The Great Supernova of 1987

On February 23 of that year astronomers gained their first closeup view of a star's cataclysmic death since 1604. Worldwide observations have tested existing theory and added new puzzles

by Stan Woosley and Tom Weaver

The collapse and explosion of a massive star is one of nature's grandest spectacles. For sheer power nothing can match it. During the supernova's first 10 seconds, as the star's core implodes to form a neutron star, it radiates as much energy from a central region 20 miles across as all the other stars and galaxies in the rest of the visible universe combined. To put it another way, the energy of that 10-second burst is 100 times more than the sun will radiate in its entire 10-billion-year lifetime. It is a feat that stretches even the well-stretched minds of astronomers.

Yet supernovas are more than distant spectacles: they make and expel the seeds of life. Only the simplest and lightest elements, hydrogen and helium, were formed in the primordial fireball of the big bang. Most of the heavier elements, including the carbon of our chemistry, the iron in our blood and the oxygen we breathe, were forged in supernovas long before the solar system took shape.

Important as they are, few supernovas have been seen nearby. The last one in our own galaxy flared in 1604, shortly before the invention of the telescope; Johannes Kepler, who observed it, was able to record only its brightness and duration. In the absence of nearby events, understanding of many features of supernovas has remained largely theoretical. Telescopes do reveal a dozen or so events each year in distant galaxies, and careful study of a few distant supernovas has served for testing some coarser aspects of theory. But none was close enough for the modern panoply of ground- and space-based instruments to chronicle the event in detail.

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All that changed on the night of February 23, 1987, when a burst of light and a pulse of the elusive particles called neutrinos reached the earth from the brightest supernova in 383 years. Light from the explosion, 160,000 light-years away in the Large Magellanic Cloud, a satellite galaxy of our own, was visible only in the Southern Hemisphere. It is a tribute to the care with which amateur and professional observers monitor the southern sky that the supernova was photographed within an hour of the time its first light must have arrived—although the observer, Robert McNaught of Siding Spring, Australia, did not realize he had captured it until later.

About 20 hours after McNaught's first photograph, Ian Shelton of the Las Campanas Observatory in Chile was photographing the Large Magellanic Cloud. Comparing a photograph made that night with one from the night before, he found a new, starlike image on the later plate. The image was very bright—so bright that it ought to be visible to the naked eye. Shelton walked outside and looked up. Supernova 1987A (*A* for the first supernova, bright or faint, to be found that year) had been discovered.

Within a day anyone who had any astronomical instrument in the Southern Hemisphere was marveling at the sight. During the following months the array of instruments trained on the supernova came to include telescopes and sensors on board balloons, rockets, satellites and an airplane, as well as ground-based instruments of all descriptions. By now, more than two years later, the supernova has been studied at all wavelengths of the electromagnetic spectrum, and it is the first astronomical source of neutrinos to have been detected other than the sun. Together the observations give a coherent picture of the grand event, a picture that vindicates theory but also holds some surprises.

A supernova's characteristics are shaped by the progenitor star. In the broadest terms, SN 1987A is a type II supernova, powered by the gravitational collapse of a stellar core—a catastrophe unique to massive stars. (Type I supernovas, which include the 1604 event, are thought to be thermonuclear explosions of white-dwarf stars to which a critical mass of material has been added.) To make sense of what was observed in SN 1987A, it is best to begin with the history of the star that exploded. The story that follows is based on computer simulations of the evolution of a hypothetical massive star, which we and others (including Ken'ichi Nomoto and his colleagues at the University of Tokyo and W. David Arnett of the University of Arizona) have developed over the past 25 years in an effort to understand type II events. Since the supernova—the first to occur in an identified star—we have recalculated our model to take into account the special features of the star known beforehand as Sanduleak −69° 202, after the astronomer Nicholas Sanduleak, who catalogued it about 20 years ago.

The story begins about 11 million years ago in a gas-rich region of the Large Magellanic Cloud known as 30 Doradus, or the Tarantula Nebula, where a star was born with about 18 times the mass of the sun. For the next 10 million years this star, like most others, generated energy by fusing hydrogen into helium. Because of its great mass the star had to maintain high temperatures and pressures in its core to avoid collapse; as a result it was much more luminous than the sun—about 40,000 times as bright—and a profligate burner of nuclear fuel.

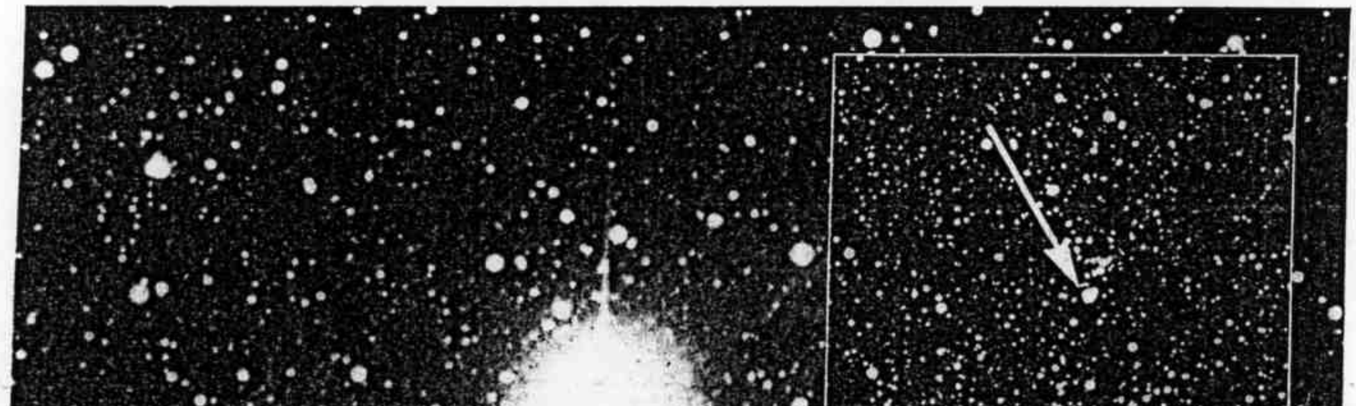
When hydrogen had finished fusing into helium in the innermost 30 percent of the star, the central regions began a gradual contraction. As the core was compressed over tens of thousands of years, from a density of six grams per cubic centimeter to 1,100, it heated up from about 40 million degrees Kelvin to 190 million degrees. The higher core temperature and pressure ignited a new and heavier nuclear fuel, helium. At the same time the outer layers of the star (mostly unburned hydrogen) responded to the additional radiation from the hotter core by expanding to a radius of about 300 million kilometers, or about twice the distance from here to the sun. The star had become a red supergiant.

