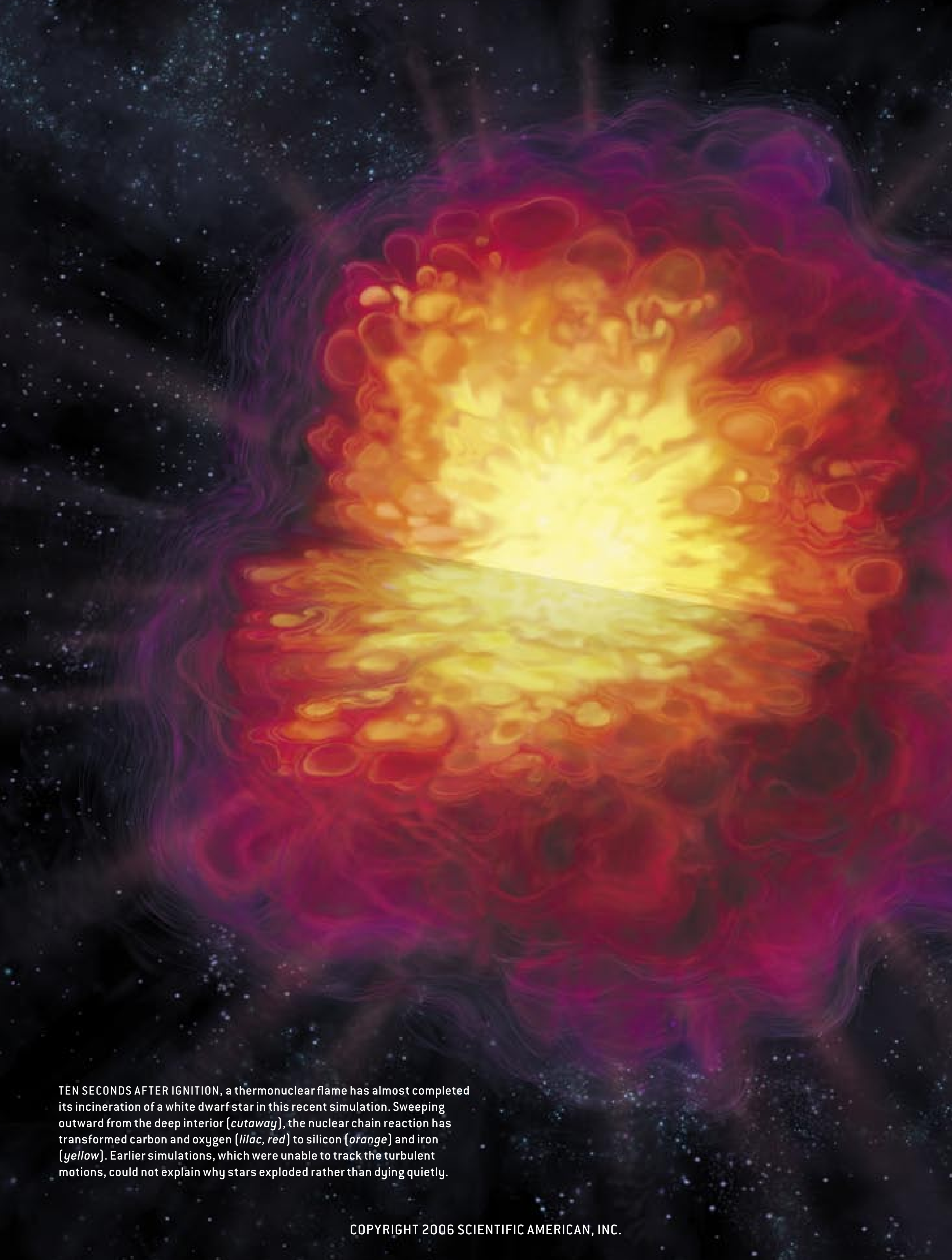


TEN SECONDS AFTER IGNITION, a thermonuclear flame has almost completed its incineration of a white dwarf star in this recent simulation. Sweeping outward from the deep interior (*cutaway*), the nuclear chain reaction has transformed carbon and oxygen (*lilac, red*) to silicon (*orange*) and iron (*yellow*). Earlier simulations, which were unable to track the turbulent motions, could not explain why stars exploded rather than dying quietly.

