Final Report

**Supernova Hydrodynamics on the Omega Laser**

A project funded by the National Laser Users’ Facility
Department of Energy
Oakland Operations Office
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January, 2004

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**Images:**

Left– Radiograph, at 13 ns, of structures from an 8-mode perturbation.
Right– Absorption spectrum demonstrating the production of a radiative-precursor shock wave.
Introduction and Motivation

We provide here the following report on our activities. We have organized this report to discuss our experimental accomplishments, our publications, and other impact of our work.

The fundamental motivation for our work is that supernovae 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, based on simulations, to be important to astrophysics but that have not been directly observed in either the laboratory or in an astrophysical system. During the period of this grant, we have focused on the scaling of an astrophysically relevant, radiative-precursor shock, on preliminary studies of collapsing radiative shocks, and on the multimode behavior and the three-dimensional, deeply nonlinear evolution of the Rayleigh-Taylor (RT) instability at a decelerating, embedded interface. These experiments required strong compression and decompression, strong shocks (Mach \approx 10 or greater), flexible geometries, and very smooth laser beams, which means that the 60-beam Omega laser is the only facility capable of carrying out this program.

The exciting nature of this work has allowed us to develop a collaborative effort that couples a core experimental team to theoretical groups at several institutions. This enables us to develop experimental designs through advance simulations, to be well prepared to obtain excellent data, and to compare the results of our experiments to simulations by more than one code. We have also developed a standardized approach to the experiments, allowing us to pursue more than one experiment simultaneously, and thus to exploit the theoretical horsepower we have assembled. These experiments are sufficiently complex yet diagnosable that they are excellent for Verification and Validation (V&V) of complex computer codes, including those produced by the ASCI Alliance Center at the University of Chicago. This program is also a critical stepping stone toward the use of the National Ignition Facility (NIF) both for fundamental astrophysics and as a critical component of ASCI V&V.
Experimental Accomplishments

1. Radiative Precursor shocks

We have designed and performed radiative-precursor shock experiments that are relevant to astrophysical modeling. These experiments involved the initial acceleration of a block of material to high velocity. This block of material then drove a shock wave through low-density foam at approximately 100 km/s, which was fast enough to produce a radiative precursor. The precursor is strongly sensitive to the shock velocity, so we were able to make it appear and change by varying the laser energy. Figure 1 shows a picture of the target used for these experiments on the Omega laser. Up to 10 laser beams struck the front surface of this target, delivering several kJ of energy to an 800 µm dia. spot in a 1 ns pulse. The laser irradiation shocked and accelerated a 60 µm thick plastic layer, which crossed a 160 µm vacuum gap to impact the low-density foam, usually of density 0.01 g/cm³.

The structure of the precursor was diagnosed using absorption spectroscopy. Additional laser beams irradiated a Thulium backlighter plate, permitting a new imaging crystal spectrometer to obtain absorption spectra like that shown in Figure 2. Absorption lines were detected from up to 6 different ionization states; Figure 3 illustrates the detection of 4 ionization states. The lines from higher ionization states appear at higher temperatures. From the entire spectrum, one could determine the location of the shock, the

Figure 1. An image of the target for the radiative precursor experiments. The laser beams approach from the left, driving a shock wave through the gold tube.

Figure 2. Absorption spectrum. The dark horizontal features are absorption lines. The dim vertical stripes are from a reference grid. The transition from green to yellow (as one scans vertically) is due to the K edge.
temperature of the shocked material, and the temperature profile in the radiative precursor, with the help of the OPAL atomic code. We observed that the precursor became longer as the laser drive energy increased, and that its behavior was consistent with a simple model of the threshold velocity for the production of a precursor. A paper based on these data has been published in *Physical Review Letters*.

Thus we produced a radiative precursor shock that evolves from a hydrodynamic intermediate state which can be a starting point for simulation with astrophysical codes. 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 4. A similar disagreement has been obtained with LASNEX. Somewhat better agreement was obtained using 2D simulations, but in detail this system requires fairly sophisticated radiation transport for correct modeling because the mean free path of the radiation varies strongly throughout the system.

### 2. Collapsing Radiative Shock

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, and such shocks arise in a number of other contexts. 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. A sketch of the target is shown in Figure 5. Figure 6 shows the data we obtained in a preliminary experiment. The overlaid profile shows the average of a 290-µm-high horizontal strip through the unobstructed portion of the image. One can clearly see the absorption feature due to the shock. Its position confirms that the shock velocity is well above 100 km/s. The laser and diagnostic settings were optimized for other experiments on this day, causing significant motional blurring (and weakening the absorption feature). Much better data can and will be obtained in future experiments.

