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J.F. Hansen, M.J. Edwards, H.F. Robey, A. Miles, D. Froula, G. Gregori
LLNL, Livermore, CA, 94550, hansen46@llnl.gov

A. Edens, T. Ditmire
University of Texas at Austin, Austin, TX, 78712

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LABORATORY SIMULATIONS OF SUPERNOVA SHOCKWAVE PROPAGATION AND ISM INTERACTION

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High Mach number shockwaves were launched in laboratory plasmas to simulate supernova shockwave propagation. The experiments were carried out at inertial fusion facilities using large lasers. Spherical shocks were created by focusing laser pulses onto the tip of a solid pin surrounded by ambient gas. Ablated material from the pin would rapidly expand and launch a shock through the surrounding gas. Planar shocks were created by ablating material from one end of a cylindrical shocktube. Laser pulses were typically 1 ns in duration with ablative energies ranging from <1 J to >4 kJ. Shocks were propagated through various plasmas, and observed at spatial scales of up to 5 cm using optical and x-ray cameras. Interferometry techniques were used to deduce densities, and emission spectroscopy data were obtained to infer electron temperatures. Experimental results confirm that spherical shocks are Taylor-Sedov, and that radiative shocks stall sooner than non-radiative shocks. Unexpected results include the birth of a second shock ahead of the original, stalling shock, at the edge of the radiatively preheated region. We have begun experiments to simulate the interaction between shocks and interstellar material (ISM), and the subsequent turbulent mixing. Comparisons between experimental data and numerical simulations of shock evolution, stall, second shock birth, and interstellar material (ISM) interaction will be presented.

I. INTRODUCTION AND MOTIVATION

Interstellar space consists not of absolute vacuum but of a very tenuous plasma, capable of propagating shocks over great distances. Shocks originate in supernova (SN) explosions[1-5] and other astrophysical phenomena, e.g., T Tauri stars and stellar winds. The nature of these shocks is interesting in itself, because of conditions not traditionally attainable in laboratories (conditions such as high Mach numbers and radiative properties), but is also important to understand as the shocks mix up interstellar matter and thus affect stellar formation and the history of the Milky Way and other galaxies.[6-8]

Recently, experiments aiming to recreate SN shockwaves in the laboratory have begun. We have carried out such experiments at inertial fusion facilities such as the Janus laser at the Lawrence Livermore National Laboratory in California, and the Omega laser at the Laboratory of Laser Energetics in New York. In the Janus experiments, spherical shocks are created and allowed to expand through a simulated homogeneous or inhomogeneous interstellar medium. In the Omega experiments, planar shocks are created and allowed to interact with various surfaces and spheres. Together, the experiments aim to answer questions surrounding three different phases of a SN event: the explosion, the expansion of the shock, and the interaction between the shock and interstellar accumulations of matter (ISM) or "clouds."

II. RESULTS AND DISCUSSION

II.A. Explosion phase

The explosion phase of a SN, whether generated by a core collapse (Type Ib, Ic, and II SN) or a thermonuclear runaway (Type Ia SN), is a poorly understood phenomena. One question in need of an answer is to what extent Rayleigh-Taylor (RT)[9-10] and Richtmeyer-Meshkov (RM)[11-12] instabilities play a role during the explosion following a core collapse.

We have carried out experiments at Omega studying these instabilities in the following manner: a small Be shocktube (1.5 – 3 mm long; 0.8 mm inner diameter) is filled with low density plastics or foams. One end of the shocktube is then ablated by laser beams, causing the ejection of ablated material in one direction to launch a planar shock in the opposite direction, down the shock tube. Good planarity of the shock is ensured by using multiple (~10), superimposed beams, each with a super-gaussian beam profile (created by a phase plate in the focusing optics) with a flat top matching the diameter of the shock tube. The total laser energy is ~4 kJ with a pulse duration of ~1 ns. A short distance (~75 μm) into the shocktube, there is an interface between two different density materials; the shock initially propagates through a denser material (~1.4 g/cm^3), then through the interface to a lighter material (~50 mg/cm^3) causing the onset of RT and RM instabilities.

The interface between the two materials can be machined to force the growth of RT modes with certain wavelengths. Dual or multiple mode interfaces have been studied, as have interfaces with modes in two directions. Tracer materials (e.g., Br, I) that are relatively opaque to x-rays can be used to dope the material prior to the interface, allowing the interface to be imaged at some desired point later in time using x-ray pinhole

