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Title:

**Hydrodynamics and Radiative Hydrodynamics
with Astrophysical Applications:
2005 Annual Report**

I. ABSTRACT

We report the ongoing work of our group in hydrodynamics and radiative hydrodynamics with astrophysical applications. During the period of the existing grant, we have carried out two types of experiments at the Omega laser. One set of experiments has studied radiatively collapsing shocks, obtaining high-quality scaling data using a backlit pinhole and obtaining the first (ever, anywhere) Thomson-scattering data from a radiative shock. Other experiments have studied the deeply nonlinear development of the Rayleigh-Taylor (RT) instability from complex initial conditions, obtaining the first (ever, anywhere) dual-axis radiographic data using backlit pinholes and ungated detectors. All these experiments have applications to astrophysics, discussed in the corresponding papers either in print or in preparation. We also have obtained preliminary radiographs of experimental targets using our x-ray source. The targets for the experiments have been assembled at Michigan, where we also prepare many of the simple components. The above activities, in addition to a variety of data analysis and design projects, provide good experience for graduate and undergraduates students. In the process of doing this research we have built a research group that uses such work to train junior scientists.

II. The overall project and its relevance

It is just over ten years since the realization that one can use High-Energy-Density (HED) facilities to study dynamical processes that matter for astrophysics.^{1,2} This complements their established use to study material properties such as opacity³ and equation of state.⁴ This realization came soon after observations of SN 1987A showed that we do not understand the structure of supernovae (SNe). It was roughly coincident with SN 1993J, whose differences with SN 1987A dramatized the importance of radiative shocks in some Type II supernovae,⁵ and was soon after simulations of the radiative phase that SN 1987A (and all supernova shocks) pass through were published.⁶ These events provide motivation for the research of our group, which at present is focused primarily on the use of Omega,⁷ with collaboration from expert experimenters, senior theorists, and major simulation groups, to address aspects of these issues. We have been awarded shots on Omega, through the NLUF program, during the remaining period of this SSAA grant. We now are observing the impact of increasingly realistic initial conditions on the structure that develops at an interface like that within an exploding star, and are studying the scaling and structure of radiative shocks in a relevant regime. These efforts and their astrophysical context are explained briefly just below, and more thoroughly later in the report.

In a radiation hydrodynamic system, radiative fluxes or pressures are large enough to significantly affect the hydrodynamic evolution. Such systems are common in astrophysics and are more difficult to understand than purely hydrodynamic systems. For this reason, our astrophysical colleagues have consistently listed radiation hydrodynamics as a key area for HED laboratory astrophysics. Figure 1 shows emission from the radiative shocks that have developed as the ejecta from SN1987A have struck the ring in that system. Developing radiation hydrodynamic experiments has not been easy, as they are an inherently more-challenging use of HED facilities than purely hydrodynamic experiments are. In addition, in the context of inertial fusion there has been much less preparatory work done for radiation hydrodynamic experiments. Our focus has been on the development of radiative shocks, which are shock waves from which the radiation is so intense that the flow of energy in the system is fundamentally altered. In consequence of the radiative cooling, these shock waves collapse in space, increasing their density beyond its value immediately after the shock. We have been working in a planar geometry to increase our ability to diagnose the shocks and to establish the potential to use them as sources. We have produced shock waves in this regime, and have submitted a paper to *Physical Review Letters (PRL)* based on this work.⁸ We have obtained radiographic data while scaling the shock velocity. These scaling experiments will clearly become a benchmark case for simulations of radiative hydrodynamic astrophysical systems. We have begun this by publishing a study modeling this system with one of the standard astrophysical codes.⁹ We are

Figure 1. November 2003 image of SN 1987A. The dominant emission now is from the radiative shocks interacting with the ring of dense material that was present before the explosion.

developing and testing additional diagnostic approaches. We obtained some data from VISAR¹⁰ and have recently obtained data (see cover) by Thomson scattering from the shock front, which is the first time anyone has done this. A senior Michigan Ph.D. student has centrally involved in these experiments, and is now analyzing data and writing her thesis. A following Ph.D. student will be heavily involved in the next such experiments. A next step in this area is to exploit the potential of x-ray spectroscopy as a diagnostic, using approaches that succeeded for Thomson scattering, described further below.

In SN1987A, the observation of heavy elements from the core of the star, and evidence of the associated heating by radioactive decay, took place much sooner than was predicted by existing models of SN explosions.^{11,12} This showed conclusively that the structure of SNe was not understood. The explosion induced by core collapse in a Type II supernova may be globally symmetric^{13,14} or highly asymmetric,¹⁵⁻¹⁷ but in either case a blast wave is formed that blows apart the bulk of the star. This in turn produces hydrodynamic instabilities that transport interior material outward. Simulations of complete SN explosions to date have been only in 2D, and hydrodynamic simulations in 3D have examined only isolated spikes of dense material. With one recent exception, neither of these has produced enough transport of dense material to directly explain the observations of SN 1987A. The recent exception remains a 2D simulation with one plausible model for the behavior at the core but without realistic initial conditions at the outer interfaces and thus not specifically relevant to our current experiments. Our experiments with specific three-dimensional initial conditions have shown much larger transport than one would expect from the relevant simulations.¹⁸ This is a dramatic and important result. The only way to know whether these observations provide the key to resolving the two-decade-old problem of mix in supernovae is to carry out the program of research we plan. We plan to do experiments to determine the causes of the larger transport, followed by experiments using initial conditions from new, state-of-the-art, three-dimensional simulations, by collaborators from the University of Arizona, of the progenitor star. The plan is to produce a definitive and well-understood result regarding the outward penetration of dense spikes of material in systems well scaled to exploding stars. We have also improved the experiments to obtain higher-quality data, recently obtaining the first ever simultaneous, dual-axis radiography using backlit pinholes and ungated detectors to obtain high-resolution physics data. Our other senior Michigan Ph.D. student is centrally involved in these experiments, which will become the core of her thesis. A more-junior Michigan Ph.D. student is already in position to learn from this work and to conduct further hydrodynamic experiments, very likely at NIKE as well as Omega.

At Michigan, our students have been engaged in construction of targets, data analysis, experiment design, and computer simulations related to these projects. There is substantial educational benefit from target construction and metrology by students; we have added this capability and have successfully built targets during the past three years. In addition, the students of our collaborators are conducting simulation studies related to the project. We emphasize collaboration, not only within our group but also across the scientific community, from the point of view that this prepares our students for the post-

degree world of modern research. Our collaborators include leaders in astrophysics, nonlinear hydrodynamics, and ICF. The participation of the FLASH 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. In support of this, the FLASH Center has hired a scientist who is now collaborating closely with us to conduct a validation study based on our experiments. Progress made utilizing state-of-the-art codes (at the University of Arizona, at Stony Brook, and at CEA (in France), the FLASH Center, and in the DOE labs) on our ICF-scale experiments should prove to be very useful to DOE/NNSA. The methods of scaling under various conditions being developed as part of this work will also find utility in scaling from current Omega experiments to ignition experiments being planned for NIF. They also will provide the basis for the first supernova-relevant experiments on NIF, once it becomes available.