HOW TO BLOW UP A STAR

By Wolfgang Hillebrandt,
Hans-Thomas Janka
and Ewald Müller

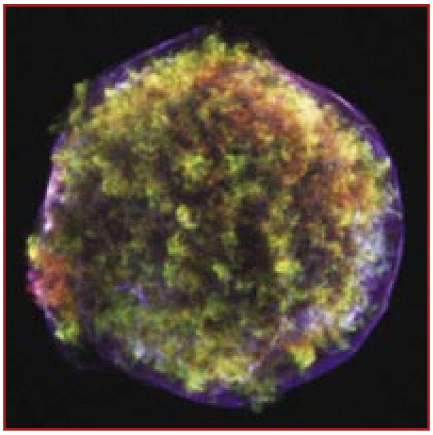
It is not as easy as you would think. Models of supernovae have failed to reproduce these explosions—until recently

On November 11, 1572, Danish astronomer and nobleman Tycho Brahe saw a new star in the constellation Cassiopeia, blazing as bright as Jupiter. In many ways, it was the birth of modern astronomy—a shining disproof of the belief that the heavens were fixed and unchanging. Such “new stars” have not ceased to surprise. Some 400 years later astronomers realized that they briefly outshine billions of ordinary stars and must therefore be spectacular explosions. In 1934 Fritz Zwicky of the California Institute of Technology coined the name “supernovae” for them. Quite apart from being among the most dramatic events known to science, supernovae play a special role in the universe and in the work of astronomers: seeding space with heavy elements, regulating galaxy formation and evolution, even serving as markers of cosmic expansion.

Zwicky and his colleague Walter Baade speculated that the explosive energy comes from gravity. Their idea was that a normal star implodes until its core reaches the density of an atomic nucleus. Like a crystal vase falling onto a concrete floor, the collapsing material releases enough gravitational potential energy to blow the rest of the star apart. An alternative emerged in 1960, when Fred Hoyle of the University of Cambridge and Willy Fowler of Caltech conceived of the explosions as giant nuclear bombs. When a sunlike star exhausts its hydrogen fuel and then its helium, it turns to its carbon and oxygen. Not only can the fusion of these elements release a titanic pulse of energy, it produces radioactive nickel 56, whose gradual decay would account for the months-long afterglow of the initial explosion.

Both these ideas have proved to be right. Of the supernovae that show no signs of hydrogen in their spectra (designated type I), most (type Ia) appear to be thermonuclear explosions, and the rest (types Ib and Ic) result from the collapse of stars that had shed their outer hydrogen layers. Supernovae whose spectra include hydrogen (type II) are thought to arise from collapse as well. Both mechanisms reduce an entire star to a shell of gaseous debris, and gravitational collapse events also leave behind a hyperdense neutron star or, in extreme cases, a black hole. Observations, notably of supernova 1987A (a type II event), have substantiated this basic theoretical picture [see "The Great Supernova of 1987," by Stan Woosley and Tom Weaver; Scientific American, August 1989].

Even so, explaining supernovae is still a major challenge for astrophysicists. Computer simulations have had trouble reproducing the explosions, let alone their detailed properties. It is reassuringly hard to get stars to explode. They regulate themselves, remaining very stable for millions or billions of years. Even dead or dying stars have mechanisms causing them to peter out rather than blowing up. Figuring out how these mechanisms are overcome has taken multidimensional simulations that push computers to, and beyond, their limits. Only very recently has the situation improved.



TYCHO'S SUPERNOVA, a thermonuclear explosion observed by renowned Danish astronomer Tycho Brahe in 1572, left behind a cloud of silicon, iron and other heavy elements glowing in x-rays (*green, red*). The shock front (*thin blue shell*) expands outward at 7,500 kilometers a second.

Overview/*Supernovae*

- By all rights, stars should be stable, sober creatures, preferring to die with a whimper than with a bang. Astronomers have struggled to understand why some of them go supernova. These explosions have resisted efforts to describe them in a simplified way, making them perhaps the most complex phenomena in all of astrophysics.
- Theorists have gradually ratcheted up the sophistication of their models and have recently succeeded at last in reproducing the two main types of supernovae. The key has been to capture all three spatial dimensions in fine enough detail to track the turbulent flow dynamics.
- They have discovered that the explosions can be seriously lopsided, stirring the debris (which includes newly synthesized chemical elements) thoroughly. In the kind of explosion that leaves behind a neutron star, this star recoils and careens across the galaxy at high speed.

Blowing Up Is Hard to Do

IRONICALLY, the stars that are thought to blow up as type Ia supernovae are usually paragons of stability—namely, white dwarf stars. A white dwarf is the inert remnant of what used to be a sunlike star. If left unmolested, it stays more or less in the state it was born, gradually cooling down and fading out. But Hoyle and Fowler argued that if a white dwarf tightly orbits another star, it may accrete matter from its companion, grow in mass and become ever more compressed at its center, until it reaches densities and temperatures sufficiently high to explosively fuse carbon and oxygen.