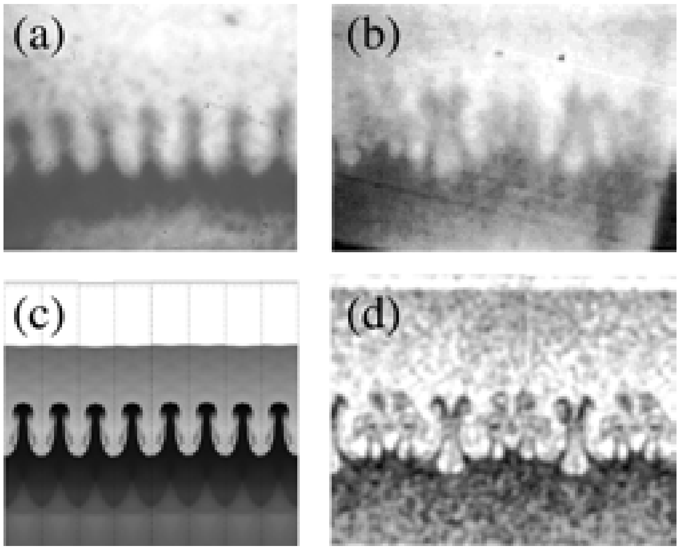

Figure 1: Experimental radiograph of the shock and interfacial structure evolving from (a) a pre-imposed single mode sinusoidal perturbation and (b) a pre-imposed perturbation with eight superposed modes. Computer simulations of the two cases are shown in (c) and (d), respectively. The simulation was computed by the CALE code,[14] an arbitrary Lagrangian-Eulerian 2D code including both hydrodynamic and radiative effects. Photon statistics have been included in (d) to simulate the appearance of an experimental radiograph.

cameras (see Figures 1a and b, and additional example in Robey et al.[13]). Numerical codes (CALE,[14] an arbitrary Lagrangian-Eulerian 2D code including both hydrodynamic and radiative effects) have been developed and can successfully model the experiments to some degree (see Figures 1c and d), although eventually there is a transition to turbulence in the experiments that is unattainable by the codes of today (due to high Reynolds numbers/broad range of spatial scales).

II.B. Expansion phase

The expansion phase of the SN shock has been successfully recreated in experiments at Janus. Here, spherical shocks are studied, and in particular we measure the radius of the shock as a function of time, as well as temperature and density profiles across the shock. The first step in creating a spherical shock is to focus a laser pulse (duration 1 – 5 ns) onto the tip of a solid (e.g., C, Fe, W) pin surrounded by an ambient gas (e.g., N_2, Xe). The laser energy (1 – 150 J) ablates pin material which rapidly expands and launches a shock through the surrounding gas.

Using a schlieren technique, we have photographed these shocks up to spatial scales of ~5 cm (see Figure 2) and found that the shocks grow as $r \sim t^{2/5}$, where r is the shock radius and t is time, i.e., like Taylor-Sedov.[15-17] This holds true even when the shocks are highly radiative (shocks in Xe instead of N_2), which is surprising; a strongly radiative shock has been theoretically[18] and numerically[19] predicted to slow down

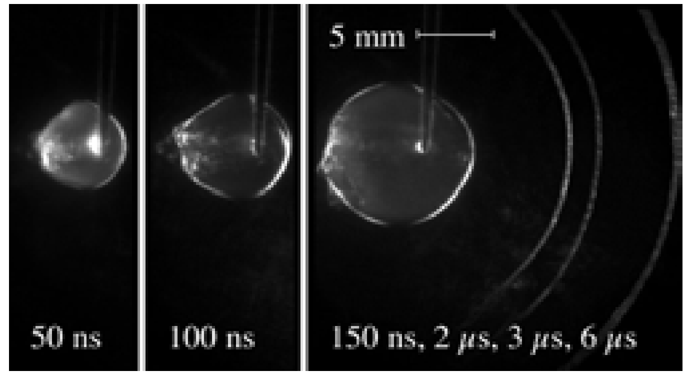

Figure 2: Spherical shocks in 1.3 kPa N_2 photographed at six different times after the initial 10 J laser pulse ablates some pin material and creates the shock. The Fe pin extends from the top of each frame (visible). Note that the last frame is a composite of four times, 150 ns, 2 μs, 3 μs and 6 μs. The shock is expanding as $r \sim t^{2/5}$ and is not radiative in N_2 (absence of glow around shock, c.f., Figure 3). The shock structure deviates from a perfect sphere on the left-hand side of each shock because of laser-plasma interaction; the laser is incident from the left and ionizes a channel through the N_2 gas.