The core's supply of helium was exhausted in less than a million years, burned to carbon and oxygen. During the few thousand years that remained to the star, this scenario of core contraction, heating and ignition of a new and heavier nuclear fuel—the ash of a previous cycle of fusion—was played out repeatedly. Carbon was the next to burn, at a core temperature of 740 million degrees K and a density of 240,000 grams per cubic centimeter, yielding a mixture of neon, magnesium and sodium. Then came neon, at 1.6 billion degrees and 7.4 million grams per cubic centimeter, followed by oxygen (2.1 billion degrees and 16 million grams per cubic centimeter) and finally silicon and sulfur (3.4 billion degrees and 50 million grams per cubic centimeter). Because ignition of successively heavier fuels took place in the very center of the star while previous fuels continued to burn in the less dense, overlying regions, the interior of the star came to resemble a cosmic onion, with elements layered in order of increasing atomic weight toward the center.

The core of the star passed through consecutive stages of burning at an accelerating pace. Whereas the burning of helium had lasted nearly a million years, carbon took 12,000 years, neon perhaps 12 years, oxygen four years and silicon, at the end, just a week. Each stock of nuclear fuel after hydrogen released about the same total energy, but at core temperatures above 500 million degrees K, beginning with carbon-burning, the star found a new and far more efficient way to spend its energy capital. Very energetic gamma-ray photons, abundant at such temperatures, were transformed into particle pairs—an electron and a positron, an electron's antimatter counterpart—as they passed near atomic nuclei. The particles promptly annihilated each other, usually re-creating the gamma rays but sometimes giving rise to neutrinos.

Neutrinos hardly interact with matter at all. They escaped from the star far more easily than the original gamma rays could have, carrying off energy. Even during carbon-burning, neutrino energy loss exceeded the energy loss by radiation. As the core's temperature rose during the later stages of its evolution, the neutrino luminosity rose exponentially to become a ruinous energy drain, hastening the star's demise.

This late evolution of the core proceeded too fast to have any effect on the star's vast envelope of hydrogen. Yet it turned out that the envelope had also evolved since the star had become a red supergiant.



AGED STAR AND ITS BRILLIANT DEATH are seen in photographs of the same region of the Large Magellanic Cloud made a few months apart. The progenitor star (*inset*), a blue supergiant called Sanduleak –69° 202, was about 80,000 times brighter than the sun; at its brightest (in May, 1987), the supernova reached 200 million solar luminosities. Even so, light represented only a tiny fraction of the total output of supernova 1987A: 30,000 times more energy was discharged in a burst of elusive particles called neutrinos. The photographs were provided by David F. Malin of the Anglo-Australian Observatory.

When workers first determined which star had exploded, they were surprised to find the progenitor star was not a red supergiant, as most stellar-evolution models for type II supernovas had predicted, but a blue supergiant—a smaller and hotter star [see "Helium-rich Supernovas," by J. Craig Wheeler and Robert P. Harkness; SCIENTIFIC AMERICAN, November, 1987].

The star's envelope, and not just its core, had apparently contracted beginning perhaps 40,000 years before the explosion, after the helium that had powered its red-supergiant stage was exhausted. Theorists are still debating the reasons, but the distinctive composition of star-forming gas in the Large Magellanic Cloud may have been the most important factor: in comparison with our own galaxy, the gas has a much lower content of elements heavier than helium. Among those elements, oxygen plays a special role in the evolution of a star. A lower oxygen content makes a star's envelope more transparent to radiation and hence perhaps more likely to contract. Oxygen also serves as a catalyst in the generation of energy by hydrogen fusion. Modeling suggests that a low initial oxygen content might subtly modify the early evolution of a massive star so as to ultimately yield a blue, rather than a red, supergiant.

The small radius of the progenitor star was to have dramatic effects later, when the star exploded, but it was irrelevant to the drama about to take place in the core. The week-long fury of silicon- and sulfur-burning had left the star with a core of iron, together with other elements in the iron group: nickel, chromium, titanium, vanadium, cobalt and manganese. Vast neutrino losses continued unabated because of the high core temperature, but having reached iron, the core had no nuclear currency left to pay its energy debt. Iron lies at the bottom of the curve of binding energy: energy must be added to fuse it into heavier elements or to split it into lighter ones. Fusion could go no further, and temperature and pressure could no longer maintain the core's equilibrium. Gravity won the 11-million-year contest, and the core began to collapse.

As the core was compressed, it did get hotter but not hot enough to stop the collapse. Two instabilities (discussed by William A. Fowler of the California Institute of Technology and Fred Hoyle, then of Cambridge University, during their pioneering theoretical work on supernovas in the early 1960's) actually accelerated the collapse. In one process, photodisintegration, high-energy photons tore apart the iron nuclei into lighter components, mainly helium—in effect reversing the fusion reactions of the star's previous history. In the second process, electron capture, free electrons were squeezed into nuclei, where they combined with protons to form neutron-rich isotopes. Both processes consumed energy, sapping critical support from the core; electron capture also removed some of the free electrons that had been a major source of pressure.

In a few tenths of a second the iron core, 1.4 times the mass of the sun and half the size of the earth, collapsed into a ball of nuclear matter about 100 kilometers in radius. When the center of the incipient neutron star exceeded the density of an atomic nucleus—270 trillion grams per cubic centimeter—the inner 40 percent of the core rebounded as a unit. The outer core, still plunging inward at close to a quarter of the speed of light, smashed into the rebounding inner core and rebounded in turn. A shock wave was born. In about a hundredth of a second, it raced out through the infalling matter to the edge of the core [see "How a Supernova Explodes," by Hans A. Bethe and Gerald Brown; SCIENTIFIC AMERICAN, May, 1985].

Workers modeling supernovas had hoped for many years that such a shock would continue outward through the many layers of the star, heating it and blowing it apart. Unfortunately, the most recent calculations for a star the size of Sk –69° 202, done by a number of theorists (including Sidney Bludman and Eric Myra of the University of Pennsylvania, Stephen Bruenn of the Florida Atlantic University, Edward A. Baron of the State University of New York at Stony Brook and Ron Mayle and James R. Wilson of the Lawrence Livermore National Laboratory), suggest that in SN 1987A the shock did not make it out of the core on its own.

The shock started out carrying enormous energy—about 10 times as much as was finally imparted to the exploding debris—but lost most of it beating outward against the infalling material. Photodisintegration and neutrino emission cooled the shock-heated material, sapping the shock's impetus. By the time the shock arrived at the edge of the iron core, the material behind it had no net outward velocity. The shock stalled and became an accretion shock, one through which material continuously flows inward. If this dismal state had persisted, the core would have swallowed the enti star. The result would have been black hole, not a supernova.

