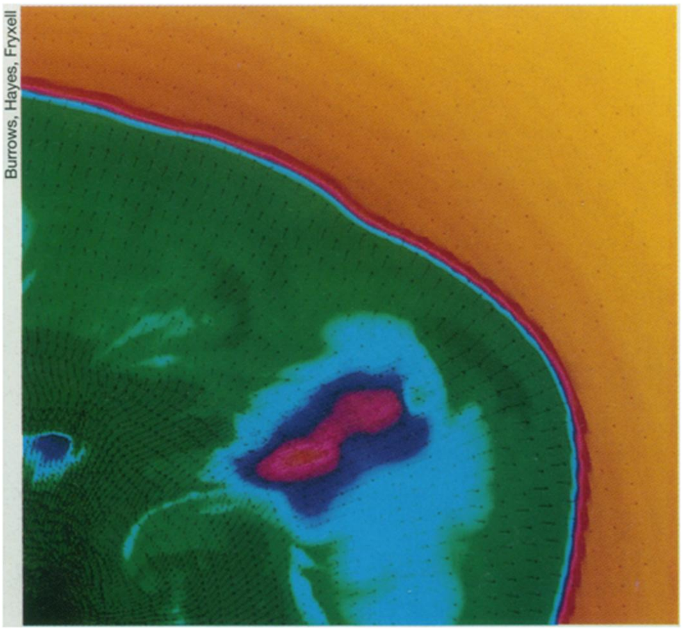
How Stars Die: The Shocking Truth

Supernova theories come of age

By RON COWEN



Burrows, Hayes, Fryxell

Graphic depicts the distribution of heavy elements, such as iron and zirconium, 100 milliseconds after a star explodes as a type II supernova. Red denotes high abundance, and green and blue denote low abundance. The curved outline shows the shock wave, no longer stalled. Red blob moves outward at about one-seventh the speed of light and is the main piece of shrapnel ejected in this simulation.

Roughly once a second, a star somewhere in the universe explodes. Some of these stars are blown to smithereens, strewing ashes through space. Others lose only their outer layers, leaving behind an unimaginably dense core.

Both kinds of explosions, known as supernovas, represent the most powerful events in the cosmos and have some of the most far-reaching astronomical consequences.

Although nature has no trouble making stars explode, researchers do. For years they couldn't find a model to account for the fireworks. Instead of producing a titanic blowup, many of their efforts just bombed out.

That's because available computer power limited scientists to simplistic, one-dimensional simulations of a complex, multidimensional problem. Now, thanks to supercomputers and improved software that enable astronomers to explore more realistic models, scientists say they have discovered how stars break up.

"This is a real breakthrough," comments Alexei V. Filippenko of the University of California, Berkeley. "For decades, people have been trying to get stars to blow up, but nothing panned out. Here, with the increase in computing power . . . astronomers are successfully explaining physics that could not be modeled in previous calculations."

Astronomers detailed their insights into two classes of supernovas last month at a meeting of the American Astronomical Society (AAS) in Tucson.

Type II supernovas, the explosion of stars at least eight times the mass of the sun, leave behind a dense core. Type Ia supernovas typically involve stars about 1.4 times as massive as the sun and burn completely.

The new view of Ia supernovas promises to narrow the gap between teams of researchers who ascribe widely different values to the Hubble constant, a measure of the expansion rate, age, and size of the universe (SN: 10/8/94, p.232).

It takes about 10 million years for a massive star to mature. For most of that time, it battles successfully against collapse by burning nuclear fuel, which generates heat and an outward pressure sufficient to counter gravity. During this time, it fuses hydrogen, helium, and other light nuclei, forming heavier elements (SN: 2/4/95, p.70). The star must continue to build increasingly heavy nuclei in order to maintain its source of energy.

But once such a star begins making nuclei as heavy as iron and nickel, it has signed its death warrant. Forming any heavier nuclei would take away energy rather than release it. Its fuel depleted, the star can no longer resist gravity's tug and collapses in a matter of hours to days.

