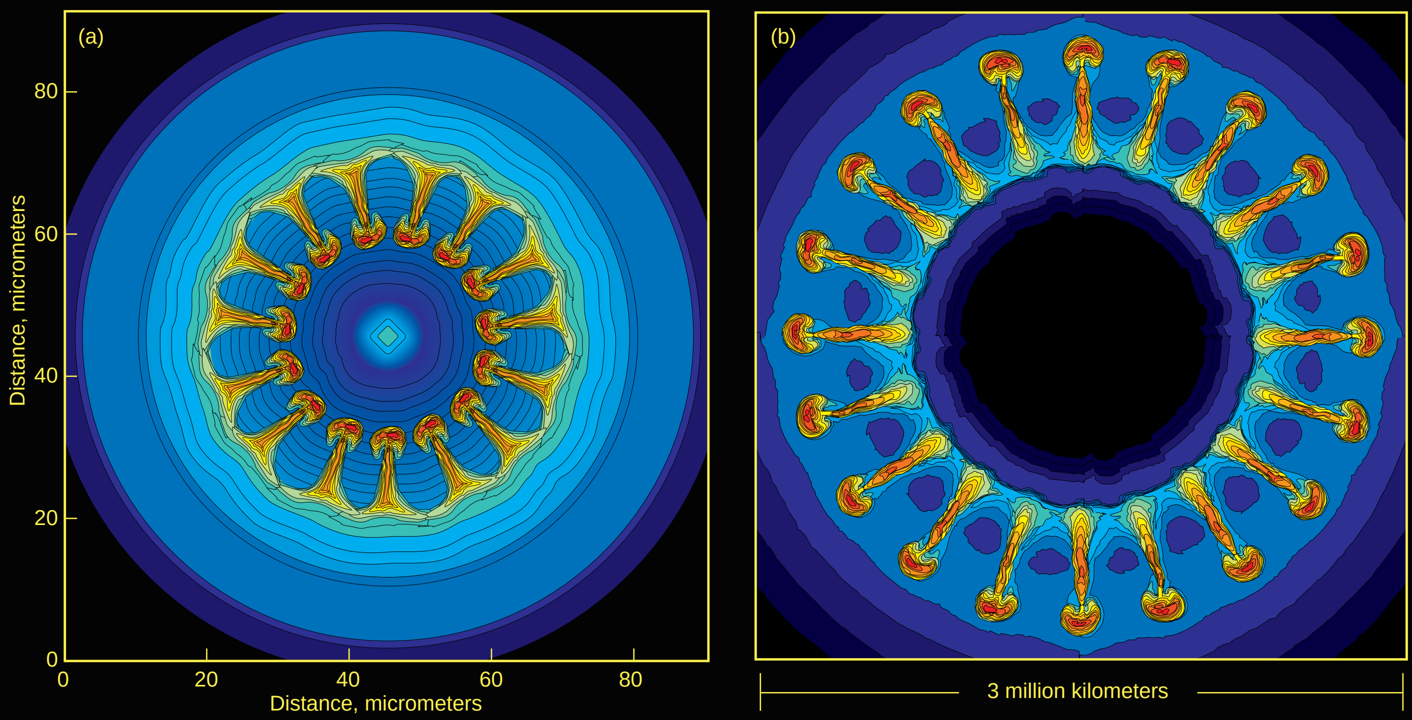
Supernova Hydrodynamics Up Close

Scientists thought they understood supernova behavior until they saw one up close in 1987. Today, ingenious laser experiments and advanced modeling are coming closer to mimicking the complex hydrodynamics of a star's death.

LIVERMORE'S Bruce Remington is no stranger to hydrodynamics. As leader of experimental hydrodynamic work on Nova and other lasers, he has participated in years of experiments related to inertial confinement fusion and high-energy-density physics. One day in 1995, he noticed the similarity between two images (shown on p. 13) in different scientific journals. One showed simulations of the turbulent splashing and mixing of plasma as a fusion capsule was hit by the powerful beams of an intense laser. The other depicted a computer model of gases mixing during a supernova explosion. Although the first picture was of an event less than a tenth of a millimeter across and the second involved millions of kilometers, the fluid behavior of the materials appeared to be virtually identical.

Remington reasoned that laser experiments might be able to mimic the behavior of the phenomenal blast of a supernova. The timing of his ruminations proved to be perfect because a way of doing supernova experiments to quantitatively test observations and models was vitally needed.