III. Radiative Shocks

A. Importance of the work

Radiation and radiative collapse both play important roles in astrophysical shock waves. The shock wave emerging from a supernova passes through a regime in which the shocked layer collapses in space because of radiative energy losses.¹⁹ Similar dynamics can occur at the accretion shocks produced during star formation,²⁰⁻²² and at the reverse shock in a supernova remnant formed from a star with a dense stellar wind²³ or pre-existing dense material as in SN 1987A.^{24,25} Stratified ionization states form in a radiative precursor of an HH object with a radiative cooling layer.²⁶ There is more generally a radiative cooling zone behind most astrophysical shocks. Collapse of an existing shocked layer can occur in some cases, as for example in aging supernova remnants in which the shocked layer is no longer driven²⁷.

One can organize the prior laboratory work on radiating shock waves by the strength of the radiative effects that were present, which scale very strongly with shock velocity, u_s . Experiments discussed by Edwards *et al.*²⁸, produced $u_s \sim 8$ km/s in a cylindrical blast wave, and observed radiative cooling effects that resulted from heating of the shocked gas by electron heat conduction. At higher u_s , experiments can exceed the threshold²⁹ for the formation of a thermal radiative precursor, in which thermal radiation from matter heated by the shock itself heats the matter ahead of (“upstream” of) the shock. Radiative precursors have been observed in experiments by Bozier *et al.*,³⁰ Grun *et al.*,³¹ Keiter *et al.*,²⁹ and Koenig, Bouquet, and coworkers.^{32,33} The experiment of Grun *et al.* produced a quasi-spherical radiative blast wave, in which radiation during the shock transition is calculated to play a key role.³⁴

The thin, dense layers that are produced when shocked material collapses are subject to hydrodynamic instabilities like those discussed by Vishniac and Ryu.^{35,36} These instabilities produce convolutions in the dense layer, observed in simulations^{19,27} and believed to be responsible, for example, for the structure of the ring nebulae in Wolf-Rayet stars.³⁷ 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.

The present experiment is the first in planar geometry 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 exceed the energy flux entering the shocked material. The approximate threshold for this can be expressed as $R_r > 1$, where

$$R_r = \frac{8}{\gamma(\gamma+1)} \frac{\sigma T_i^4}{\rho_o c_v T_i u_s} = \frac{8\sqrt{2}}{\gamma(\gamma+1)^2} \frac{\sigma T_i^{5/2}}{\rho_o c_v^{3/2}} = \frac{64}{\gamma(\gamma+1)^7} \frac{\sigma}{\rho_o c_v^4} u_s^5, \quad (1)$$

in which u_s is the shock velocity, σ 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_i , which assumes that the ions and electrons rapidly equilibrate behind the shock, as is the case in most laboratory experiments. The second two equalities exploit the strong-shock relation for the post-shock temperature,

$$T_i = \frac{2}{(\gamma+1)^2} \frac{u_s^2}{c_v} = \frac{2}{(\gamma+1)^2} \frac{(\gamma-1) A m_p}{k_B (Z+1)} u_s^2, \quad (2)$$

in which k_B is the Boltzmann constant, A is the atomic weight of the upstream material, m_p is the proton mass, and Z is the average post-shock ionization. The second equality here serves to define c_v . Note that c_v and γ both should include the effects of ionization, especially in a material like xenon. The corresponding threshold velocity³⁸ in xenon at 10 mg/cm³, is about 50 km/s. If the optical depth of the downstream and upstream regions is not comparable, then R_r should be multiplied by the ratio of downstream to upstream optical depth, to account for the finite emissivity and absorptivity of these two layers.

B. Recent research

We have driven a planar, radiative shock through a xenon-filled target and observe the structure of the shocked xenon layer. Figure 2 shows a target schematic. The inside diameter (ID) of the gas cell was either 600 μm or 912 μm . We used the fill tube to evacuate the target and then fill it with xenon. The xenon pressure was measured for each experiment, and was 1.1 ($\pm$

Figure 2. Target diagram. In this view the backlighter source would sit directly behind target, below the plane of the figure. When the VISAR (Velocity Interferometer System for Any Reflector) diagnostic was used, additional arms were added to hold a quartz window and a mirror for the VISAR laser, and shielding was added behind the drive disk and to the left of the arms to reduce preheating of the gas in the arms.

10%) atm. for the cases of interest here corresponding to $\rho_o = 6 \text{ mg/cm}^3$ or to $2.7 \times 10^{19} \text{ atoms/cm}^3$. The drive disk was either 51 μm of polyimide ($\pm 3\%$ and at 1.41 g/cm^3) over-coated with 20 (+5/-10) μm of polyvinyl at 1 g/cm^3 , or 20 μm or 40 μm ($\pm 7\%$) of Be. We focused ten laser beams of wavelength 0.35 μm onto a 1 mm spot centered on the $\sim 2.5 \text{ mm}$ diameter drive disk in a square, 1-ns flat-top pulse, with the midpoint of the rising edge defining time $t = 0$. The total energy was $\leq 4000 \text{ J}$. Distributed Phase Plates (DPPs) created super-Gaussian focal spots of 720 or 820 μm diameter (FWHM), with small-scale structure which fluctuated via Smoothing by Spectral Dispersion (SSD). The resulting laser irradiance was up to 10^{15} W/cm^2 . The pressure from laser ablation first shocked and then accelerated the drive disk, launching it into the xenon and driving a shock. These experiments have benefited from collaborations with Jim Knauer of LLE and with a sequence of LLNL scientists (Bruce Remington, Ted Perry, Gail Glendinning, and Freddy Hansen).