Just before it collapses, the core of such a star may have a diameter of 3,000 kilometers, a temperature of a few billion kelvins, and a density of 10 billion grams per cubic centimeter. Afterwards, the core shrivels to a diameter of 30 km, the temperature climbs to 200 billion kelvins, and the density increases 10,000-fold. Protons and electrons squeeze together, and the compact core soon becomes a tiny, rapidly whirling ball of neutrons — a neutron star.

Soon after the implosion, material from outside the core begins raining down. At the same time, the core rebounds, sending out a shock wave. The speeding wave rapidly loses energy, stalling some 100 kilometers beyond the core. Moreover, the infalling gas acts as the lid on a pot, containing the wave.

Will this massive star ever explode?

The answer, according to earlier, independent work by James R. Wilson of Lawrence Livermore (Calif.) National Laboratory and Hans A. Bethe of Cornell University, lies in subatomic particles called neutrinos.

In addition to generating a shock wave, the neutron star emits a fireball of neutrinos equivalent to the radiation that would be produced if 50,000 bodies with the mass of Earth were suddenly converted into energy. These neutrinos carry heat from the star's core to the outlying layers of gas.

It seems that this heat should give the shock wave the extra oomph it needs to blow the lid off the star. But in the one-dimensional model that astrophysicists had relied on, matter has the same restrictions as beads on a string — it can't push aside material directly in front of it. Thus, the neutrino-heated gas just above the core can't rise and energize the shock wave stalled above it.

Instead, the neutrinos heat only the thin layer of gas directly above the core.

Unable to cool by rising and expanding, this gas lowers its temperature by emitting neutrinos of its own. Thus the core stays hot, the gas raining down stays cold, and the shock wave goes nowhere.

In this scenario, the star has only a slim chance of going bang.

Theorists got a dose of reality 8 years ago with the dazzling debut of 1987A, the first type II supernova visible to the naked eye since the time of Johannes Kepler. In the first few hundred days after they observed the outburst, researchers found clear signs that 1987A wasn't the spherically symmetrical explosion that theory predicted.

X rays and gamma rays from deep within the exploded star appeared sooner than expected, indicating that the inner and outer parts of the star had mixed thoroughly in the outburst. Some material from the deepest layers was found in the first one-third of the ejected debris. And some material from the star's outer layers was observed only later in the explosion.

"It was more like scrambled eggs than sunny-side up," recalls Willy Benz of the University of Arizona in Tucson. Further analysis suggested that the star had ejected more material in some directions than in others.

Prompted by these findings, several research groups developed multidimensional models to account for the lopsided explosion. But the models couldn't explain the mixing. So Benz, in collaboration with Marc Herant and Stirling A. Colgate of Los Alamos (N.M.) National Laboratory, began work on a two-dimensional model that would. Another team, which includes Adam S. Burrows and John C. Hayes of the University of Arizona and Bruce A. Fryxell of NASA's Goddard Space Flight Center in Greenbelt, Md., developed a similar model. They described their simulations at last month's AAS meeting.

In the new models, colder gas from outside the core still rains down on the core and meets an increasingly higher concentration of neutrinos. But in two dimensions the gas is free to rotate like a ferris wheel.

This swirling motion has a profound effect. As the infalling gas absorbs neutrinos and grows hotter, it floats upward in huge bubbles, like giant hot-air balloons. The heated gas imparts its energy to a much larger percentage of the star than it did in the one-dimensional model. By converting heat into motion, the neutrinos aid the shock wave expanding from the collapsed core.

The wave still stalls, but it does so farther from the star's center, in a considerably less dense region, notes Burrows. This time, the shock wave stops only momentarily. In a few seconds, the wave gathers enough speed to explode as a type II supernova.

If the bubbles of heated gas are large enough, they rocket the neutron star core into space. This may explain the high velocity of neutron stars, Burrows says.

Although the broad outline of their studies seems to match observations, Burrows and Benz both emphasize that they need to extend their work to three dimensions. In both models, the exploded stars produce far too much yttrium, thorium, and strontium.

The two teams differ in their exact interpretation of why massive stars explode as type II supernovas. Burrows, for example, eschews the pot lid analogy, arguing that the neutrino-driven transfer of heat by rising gas bubbles holds the key. Nonetheless, notes Benz, "we've moved from having models that failed to arguing about the interpretation of models that are successful."