Neutrino emission played a role stalling the shock, and neutrino emi sion may also have helped to revi it. The core, having shrunk to a radi of 100 kilometers, had not reache nuclear density except at the cente It would become a true neutron st only when it had contracted to a r dius of about 10 kilometers. Yet th protoneutron star was already ver hot (Wilson and other modelers ha predicted a temperature of about 10 billion degrees K) because of the grav itational energy released in the col lapse. To contract further, the neutro star had to lose heat.

It did so through vast neutrino loss es. The neutrinos were produced, a before, by the annihilation of electron positron pairs made by the energet ic gamma rays that pervade materia at such high temperatures. This time however, the neutrinos did not strea promptly out of the material: the density of the collapsing core was so high that it impeded even neutrinos. They diffused out of the core gradually, in seconds rather than milliseconds, slowing the star's contraction.

Even so, the power radiating from the contracting neutron star was outrageous, exceeding that of the rest of the visible universe. The total energy emitted in the 10-second neutrino burst was 200 or 300 times the energy of the supernova's material explosion and 30,000 times the energy of its total light output. It is now widely (but by no means universally) believed that a small fraction of the neutrino energy was somehow harnessed to revive the stalled shock and power the explosion. Building on a basic idea put forward in the mid-1960's by Stirling Colgate, now of the Los Alamos National Laboratory, Mayle and Wilson recently did a set of calculations that show just such an effect. Only a few percent of the neutrinos, interacting with the material just behind the stalled shock for about a second, deposit enough energy to accelerate the shock outward.

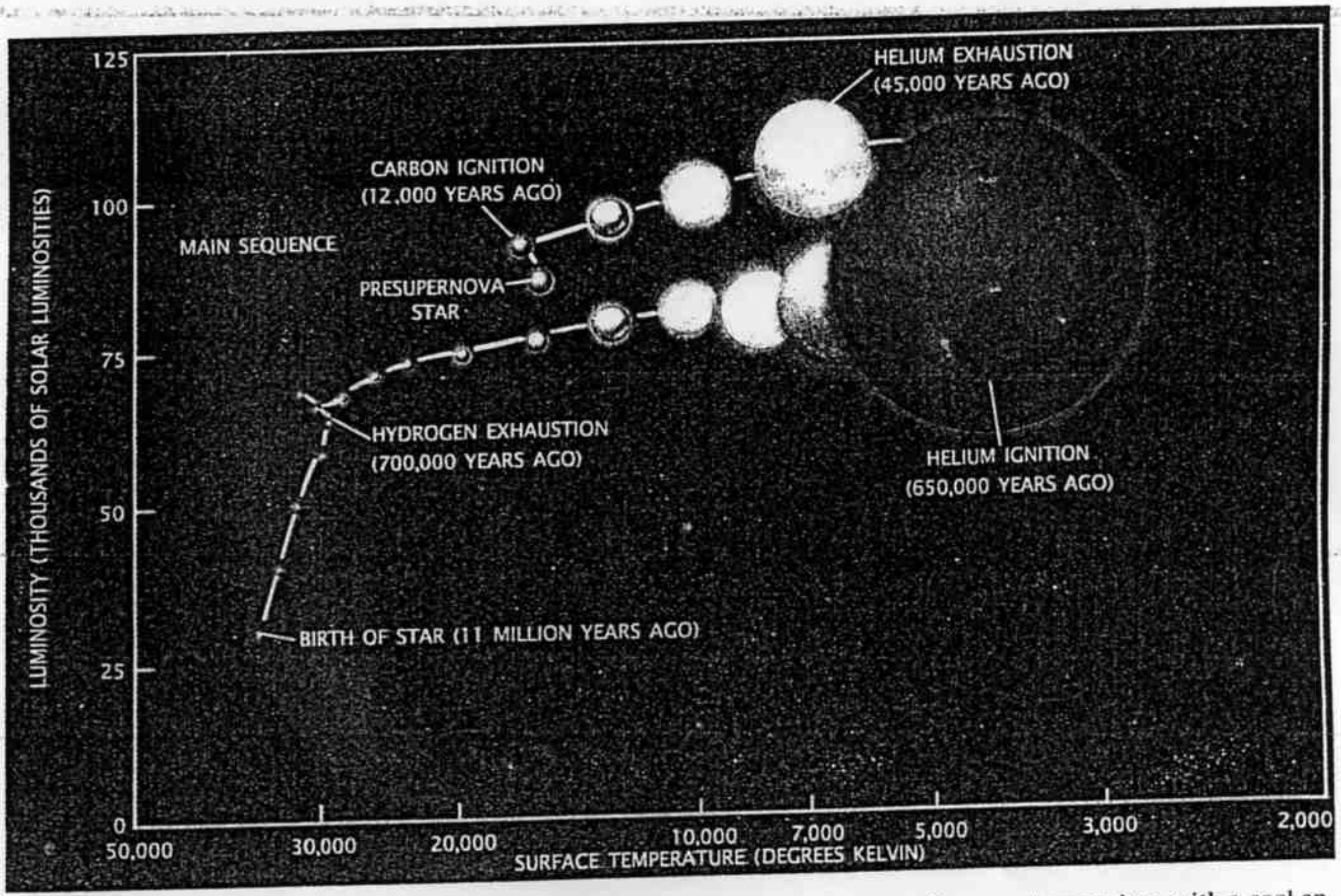
By heating and expanding the star and triggering a new flurry of nuclear reactions in its layered interior, the revived shock was responsible for the supernova's optical display. The effect was delayed by about two hours: the shock traveled at perhaps a fiftieth of the speed of light and had to traverse the entire star before any light leaked out. The neutrinos from the collapsing core easily outraced the shock. Passing through the rest of the star very close to the speed of light, they were the first signal to leave the supernova.

Some 160,000 years later, still hours ahead of the light front, the neutrinos swept over the earth—and were detected. Investigators searching for rare subatomic events such as the decay of the proton have built detectors deep in mines and under mountains, where they are shielded from interference by cosmic rays. Typically they consist of a swimming-pool-size tank of water flanked by arrays of photodetectors, poised to sense the faint flashes of light that would signal the decay of any one of the perhaps 10^{32} protons in the water. To date no proton has been seen to decay, but the detectors are also sensitive to another rare, energetic event, the capture of a neutrino by a proton.