X-ray radiography was the principal diagnostic, using two types of x-ray sources called “backlighters”. The laser beams producing the x-rays were of the same wavelength and laser pulse as the above, at a nominal energy of 450 J/beam, without SSD and usually without DPPs. Some shots included an “area backlighter”, in which such laser beams were focused to a $\sim 1 \text{ mm}$ spot on a vanadium foil several square mm in area and 5 μm thick, to produce K-shell emission at $\sim 5.4 \text{ keV}$. This mm-sized source was placed $4 \pm 0.25 \text{ mm}$ from the target, and imaged onto a framing camera³⁹ through pinholes. A “backlit pinhole” was also used on some shots, where the laser beams were focused to a 400 μm spot on a 5 μm thick V foil, spaced by 100 μm of CH behind an 80 μm thick Ta substrate with a 20 μm through hole, covered by 100 μm of CH. This small x-ray source was located $12 \pm 0.1 \text{ mm}$ from the target, and projected a radiograph of the target onto a framing camera located $\sim 229 \text{ mm}$ beyond it. Due to vignetting, the effective source size for this measurement was $\sim 15 \mu\text{m}$. A gold grid was placed on the target to calibrate the location and magnification of the image. A VISAR diagnostic (see Fig. 1) was also used in some cases, in collaboration with Tom Boehly of LLE and with Michel Koenig and Tommaso Vinci of Ecole Polytechnique.

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.⁴⁰ HYADES was run using multigroup, diffusive radiation transport with 90 photon groups at energies up to 20 keV, adjusted to resolve the edges in the xenon opacity near 5 keV. The equation of state of xenon was the SESAME table. In the regime of this experiment, the polytropic index (γ) 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.⁴¹ It is worth noting that the effective γ 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.^{34,42} The xenon was modeled using an average-atom, LTE description, which one would expect to be only qualitatively accurate. The laser irradiance used in such 1D simulations must be reduced to give accurate results, because radial heat transport reduces the ablation pressure.⁴³ Here it was adjusted to the level required to match the behavior of hydrodynamic experiments at similar laser intensity.

Figure 3. Density vs position from two simulations, at 18 ns, for experiments at a laser intensity of 8.5×10^{14} W/cm². The boundaries between the drive plasma, in this case Be, and the xenon are shown, labeled “contact surfaces.” The solid line shows the result for multigroup, diffusive radiation transport, while the dashed line shows the result for a non-radiative system. When radiation is suppressed (dashed line), a collapsed layer does not form.

layer has been established during the laser pulse, when there is shock reverberation in the driving material. The radiation has two effects. First, it narrows the shocked xenon layer by increasing its density. This 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. As the layer radiates, radiation-driven ablation creates a distinct, low-density region between the dense driver material and the dense collapsed layer.⁴⁴ This produces conditions favorable to the Vishniac instability mentioned above.

To assess the role of two-dimensional effects in these experiments, our collaborators Laurent Boireau and Serge Bouquet of CEA Bruyeres ran 2D simulations using the code FCI, a Lagrangian, one-fluid-three-temperature code with multigroup diffusive radiation transport, an average atom LTE treatment of the materials, and flux-limited electron heat transport. Figure 4 shows the calculated profile of electron density, at 7 ns, for a target with an initial gas density of 6 mg/cm³. One can see that the shock remains quite planar at this time, in this case with a 600 μ m gas cell and an 820 μ m laser spot. The density in the shocked layer at this time is ~ 50 times the initial density, and there has been very little radial flow of mass out of the shocked layer. The decrease of temperature ahead of the shock in these simulations is more rapid than in the 1D

Figure 4. Density profile at 7 ns, from a 2D simulation of the experiment, using the FCI code run at CEA. The shock is moving to the right. The color bar calibrates the density as a ratio to the initial gas density.

Figure 5. Radiography images from gas target experiments. (a) Area backlighting image with a 70 μm plastic drive disk, at 13.5 ns, providing the image that has shown the narrowest dense layer to date. (b) Image from backlit pinhole image with a 20- μm Be drive disk, at 8.0 ns. (c) Image from backlit pinhole image with a 20- μm Be drive disk, at 14.6 ns.

case, as one would expect with the inclusion of radial radiation losses.

Radiography of the shock in xenon shows clear indications of a thin, dense shock. On a range of experiments, we have seen dense shocked layers with thicknesses ranging between 45 and 80 μm . Some layers were tilted with respect to the target axis in the plane of the radiograph by as much as 10 degrees. We show the thinnest of these layers in Figure 5a, taken at 13.5 ± 0.3 ns, with the region of highest opacity being 45 μm thick. One can see the center of the shock (which is moving to the right) at approximately 1600 μm from the initial driven surface, with indications of a trailing layer of dense xenon along the wall of the tube. The velocity averaged over the first 13.5 ns is 118 km/s. Figures 5b and 5c show typical radiographs with a thicker layer, from experiments with nominally 20- μm thick drive disks and the higher-resolution, backlit pinhole diagnostic. Figure 5b is for a 22 μm drive disk and a 10% lower drive irradiance. In this image, the center of the layer has moved 1150 μm in 8.0 ± 0.3 ns, where its thickness is 65 μm . The average velocity of the shock at this time is ~ 140 km/sec.

In experiments using the VISAR diagnostic,⁴⁵ fringe patterns ceased before the drive laser shut off, as can be seen in Figure 6. Based on calculations, we attribute this to collisional absorption in the Xe gas, heated to a few eV by radiative preheat. At a late time, a thin feature which showed no fringes and which was non-uniform in space and duration was seen. We attribute this signal to reflection of the interferometer beam off from the edge of the shock front. The inferred shock velocity, based on this interpretation, is consistent with that determined from the radiographic data.

The data of Fig. 5 clearly show a very thin shocked layer. The layer of xenon produced by a non-radiative shock, with an effective γ of 1.2 to 1.3, would be 140 to 220 μm thick at the location seen,

Figure 6. 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 volume.

and the observed layer is $45\text{ }\mu\text{m}$. Thus, one might suggest that the density has increased another factor of 3 to 4 in consequence of radiative losses, reaching a total of 34 times the initial xenon density. On the one hand, the inferred density increase would be reduced to whatever extent material has left the shocked region by flowing radially, although the 2D simulations find this to be small. On the other hand, this line of sight measurement will have a strong tendency to over-estimate the thickness of the shocked layer, due to any tilt, curvature, or rippling of the shock front. On balance, it appears reasonable to conclude that we have observed a thin layer of shocked xenon whose density has been increased significantly by radiative losses.

Figure 7. Scattering geometry for Thomson scattering.

Figure 8. Target for Thomson scattering.

In addition to the above work, this past year we added significant new achievement by becoming the first research team (ever, anywhere) to obtain Thomson scattering data from a shock front. This involved using an Omega beam to inject a UV laser, at the fourth harmonic of the infrared wavelength of Omega, into our target. The scattered light in the direction of the diagnostic exited the target and was collected by the Thomson scattering optics already developed and tested by the LLNL group of Siegfried Glenzer. Dustin Froula participated directly in the experiments. The experiments used Argon gas because calculations showed that the probe beam was unlikely to penetrate xenon without greatly disturbing it. Figure 7 shows the scattering geometry. This geometry guaranteed that the waves scattering the probe beam were traveling directly up or down the Argon-filled shock tube. Figure 8 is an image of the target from a CAD program used in preparing for the experiments. It shows the main shock tube below the drive disk and the two additional tubes that were attached, allowing the probe beam to enter from the lower left and the scattered light to exit toward the lower right. The structure had to be gas tight, and so these two tubes were covered with thin ($\sim 0.2\text{ }\mu\text{m}$) polyimide windows. The probe beam was energetic enough ($\sim 100\text{ J}$) and long enough (4 ns) to vaporize the input window. We used an additional Omega beam to vaporize the output window, a few ns before the probe beam fired.

