. Dimonte, M. Zingale, L.J. Dursi, F.X. Timmes, K. Olson, P. Ricker, P. MacNeice, H.M. Tufo, "On validating an astrophysical simulation code", *Astrophys. J. Suppl.*, **143**, 201-229 (2002)
- H. F. Robey, Ye Zhou, A. C. Buckingham, P. Keiter, B.A. Remington, and R.P. Drake, "The onset of turbulence in high Reynolds number, accelerated flows." *Phys. Plasmas* **10** 614 (2003).
- R.P. Drake, B.A. Remington, D.D. Ryutov, "Experimental Astrophysics with Intense Lasers", *Rev. Mod. Phys.*, submitted (2003)
- A.Y. Poludnenko, K. Dannenberg, R.P. Drake, A. Frank, J. Knauer, D.D. Meyerhofer, M. Furnish, J. Asay, "A laboratory investigation of supersonic clumpy flows: experimental design and theoretical analysis", *Astrophysical Journal*, in press 2003.
- A. Miles, D. Braun, J. Edwards, H.F. Robey, R.P. Drake, D.R. Leibbrandt, E.C. Harding, J. Knauer, D. Arnett, "Numerical simulation of supernova-relevant laser-driven hydrodynamics experiments on Omega," *Phys. Plasmas*, in press (2003).

VI. STUDENTS AND POST-DOCTORAL FELLOWS

supported by this grant

Post-Doctoral Fellows (both US Citizens)

James J. Carroll, now an associate professor at Eastern Michigan University

Paul Keiter, now a postdoctoral fellow at Los Alamos

<u>Graduate Students (6)</u>	<u>Citizenship</u>
Korbie Dannenberg	USA
Kelly Korreck	USA
Amy Reighard	USA
Carolyn Kuranz	USA
Melanie Blackburn	USA
Eric Harding	USA

<u>Undergraduate Students (8)</u>	<u>Citizenship</u>
Peter Susalla	USA
Eric Harding	USA
David Leibrandt	USA
Mike Grosskopf	USA
Erika Roesler (N. Ariz. U.)	USA
Saida Caballero	USA
Rebecca Gabl	USA
Douglas Kremer	USA

VII. INVITED LECTURES

supported in whole or in part by this grant

“Laboratory Astrophysics Experiments Using Large Lasers”, New Frontiers in Laboratory Astropasma Physics, Opening Lecture, Workshop by the Royal Astronomical Society and the Institute of Physics, London, October 1999.

“Laser Experiments to Simulate Supernova Remnants”, Annual Meeting of the Division of Plasma Physics of the American Physical Society, New Orleans, LA, November 1999.

“Overview of Laser Astrophysics Experiments”, American Astronomical Society, Rochester, NY, June 2000

“Plasma Laboratory Astrophysics: Mildly Relativistic Plasmas”, National Research Council Committee on the Physics of the Universe, Pasadena, CA June 2001

“Supernova Hydrodynamics on the Omega Laser”, International Conference on Fusion Sciences and Applications, Kyoto, Japan, Sept. 2001

“Breakthrough Science and the Role of Universities in High Energy Density Physics”, National Research Council Committee on High Energy Density Physics, Irvine, CA Nov. 2001

“Laboratory Astrophysics with Intense Lasers: Introduction and Overview”, Annual Seminar of the Laboratoire d’Utilisation des Lasers Intenses, Saint-Lary, Pyrenees, France, March 2002.

“Understanding Hydrodynamics of High Energy Density Matter: Laboratory Experiments and Astrophysical Connections”, April Meeting of the American Physical Society, Albuquerque, NM, April, 2002

“Connecting Laboratory Experiments and Astrophysical Phenomena, Meeting on Intercomparison of Plasma Experiments in Laboratory and Space (IPELS), Whitefish, Montana June, 2003.

“Progress in Experimental Astrophysics at High Energy Density”, Annual Meeting of the Division of Plasma Physics of the American Physical Society, Albuquerque, NM, October, 2003

VIII. SEMINARS AND COLLOQUIA

supported in whole or in part by this grant

- “Laboratory Supernovae: Using big lasers to model exploding stars”
 - Sandia National Laboratory, Feb. 1999
 - Univ. of Toronto, Feb. 1999
 - Lawrence Livermore National Laboratory, Aug. 1999
- “Laboratory Experiments to Simulate Supernova Remnants”
 - Univ. of Chicago, Sept. 1999
 - Naval Research Laboratory, Nov. 1999
 - Los Alamos National Laboratory, Jan. 2000
- “Plasma hydrodynamics”, and “Laboratory simulation of astrophysical phenomena”
 - DOE National Undergraduate Fellowship Program, June 2000
- “The quest for fusion: when and how will humans make power like the stars do?”
 - Michigan Alumni Association, July 2000
- “Laboratory Supernovae: Using big lasers to simulate exploding stars”
 - Michigan Alumni Association, July 2000
- “Astrophysics Experiments with Lasers and Z Pinches”
 - Univ. of Toledo, November 2000
 - Univ. of Rochester, April 2000
- “Connecting Laboratory Experiments with Astrophysical Phenomena”
 - Brigham Young University, Feb. 2003
 - Rochester Inst. Of Technology, Feb. 2003
 - West Virginia Wesleyan, Feb. 2003
 - Swarthmore, Feb. 2003
 - UC Irvine, March 2003
 - Optical Society of America, March 2003
 - Rutgers, April 2003
 - Imperial College, November 2003

IX. COLLABORATORS

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Dimitri Ryutov <i>LLNL</i>	James Glimm <i>SUNY-Stony Brook</i>	James Stone <i>Univ. of Maryland</i>	Alexei Khokhlov <i>Naval Research Laboratory</i>
Jave Kane <i>LLNL</i>	Omar Hurricane <i>LLNL</i>	John Grove <i>LANL</i>	James Carroll <i>Eastern Michigan Univ.</i>
Adam Frank <i>University of Rochester</i>	Kim Budil <i>LLNL</i>	Keisuke Shigemori <i>Osaka University; LLNL</i>	Riccardo Betti <i>University of Rochester, MIT</i>
Mary Jane Graham <i>West Point</i>	Christof Litwin <i>University of Chicago</i>	Gail Glendinning <i>LLNL</i>	Grant Bazan <i>LLNL</i>
Serge Bouquet <i>CEA Bruyeres</i>	Michel Koenig <i>LULI</i>		

Sandia Collaborators: Marcus Knudsen, Tom Mehlhorn, Chris Deeney, Clint Hall, Mike Furnish, Diana Shroen, Jim Asay, Guy Bennet, Dan Sinars

Additional Jet Collaborators: Bernie Wilde, Paul Keiter (LANL),
John Foster, Paula Rosen (AWE).