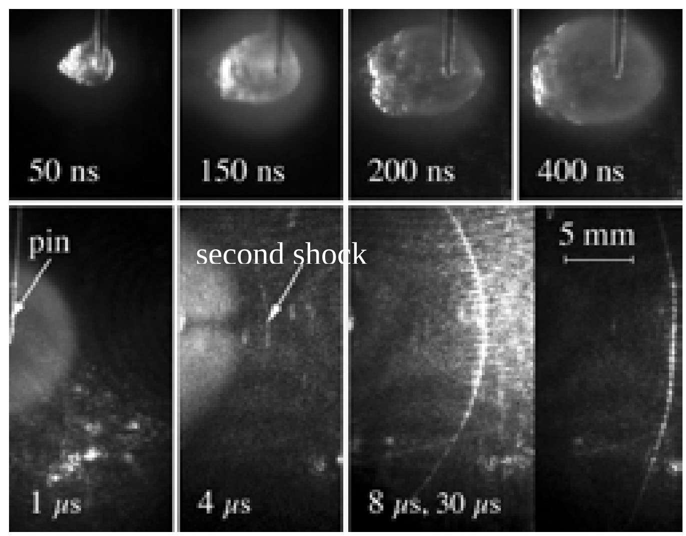

Figure 3: Spherical shocks in 1.3 kPa Xe photographed at eight different times after the initial 10 J laser pulse ablates some pin material and creates the shock. The Fe pin is located at the left edge of each frame, as indicated in the 1 μs frame. Note that the last frame is a composite of two times, 8 μs and 30 μs, again with the pin located at the left edge of this frame. The initial shock is expanding as $r \sim t^{2/5}$ and is visible until 4 μs before it stalls (not visible at 8 μs). The shock is strongly radiative and creates a heat wave ahead of itself, visible as a glow around the shock, e.g., at 150 ns. A second shock is born at the edge of this heat wave, and first becomes visible at 4 μs. The second shock continues expanding to late times (8 μs, 30 μs).

faster, like $r \sim t^{2/7}$ or $r \sim t^{0.33}$, respectively. Why this is not the case in the experiment is currently under investigation.

We have previously reported on the temperature and density profiles in these shocks.[20] Number densities have been measured using interferometry techniques. Temperatures were obtained using emission spectroscopy data. For example, at t = 150 ns the peak density (density at the shock) is ~9×10^{20} m^{-3} in N_2 and ~7×10^{20} m^{-3} in Xe. Temperatures at t = 150 ns were 4 – 7 eV in N_2 and 2 – 5 eV in Xe. These values are in good agreement with 1D numerical simulations using the Lasnex code.[21]

The most interesting result from the expansion phase experiments is the discovery of a second shock, forming ahead of the original shock (see Figure 3). The discovery was made while creating strongly radiative shocks, using Xe as the ambient gas. The original shock radiates and heats the surrounding gas, creating a heat wave that is also expanding toward larger radii. The second shock forms at the edge of this heat wave. Eventually, the original shock stalls as it loses much of its energy by radiation, accumulates mass, and runs into the thermal pressure of the heated gas ahead. However, the second shock keeps expanding to much later times. The existence of the second shock has subsequently been noted in Lasnex simulations.

II.C. Interaction between the shock and simulated ISM

We have begun experiments at both Janus and Omega to simulate the interaction between shocks and ISM, and to study the subsequent turbulent mixing. At Omega we use shocktubes similar to those described in II.A, but filled with a ~300 mg/cm^3 foam and with an embedded 120 μm diameter Al sphere (2.7 g/cm^3) located on the shock tube axis 500 μm from the ablative surface. Results from the experiment can be seen in Figure 4. As the shock runs over the sphere (t = 5 ns), its speed inside the sphere is greatly reduced, leading to a Kelvin-Helmholtz instability and its characteristic roll-up (t = 12 ns). Soon thereafter, a Widnall-type instability occurs, typically creating a mode five azimuthal periodicity when viewed from a point on the extended shock tube axis (not visible in the view of Figure 4). Sphere material is then stripped away from the bulk of the Al plasma by a possibly turbulent mechanism (t = 19 ns), and a second Kelvin-Helmholtz roll-up appears (t = 26 ns). Experiments are planned to go to much later times (up to 100 ns) to follow the transition to a fully turbulent state. Compared to the performance in II.A, numerical simulations with the CALE code have not been as successful in reproducing the experimental data. Only the very early behavior of the shocked sphere is accurately reproduced. The Widnall