Figure 9 is a plot of the Thomson scattering data. The y-axis is 'Normalized Intensity' ranging from 0 to 1. The x-axis is 'Wavelength Shift (Å)' ranging from -3 to 5. The data is shown as a jagged green line, and a smooth blue curve is fitted to it. The spectrum shows two main peaks: a smaller one around -1 Å and a larger one around 2.5 Å.

Figure 9. Thomson scattering data (jagged, green) and fit to spectrum (smooth curve, blue).

Figure 9 shows the data obtained by this diagnostic. We observed a spectrum of scattered light whose overall Doppler shift give the shock velocity and whose structure places bounds on the electron temperature and the ion temperature. A preliminary fit is shown (the smooth curve) for an electron density of 10^{21} cm^{-3} , $Z = 10$, a velocity of 100 km/s, an electron temperature of 250 eV, and an ion temperature of 700 eV. Further analysis of these data is proceeding. Our next opportunity to obtain Thomson scattering data will come in about 2 years, once the instrument rebuilding necessary because of Omega EP is complete.

C. Planned research

We are planning two types of experiments in order to improve our understanding of this type of radiative shock. These experiments will continue to be done in the geometry that has been successful. We will continue to build the targets at Michigan. We plan to combine a further radiographic scaling experiments with experiments that will exploit some possibilities demonstrated by the Thomson scattering experiments to obtain x-ray spectroscopy data.

The radiographic scaling experiments will have two goals. These are to extend the set of scaling data and to improve the quality of the data. Thus far, we have limited data with 10 μm drive disks and in general at very early and very late times. The quality of the present data is also limited by the use of a framing camera, which introduces substantial noise in the images and some unreliability in the operation. Because of this, the resolution does not reach the level permitted by the backlit-pinhole imaging. By doing ungated imaging using a backlighter pulse of 100 ps or less we can get adequate time resolution and much improved images. We plan to attempt this next summer.

Meanwhile, there is clear potential in x-ray spectroscopy as a diagnostic, in several ways. We can potentially measure the self-emission of the xenon, the self-emission of a dopant such as argon, and the transmission of a dopant material using backlighting. Recent measurements of xenon emission from imploding, xenon-filled capsules by Bob Heeter show that this is feasible. Dr. Heeter has also indicated an interest in collaborative work that would enable a Michigan student to apply gated, imaging spectrometers developed at LLNL to our radiative-shock experiment. The key challenge for x-ray spectroscopy has been that the tube walls, even though physically thin, are optically thick to all the relevant x-rays. Our Thomson scattering experiments showed how to overcome this, by proving that we can open up a line of sight into the shock tube during the experiment and get data out. We are now designing targets that will allow us to open a line of sight looking directly up the tube. We will first try this next summer, attempting to obtain soft x-ray signals with the k-edge spectrometer (Dante) and UV signals with the streaked optical pyrometer. Each of these are potential diagnostics of the temperature in the zone from which they receive signal.

IV. Structure in Supernovae

A. Importance of the work

Human understanding of stellar explosions is in a period of significant advance. Improvements in instrumentation, in computer simulations, and in laboratory experiments all are contributing. One particular recent supernova, SN1987A, has played an important role because, at a distance of 150,000 light years, it is relatively close to Earth. SN 1987A was a core-collapse supernova -- the gravitational collapse of its iron core released the energy that drove the explosion. One process that occurs during such explosions is the Rayleigh-Taylor (RT) instability, which has the potential to transport some material from deep within the star to its outer layers. Our recent experiments show the transport of material much further than one would anticipate from existing theories and relevant supernova simulations.

In SN1987A, the early observation of γ -rays from ^{56}Co , relative to the timing anticipated from simulations assuming spherical symmetry, the shape of the x-ray and visible light curves, and the high velocity of Ar, Ni, Co, and other elements (~ 3000 km/s), provided compelling evidence that the explosion was not spherical.^{11,12,46} These observations suggested that a small fraction of the heavy elements from the interior of the star had somehow been mixed into its outer layers. Furthermore, the shape of the x-ray spectrum implied that such mixing was non-uniform.¹² Explaining these observations in detail has proven to be an enduring challenge. Straightforward modeling of hydrodynamic instabilities has not produced enough mixing to explain them.^{13,47-52} Our past and planned experiments, in combination with simulations, should impact the consideration of instabilities as a potential explanation for the observations from SN1987A.

Two hypotheses that might explain the astrophysical observations have had a significant presence in the literature. First, the transition zones between regions in the star, across which the dominant element changes and the density drops more rapidly, become unstable to the Richtmyer-Meshkov (RM) instability^{53,54} and then to the Rayleigh-Taylor (RT) instability^{55,56} in response to the passage of the blast wave that blows the star apart.⁵⁷⁻⁵⁹ The hypothesis is that these instabilities produce spikes of dense material that penetrate into the hydrogen layer of the exploding star. We emphasize that explaining the observations from SN1987A requires only that a tiny amount ($\sim 1\%$) of the ^{56}Co be accelerated to velocities above 3,000 km/s.^{11,12} From spherically symmetric models one can conclude that mixing is necessary but can gain little insight regarding the mechanisms.^{60,61} In symmetric 2D models, one can observe the evolution of structure due to RT and RM.^{13,47-51} The amount of penetration turns out to be strongly sensitive to the initial conditions. Fryxell, Muller, and Arnett^{13,47,51} perturbed the unstable interfaces, but did this randomly rather than on a physical basis and also did not evaluate or include the structure produced by neutrino-driven convection. They found penetration of high-Z material out into the hydrogen layer, though not to high-enough velocity to explain the observations. In contrast, Kifonidis *et al.* reported in 2000 modeling of the perturbations produced by neutrino-driven convection but included no perturbations of the outer interfaces.¹⁴ They found that the spikes of high-Z material encountered a well established “reverse shock” at the He-H interface, which slowed them significantly. Spikes do

experience less drag and reach higher velocities in 3D than in 2D. However, there are no 3D simulations of SN explosions, and the velocities remain too small to explain SN 1987A in 3D simulations^{52,62-64} and buoyancy-drag models^{65,66} of isolated 3D spikes. Other existing studies of 3D RT instabilities, reviewed in Drake *et al.*,¹⁸ are of limited relevance for reasons discussed there.