The thermonuclear reactions should behave rather like an ordinary fire. A front of burning should sweep through the star, leaving behind a pile of nuclear ash (mainly nickel). At any moment, the fusion reactions would occur in a tiny volume, most likely at the surface of ash-filled bubbles floating in the deep interior of the white dwarf. Because of their lower density, the bubbles would be buoyant and try to rise toward the surface of the star—much like steam bubbles in a pot of boiling water.

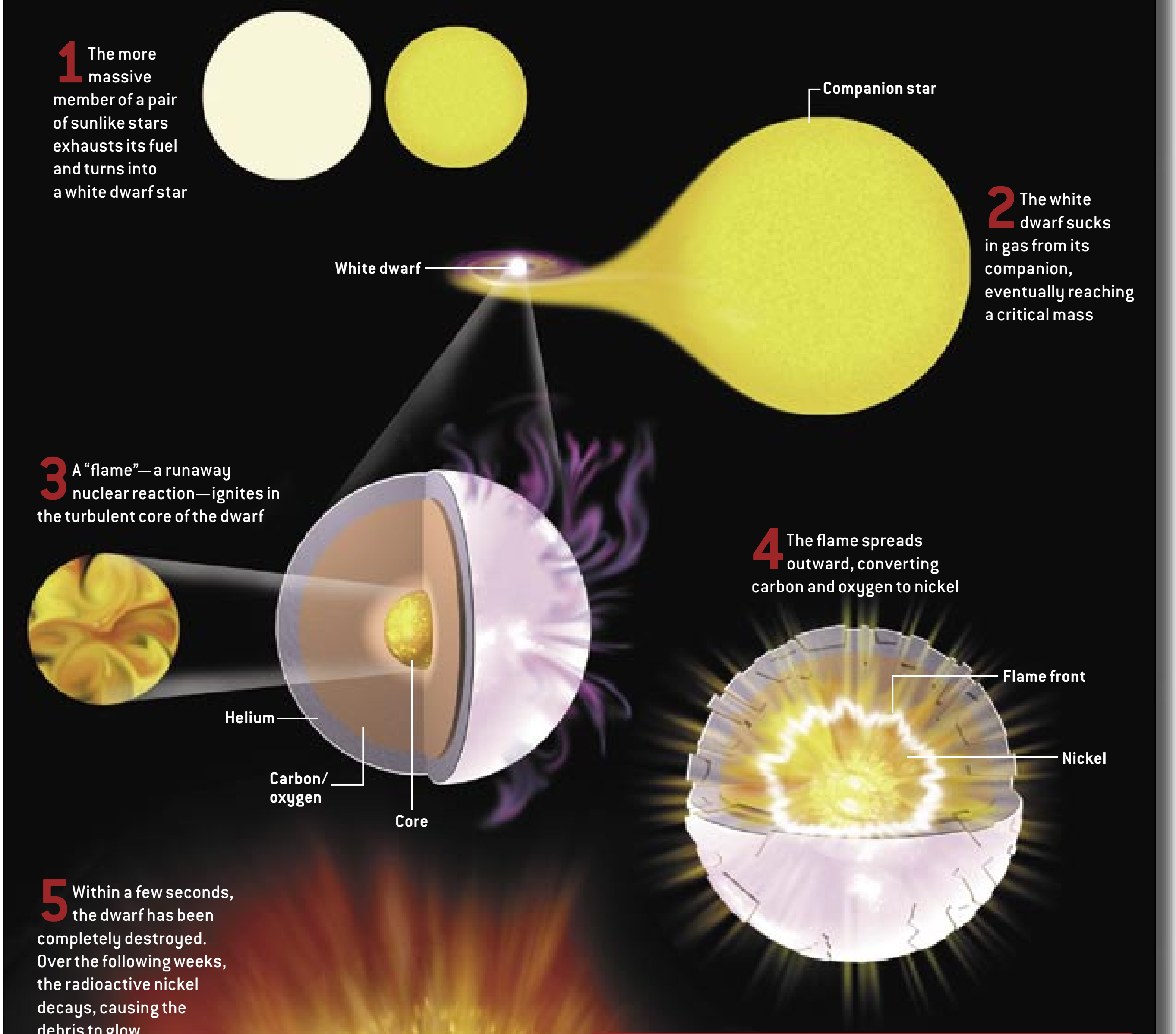
The trouble with this picture was that the thermonuclear flame should fizzle; the energy released would cause the star to expand and cool, thereby quenching the burning. Unlike an ordinary bomb, a star has no walls to confine it and prevent this self-extinguishment.

