Bringing the Stars Down to Earth

With plasma discharges and giant lasers, physicists are creating miniature supernovae and solar eruptions in their laboratories, opening an era of hands-on astrophysics

The resemblance immediately caught his eye, Bruce Remington recalls. Images in two different journals depicted daisylike patterns, formed when small ripples on a ball of plasma—or ionized gas—bloomed explosively into long, turbulent splashes. But the floral analogy wasn't what glued the Lawrence Livermore National Laboratory researcher to the pages; it was the gulf between what the look-alike images actually showed. One depicted the mixing of a speck of plasma less than a tenth of a millimeter across as a converging array of powerful laser beams at Livermore's Nova facility slammed into it. The other was a computer model—much simplified—of mixing in a supernova blast, millions of kilometers across.

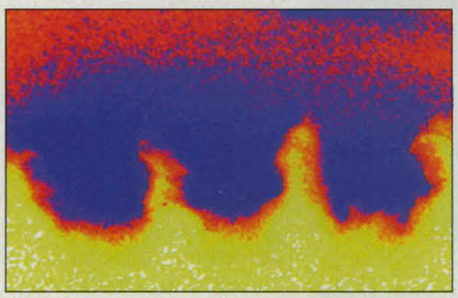
His first thought, Remington says, was: "'This must be a fluke.'" But when he worked out some of the numbers describing both systems, "it dawned on me that the physics was identical." If so, the Nova laser, ordinarily used to compress dollops of plasma to the temperatures and pressures needed for fusion, might also be able to mimic the roiling, radiating, three-dimensional (3D) dynamics of exploding stars. Now, nearly 4 years later, Remington's hunch has borne fruit, as data begin pouring from a successful preliminary run of supernova experiments at Nova.

The work has put him and his colleagues in the vanguard of a scientific movement that aims to bring astrophysics into the laboratory for study, rather than relying only on remote observations and computer simulations. With devices ranging from giant lasers to plasma-filled flasks, these experimenters are trying to mimic the huge solar eruptions called coronal mass ejections, the collision of material flung from supernovae with surrounding gases, and even some of the extreme conditions felt by particles near the boundaries of black holes. "There are very few contexts in which you can test the quite exotic physics you find in astrophysics," says Adam Burrows, an astrophysicist at the University of Arizona. These high-energy plasma experiments, he says, "approach the conditions found in stars."

Already, the experiments have boosted astrophysicists' confidence in the computer codes they use to describe the heavens, while providing some uncanny miniatures of events that could only be seen from afar. But Burrows cautions that the current round of lab work should be considered "first generation," and other astrophysicists are even warier. The scale differences between space and the lab "really clobber you" in mocking up some effects, says B. C. Low of the National Center for Atmospheric Research in Boulder, Colorado. Still, he says, the new work "can enrich your experience with astrophysical phenomena."

One spark for this burst of activity came just 10 years ago in February. The iron core of an old star in the Large Magellanic Cloud, just 170,000 light-years away, had grown so cool that it could no longer support the weight of the overlying layers. The core collapsed and then rebounded when it was compressed to the density of nuclear matter. The resulting shock wave, like a hellish version of the ripple created by dropping a rock into a pond, heaved all but the core of the star into space in a giant explosion. It also dealt a blow to prior understanding of how those explosions take place.

E. MÜLLER, B. FRYXELL, D. ARNETT/ASTRONOMY AND ASTROPHYSICS 251, 505 (1991)



G. GLENDINNING/LLNL

Uncanny likeness. Instabilities in a computer model of a supernova (*top*) and a submillimeter-size laser-fusion target.

In its old age, explains David Arnett of the University of Arizona, such a star has a layered structure, much like an onion. At the center is an iron core, which is enclosed in layers of successively lighter elements, topped off by helium and an outer envelope of hydrogen. Stellar modelers thought this onion structure would be preserved in the explosion, says Arnett, but their close look at supernova SN 1987A "provided evidence that the inside was drastically stirred up."

The first hint came just 3 weeks after the collapse, when the supernova starting glowing unexpectedly at certain wavelengths, suggesting that radioactive cobalt-56—generated deep in the star during the explosion—was already warming the expanding surface. In addition, Doppler shifts of the light showed that some of the debris was moving at thousands of kilometers per second, much faster than expected. It was as if "fingers" of fast-moving plasma were poking through the rest of the material. That interpretation seemed to be clinched when gamma rays from the cobalt-56 became directly visible 6 months earlier than expected. "It's a big turbulent mess, not at all like an onion skin," says Jave Kane of the University of Arizona. "It would be nice if you could find a turbulent plasma at high pressure here on Earth" to study that mess up close.