Astrophysical research has traditionally been divided into observations and theoretical modeling or a combination of both. But scientists had discovered that existing models did not explain their observations of the great supernova of 1987. That event, known as Supernova 1987A, gave astronomers their first close-up view since 1604 of a star's cataclysmic death. Although supernovas take place fairly frequently all over the universe, they are usually too far away and too dim to be



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]

viewed with much clarity from Earth. This one was a mere 165,000 light years away in the Large Magellanic Cloud, a satellite galaxy of our own.

Supernova 1987A is a type II supernova, which heralds the demise of a particularly massive star. Toward the end of its life, the star's supply of hydrogen for fusion began to wane. Its central regions began to contract, bringing higher core densities and temperatures. As core temperatures increased, successively heavier nuclear fuels began to ignite—first helium, then carbon and oxygen, and on up through neon, magnesium, sodium, and so on. Each consecutive stage of burning happened more quickly. Helium burned for nearly a million years, carbon took about 12,000 years, and neon burned for perhaps 12 years. Toward the end, silicon took just a week. Iron and its cohorts (nickel, chromium, titanium, vanadium, cobalt, and manganese) lie at the bottom of the curve of binding energy because energy must be added to fuse them into heavier elements or to split them into lighter ones. Fusion could go no further.

As ignition of successively heavier fuels took place in the center of the star, previous fuels continued to burn in the overlying regions, so that in its final moments, the star resembled an enormous layered onion. Ultimately, however, gravity won. In a few tenths of a second, the core collapsed, and almost immediately, its center rebounded, smashing into the still-collapsing outer core and giving birth to a shock wave that burst through the matter at the outer edges of the "onion."

Supernova models in place at the time of the spectacular 1987A event predicted that the onion structure would be preserved in the explosion and that the material in the various layers would gradually dissipate. But, in fact, some of the debris moved much faster than expected, as if fingers of fast-moving gas were poking through the rest of the material. Gamma rays from cobalt-56, generated deep in the star during the explosion, became visible six months earlier than expected. The tidy onion model had to be discarded for a messier one that incorporated more turbulence and mixing (see p. 15, lower left).

Turbulence Up Close

It was this turbulence—in a Nova inertial confinement fusion experiment and in models of 1987A—that

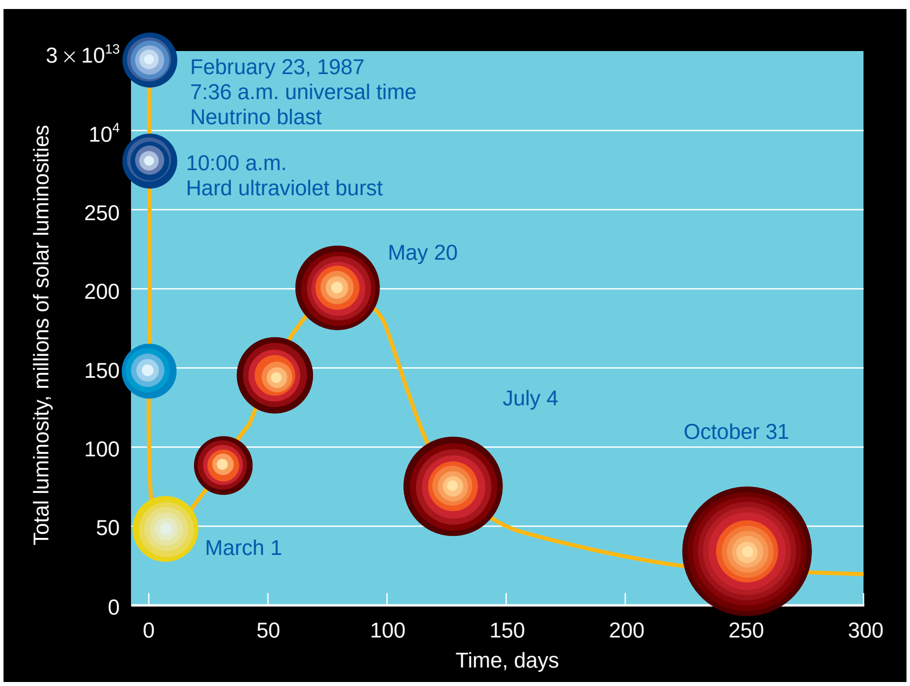
Remington saw in 1995. When fluids or fluidlike matter of different densities is oriented such that the heavier fluid sits on top of the lighter fluid, the system is unstable and tends to mix. At the interface between the two surfaces, the heavier fluid always sinks downward into the lighter one in fingers. This basic fluid dynamic process is known as the Rayleigh–Taylor instability. A related type of hydrodynamic instability, known as the Richtmyer–Meshkov instability, also occurs when there is a shock wave, as in a supernova.