The second hypothesis that might explain the observations of SN 1987A is that the explosion might be significantly asymmetric. There is evidence that SN1987A and many other SN explosions are asymmetric, but the detailed mechanisms that might produce the asymmetry are not well understood. Very recent simulations by Kifonidis *et al.* with new models of the neutrino effects have produced asymmetric explosions in 2D.¹⁷ This may have the potential to produce spikes of high-Z material that can couple to instabilities at the H/He interface and explain the observations. However, the H/He and other interfaces were not treated in much detail or with realistic initial conditions in this recent work. Alternatively, the explosion might have been driven by a jet from the core, which could also rapidly transport high-Z material outward, at least near the poles (See Wang *et al.* and refs therein⁶⁷). Note that in order to blow apart the bulk of the star, even in a jet-driven explosion, a blast wave must be driven through it. The blast wave is presumably the bow shock from the jet, but the details of jet-driven explosions are not understood and research in this direction has only been initiated [see, for example,¹⁵ Khokhlov *et al.*] Any such blast wave will produce RM and RT instabilities, and our work here contributes to the understanding of their impact in such models.

Experiments at high energy density now provide an independent option for the examination of hydrodynamic processes that may occur in astrophysical environments. Our experiment is in the correct scaling regime, described by the same equations that describe the plasma in supernovae. As has been discussed in several papers,⁶⁸⁻⁷⁰ under such conditions the evolution of a laboratory system can be identical to an astrophysical one. This requires that the spatial structure and boundary conditions of the two systems be identical in an appropriately scaled sense and that the structure of the equation of state be the same. In practice, one can produce an experimental system whose evolution will parallel the astrophysical one over some period in time and space, beyond which the evolution of the experimental system is affected by its limited boundaries.

B. Recent Research

To perform these experiments we use targets like those shown in Figure 10. An interface was produced in a laser target by assembling a dense layer,

Figure 10. Drawing of target used for supernova hydrodynamics studies. The backlit pinhole is actually about 1 cm from the target, which is 1 mm in diameter, 3.5 mm long and attached to a 20 mm conical Au shield (not shown)

here a plastic cylinder 800 μm in diameter and 150 μm long of density 1.41 or 1.42 g/cm^3 , next to a layer of C foam, here of density 50 mg/cm^3 , within a polyimide shock tube. The foam had open cells of dimension $< 0.1 \mu\text{m}$. The dense plastic was irradiated by ten laser beams on the Omega laser, producing an ablation pressure of $\sim 5 \times 10^{13} \text{ dynes}/\text{cm}^2$ for 1 ns to initiate the experiment. The Sc or Ti backlighter foil was struck with up to 4 laser beams to produce diagnostic x-rays, which were directed by a pinhole toward the target and onto x-ray film. A large conical shield (not shown) prevented the film from seeing the laser-produced plasma. Further details of the experiment, the diagnostics, and the data are provided elsewhere. A number of papers have reported the development of such experimental systems in recent years.^{18,71-80} Aside from significant improvements in diagnostic techniques, the primary difference among such experiments has been in the initial conditions imposed at the interface. Like the supernova plasma, the experimental plasma has high Reynolds number, high Peclet number, and small radiation cooling, and is accurately described by the Euler equations. Our collaborators in conducting the experiments have included Jim Knauer of LLE and scientists from LLNL (Harry Robey, Brent Blue, and Freddy Hansen).

Figure 11. Interferometric image of modulated surface of dense layer.

In the present phase of these experiments, we are studying the effect of a combination of a basic 3D modulation of the surface with additional 2D structure. Figure 11 shows an example. One can see the global modulation, present on all targets except for planar comparison targets, with a spatially varying amplitude given by $a_0 \sin(k_x x) \sin(k_y y)$, in which $a_0 = 2.5 \mu\text{m}$ and the wavenumbers in two orthogonal directions, k_x and k_y , were $k_x = k_y = 2\pi/(71 \mu\text{m})$. In current targets, the dense plastic is composed mostly of polyimide, of composition $\text{C}_{22}\text{H}_{10}\text{O}_5\text{N}_2$ and density 1.41 g/cm^3 , with a 200 μm wide, 75 μm deep, 800 μm long strip of CHBr, of density 1.42 g/cm^3 , glued into a slot in the polyimide. The CHBr strip allows one to image the interior structures without interference from the edges of the cylinder. In the case shown in Fig. 11, the strip is recessed 4 μm relative to that of the polyimide. In more recent targets, 2D sinusoidal patterns are imposed across the entire target but the strip is not significantly displaced, as Fig. 12 shows. In addition, tearing of the plastic material introduces

Figure 12. Idealized initial conditions for 2-mode experiment imposing a 2D sinusoid of 212 μm wavelength on our base 3D eggcrate pattern.

additional structure at shorter wavelength and smaller amplitude, which we are hoping that our supplier (GA) can reduce in the future.

Figure 13 shows the evolution of density structure in the experiment, from a simulation with the 1D, Lagrangian, single-fluid, three-temperature, radiation-hydrodynamic code HYADES with multigroup diffusive radiation transport.⁴⁰ At

1 ns, pressure from laser ablation has driven a shock wave into a block of dense material. The pressure ends at 1 ns, so that the rarefaction of the driving surface overtakes the shock, forming a blast wave, before the shock reaches the interface, as seen at 2 ns. The structure at later times is then characteristic of an interface that has been processed by a blast wave, with a forward shock in the foam and a developing reverse shock in the plastic. The density drops roughly fivefold at the interface between the plastic and the foam. This ratio stays constant as the interface decelerates and the pressure decreases. This plasma is dense enough that the electron and ion temperatures equilibrate rapidly. The plasma parameters for the experiment and for the hydrogen-helium interface in SN 1987A confirm the validity of the scaling between the experiment and SN 1987A.⁶⁸

Figure 13. Evolution of density structure.

Some previous data, using initial conditions like those of Fig. 11, produced spikes that extended much further and that appeared to overtake the forward shock. These spikes were much longer than typical buoyancy-drag models would predict.¹⁸ The precise cause of this is the subject of ongoing research, but reasonable hypotheses include the introduction of additional vorticity to the spikes by the additional structures at the interface and increased interactions of the spikes due to the influence of the additional structures. It is quite clear, however, that initial conditions determine how far the spikes penetrate. [This has also been seen in hydrodynamic simulations of planar systems in two dimensions.⁸⁰] These experiments show that penetration of the spikes to the region of the forward shock is possible. This could be a key to explaining the observations from SN 1987A.