Coupled with this theoretical stumbling block has been a practical one. No lab experiments that reproduce the conditions in supernovae can be performed, and observations are subject to their own limitations. The best approach that astrophysicists have is to try to simulate the explosion on a computer. That is a momentous task. Currently the most precise simulations, which our group has conducted using an IBM p690 supercomputer, divide the star into a grid of up to 1,024 elements on a side, capturing details as small as a few kilometers across. A single run requires a few times 10^{20} arithmetic operations, and for such a complex problem, the supercomputer can perform several 10^{11} operations a second. All in all, it takes al-

PAT RAWLINGS SAIC (*preceding pages*); NASA/CXC/JESSICA WARREN, JOHN P. HUGHES ET AL. *Rutgers University*

THERMONUCLEAR SUPERNOVA

One class of supernova, known as type Ia, is the sudden nuclear detonation of an entire star.



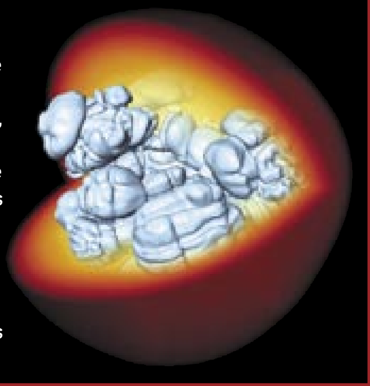
1 The more massive member of a pair of sunlike stars exhausts its fuel and turns into a white dwarf star

2 The white dwarf sucks in gas from its companion, eventually reaching a critical mass

3 A "flame"—a runaway nuclear reaction—ignites in the turbulent core of the dwarf

4 The flame spreads outward, converting carbon and oxygen to nickel

5 Within a few seconds, the dwarf has been completely destroyed. Over the following weeks, the radioactive nickel decays, causing the debris to glow



The breakthrough in modeling these supernovae has been the ability to capture turbulence. In this frame, showing the interior 0.6 second after ignition, the nuclear burning front has a turbulent, bubblelike structure (*blue*). Turbulence causes the front to spread quickly and overwhelm the star's stabilizing mechanisms.

DON DIXON (*illustrations*); WOLFGANG HILLEBRANDT AND FRIEDRICH ROEPKE *Max Planck Institute for Astrophysics* (*simulation*)

most 60 processor-years. The computational tricks that simplify simulations in other areas of science do not apply to supernovae, which involve highly asymmetrical flow, extreme conditions, and a huge range of spatial and temporal scales. Particle physics, nuclear physics, fluid dynamics and general relativity are complicated enough on their own, but a supernova simulation must consider all of them at once.

Under the Hood

THE SOLUTION has come from an unexpected quarter: the physics of car engines. Mixing and igniting gasoline and oxygen in an engine generates turbulence. Turbulence, in turn, increases the surface area of the flames by wrinkling and stretching them. The rate of fuel consumption, proportional to flame area, goes up. A star, too, is naturally turbulent. Because the gas moves vast distances at high velocities, even a slight disturbance quickly turns a smooth flow into a turbulent one. In a supernova, the rising hot bubbles should stir up the material, causing the nuclear burning to spread so fast that the star has no time to compensate.

In a properly working internal-combustion engine, the flame propagates at a subsonic speed limited by the rate at which heat diffuses through the material—a process called deflagration. In an engine suffering from knocking, the flame propagates at a supersonic rate, driven by a shock wave passing through the fuel-oxidizer mixture and compressing it—a process known as detonation. Thermonuclear flames can spread in the same two ways. Detonation, being the more violent, would incinerate the star more thoroughly, leaving behind only the most highly fused elements, such as nickel and iron. Observationally, however, astronomers detect a wide variety of elements in these explosions, including silicon, sulfur and calcium. That pattern suggests the nuclear burning propagates, at least initially, as deflagration.

CRAB NEBULA is the gaseous debris of a core-collapse supernova observed in 1054. At the center is a neutron star (*arrow*) spewing particles that cause the gas to glow (*blue*). The outer filaments consist mostly of hydrogen and helium from the disrupted massive star.