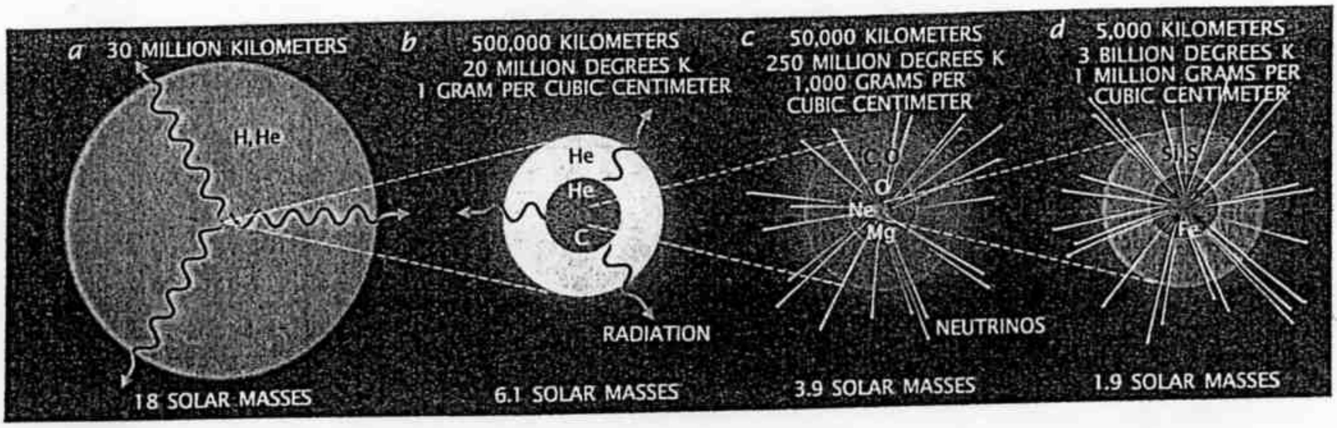
On February 23 at 7:36 A.M. Universal Time, the Kamiokande II detector, in the Kamioka lead mine in Japan, and the IMB detector (named for the collaborating institutions, the University of California at Irvine, the University of Michigan at Ann Arbor and the Brookhaven National Laboratory) in the Morton Thiokol salt mine near Cleveland, Ohio, simultaneously recorded a series of events that were later interpreted as neutrino captures. A detector of a different design, at Baksan in the Soviet Union, registered anomalous events at the same time. Approaching from out of the southern sky, the wave of neutrinos from the supernova had swept through the earth (the earth is far more transparent to these weakly interacting particles than a thin sheet of the clearest glass is to light). Emerging in the Northern Hemisphere, it had left the faintest signature of its passage in the detectors.

The theoretical significance of the neutrino detection was considerable. The Kamiokande and IMB detectors are most sensitive to a small component of the burst: electron antineutrinos. The same proportion of the burst energy is believed to have come from each of the other five neutrino flavors—electron neutrinos and mu- and tau-neutrinos and their two antiparticles. By extrapolating from the number and energy of the neutrinos that were detected, workers have calculated the total neutrino energy released by SN 1987A: 3×10^{53} ergs. It is just equal to the theoretical binding energy of a neutron star of 1.4 solar masses—the gravitational energy that should be released in its formation.

Thus, the fleeting detection of the neutrino burst shows that, as theory had predicted, a neutron star is formed in a type II supernova. More specifically, it is a sign that computer models of the formation and collapse of massive stars are on the right track: they had accurately predicted the mass of the imploding core. The average energy of the detected neutrinos confirms theoretical predictions for the temperature of a collapsing protoneutron star. Furthermore, the burst lasted several seconds: the neutrinos actually did have to diffuse out of the



HISTORY of the progenitor star began some 11 million years ago on the "main sequence"—the region hydrogen-burning stars (most stars in the sky) occupy on graphs of luminosity versus surface temperature. After about 10 million years the hydrogen in the star's core was burned to helium, and the core contracted and became hotter. In response the star's envelope expanded and cooled, and the star moved to the right, off the main sequence. As the core got hot and dense enough to burn helium, the star bloated into a red supergiant, with a cool envelope several times the size of the earth's orbit. After helium was exhausted, the envelope contracted and heated up again, and the star became a blue supergiant. In that form it burned successively heavier elements, ultimately making the iron core whose collapse triggered the supernova. The scenario is based on the authors' calculations for an 18-solar-mass star with a starting composition typical of the Large Magellanic Cloud.



COSMIC ONION—the structure of the presupernova star in its final moments—is made up of concentric shells of successively heavier elements undergoing nuclear fusion. The radius of each shell, the temperature and density at its surface and the mass the shell includes are given; stippling indicates regions undergoing convection. When the center of the star's vast, tenuous envelope of hydrogen and helium (*a*) is magnified by a factor of 30 (*b*), a core of helium four times the diameter of Jupiter is revealed. Enlargement by another factor of 10 (*c*) exposes the ash from helium-burning: a core of carbon and oxygen. The carbon is burning to make neon and magnesium, which, together with oxygen, are being turned into silicon and sulfur (*d*). A final step of fusion has turned silicon and sulfur into 1.4 solar masses of iron at the very center of the star. Iron is fusion's end point; lacking any way to maintain adequate heat and pressure, the Mars-size iron core is starting to collapse. At its center the density is 10 billion grams per cubic centimeter and the temperature is 10 billion degrees Kelvin.

dense matter of the collapsed core.

Of even broader significance was the fact that the neutrinos arrived as a close-packed bunch a few hours ahead of the light burst after a journey of 160,000 years. The universe is widely believed to contain far more mass than can be seen, and neutrinos have been proposed as the carrier of this "missing mass." The fact that the neutrinos traveled so close to the speed of light sets strict limits on their mass: neutrinos with significant mass traveling at such speeds would have been far more energetic than the detected particles. Furthermore, neutrinos of quite different energies arrived within seconds of one another: in contrast, the arrival times of particles with significant mass would have been spread out in order of decreasing energy.

Independent analyses of the timing by John Bahcall of the Institute for Advanced Study in Princeton, N.J., Adam Burrows of the University of Arizona and Tom Loredo and Don Lamb of the University of Chicago have yielded a firm upper limit on the electron antineutrino's mass: about 20 electron volts (.00004 times the mass of the electron). If the masses of mu- and tau-neutrinos could be limited to similar values, neutrinos could confidently be dismissed as a missing-mass candidate.

The neutrino burst bore tidings of the core collapse, but it had very little to say about how the shock generated by the collapse got out of the core. The revival of the shock by neutrino energy remains in the realm of theory. Nevertheless, it is clear that a strong shock did propagate through Sk −69° 202 on February 23, 1987 (minus 160,000 years). To state the obvious, the star did explode.

Two hours after the neutrinos had been registered in the Kamiokande and IMB detectors (nobody knew it at the time, of course), Albert Jones, an amateur astronomer in New Zealand, happened to be observing the exact spot at which the supernova would appear. He did not see anything unusual. An hour later, in Australia, McNaught exposed the two plates that, when they were developed after Shelton's announcement of the discovery, showed the earliest recorded light from the supernova. Sometime between the two observations, perhaps even as Jones observed the spot, the shock erupted through the surface of the star, triggering a hard (short-wavelength) ultraviolet burst that quickly gave way to visible light.