Our work during the past year has focused on obtaining higher-quality data through the use of ungated, backlit-pinhole images. By eliminating the noise introduced by a gated framing camera, and by projecting a single image onto a detector, this technique achieves data with much better actual resolution than one finds using a framing camera and multiple pinholes. We have been one of several groups working for some years toward the development of reliable methods for accomplishing this. We have notably benefited from developments by John Foster and collaborators at AWE and by several of our collaborators at LLNL. While doing this, we have also been working to develop GA as a new supplier of the key component – the plastic disk with a CHBr strip and a modulated interface.

This work enabled us this year to be the first group to successfully obtain two independent images on the same shot both using backlit pinhole diagnostics. Figure 14 reproduces the example shown on the cover. These data are from a case with only the initial 3D eggcrate pattern. In (a) the view across the strip (using a Sc source) shows the shock and the spikes, which penetrate less close to the shock than was the case in the previous experiments discussed above. The shock and the interface are also both tilted, which probably represents a target fabrication problem. We have made some improvements to fabrication technique and characterization with the intent of avoiding this in the future. One value of the orthogonal views is that they allow one to detect and characterize the degree of any such tilt. In (b) one sees the view down the strip, with a very bright Ti source. This allows one to see the spikes from the strip and also (less well) those in the polyimide, in addition to the shock.

Thus, we are now in a position to systematically test our previous conclusion that initial conditions are the critical issue that determines whether RT can explain SN 1987A data. While the initial conditions to which the stellar explosion is subject may seem like an impenetrable mystery, in fact researchers have begun to make progress in specifying them. It has become clear that the interfaces between shells in the presupernova star are structured. Convective burning shells in pre-core-collapse stellar models are unstable, and determine the structure of composition interfaces, as well as the associated spectrum and amplitudes of

Figure 14. First (anywhere) physics data from dual orthogonal backlit pinhole radiographs using ungated detectors. a) shows an image across the CHBr strip and b) shows an image down the CHBr strip. In both images dense spikes and the shockwave can be seen moving to the right. The grid is for calibration of position and magnification.

Figure 15. Density perturbations at the He-H composition interface. Shown here as a surface plot is density from a slice at fixed radius of a 3D computational wedge that is 15 degrees on a side. Simulations in 3D were necessary to accurately capture the scale of the convective perturbations. These simulations of convection used Prometheus, a piecewise-parabolic-method (Godunov-type) hydrodynamics code with diffusive radiative transfer and state-of-the-art stellar microphysics and nuclear reaction rates. The initial conditions for these calculations are a 23 solar mass model, approximately the mass of the SN1987A progenitor, which was evolved with TYCHO, a publicly available, one-dimensional, stellar-evolution code developed at the University of Arizona by Dave Arnett and his students. The typical resolution is 300 radial zones and 40,000 angular zones.

density perturbations at these interfaces. These perturbations will ultimately give rise to and shape instabilities in the passage of an outward moving supernova blast wave. The nature of these conditions is now being examined for the first time in three-dimensional, hydrodynamic stellar models. Figure 15 shows the distribution of perturbations that arise at a composition interface at the outer edge of a convection zone in a supernova progenitor star. Note the presence of three-dimensional structure with local perturbations at a range of spatial scales.

C. Planned research

The planned experiments during the next year will employ backlit pinhole diagnostics and will use interfaces modulated by the eggcrate pattern plus a second mode of various wavelengths. These experiments will be intended to provide an understanding of why we saw such dramatic spike penetration previously, by the systematic variation of the initial conditions.

These initial experiments will provide a basis for the interpretation of an experiment we hope to undertake in the following years. This experiment will use the three-dimensional structure of a presupernova interface, like that shown in Figure 15 but consistent with the state-of-the-art simulations at that time, and will impose this structure on an interface for our experiments. This will amount to a direct test of whether the structure at one such interface can produce significantly increased spike penetration. In the context of experimental astrophysics in hydrodynamic systems, this will be the first direct test of an astrophysical case, supported by detailed experiments that can be used to assess the causes and the significance of the result.

We are well prepared to provide simulations in support of these experiments. Some previous

Figure 16. Density structure from CALE simulations of experiments with variations in initial conditions. The top shows a single mode, the middle shows two modes in phase, and the bottom shows two modes out of phase.

Figure 17. Spatial subdomain from a preliminary FLASH simulation of these experiments. In this run, the planar interface had a two-mode sinusoidal perturbation (with 71- and 213-micron wavelengths). Here we display mass density isocontours, superimposed on a field colored by x-velocity, for a point in time after the shock has crossed the interface. The shock wave from the laser ablation has moved from the left to the right side of this plot, here the shock front is just slightly past the 800-micron x-coordinate. The interface between the CH and CRF media lies at the edge of the plume-like structures ("spikes" and "bubbles") in the central vertical region. Note the presence of acoustic waves between the interface and the shock front, seen here as faint diagonal structures in the x-velocity.

data were simulated by Aaron Miles as part of his thesis research for the Univ. of Maryland. Figure 16 shows one of the results, from CALE. Dr. Miles has been hired by LLNL, where he is authorized to continue to spend time on these experiments. In addition, our collaborators from Stony Brook are using their code FrontTier to simulate this experiment with a higher-quality treatment of the interface than is possible by other techniques. Moreover, as mentioned above, the FLASH Center has hired a scientist whose first major project will be a validation study based on our experiments. Figure 17 shows a preliminary example from the beginning of this work.

V. Other recent progress

A. Jet Experiments

A variety of recent evidence indicates that core-collapse supernova explosions may be globally asymmetric. Recent simulations¹⁵ have explored one possible mechanism, in which the collapsing core emits polar jets that drive the subsequent, asymmetric explosion. Motivated by this work, the P.I. and a student (Eric Harding) developed a design for such an experiment, shown schematically in Fig. 18. The technique builds

Figure 18. Schematic of jet-induced explosion experiment.

Figure 19. Simulation of jet-induced explosion experiment.

upon our designs for supernova remnant simulation experiments.⁸¹⁻⁸⁵ The laser produces a strong shock in a thick layer of plastic. The ejecta (produced when the shock breaks out of the plastic) accelerate across a fairly large vacuum gap and then penetrate a large layer of low-density foam, driving a supersonic jet through the foam. The resulting bow shock blows the foam apart laterally. Fig. 19 shows results of a hydrodynamic, 2D simulation of this system by Dr. A. Khokhlov of NRL (initialized by our 1D rad-hydro simulation of the laser-driven shock). A large collaborative team^{86,87} in which we participate has been conducting these experiments, which required extensive diagnostic development in order to succeed. This led to the dramatic data shown in Fig. 20,

Figure 20. Data from a jet experiment on Omega based on a design originated by us.

which includes greatly improved signal-to-noise, a several-mm field of view, and an apparent transition to turbulence. All of these are firsts in this type of experiment. Subsequent work has begun to explore the interaction of jets and clumps. We look forward to applying these improved techniques to our other experiments.