NASA/ESA/ALLISON LOLL AND JEFF HESTER *Arizona State University*

In the past few years, thermonuclear deflagrations have finally been convincingly modeled by our group as well as teams at the University of California, Santa Cruz, and the University of Chicago. The computer code we have honed draws on methods developed for the study of chemical combustion and even of weather. Turbulence is inherently a three-dimensional process. In a turbulent cascade, kinetic energy shifts from large length scales to small ones, where ultimately it dissipates as heat. In other words, the flow becomes ever more finely patterned. Therefore, the simulations have to be three-dimensional, too. That has become feasible only very recently.

Simulating supernovae in their full dimensionality has revealed complex mushroomlike structures—hot bubbles rising in a layered fluid, wrinkled and stretched by turbulence. The increase of the fusion reaction rate wrought by turbulence leads to the disruption of the white dwarf in just a few seconds. The debris expands at about 10,000 kilometers a second, in fair agreement with what the observations show.

That said, many open questions linger. What initially ignites the white dwarf is not understood at all. Another problem is that deflagration should eject a large fraction of the white dwarf essentially unchanged, whereas observations suggest that at most a small part of the star remains unaltered. So the explosion cannot be a pure deflagration; some detonation must be involved. Theorists have yet to explain why both processes would operate. Nor can they account for the observed variety of explosions. It may well be that accretion onto a white dwarf is not the only way to set off a type Ia supernova; a merger of two white dwarfs might, too.

Gravity's Tomb

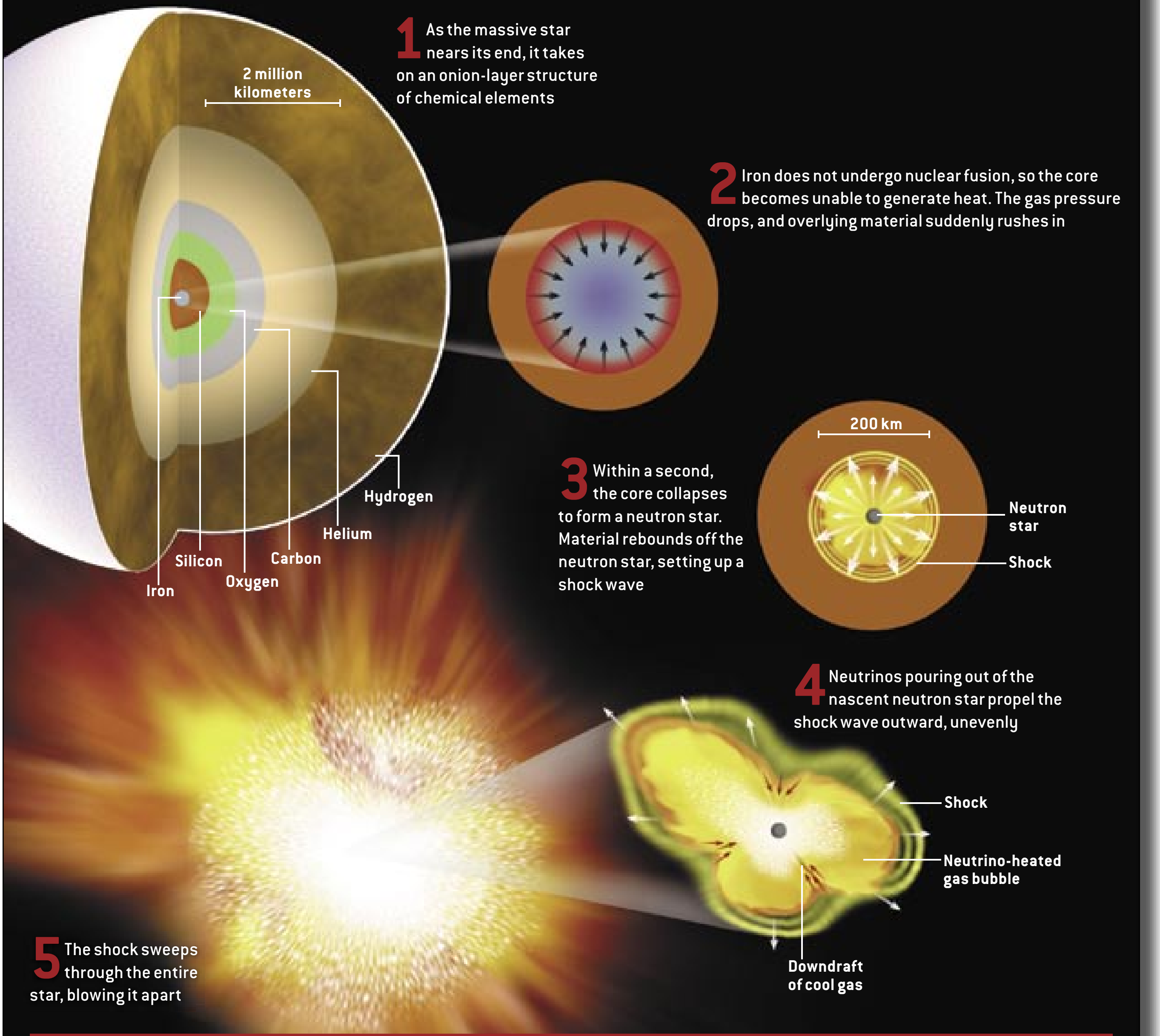
THE OTHER MAJOR TYPE of supernova, arising from the collapse of a stellar core, is even trickier to explain. Observationally, these events come in a wider variety than thermonuclear supernovae do: some have hydrogen, some do not; some explode into a dense interstellar environment, some into nearly empty space; some eject large amounts of radioactive nickel, some do not. The range of explosive energy and expansion velocity is enormous. The most powerful produce not only the classic supernovae blasts but also long-duration gamma-ray