Scale models of stars

At Livermore, says Kane, "we've created just such a plasma." In the late 1980s, Barrett Ripin and his collaborators at the Naval Research Laboratory, and an independent Russian group, had proposed that laser implosions could mimic aspects of supernova explosions. Remington and his colleagues have now revived this analogy independently at Nova, the world's largest laser.

Remington had realized that the turbulent fingers in the supernova probably result from the same sort of instability that causes a fuel pellet to resist uniform compression when Nova's beams converge on it. In the pellet, the instabilities develop as a compressed, fast-moving surface layer driven inward by the lasers runs into resistance from deeper, hotter, lower density material. In the supernova, the fingers grow as the fast-moving helium layer propelled outward by the explosion runs into the star's hydrogen envelope.

The correspondence is close enough, says Remington, that "instead of thinking in kilometers, I change that to micrometers, seconds to nanoseconds—that's it, and the equations are the same." The miniature supernovae, he thought, might be able to offer insights into questions that simulations in supercomputers can't answer. Among them: why the fingers of SN 1987A are moving so fast—much faster than they do in the best supercomputer simulations that try to mimic the instabilities.

To produce its miniature supernovae, the Nova team, which includes Livermore's Gail Glendinning as the hands-on experimentalist, replaces the spherical pellet used for laser-fusion experiments with a target consisting of a sheet of copper, representing the supernova's helium layer, coated on one side with plastic, representing the hydrogen layer; the researchers mold minute ripples into the copper to "seed" the explosion with instabilities. They then install the target in a tiny window in the side of a millimeter-size, gold cylinder called a hohlraum, with openings at the ends through which the lasers fire. This heats the gold, producing a uniform background of x-rays that smack into the target from behind, on the copper side. In the subsequent explosion, the ripples in the target get amplified and are recorded by means of the shadows they cast against a separate x-ray source.

In the first round of experiments—about 20 shots last year—long, two-dimensional ripples resembling the corrugations on a tin roof served as initial perturbations. The team showed that the instabilities spawned in the shots nicely match the instabilities predicted by the PROMETHEUS supernova computer model developed by Arnett and others, adding to their confidence in the approach. "I was surprised at how well it did," Arnett says. "We certainly weren't tuning [the computer code] for those experiments."

The next step is to see whether the instabilities in these miniature supernovae can grow faster than those in the computer models. To find out, the team is already making laser targets that have more realistic, 3D perturbations, something like the bumps on an egg carton. The fingers that grow from such bumps may well shoot through the surrounding fluid faster, with less drag, than the 2D ripples, says Remington. After the first 3D shots late last year, an excited Remington would only say that "the experiment worked." If it did succeed in reproducing the fast-moving instabilities, says Arnett, astrophysicists will feel more confident in their basic understanding of how SN 1987A exploded.

F. HANSEN AND P. BELLAN/CALTECH

Dancing plasmas. Plasma arches meet and erupt in a laboratory simulation of an outburst on the surface of the sun.

A second set of Nova experiments focuses not on the observed part of the supernova explosion but on what is yet to come: the collision of the expanding debris with the strange, wispy set of rings surrounding it, which are thought to be gases blown out from the star for millions of years before it exploded. The collision should heat the rings, rebrightening the supernova as a whole by about a factor of 1000 over the next decade.

Astrophysicists like Richard McCray of the University of Colorado, Boulder, hope those fireworks will reveal the rings' detailed structure, and perhaps their origin. In preparation, McCray and John Blondin of North Carolina State University are simulating the smashup in two dimensions on the computer, hoping to learn how to interpret the actual observations. As McCray explains, however, "The computer will never tell you what you've forgotten to include." So, to make sure that their simulations are as realistic as possible, McCray, Paul Drake of the University of Michigan, and others are building and detonating plastic models of the supernova and its rings.

In these experiments, the researchers spray x-rays from a Nova hohlraum onto a slice of plastic—playing the role of the exploding star—which then vaporizes and forms a shock. As the material expands, it plows through a tenuous foam called an aerogel, representing the wind of particles from the progenitor star. The team hopes to learn just how wrinkled the shock front between the "explosion" and the "wind" becomes, because such wrinkles should affect the display that results when the real supernova finally slams into the ring. "We'll get a lot more out of the real collision when it happens" after poring over data from the miniature system, says Drake, a veteran laser-fusion experimenter.