The fact that it took only about two hours after the core collapse for the shock to arrive at the surface and ignite the optical display helped to dispel initial doubts about whether the blue star Sk −69° 202 really was the star that exploded. The quick arrival of the light ruled out a red supergiant as the progenitor: it takes even a high-velocity shock the better part of a day to go through a red supergiant.

Further evidence about the size of the progenitor star came from the ultraviolet flash, even though only its aftermath was seen. In addition to being invisible, ultraviolet light is absorbed by the earth's atmosphere. The telescope on board the *International Ultraviolet Explorer* satellite could have detected this earliest light but was not aimed in the right direction at the time. Within 14 hours, however, the observing team, headed by Robert P. Kirshner of the Harvard-Smithsonian Center for Astrophysics and George Sonneborn of the National Aeronautics and Space Administration's Goddard Space Flight Center, had reoriented the satellite. By that time the initial burst was fading, but the supernova was still clearly visible at ultraviolet wavelengths.

Moreover, the workers got an indirect look at the ultraviolet flash months later, when the IUE detected emissions from a shell of gas surrounding the supernova at a distance of about a light-year. The gas, presumably material ejected from the presupernova star in a stellar wind during its red-supergiant stage 40,000 years before, was flash-ionized when the intense ultraviolet burst reached it. Based on this secondary radiation, Claus Fransson of the University of Stockholm concluded that the first light from the supernova came from material at a temperature of about half a million degrees K. (Perhaps 10 years from now, according to a model developed by Roger A. Chevalier of the University of Virginia, the shell will radiate again, this time in the radio and X-ray bands, when the supernova ejecta finally collide with it.)

Such high temperatures, and the

very hard ultraviolet radiation they produce, are expected when a powerful shock wave breaks through the surface of a relatively small progenitor star. With less surface area in which to deposit its energy, the shock generates a correspondingly higher temperature, and it also accelerates the material to higher velocities. Doppler-shifted lines in the early ultraviolet and optical spectra indicated that the material had been ejected from the star at roughly one tenth the speed of light.

This expansion cooled the outermost layers of the young supernova, and the dominant emissions quickly shifted from the ultraviolet to the cooler, visible wavelengths recorded in the earliest photographs. The bolometric luminosity (the combined radiation at all wavelengths from the infrared through the ultraviolet) declined steeply during these first hours, but because the visible portion of the emissions was strengthening, the supernova was brightening into an impressive display in the night sky.

During the first day or so, little radiation could escape from deep inside the supernova: free electrons in the ionized gas of its envelope scattered light from deeper layers. When the outermost material had cooled to about 5,500 degrees K, however, the hydrogen nuclei recombined with the free electrons. As the supernova continued to expand and cool, a surface defined by the hydrogen recombination temperature moved into the envelope. At this surface energy previously deposited by the shock was released—mostly at visible wavelengths—and streamed freely into space. For weeks to come, as Arnett and Sydney W. Falk of the University of Texas at Austin had predicted some 15 years ago, radiation at the hydrogen recombination temperature dominated the supernova's emissions.

At the same time another effect of the small progenitor star became apparent. As an optical display the supernova was at first unexpectedly faint—about a tenth as bright as other type II supernovas at a similar stage. To cool to the hydrogen recombination temperature, any supernova has to expand. The shock had deposited about the same amount of energy in the relatively small envelope of this progenitor star as it would have left in a red supergiant's extended envelope, heating the small envelope to a correspondingly higher temperature. As a result SN 1987A had to expand by a much larger factor before it could release its light, and the process consumed energy that would otherwise have come out as radiation.

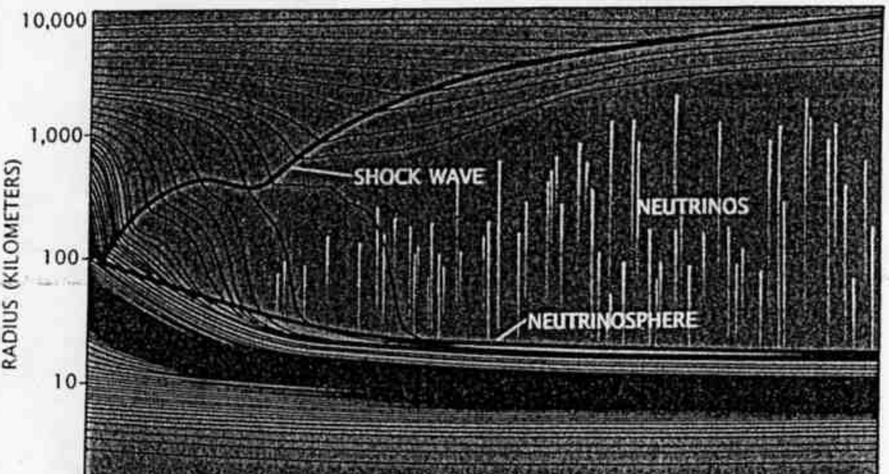
After about a month, it is calculated, all the energy deposited by the shock had either escaped as radiation or gone into accelerating the ejecta. Yet the supernova was still brightening at visible wavelengths. By this time, in April, another source of energy was providing most of the light: the decay of radioactive isotopes produced in the explosion. Most theorists had expected such materials to be made in a type II supernova, but they watched eagerly to see how much had been generated in SN 1987A and what role the isotopes would play.

The shock wave's passage through deep layers of the progenitor star during the first minutes of the event had triggered new nuclear reactions. In particular, part of the silicon shell was turned into iron-group elements, chiefly the radioactive isotope nickel-56. A month later the highly unstable nickel-56 had already decayed (its half-life is 6.1 days), heating and expanding the deep layers of the supernova. But its decay product, cobalt-56, is also radioactive, and because it has a half-life of 77.1 days, it was still abundant. It decays into an excited iron-56 nucleus, which releases gamma rays at specific energies as it relaxes to the ground state. These gamma rays now powered the display.

At first the gamma rays themselves did not escape: because of their high energy they scattered repeatedly from electrons in the expanding gas, turning into X rays of progressively lower energy. At a sufficiently low energy the X rays were absorbed, heating the material and so contributing to the optical display. As the supernova continued to thin, increasing amounts of the decay energy escaped in this way. On May 20, 80 days after the explosion, the brightness peaked.

By early July the light curve was declining at precisely the rate expected on the basis of cobalt-56's half-life. From the brightness of the supernova on a given day and the time since the explosion, it was straightforward to calculate how much nickel-56 had been formed in the first place. The answer, .08 solar masses, is within a factor of two of what we and others had predicted for type II supernovas.