Dozens of laser experiments with Nova tried to simulate the behavior of Supernova 1987A. Early one-dimensional simulations used a tiny, flat stacked target of metal, plastic, and foam to represent the composition and densities of various parts of the supernova. As Nova's laser light hit the hohlraum surrounding the target, a flood of x rays ensued that bathed the target in radiation. The x rays rapidly heated the metal and sent a powerful shock through it, mimicking a supernova blast wave passing through a layer of the star. One-dimensional modeling and laser simulations are useful for determining when the shock wave hit the various shells of the supernova. But one-dimensional work cannot examine the mixing that was obviously taking place.

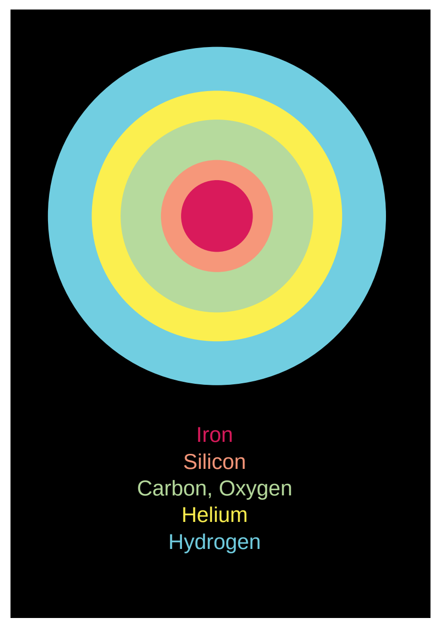
To examine mixing between the helium and hydrogen layers of Supernova 1987A, the most hydrodynamically unstable region of the exploding star, scientists have performed modeling studies using PROMETHEUS, a multidimensional hydrodynamics code, and the two-dimensional code CALE. They compared these simulation results with data from laser experiments that use planar foils with a tin-roof-like sinusoidal ripple to examine in two dimensions a localized region of activity. As shown in the figure on p. 15 (bottom right), the two codes give similar results, both of which agree well with experimental results.

But two-dimensional models predict maximum velocities of only about 2,000 kilometers per second for radioactive materials moving outward from the core, whereas observed velocities for these materials were actually more than 3,000 kilometers per second in Supernova 1987A. Three-dimensional hydrodynamic effects must be considered to explain these and other discrepancies between models and observations.

Laser targets for examining hydrodynamic behavior in three dimensions incorporate a miniscule dimple, invisible to the naked eye, that follows the same laws of hydrodynamics as 1987A. The figure on p. 16 compares a Nova radiograph of a dimpled experiment with a two-dimensional model. (Three-



Supernova 1987A, like other type II supernovas, occurred when the star's iron core collapsed.



In its death throes, Supernova 1987A resembled an enormous, many-layered onion as successively heavier layers of fuel ignited and burned.

dimensional supernova hydrodynamics are unfortunately prohibitively expensive to calculate, but three-dimensional laser experiments are no more expensive to run than two-dimensional ones.)