Here comes the sun

Less cataclysmic explosions are the subject of other miniaturization efforts, such as ones by Paul Bellan and Freddy Hansen of the California Institute of Technology. They are trying to mimic the turmoil in the atmosphere of the sun, where immense, plasma-laden arches of magnetic field may linger quiescently for days before suddenly rousing themselves—sometimes after merging—and erupting into space.

One goal of the experiment is to explore a theory proposed by David Rust of Johns Hopkins University and his colleagues, which holds that the eruptions are triggered when the magnetic field becomes too tightly twisted, like a toy Slinky bent into an arch (*Science*, 15 September 1995, p. 1517). To produce twisted plasma arches, Bellan and Hansen started by placing a small horseshoe magnet against the side of a 1.4-meter vacuum chamber into which they could puff hydrogen gas. Then, they discharged a capacitor bank between the magnet's poles, turning the hydrogen into a plasma, which followed the arch of the field lines between the poles. Electric current running along the field lines added the twist, or helicity, that Rust's theory requires.

The experiment promptly yielded support for a link between twist and instability. Two "satellite" arches formed spontaneously. "They started getting bigger, and they danced around," says Bellan, "and they coalesced," forming a new arch with a double dose of helicity. This new structure soon exploded. Richard Canfield of Montana State University, who is organizing an American Geophysical Union–sponsored conference on helicity in laboratory and space plasmas, says, "There is certainly a possibility that [the results] bear on the stability of natural phenomena like solar prominences." But he cautions, "We'll just have to wait and see."

Instead of trying to bring entire astrophysical events into the lab, other researchers are trying to isolate and reproduce underlying processes—magnetic reconnection, for example, which is what allows magnetic arches to merge in the first place. Reconnection, in which the looping, arching, or spiraling field lines in two different blobs of plasma splice together, is also the driver for everything from solar flares to storms in the magnetosphere, the envelope of plasma trapped by Earth's magnetic field.

Building on earlier work by Reiner Stenzel and Walter Gekelman at the University of California, Los Angeles, Masaaki Yamada and Hantao Ji of the Princeton Plasma Physics Laboratory are puffing out plasma "smoke rings" within a laboratory vessel by firing carefully controlled bursts of current through donut-shaped metal cores. They then allow the plasmas to merge. Because Yamada and Ji can control the angle at which magnetic field lines wind through these plasmas, called spheromaks, they can study how reconnection rates depend on the relative angles of the merging field lines. In this 3D geometry, they can also search for effects neglected in oversimplified, 2D theories, says Amitava Bhattacharjee, a theorist at the University of Iowa. "Real solar and magnetospheric configurations are three-dimensional," says Bhattacharjee.

So far, the team has shown that the reconnection rate is fastest when the merging field lines are nearly antiparallel. That matches a relationship seen in the "space weather" generated when magnetized plasma flies outward from the sun and strikes Earth's magnetosphere, notes James Drake, a plasma theorist at the University of Maryland, College Park. Storms are most likely, Drake notes, when the fields of the solar wind and the magnetosphere are antiparallel. The size of the reconnecting region also roughly matches the predictions of Drake's own computer model of reconnection. "This experiment is going to be a very nice place to test my theory," he says.

These laboratory flares and exploding stars mimic relatively familiar events. But researchers are considering other experiments that would probe far more exotic astrophysical environments. Toshiki Tajima of the University of Texas, Austin, and Pisin Chen of Stanford University have pointed out that the pressure of light from ultraintense, tabletop lasers (*Science*, 5 January 1996, p. 25) can shove electrons with a force equivalent to that of gravity's tug in the vicinity of a black hole with the mass of millions of suns.

By colliding with the sea of "virtual" photons that, according to quantum mechanics, pop in and out of existence throughout space, such electrons might scoop an occasional photon out of the vacuum, causing empty space itself to glow. The process would mimic the so-called Hawking radiation that theorists predict is sparked by the powerful gravity of black holes. Tajima cautions that "the practical difficulties would be formidable"—especially picking the radiation out of a background of ordinary light.