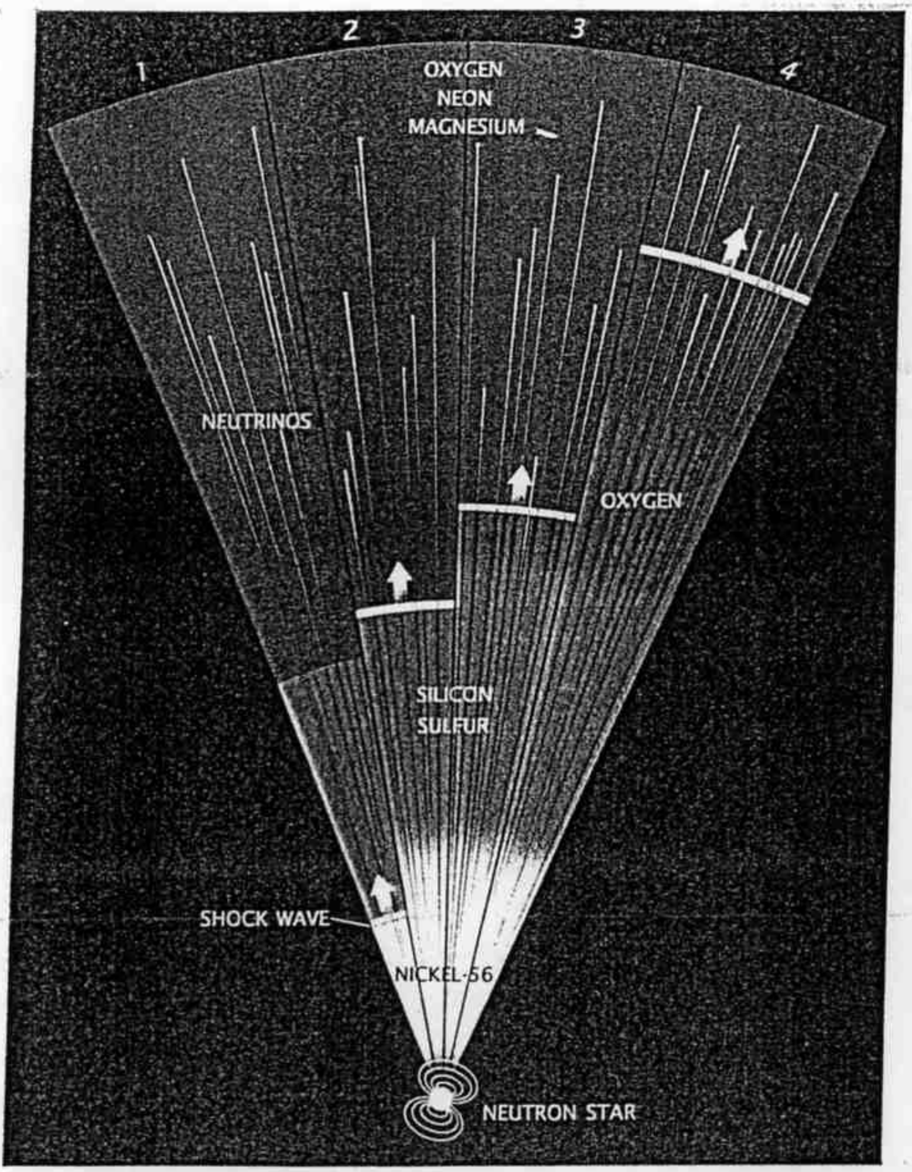
For weeks after peak brightness the radioactive material still could not be seen directly. By August, however, the expanding debris had thinned enough to allow some radiation from the decay to escape with little or no scattering. First the Japanese satellite *Ginga* and, shortly thereafter, instruments on the Soviet space station *Mir* detected X rays at the energies that Philip A. Pinto of the University of California at Santa Cruz, Rashid A. Sunyaev and S. A. Grebenev of the Soviet Space Re-



NEUTRINOS REVIVE THE SHOCK WAVE generated by core collapse in a simulation calculated for a star about the mass of supernova 1987A's precursor. Each line on the graph traces the radial position of a shell of constant mass. As the time scale begins, the shock has lost energy and stalled, a few hundredths of a second after its birth, within the infalling material of the outer core. The graph shows how the collapsed core (*purple*)—a protoneutron star—contracts further and emits a powerful flux of neutrinos, which escape from its surface (the "neutrinosphere") after diffusing through the nuclear matter. A trace of energy deposited by neutrinos heats and accelerates material behind the shock. The revived shock is sufficient to destroy the star. The calculations were done by Ron Mayle and James R. Wilson of Livermore.

search institute, and others had predicted would be seen when the gamma rays from cobalt-56 decay were scattered. Once the X rays had been seen, the gamma rays themselves could not be far behind, and in December their discovery was announced based on data from the *Solar Maximum Mission* satellite. Confirmation came quickly from balloon-borne detectors flown in Australia and in Antarctica.

Donald D. Clayton of Rice University and his co-workers had predicted some 20 years ago that a supernova would produce gamma rays of the observed energies, but the timing of the observations was a surprise. Theorists had expected that in a type II supernova the layers of the exploded star would expand in radial symmetry, in which case the X rays would have been obscured until perhaps 100 days after they were actually observed. Their early appearance meant, instead, that the core had been mixed: material from the inner layers had been blown into the overlying layer of helium or even into the hydrogen envelope. Indeed, Doppler broadening of the gamma-ray lines showed that some cobalt was moving as fast as 3,000 kilometers per second—fast enough to have overtaken the slower-moving material at the base of the hydrogen envelope.



EXPLOSIVE NUCLEOSYNTHESIS takes place as the shock wave rips out through the progenitor star's layered interior. Shock-heated to more than five billion degrees K, part of the silicon and sulfur fuses to form radioactive nickel-56 (*stage 1*); some of the oxygen at the bottom of the next shell burns to silicon and sulfur (*stage 2*), and neon and magnesium in the inner part of the shell burn to oxygen (*stage 3*). The shock propagates through the remaining material without triggering further transmutations (*stage 4*). The decay product of the nickel, cobalt-56, is also radioactive and yields much of the energy for the supernova's light. Neutrinos from the hot, contracting neutron star at the center of the supernova outrace the shock wave.

At about the time the cobalt appeared, emissions from deeper in the supernova revealed other heavy elements. Gamma rays and X rays from the core of the supernova were still being scattered, and visible and ultraviolet emissions were blocked by a thicket of atomic absorption lines. The infrared, it turned out, offered the earliest look at the heavy elements the supernova was dispersing into space.