THE AUTHORS

WOLFGANG HILLEBRANDT, HANS-THOMAS JANKA and *EWALD MÜLLER* are scientists at the Max Planck Institute for Astrophysics (MPA) in Garching, Germany, and teach at Munich Technical University. Hillebrandt is one of the three directors of the MPA. His main research areas are nuclear astrophysics, stellar evolution and supernovae explosions, which he says he got into because he was fascinated by "really big explosions." He won the Physics Prize of the German Physical Society in 1982 for his work on rapid neutron-capture nucleosynthesis. In winter he can often be found on the ski slopes and in summer on a sailboat. Janka is interested in neutrino astrophysics, neutron star evolution, and supernovae and gamma-ray bursts. One month after he had started his Ph.D. project, Supernova 1987A was detected, and his career (let alone the universe) was never the same again. He spends his spare time painting, drawing and doing handicrafts. Müller is leader of a research group on numerical and relativistic astrophysics. Together with Janka, he won the Heinz Billing Award for Scientific Computing in 1993. His fascination with astrophysics was inspired by science-fiction novels. He is still a big fan of sci-fi movies and enjoys hiking in the Bavarian Alps.

CORE-COLLAPSE SUPERNOVA

The other class of supernova involves the implosion of a star at least eight times as massive as the sun. This class is designated type Ib, Ic or II, depending on its observed characteristics.



1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

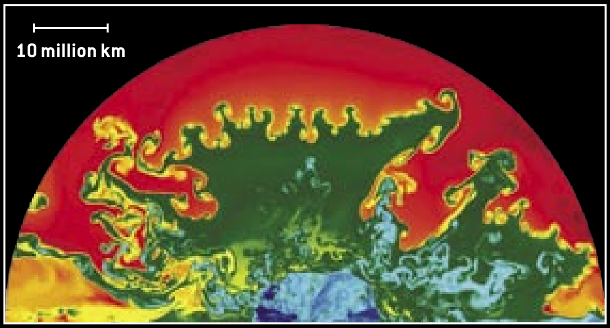
2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

Recent simulations have made huge progress in tracking the chaotic motions during the explosion. In this frame, showing the interior five and a half hours into the explosion, large rising bubbles have helped drive the shock wave a distance of 300 million kilometers. Neutrinos, usually an antisocial breed of particle, stream out of the initial implosion in such quantities and with such high energies that they play a decisive role. The turbulence mixes carbon, oxygen, silicon and iron from deep down (*blue, turquoise*) into the overlying helium (*green*) and hydrogen (*red*).



DON DIXON (*illustrations*); KONSTANTINOS KIFONIDIS *Max Planck Institute for Astrophysics* (*simulation*)

bursts [see "The Brightest Explosions in the Universe," by Neil Gehrels, Luigi Piro and Peter J. T. Leonard; SCIENTIFIC AMERICAN, December 2002]. This heterogeneity is only one of many longstanding puzzles. Core-collapse supernovae are the prime candidates for the origin of the heaviest of all elements, such as gold, lead, thorium and uranium, which can be created only under special conditions. But nobody knows whether such conditions are indeed realized when stellar cores implode.