B. Target Fabrication and Diagnostics

During the past three years we have developed the capability to build our own targets for experiments at Omega or elsewhere. This was a necessity as, with the advent of experiments on NIF, LLNL became increasingly unable to provide targets. In the process we found that direct involvement with target fabrication has substantial educational benefits. The benefit to the graduate students is large. They are forced to grapple with the full, three-dimensional challenges of target definition and target metrology. They gain direct experience with the tradeoffs involved in devising a target that does the desired physics yet actually can be built. They also gain hands-on experience with target construction. Undergraduates or junior graduate students do much of the construction, which is an excellent introduction to the rigorous demands of experimental science and an excellent opportunity to gain hands-on experience. A scientist supervises this effort and collaborates with the graduate students, providing a level of project planning and technical continuity that would not be feasible for the graduate students alone. Our long-term goal is to obtain the technically complex components from GA, LLNL, or industrial suppliers while continuing to carry out the design, assembly, and metrology at Michigan.

All the experimental data shown here from radiative shock and from hydrodynamic instability experiments is from targets assembled at Michigan. We produce many of the simple components, such as polyimide tubes and grids, very inexpensively using processes we have developed. The more complex components, such as the plastic disks for the hydrodynamic experiments, we obtain from suppliers. To perform a full day experiment with two backlit pinhole targets and the main targets requires building nearly 50 targets. We are capable of doing this a few times a year, at a cost far below that necessary to do so within national or industrial laboratories. (However, our methods for doing this with student labor imply that we would be unable to produce the constant stream of continually changing targets produced by target fabrication and assembly at these laboratories.)

Figure 21. Low-resolution radiograph of a CRF foam for our instability experiments.

Under independent funding, we have built and activated an x-ray source for operation at a few keV. This is a steady-state, Manson-type source. We use it primarily for undergraduate research projects aimed at the long-term improvement of x-ray diagnostics. We plan to use it as well for applications to the present project. We can adapt this source to radiography, in order to produce preshot radiographs of our experimental targets. This is useful in certifying the quality of these targets and to enable the best-possible interpretation of data from them. It may be particularly important for targets with machined foams, in order to certify the integrity of the foam components. Beyond this, our research may lead to questions about x-ray diagnostic performance that can be addressed using this x-ray source. Figure 21 shows the first, low-resolution radiograph produced by these efforts.

VI. Project Participants

Extensive student involvement is an aspect of this project. During the past two years, 7

Table 1. Undergraduate participation in research under this grant.
Student support from this contract is shown as FTE. Many students
were supported in part from various undergraduate research programs.

First Name	Last Name	9/03-8/04	9/04-8/05	9/05-8/06	Non-salary Support	04-05 FTE
Saida	Caballero	X	X		Supplies, Travel	0.01
Trisha	Donajkowski	X	X	X	Supplies, Travel	0
Natalie	Estrada			X	Supplies	
Carlos	Fernandez	X			Supplies	0
Rebecca	Gabl	X			Supplies, Travel	0.12
Jonathan	Garrett	X			Supplies	0
Joe	Garland		X		Supplies	0
Michael	Grosskopf	X	X	X	Supplies, Travel	0.36
Kyle	Hubb			X	Supplies	
Christing	Krauland		X	X	Supplies, Travel	
Douglas	Kremer	X	X	X	Supplies, Travel	0.04
Devon	Lafferty		X		Supplies	
David	Leibrandt	X	X		Supplies, Travel	
Mariano	Lowenstein			X	Supplies	
Willie	Luckett		X		Supplies	0
Donna	Marion		X	X	Supplies, Travel	0
Rafael	Martinez	X			Supplies	0
Kwasi	Mendoza		X		Supplies	0
Neal	Meyer	X			Supplies, Travel	0
Eduardo	Mucino			X	Supplies	0
Koichi	Murai	X			Supplies	0
Christopher	Muscatello	X			Supplies, Travel	0
Rafael	Perez	X			Supplies	0
Gurlovleen	Rathog		X	X	Supplies	0
Kai	Ravariere			X	Supplies	
Erica	Roesler	X			Supplies, Travel	0.06
Jasmine	Santana			X	Supplies	
Zenka	Sellinger	X			Supplies	0
Paul	Skowronek		X		Supplies	0
Mark	Taylor		X		Supplies, Travel	0
Christopher	Tien	X	X		Supplies	0.05
Zhengfei	Zhang	X			Supplies	0
TOTAL		17	15	12+		

graduate students have made a total of 19 trips to our Omega experiments, and 13 undergraduate students have made a total of 28 trips. During this period, one Ph.D. thesis from U. Maryland has been based on simulations of the data obtained by our hydrodynamic experiments.⁸⁸ and a Ph.D. thesis in France has included work simulating our radiative shock experiments.⁸⁹ At Michigan, students are engaged in construction of targets, data analysis, experiment design, and computer simulations related to this project. There is substantial educational benefit from target construction and metrology by students; we have added this capability and have successfully built targets during the past three years. In addition, the students of our collaborators are conducting simulation studies related to the project. In this section, we discuss undergraduate participation, graduate participation, and then other participants.

This project contributes significantly to the education of undergraduates at the University of Michigan. Each year, we bring 5 to 10 first and second year undergraduates into our lab through Michigan's Undergraduate Research Opportunity Program, and several more through the summer NSF Research Experience for Undergraduates program, through work study, and through other programs. During the past two summers, we also hosted two high-school students for several weeks. We give these students projects appropriate to their abilities. They typically incur no costs for salary, although there are supporting costs associated with supplies and computers. Following these experiences, 1 to 2 undergraduates per year typically stay with the group for 2 to 3 more years. Having gained experience in their initial projects, these undergraduates prove useful and productive in building targets, modifying lab equipment, writing software, performing simulations, and analyzing data. The most-involved students typically work about 10 hours per week during the academic year and full-time during the summer, costing roughly 15 k\$ per year including overhead. We support such students from a number of grants and contracts, including this one. We also take them to experiments supported by this grant, where they prepare targets, keep records, and analyze data. We give undergraduate seniors who have been with the group for some years the opportunity to present a paper at the Division of Plasma Physics annual meeting. These have included Dave Leibrandt in 2003, Doug Kremer in 2004, and Mike Grosskopf in 2005. Table 1 provides a list of these students during this grant to date.