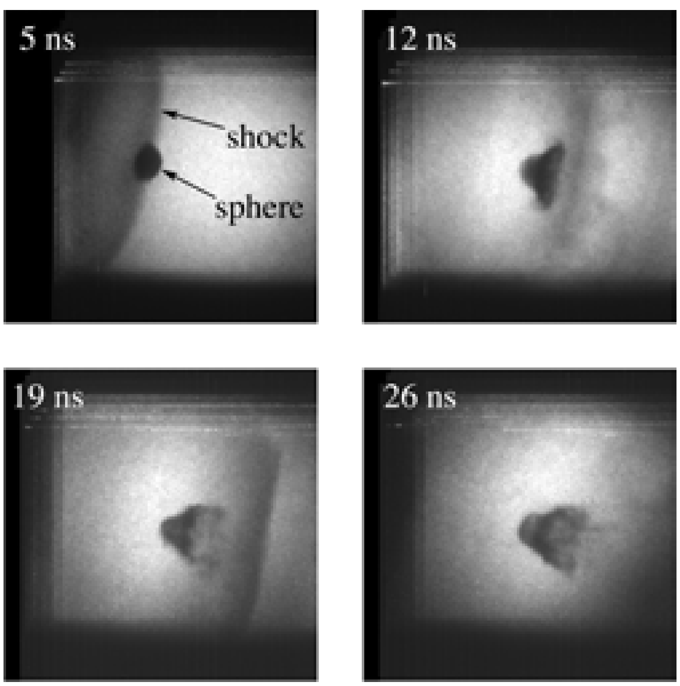

Figure 4: Planar shock running over a sphere (from left to right), photographed at four different times (actually four different experiments). The sphere is nine times denser than the surrounding material. Note the Kelvin-Helmholtz roll-up at 12 ns, the stripped away material at 19 ns and 26 ns, and the second Kelvin-Helmholtz roll-up in the very faint, stripped away material at 26 ns.

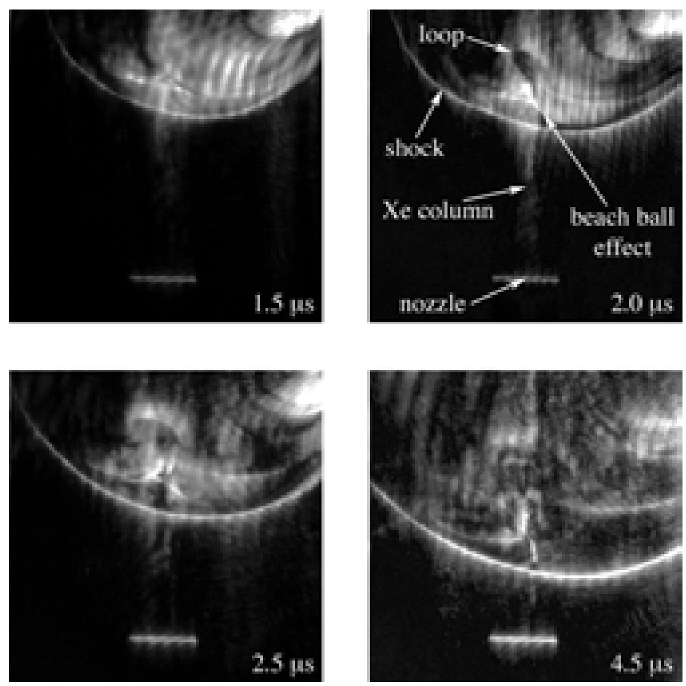

Figure 5: Spherical shock in N_2 running over a column of Xe gas, photographed at four different times (actually four different shocks). Note how the shock slows down in the denser Xe, creating a "beach ball effect," and leaving behind a loop structure. The schlieren knife-edge was oriented horizontally for these images, emphasizing horizontal features (like the shock) and deemphasizing vertical features (like the Xe column).

instability is inherently 3D and cannot be modeled with the 2D CALE code, but also the stripped away sphere material does not appear in the numerical simulation.

Experiments at Janus used the same set-up as described in II.B, but with an added object near the pin for the expanding spherical shock to interact with. Initially, low density aero-gel foams were placed 3 – 10 mm from the pin, but the energy inthe shock proved insufficient in ionizing the foam (the foam would merely shatter, and the fragments accelerate while remaining in solid form).

Recently, a low-pressure gas jet was used to locate a small amount of Xe gas surrounded by ambient N_2 and then the shock was allowed to interact with the Xe. The N_2 pressure was chosen to be 8.00 kPa, the highest possible pressure through which we were able to propagate a 5 ns, 10 J, 1064 nm laser beam without creating shock waves other than at the pin. The Xe jet pressure was chosen by trial and error to give the best contrast in the schlieren images, and we found that a pressure ratio of approximately eight (Xe pressure of 66.7 kPa) worked the best. Some resulting images are shown in Figure 5. The shock is here propagating in a direction parallel to the column of Xe gas, in a direction toward the nozzle. The shock slows down in Xe, as expected, and in the schlieren images this slow-down causes the spherical shock to look like a beach ball where the Xe column is like a finger pushing in the surface of the ball. The shock now turns in toward the Xe column, i.e., the shock takes a conical shape, and self-interaction in this conical shock results in the formation of a loop or drop structure, as seen in Figure 5.

III. SUMMARY

Laboratory astrophysics experiments provide a new tool to use in learning about the universe around us. Experiments can be used to verify theoretical or numerical conjectures, but can also go beyond that; we report here on the discovery of a second shock ahead of an expanding supernova-like shock, which has not been predicted theoretically. We also present results from shock interaction with simulated interstellar material, approaching a 3D, turbulent regime currently unattainable by numerical simulations.

IV. ACKNOWLEDGMENTS

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