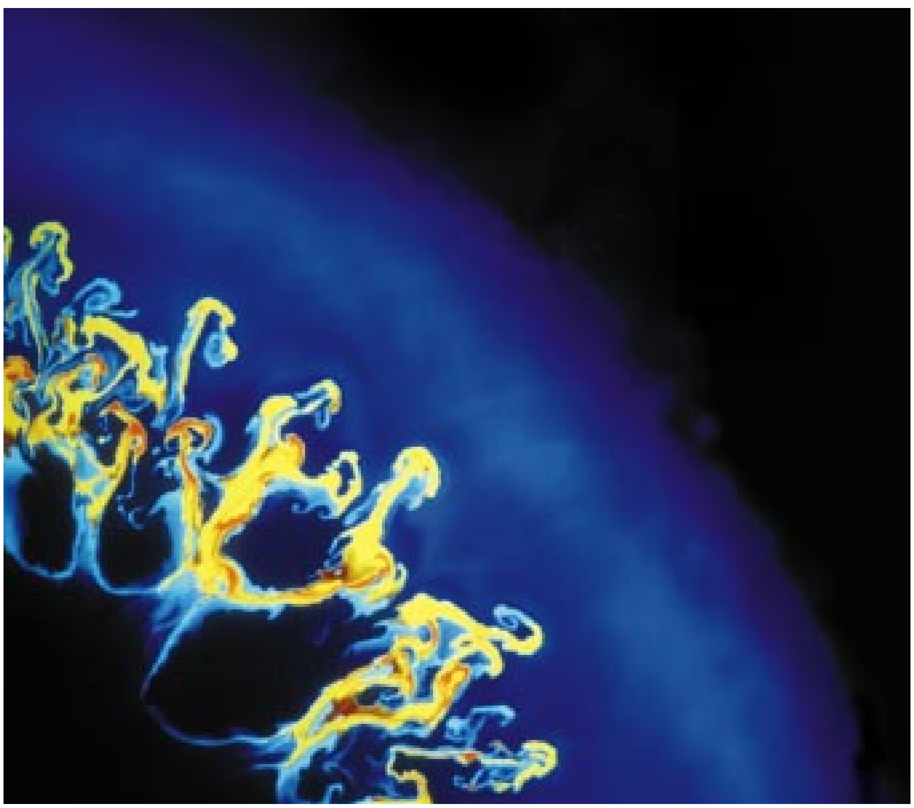
Laser experimentation for supernovas is becoming more complex all the time in an effort to incorporate as many features of supernovas as possible. Remington's team has begun to use multilayer targets in supernova experiments on the Omega laser at the University of Rochester (currently the world's largest operating laser), because an actual supernova does not have just two layers but many. The team is also considering creating density gradients in laser targets because the density within each layer of a supernova is not constant but rather drops smoothly with distance from the core. This density gradient would allow the shock wave to speed up with distance. An actual supernova is also spherical, not planar. Spherical geometry would cause the shock wave to expand, weaken, and slow, which is precisely the opposite of the effect due to the density gradients.

Initial spherical experiments have also been done on Omega. Consideration of the many factors involved will, over time, bring Livermore's laser experiments more in line with actual supernova behavior.

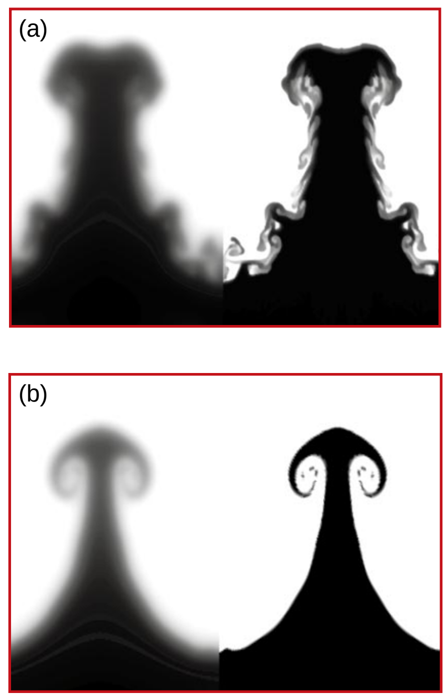
The Issue of Scale

The Euler equations, which describe the conservation of mass, momentum, and energy for fluids, do not know the difference between a tiny laser experiment and a huge supernova. At first, though, not all scientists were convinced that a laser simulation could be considered an accurate representation of the much larger event. Supernova 1987A is about 100 trillion times larger than a laser experiment. Its initial radius equals 20 million kilometers versus 0.2 millimeters for the laser experiment.