Although they have less mass, Ia supernovas flash even more brightly than type II supernovas because they produce 10 times as much radioactive nickel. Astronomers believe that Ia supernovas form a set of "standard candles," meaning that they all have the same intrinsic brightness, like lightbulbs of a particular wattage (SN: 10/8/94, p.232).

Standard candles enable researchers to measure the distance from the Milky Way to various galaxies. If a galaxy lies far enough away, astronomers can use that measure to calculate the Hubble constant. The premiere standard candle remains a type of pulsating star known as a Cepheid variable. But astronomers can detect Ia supernovas in galaxies 10 to 100 times farther away than the Cepheids, potentially improving measurements of the Hubble constant.

Allan R. Sandage of the Carnegie Observatories in Pasadena, Calif., and his colleagues have used Ia supernovas to calculate a Hubble constant of about 50, a number that implies the universe is about 20 billion years old. That makes many theorists happy, because it doesn't conflict with the ages of some of the oldest known groupings of stars in the cosmos, estimated to be 16 billion years old.

However, his team's calculations conflict with those of many other research groups, who get a higher value for the Hubble constant and a correspondingly younger age for the cosmos.

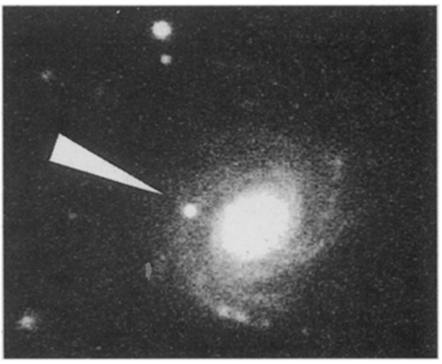
Results of a survey of Ia supernovas suggest a way to reconcile the disparity. In analyzing half of the 50 type Ia supernovas discovered during the past 4 years at the Cerro Tololo Inter-American Observatory (CTIO) in La Serena, Chile, researchers found that not all of these exploded stars have the same intrinsic brightness.

In particular, Ia supernovas that have the longest peak brightness are in fact more luminous than those that fade faster. CTIO astronomers Mario Hamuy, Mark Phillips, and their colleagues also announced at the Tucson meeting that the brightest Ia supernovas typically reside in either spiral galaxies or galaxies with many bright, young stars.

Phillips and his colleagues note that, in order to calibrate the distance to supernovas in galaxies farther from the Milky Way, Sandage's team relied on two nearby Ia supernovas. One of these supernovas exploded in 1972, the other in 1937, but both faded slowly.

The slow decline indicates that each of these reference supernovas was slightly more luminous than Sandage's team had assumed, Phillips says. The Chile-based astronomers assert that when the true luminosity of these supernovas is taken into account, their survey will yield a Hubble constant of between 60 and 70, a value more in line with recently reported results that give the universe an age of 8 to 12 billion years.

But what makes the intrinsic brightness of Ia supernovas vary in the first place? Philip A. Pinto of the University of Arizona suggests that the answer lies in the properties of the stars that end their lives in these explosions.



National Optical Astronomy Observatories

Image of the spiral galaxy UGC 5691 shows a type Ia supernova (arrow) discovered during a 1991 survey at CTIO.

Astronomers believe that Ia supernovas occur when a kind of dense star known as a white dwarf gravitationally grabs a critical amount of matter from a companion star, sparking a thermonuclear explosion.

Standard theory holds that all white dwarfs that give rise to Ia supernovas have the same mass — about 1.4 times that of the sun. But Pinto proposes that some white dwarfs steal more matter than others, resulting in explosions that can vary slightly in power and luminosity.

Other researchers have other explanations, and thinking remains unsettled. Even though computer simulations of type Ia events are more advanced than those of the type II phenomenon, "we still don't understand how these stars explode," Pinto says. The CTIO findings may well spark a minor revolution in the way astrophysicists think about these explosions, he adds.

"Every kid loves an explosion," notes Colgate. "This is just the biggest one you can play with — at least in your head." ☐