We have supported seven graduate students at Michigan who have participated in this project. These students are listed in Table 2. We support these students through several projects, including this grant, our NLUF project, support from NRL, and fellowships. (Full support is 0.5 FTE.) In my view the ideal group would graduate one Ph.D. per year, as this provides a group of manageable size yet with good opportunities for learning among the graduate students and for experience as part of a group. We are approximately at this level, thanks to the expansion of scope proposal that NNSA funded last year. The newest student, Forrest Doss, is in England at Cambridge this year on a fellowship and will begin serious research with us next summer. In addition, we hosted graduate student Bobby Carver of Rice University (where he works with Prof. Hartigan) for several weeks this summer. He worked with the group in order to learn from us.

Table 2. Graduate students.

Student		Expected Degree	Expected Year of Degree	Salary FTE 9/03 to 8/04	Salary FTE 9/04 to 8/05	Expected salary FTE 9/05 to 8/06	Conference Presentations
Melanie	Blackburn	M.S.	2004	0			APS03, HEDLA04, APS04
Amy	Reighard	Ph.D.	2006	0	0	0.25	IFSA03, APS03, HEDLA04, APS04, SSAA05, IFSA05, APS05
Paul	Kominsky	Ph.D.	2006	0.19	0	0	None (trying to get him to finish)
Carolyn	Kuranz	Ph.D.	2007	0	0.45	0.2	APS03, HEDLA04, Anom. Abs 04, APS04, IFSA05, APS05
Eric	Harding	Ph.D.	2008	0.014	0	0	APS03, APS04, Anom. Abs. 05, SSAA 05, APS05
Anthony	Visco	Ph.D.	2009	0	0.22	0.25	None yet
Forrest	Doss	Ph.D.	2010		0.1	0.1	None yet

The graduate students learn to design experiments, which includes running simulations, analyzing diagnostic approaches, and developing target designs. They then learn to prepare for experiments, which includes involvement in target assembly and responsibility for target metrology. They conduct experiments at Omega or some other facility. After the experiment they analyze the data and present and publish the results. The table includes a list of the conferences at which each student made a presentation.

The remainder of the team at Michigan (see Table 3) has included the PI and Korbie Dannenberg. Korbie Dannenberg was a former student who graduated with an M.S. degree, after which she developed our target fabrication capability. She was recently hired by General Atomics to manage the target fabrication effort at Sandia Labs. A current undergraduate, Mike Grosskopf, will work for some time as a scientist beginning when he graduates in December 2005. Having one such person in the group has proven essential to our experimental preparations and to managing our undergraduate student effort.

Table 3. Faculty and staff supported by this grant.

Name	Position	'04 FTE	'05 FTE	'06 est FTE
R. Paul Drake	Faculty	0.25	0.32	0.22
Korbie Dannenberg	M.S. Scientist	0.91	0.65	.05
Peter Susalla	Technician	1.00		
Mike Grosskopf	B.S. Scientist			0.67
Chuck Navarre	Machinist	0.09	0.03	
Rob Gillespe	Machinist	0.11	0.01	

Our extensive group of external collaborators includes leaders in astrophysics, nonlinear hydrodynamics, and ICF to attack these problems of fundamental interest to astrophysics and to DOE. The participation of the ASC FLASH 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. In support of this, the FLASH Center has hired a scientist (Nathan Hearn) whose first major project is a validation study based on our supernova experiments, working with graduate student Carolyn Kuranz. Progress made utilizing state-of-the-art codes (at the University of Arizona, at Stony Brook, and at CEA (in France), the FLASH Center, and in the DOE labs) on our ICF-scale experiments should prove to be very useful to DOE/NNSA. The rigorous scaling under various conditions being developed as part of this work will also find utility in scaling from current Omega experiments to ignition experiments being planned for NIF. They also will provide the basis for the first supernova-relevant experiments on larger lasers.

VII. Publications

Here we list the publications having partial or full support from this grant that have been printed, gone into press, or been submitted during the period of this grant. Eighteen of these 21 papers are in refereed journals.

- Calder, A, J. Dursi, B. Fryxell, T. Plewa, G. Weirs, T. Dupont, H. Robey, J. Kane, B. Remington, F. Timmes, G. Dimonte, J. Hayes, M. Zingale, P. Drake, P. Ricker, J. Stone, K. Olson, "On Validating an Astrophysical Simulation Code", *Computing in Sci. & Eng.* **6**, 10-20 (2004)
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- Miles, A.R., D.G. Braun, M.J. Edwards, H.F. Robey, R.P. Drake, and D.R. Leibbrandt, Numerical simulation of supernova-relevant laser-driven hydrodynamics experiments on Omega, *Phys. Plasmas*, **11** (7), 255-277, 2004a.
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IX. Conclusion

We have developed a research group that is accomplishing forefront research in high-energy-density physics, and that in the process provides outstanding training for graduate students. The specific focus of these students is radiation hydrodynamics or deep nonlinear hydrodynamics, with a connection to astrophysics. Actually accomplishing this involves these students in a very broad range of topics in high-energy-density physics. Our group is large enough to permit some interaction between junior students and more-senior students, benefiting both groups.

We believe that our work under this grant is the shining example of world-class academic HED research on the NNSA facilities. It has had a broad impact, both within the refereed literature and beyond. Its publications are listed above. In addition, we have had an impact in other ways. Our work has produced numerous invited talks at scientific conferences, including a plenary lecture at the 2005 European Physical Society conference, one talk at the 2005 Target Fabrication Conference, one at the April 2005 general APS meeting, one at the 2004 HEDLA conference, one at the 2003 APS/DPP meeting, two at the associated miniconference on Laboratory Astrophysics, and one at the IPELS meeting in 2003, and two talks 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 in 2003. Our work and our presentations to the panels played a role in the recommendations and reports of two NRC panels: the "Committee on the Physics of the Universe" and the "Committee on High Energy Density Plasma Physics". In addition, a BBC documentary entitled "Hyperspace, which includes a segment shot at Omega and featuring our work, is available in bookstores. In related work, the book by the P.I., High-Energy-Density Physics: Foundation of Inertial Fusion and Experimental Astrophysics, is scheduled to be published in March 2006 by Springer-Verlag.

Further evidence of our impact comes from Prof. Nomoto of the University of Tokyo, who is one of the world's leading theorists of supernova explosions. Following the most-recent conference on High Energy Density Laboratory Astrophysics (HEDLA), he wrote to the PI: "I enjoyed very much HEDLA-2004 in Tucson. It was rather a surprise to see how the experimental approach has been actually successful. My impression in earlier meetings (already a few years ago) was that most of presentation were planning or numerical simulations, but this time I saw real experimental results, which was fun." Much of the data to which Dr. Nomoto refers was obtained on Omega by our collaboration, from which there were 7 presentations at the conference.

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