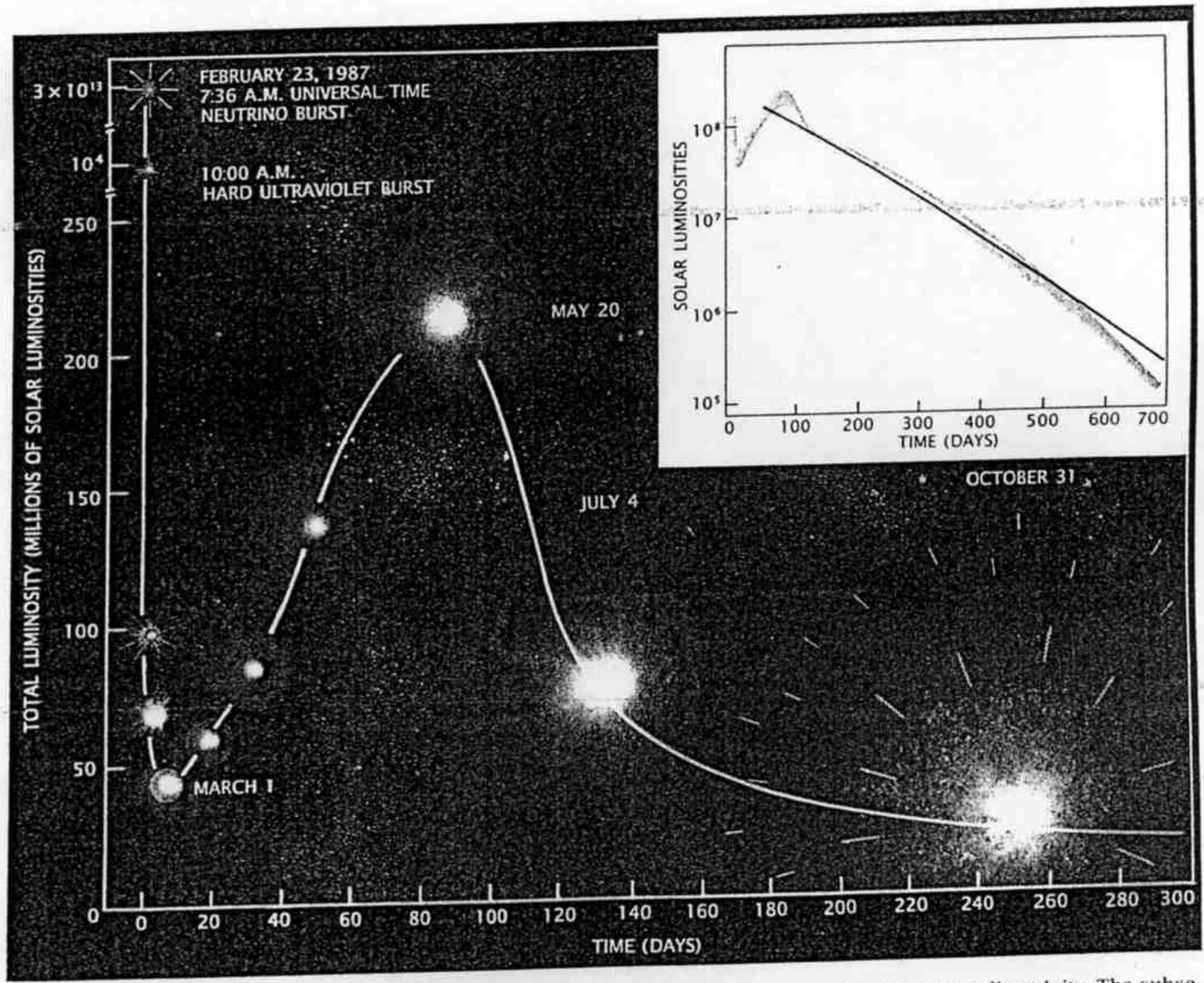
Most infrared radiation is absorbed by the earth's atmosphere, but the wavelengths that do reach the ground were studied, beginning soon after the supernova exploded, by the Anglo-Australian Telescope at Coonabarabran and the Mount Stromlo and Siding Spring Observatories in Woden (both in Australia) and by the Cerro Tololo Inter-American Observatory in Chile. NASA's Kuiper Airborne Infrared Telescope, flown at 39,000 feet on a jet transport, gained more complete coverage on flights starting in the fall of 1987. Beginning around November, spectra from the Kuiper and from Australia together revealed an entire zoo of elements in the supernova core—not just iron, nickel and cobalt but also argon, carbon, oxygen, neon, sodium, magnesium, silicon, sulfur, chlorine, potassium, calcium and possibly aluminum. Their intense infrared lines signaled larger quantities than could have been present in the star at its birth. The elements—the components, perhaps, of some future solar system—were made in the core of the star or in the explosion itself.

In early 1989, two years after the explosion, the supernova's luminosity was declining steadily, in keeping with the exponential decay of radioactive cobalt-56 (save that some of the X rays and gamma rays could now escape directly and hence did not contribute to the light curve). The lack of evidence for any energy source other than radioactive decay was starting to puzzle some theorists. The neutrino burst had announced the birth of a neutron star. Yet a neutron star usually emits a great deal of radiation, either by heating any material falling into it or by acting as a pulsar: a spinning neutron star with a strong magnetic field that generates a rotating beacon of radiation.

Where was the neutron star in SN 1987A? Had it formed initially but then vanished by turning into a black hole? The neutrino burst would have been cut short if a black hole had formed during the first few seconds of the event, and in any case the mass of the collapsing iron core alone fell short of the threshold—about two solar masses—for forming a black hole. If enough additional mass had later fallen onto the neutron star to drive it over the limit, all the radioactive nickel would have been lost and the supernova would have been much fainter. As the supernova neared its second anniversary, most astronomers were still betting on a neutron star, although the exponential decline of the light curve ruled out a very bright pulsar such as the one in the Crab Nebula, the remnant of a brilliant supernova in 1054.

During the night of January 18, 1989, Universal Time, the supernova answered one puzzle with several more. At Cerro Tololo a group headed by Carl Pennypacker of the Lawrence Berkeley Laboratory and John Middleditch of Los Alamos detected optical pulsations from the supernova. The pulsations, which amounted to about .1 percent of the total light, came nearly 2,000 times a second, suggesting a rotation rate three times faster than the fastest pulsar ever seen. Spinning that fast, only the densest, most massive neutron star allowed by theory could avoid flying apart.

What is more, the signal of the pulsar showed a regular variation in frequency, as if an orbiting companion several times as massive as Jupiter were tugging the pulsar back and forth every seven hours, Doppler-shifting its signal. Because the radius of the companion's calculated orbit, about a million kilometers, would have placed it inside the presupernova star, the companion could only have been created after the explosion. Spec-



EXPLOSION of the supernova began with an enormously powerful burst of neutrinos, marking the birth of the neutron star, followed some two hours later by a flash of hard ultraviolet light as the shock wave broke through the surface of the star, heating it to half a million degrees K. Over the next few days the surface of the supernova expanded and cooled to red heat. Energy deposited by the shock deep inside the envelope began leaking out, joined several weeks later by heat from the decay of radioactive cobalt. The supernova brightened slowly until May 20, by which time the shock energy had been spent and the display was powered entirely by radioactivity. The subsequent decline in brightness, plotted on a logarithmic scale (*upper right*), matched the decline calculated for the decay energy of .08 solar masses of cobalt-56 (*dark curve*). Months after the explosion, as the supernova thinned into a clumpy nebula many times the size of the solar system, X rays and gamma rays (*blue arrows*) from the decay of the cobalt began to escape directly. Even today the supernova is an unresolved point of light in telescopes; the paintings are based on each stage's observed color and spectrum and on theoretical inferences.