Although the basic idea of core collapse sounds simple—the collapse releases gravitational binding energy that blasts out material—the details are hard to grasp. By the end of its life, a star with more than about 10 solar masses has developed an onionlike structure, comprising layers with successively heavier elements. The core is composed mainly of iron, and its structural integrity is maintained by quantum repulsion between electrons. Eventually, though, the weight of the star overwhelms the electrons. They get squeezed into the atomic nuclei, where they react with the protons to form neutrons and electron neutrinos. The neutrons and remaining protons, in turn, get packed closer and closer until their own repulsive forces come into play, stopping the collapse.

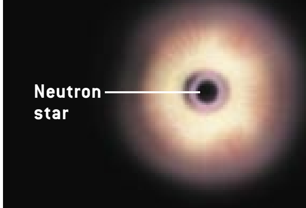
At this point, the implosion somehow reverses and becomes a powerful outflow. Matter diving deep into the gravitational well is lifted out again. In the classic theory, this task is achieved by the shock wave that is set up as the outer stellar layers crash with supersonic speed onto the abruptly decelerated inner core. This shock wave moves outward, compressing and heating the material it encounters.

The trouble is that the shock uses up its energy and eventually stalls. Simulations show that the energy of the implosion quickly dissipates. So how does the star blow itself apart?

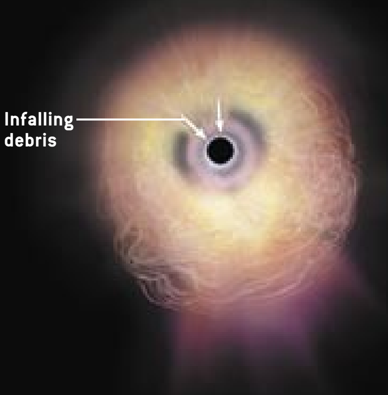
The germ of an answer emerged in pioneering work by Stirling Colgate and Richard White in 1966 and in more modern computer simulations by Jim Wilson in the early 1980s. (All three worked at what is now known as Lawrence Livermore National Laboratory.) They suggested that the shock wave is

THE SUPERNOVA ROCKET EFFECT

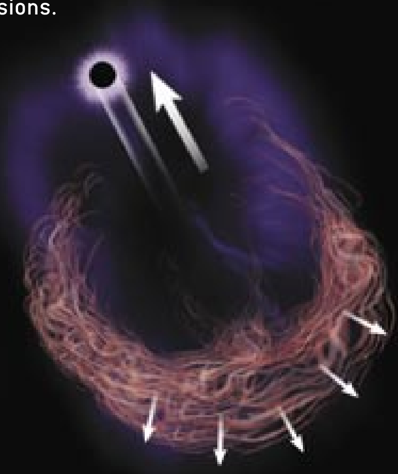
Observers have puzzled over why neutron stars zip through the galaxy at high speed. The new models of core-collapse supernovae offer an explanation based on the intrinsic asymmetry of these explosions.



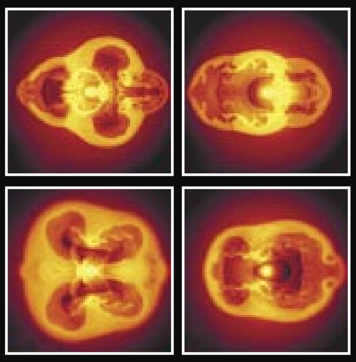
The newborn neutron star, at the center of the incipient explosion, is nearly still.



The gravity of the lopsided debris pulls the neutron star in a certain direction, and debris falling onto the neutron star provides an additional kick.

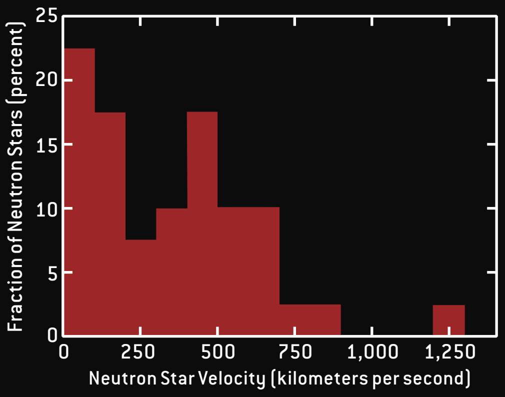


These forces eject the neutron star. (Because of the overall momentum balance, the neutron star is pulled in the direction from which the infalling debris is coming.)



According to simulations, the asymmetry develops early in the explosion. Tiny differences in the way stars die lead to large variations in the degree of asymmetry.

These variations, in turn, lead to a range of neutron star velocities. Comparing the predicted velocities to observations can provide a test of the models.