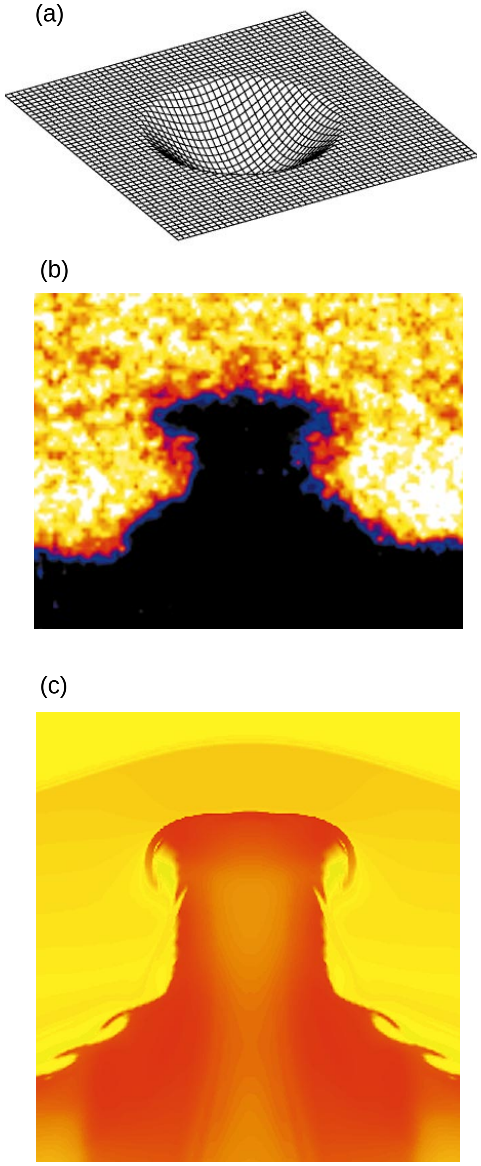
Remington notes that he and others spent a year and a half studying the scaling issue, performing laser experiments and innumerable calculations. Ultimately, they



Supernova 1987A provided strong evidence of turbulence emanating from the core of the exploded star because core materials were observed well before they were predicted. The turbulence caused mixing among the layers and greatly complicated the tidy "onion" model of dying stars. [Image reproduced from Muller, Fryxell, and Arnett, *Astronomy & Astrophysics* **251**, 505 (1991).]



The hydrodynamic mixing of the most unstable region (the hydrogen and helium layers) of Supernova 1987A has been modeled using (a) the multidimensional PROMETHEUS code and (b) the two-dimensional CALE code.



Using (a) "dimpled" targets, Nova experiments yielded (b) three-dimensional radiograph data of a laser implosion's hydrodynamics that show strong similarities to (c) a two-dimensional model of supernova hydrodynamics.

concluded that for the "intermediate" time frame of a supernova explosion, the hydrodynamics can be transformed from the microscopic to the astronomical scale. The intermediate time frame for the laser experiment is in the range of 20 nanoseconds after the initial shock, which, as it happens, is when bubble and spike growth typically occurs. The equivalent time for the supernova is roughly 2,000 seconds, that is, 11 orders of magnitude longer.

The Challenge Continues

The decommissioning of the Nova laser last year ended a four-year program of groundbreaking supernova hydrodynamics experiments at Livermore. With the Nova experiments, Remington and his team demonstrated the value of laser experiments to validate astrophysics codes and study hydrodynamics issues that are difficult to simulate. Nova also helped put to rest the issue of scale. Increasingly complex experiments continue on the Omega laser.

The spectacle of 1987A may not be over yet. Even before the star exploded in 1987, it had what appear to be gaseous rings around it. Those rings are still there, at an estimated distance of about a half light year (5 trillion kilometers) from the supernova's core. Late last year, the shock wave launched by the expanding debris from the supernova began to collide with the rings. Scientists predict that over the next decade, the collision should heat the rings, brightening the supernova again to produce another spectacular light show. Livermore's models and laser experiments will again be put to the test.

—Katie Walter

Key Words: hydrodynamics, modeling, Nova laser, Omega laser, Supernova 1987A, supernovas, turbulence.

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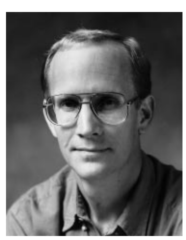
About the Scientist



BRUCE REMINGTON received a B.S. in mathematics from Northern Michigan University in 1975 and a Ph.D. in physics from Michigan State University in 1986. He joined the Laboratory as a postdoctoral associate in 1986 doing nuclear physics research and became a permanent staff physicist in the Laser Programs Directorate in 1988. As leader of the hydrodynamics group of the Inertial Confinement Fusion Program, he initiated and managed direct- and indirect-drive hydrodynamics experiments on the Nova laser related to high-energy-density regimes, compressed solid-state regimes, fluid dynamics, and astrophysics, work that continues on the Omega laser at the University of Rochester since Nova laser operations were discontinued. He is currently chair of the American Physical Society's Topical Group on Plasma Astrophysics.