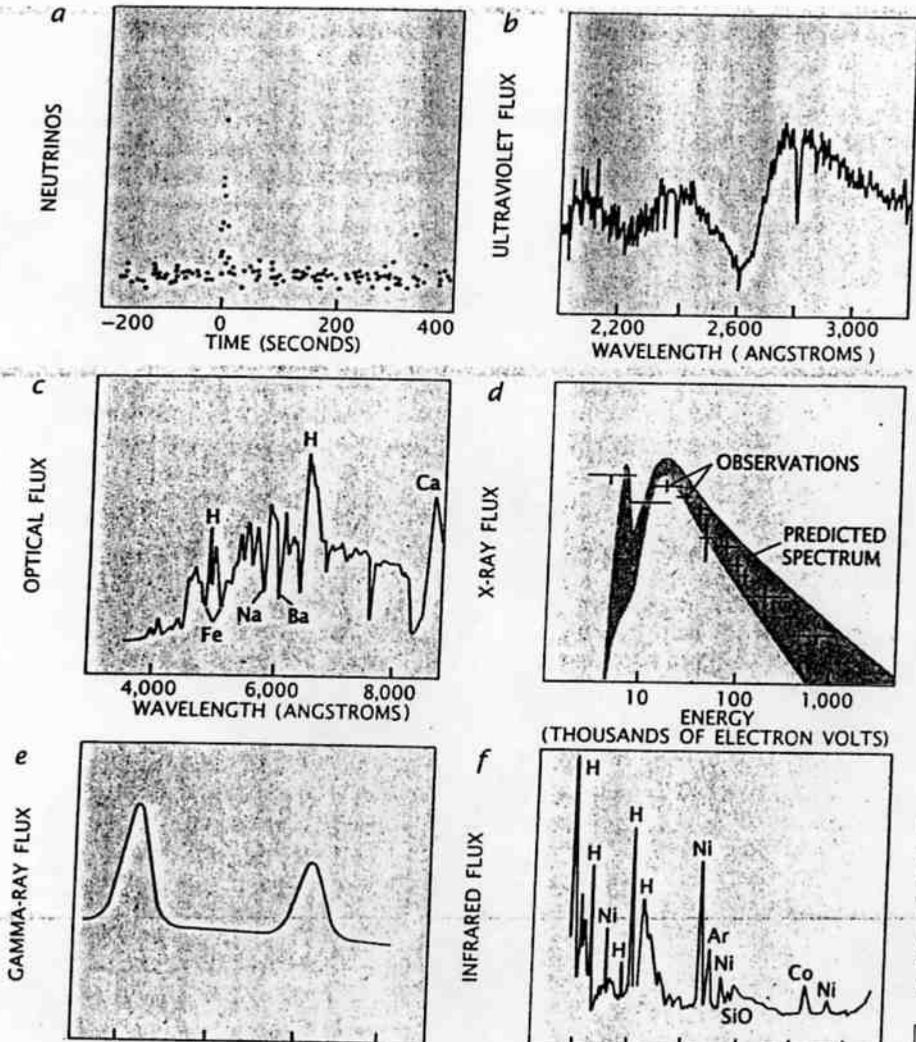
ulation is rife: if the companion is real, could it be a piece of neutron star that was somehow ejected, some other fragment that fell back and was captured, or something even more exotic?

What is really needed is another look at the pulsar. Yet several months of observations of equal and greater sensitivity have failed to recover it. Again, one can speculate. Clouds deep in the supernova may be obscuring the pulsar, for example, or it may have been extinguished: matter falling onto the neutron star may have short-circuited the electric field (generated by the rotating magnetic field) that powers the beam. No one knows.

The fate of the neutron star joins other mysteries that have accompanied SN 1987A. We have emphasized the success of theory and the beautiful complementarity amon the observations. Yet there had bee anomalies even before the putativ pulsar. Four hours *before* the neutrino detection at Kamiokande and IMB, fo example, a detector in a tunnel unde Mount Blanc had registered a separate neutrino burst. Gravity-wave detectors (sensitive to massive releases of gravitational energy) in Rome and in Maryland are said to have recorded signals coincident with those early neutrinos. What could account for a stupendous burst of energy four hours before the core collapse? Again, no one knows. Several months after the explosion came another mystery: a second light source, roughly one tenth as bright as the supernova and resolvable from the main explosion only by an indirect technique known as speckle interferometry. The mysterious second source had disappeared by June, 1987, and was not seen again.

Doubts about such observations, and controversy about their interpretation, bring home an important point about the supernova. In much of science a result is accepted only if it is reproducible. Yet in the case of supernova 1987A we deal with an event that may not be repeated nearby for centuries. When our ability to interpret the observations breaks down, the best we can do is to record and archive the findings carefully, so that future scientists, with greater insight, may come to understand them.

Even so, the last two and a half years have yielded breathtaking advances in the understanding of type II supernovas. For us and hundreds of others, theorists and observers at all wavelengths collaborating to document and explain one of the heavens' grandest events, it has been a time of matchless exhilaration, scientific cooperation and intellectual reward—the event of a lifetime.



EMISSIONS from SN 1987A began with a brief burst of neutrinos, shown in a record from the Kamiokande detector in Japan (*a*). Hours after the shock wave burst from the star, the *International Ultraviolet Explorer* satellite recorded an ultraviolet spectrum testifying to the very high temperature of the shock-heated surface (*b*). A spectrum at visible wavelengths, made 50 days after the explosion, shows strong spectral lines of hydrogen, characteristic of the expanding, cooling envelope (*c*). After about six months instruments on the Japanese satellite *Ginga* and the Soviet space station *Mir* detected X rays from the decay of radioactive cobalt (*d*); the detection of gamma rays from the same decay by the *Solar Maximum Mission* satellite was reported a few months later (*e*). Infrared emission lines captured by the National Aeronautics and Space Administration's Kuiper Airborne Infrared Telescope reveal a variety of newly made elements deep in the expanding ejecta (*f*). The ultraviolet spectrum was provided by Robert Kirshner of the Harvard-Smithsonian Center for Astrophysics, the gamma-ray data by Mark D. Leising of the Naval Research Laboratory and the infrared spectrum by Fred C. Witteborn of the NASA Ames Research Center.

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