4. Spherically diverging experiments

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 7 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 µm and 109 µm, respectively. The initial perturbation wavelength and amplitude were 70 µm and 10 µm, respectively. The dimensions of the wire grid in the image are 63.5 µm 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 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 hydrodynamic models to this system can begin at 2 ns. We mapped the CALE output into FronTier at 2ns, after the 1 ns laser pulse but before the shock exited the capsule. Figure 8 shows the results. (Later versions of CALE did better at calculating the growth of peak-to-valley amplitude.) In addition, we conducted planar experiments designed to be directly comparable with the spherical ones, by using the same target structure and the same initial perturbation wavelength and amplitude. We observed significantly larger growth from the planar targets. A paper describing this work has been published in *The Astrophysical Journal*.

4. Multimode Rayleigh Taylor (RT) instability at a decelerating, embedded interface

We have concluded that it will prove fruitful to examine multimode systems, because (a) the actual stellar explosions involve many modes, (b) the growth of multimode structures is a more severe test of simulations, and (c) we may see a new stage of turbulence, especially late in time, that may be present in the star but not in simulations. We have obtained data showing the time evolution of the structures produced from initial conditions including 1 mode, 2 modes, and 8 modes. The perturbations were designed to keep the global peak-to-valley amplitude constant at 5 µm as the number of modes changed. Figure 9 shows some data we obtained using a 2-mode perturbation and Figure 10 shows some data using an 8-mode perturbation. At earlier times, the
multimode data show articulated spikes, as is shown in Figure 11, taken at 13 ns. Later, as in Figs. 9-10, the data show the emergence of large-scale features. These experiments have been analyzed in detail in 2D simulations using CALE. The analysis is discussed in the Ph.D. thesis of Aaron Miles (Univ. of Maryland, in preparation) and in the paper by Miles et al. in press with *Physics of Plasmas*.

3. 2D vs. 3D Rayleigh Taylor

One of the major issues in the evolution of supernovae is 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 goal is to provide the benchmarking. We have performed a number of laser shots to this end. Figures 4 and 5 show data (on the same spatial scale as the grid indicates). In this case, the surface which includes the 3D modulation, produced by a mold, is quite smooth. The RT spikes do more closely approach the shock in the 3D case, as expected. However, the doping that makes the features visible extends across the entire target, so any finer-scale structures may be obscured. Very different results were obtained using an initial 3D perturbation that included a single mode with 71 µm wavelength and noise at much shorter wavelengths introduced when the (50 mg/cc) foam was machined. In these latter targets, the doped material was confined to a central strip but the resulting target could not be molded, which is why it was machined. Figure 14 shows the results. By the time of the image, the unstable fingers have developed much additional modal structure and have
moved forward and overtaken the shock. Earlier, the fingers have a simpler spectral structure and remain well behind the shock. Later, we lose the ability to distinguish the fingers, perhaps due to rapid diffusion caused by turbulence. Continuations of these experiments will determine whether we are in face seeing an onset of turbulence, and further analysis will evaluate the implications for astrophysics.

Other impact
In addition, we have had an impact in other ways. Numerous invited talks and colloquia have been based on this work. A few examples: Two invited talks at both the 2001 and the 2003 Division of Plasma Physics meetings of the APS were based on this work. Drake and Remington were both asked to speak at the meeting of the NRC “Committee on the Physics of the Universe”, and both gave invited talks at the IFSA meeting in Japan in September 2001. Drake was asked to speak for the NRC Panel “Committee on High Energy Density Plasma Physics”. In addition, Discover magazine featured our work at Omega in its June, 2001 cover story “Star in a Jar”, and during one of our experiments, the BBC came to Omega to film footage for a documentary on the origin of the elements, which has aired in Britain and the U.S. and is sold in bookstores under the title “Hyperspace”.

Figure 14. An experiment with an a 3D initial single-mode perturbation produced these structures by 17 ns.
Publications

The following refereed papers based on our work at Omega have appeared in print or been submitted during the period of this grant. They are


STUDENTS AND POST-DOCTORAL FELLOWS

The following students and post-doctoral fellows participated in preparation for, carrying out, or analyzing data from the experiments supported by this grant.

Post-Doctoral Fellows
Paul Keiter (US Citizen), now a postdoctoral fellow at Los Alamos

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

Undergraduate Students (8) Citizenship
Peter Susalla       USA
Eric Harding        USA
David Leibrandt     USA
Mike Grosskopf      USA
Rebecca Gabl        USA
Douglas Kremer      USA