Such challenges, together with the vast gulfs in scale between the cosmos and the lab bench, mean that these astrophysical microcosms won't be putting telescopes and supercomputers out of business anytime soon. But there is no question that a new player has arrived on the scene, says Bhattacharjee: "There is, in the final analysis, no substitute for comparison with experiment."

–James Glanz

Additional Reading

B. A. Remington *et al.*, "Supernovae hydrodynamics experiments on the Nova laser," *Physics of Plasmas* **4**, 1994 (1997).

M. Yamada *et al.*, "Identification of Y-shaped and O-shaped diffusion regions during magnetic reconnection in a laboratory plasma," *Physical Review Letters* **78**, 3117 (1997).

P. M. Bellan, "Solar Drivers of Interplanetary and Terrestrial Disturbances," in *Astronomical Society of the Pacific Conference Series* **95**, 1996, K. S. Balasubramaniam, S. L. Keil, R. N. Smartt, Eds., p. 242.

ECOLOGY

Taking the Measure of Life in the Ice

At first glance, the seventh continent's pack ice seems like an eerie wasteland. But looks can be deceiving. Hidden inside the meter-thick slabs of ice that form each year across 20 million square kilometers of the Southern Ocean, a diverse ecosystem is thriving. The interior of an ice floe is much like a frozen honeycomb, laced with channels of slushy brine. These waterways teem with algae, which capture light filtering through the ice and help form the basis of a frosty food web that cycles carbon and other nutrients up through krill and fish to penguins, seals, and whales.

Scientists have long known that this "crop" of algae grows each year in the ice. But they have had difficulty quantifying it because the ice—and its suitability as algae habitat—varies enormously across the ocean. Now, on page 394, ecologist Kevin Arrigo of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and colleagues unveil a mathematical model that uses data and equations derived from remote-sensing satellites and laboratory and field studies to put real numbers on the total primary production, or plant life produced through photosynthesis, in pack ice. Among other findings, the model reveals that this ice yields fully one-quarter of the primary production in the part of the Southern Ocean that is covered with ice.

ARRIGO ET AL.

Bumper crop. The most productive (red) ice surrounding Antarctica forms annually.

With the model, researchers say they will finally be able to begin unraveling the Southern Ocean's complex food web and better understand the role these tiny organisms play in cycling carbon through the biosphere. "It's great progress for the field," says Cornelius Sullivan, director of the Office of Polar Programs at the U.S. National Science Foundation, who adds that the study is one of the first to look at the overall contribution of algae in pack ice to the ocean ecosystem.

More than 150 years have passed since British botanist Sir Joseph Dalton Hooker first described "microscopic vegetables," or brown algae, in Antarctic sea ice. Since then, researchers have learned that sea-ice populations of algae are determined by basically two resources: sunlight and nutrients—the phosphates, nitrates, and silicates in seawater. But getting a fix on the total algal production in pack ice has proved difficult. The ice is vast, cold, and unstable, making it a dangerous place for fieldwork. "Scientists have not been able to carry out large-scale synopses or studies on sea-ice ecology," says study coauthor Gerhard Dieckmann of the Alfred Wegener Institute for Polar Marine Research in Bremerhaven, Germany.

What's more, says Arrigo, "the ice isn't a single slab. It's dynamic and heterogeneous." As a result, the amount of algae can vary considerably even within the layers of a single floe. In the deeper layers, for instance, algal growth may be stifled by lack of light, while populations near the top may not get the nutrients that flood into the base of the ice from the seawater below.

So, Arrigo and his colleagues set out to estimate primary production by simulating this icy habitat in a computer. They turned to satellite images of the region for basic information about cloud cover and snow cover. From field studies, they incorporated information about the pack ice's porosity and other physical characteristics. Then they worked in equations describing how algal growth responds to changes in light, temperature, and nutrient supply.

According to the model, even during the gloomy Antarctic winter, an average of 50 micrograms of algae grow in each square meter of ice every day. The total production each year turned out to be about 35 billion kilograms of carbon, or about one-fourth of the total primary production in the ice-covered Southern Ocean, say the researchers.

According to the model, the most important factor in algae production was snow cover. In general, regions that got a lot of snow produced the most algae per square meter of ice, says Arrigo. The snowy Weddell Sea, for instance, just one-quarter of the ice-covered waters around Antarctica, produced half the algae in pack ice. While a light dusting of snow can limit algal growth by blocking out sunlight, a heavy snow can dunk an ice floe, flooding it with fresh nutrients from deeper seawater. Algae in the ice then feast on the