ASTRONOMY

For a Successful Supernova, Mix Well, Then Explode

TUCSON, ARIZONA—At the American Astronomical Society's meeting here last month, Alexei Filippenko introduced a lecture on supernovae with an old stunt. Carefully placing a tennis ball directly on top of a basketball, the University of California, Berkeley, astronomer dropped the two objects simultaneously. The basketball hit the floor, quickly compressed, and then rebounded, rocketing the tennis ball high above Filippenko's head. Then gravity won out and the ball fell back to the floor.

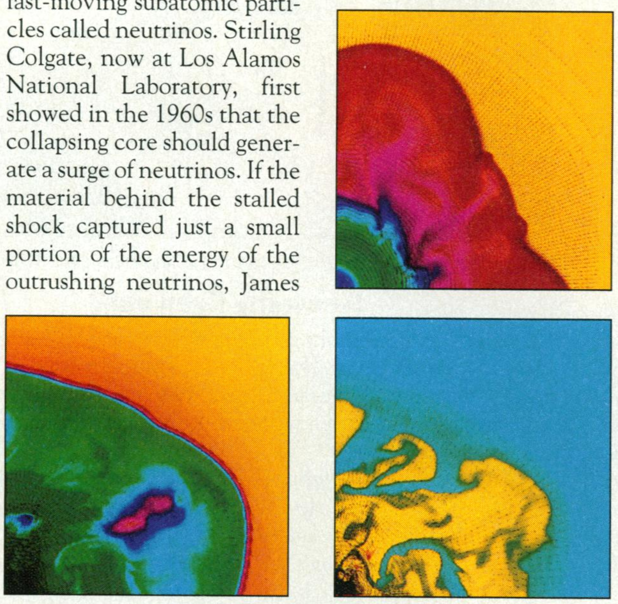
Filippenko's sporting demonstration illustrated what frustrated astronomers call the "supernova problem"—a puzzle that several groups believe they have now taken a big step toward solving. At the end of their lives, massive stars collapse and then rebound, blowing off their outer layers by a mechanism much like the one that launches the tennis ball toward the ceiling. Yet although nature explodes massive stars with ease, researchers trying to simulate the event can't match the feat on their computers. The models start with a bang but end with a whimper: The shock wave from the star's rebounding core stalls before it can blow the star apart.

But the Tucson meeting saw the debut of new supernova simulations, exploiting powerful supercomputers, that really do blow up. The key to a successful model seems to be simulating the explosion in two dimensions—on a plane slicing through the exploding star—rather than the traditional one dimension. That way, the hot gases can circulate like water at a rolling boil, a process that somehow revives the arrested shock wave. Says University of Arizona theorist Willy Benz, a member of one group: "They explode a heck of a lot easier in 2D than 1D."

The explosions Filippenko, Benz, and others want to understand are known as type II supernovae. These cataclysmic events occur when the core of a star many times more massive than the sun runs out of fuel. Having fused hydrogen to helium, helium to carbon and oxygen, and so on, it finally arrives at iron, from which no more fusion energy can be extracted. The inner core can no longer sustain itself against the crushing force of gravity, and it collapses in less than a second from a radius of thousands of kilometers to less than 30.

At that point the inner core rebounds, rather like Filippenko's basketball, collides with the still-collapsing outer core, and generates a shock wave. Theorists believe that this shock wave is what destroys the star, igniting the supernova's brilliant display and triggering new waves of nuclear fusion as it races through the star's outer layers. In the models, however, the shock loses energy fighting its way out through the collapsing outer core and stops dead.

Many researchers have guessed that the key to reviving the stalled explosions is the fast-moving subatomic particles called neutrinos. Stirling Colgate, now at Los Alamos National Laboratory, first showed in the 1960s that the collapsing core should generate a surge of neutrinos. If the material behind the stalled shock captured just a small portion of the energy of the outrushing neutrinos, James Wilson of Lawrence Livermore National Laboratory and others calculated in the 1980s, the simulated stars should explode. But when "neutrino heating" was incorporated into models of the day, the simulations still fizzled.



PHOTOS BY ADAM BURROWS, JOHN HAYES, AND BRUCE FRYXELL

Reviving a supernova. A shock wave stalled inside a giant star (red-yellow boundary in the computer simulation at top) revives within milliseconds when rising bubbles of hot material (red and yellow in the images above) thrust it outward.

Wilson and others, including Hans Bethe of Cornell University, then began to argue that the key to turning neutrino heating into an explosion might be circulation patterns within the collapsed star—something that could only be captured in more complex models that operate in two or more dimensions. An early confirmatory hint came when, through programming tricks, Wilson got his one-dimensional models to incorporate aspects of two dimensions. "Jim said he could get explosions, but how he did it was magic and nobody else could do it," recalls theorist Stanford Woosley of the University of California, Santa Cruz.

Now more powerful computers that can run full-fledged 2D simulations are letting others share Wilson's magic. In one model, by Benz, Mark Herant of the theory division at Los Alamos, and their colleagues, large bubbles of material heated by the neutrinos rise buoyantly, while colder material plunges toward the core. This "overturning," the modelers say, efficiently transfers energy from the neutrinos outward to the stalled shock, building up the pressure behind it until the star explodes like a pressure cooker blowing off its lid.

Adam Burrows of the University of Arizona sees similar circulation patterns in his own group's simulations, but he offers a slightly different description of how they open the way to an explosion. He explains that the rising plumes of material nudge the stalled shock outward, where the pressure of infalling matter drops. Over time the infall drops even more, until the shock can blow off the pressure cooker lid. That's only a subtle difference in interpretation, argues Herant, who says that "the similarities [between the two models] are more important than the differences."

Among those similarities is the ability to explain not only supernova explosions themselves but also the heterogeneous appearance of the debris. One-dimensional models imply that supernovae should expand evenly, but observations of the great supernova of 1987 showed that some of the ejected material was churned up from deep inside the progenitor star. Mixing within the star just before it explodes can explain that observation and may also explain why pulsars, the remnants of ancient supernovae, are often spotted moving at high speeds across the sky. In the models, the churning results in lopsided blasts that could deliver a rocketlike "kick" to a pulsar, suggests Burrows.

Even so, modelers are not ready to say that they've truly licked the supernova problem. For one thing, the fusion triggered by the revived shock in the models creates a glut of elements such as krypton and yttrium, which are scarce in the real thing. "You end up with enormous amounts of things that are rare in the universe. That can't be right," says Woosley. And nobody knows what will happen when future increases in computer power make it possible to extend the simulations to a full three dimensions—the explosions may fizzle again. As Burrows and his collaborators write in a recent preprint, "The supernova problem has been solved many times in the last 30 years, but never yet for long."

–John Travis