DON DIXON (top illustrations); LEONHARD SCHECK Max Planck Institute for Astrophysics (simulations); TINNI CHOWDHURY (graph)

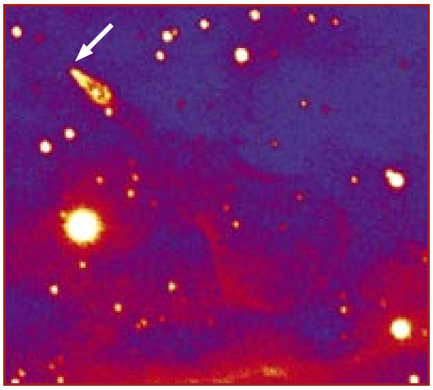
not the only way that energy from the core can reach the outer layers of the star. Maybe the neutrinos generated in the collapse play a role. At first, the idea sounds strange: neutrinos are notoriously unsociable; they typically interact with other particles so weakly that they are difficult even to detect. But in a collapsing star, they are endowed with more than enough energy to drive an explosion—and in the extremely dense conditions, they couple to matter more strongly. They heat a layer around the inner core of a supernova, raising the pressure behind the stalled shock wave.

Rocket Science

IS THAT EXTRA PUSH enough to revive the shock, drive it outward and complete the explosion? Computer simulations of the process indicated that it was not. Although the gas absorbs neutrinos, it also emits them, and the models suggested that the losses would dominate and the explosions would fizzle out. These models, however, made a radical simplification: they assumed the star to be spherically symmetrical. Thus, they ignored critical multidimensional phenomena, such as convection and rotation, which are clearly important because observed supernovae leave behind highly aspherical, jumbled debris.

This realization seems to be the key to solving the supernova problem. Multidimensional simulations show that the plasma in the neutrino-heated layer around the inner core of a supernova develops buoyant bubbles and mushroom-like plumes. Convection carries energy to the shock wave, pushing it farther out and triggering an explosion.

The new picture has very appealing implications. When the explosion sets in relatively slowly, the bubbles of hot, expanding plasma, separated by downflows of cooler matter, have time to merge together. Eventually the flow pattern consists of just a few or even a single rising bubble surrounded by downdrafts. The consequence is a lopsided explosion, explaining why supernova remnants are so skewed. Another asymmetry is that the stalled shock front can deform, causing the explosion to develop an hourglass shape. Additional flow instabilities occur when the revived shock rushes outward and passes through the layers of the progenitor's onion-shell structure. The chemical elements synthesized during the star's life and in the explosion event get mixed together.



GUITAR NEBULA is a shock wave set off by a neutron star (*at arrow*) zipping through gas at 1,600 kilometers a second. The explosion that created the star must have been seriously lopsided to fling it to such a speed.

S. CHATTERJEE AND J. CORDES *Cornell University*

Because the stellar debris is ejected with more power to one side, the neutron star at the middle is kicked in the opposite direction, just as a skateboard skids away when you jump off it. Our group has found recoil velocities of more than 1,000 kilometers a second, which matches the observed motions of most neutron stars. Some neutron stars move more slowly, which suggests that the bubbles in the explosion that created them did not have time to merge. A unified picture thus emerges, in which a variety of phenomena stem from just one underlying effect.

Despite considerable progress over the past years, however, no existing model has yet reached sufficient realism to demonstrate how these supernovae work in their full glory. All the models still involve approximations and simplifications. A full model would have seven dimensions: space (in three coordinates), time, neutrino energy, and neutrino velocity (described by two angular coordinates). Moreover, it would allow for all three types, or flavors, of neutrino. Around the world, a major effort is on to develop new computer hardware and software to achieve such a model.

One of researchers' many aims is to study whether explosions might be triggered in more than one way. Magnetic fields, for example, might tap the rotational energy of the newly formed neutron star, giving the shock wave an extra push. Magnetic fields might also squeeze matter outward along the rotational axis in two polar jets. Such effects might explain the most powerful explosions. Gamma-ray bursts, in particular, appear to involve jets moving almost at the speed of light. The core of such a burst may collapse not to a neutron star but to a black hole.

As modelers make progress, observers, too, are poking into barely explored realms, looking not just for electromagnetic radiation but also for neutrinos and gravitational waves. The collapsing stellar core, its violent boiling at the onset of explosion, and its possible transition to a black hole not only produce an intense burst of neutrinos but also shake the fabric of spacetime. Unlike light, which is heavily processed by the overlying layers, these signals escape directly from the cataclysmic abyss at the center of the explosion. New neutrino and gravitational-wave detectors may be the source of our next surprise in the saga of how stars die. SA

MORE TO EXPLORE

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