Supernova 1987A on Center Stage

The event has provided a triumphant vindication of the standard model of supernovas; but a detailed understanding of the progenitor star has proved more elusive

NINE months after its eruption on 23 February, supernova 1987A is fading at a steady 0.01 magnitude per day; by Christmas it will be lost to the naked eye. For the astronomers, however, it is still very much on center stage. Given its location in the Large Magellanic Cloud—a small, irregular satellite galaxy of our own Milky Way lying just 160,000 light-years from Earth—1987A is the closest and best studied supernova in nearly 400 years. The debris from its explosion will be observable through the telescope for decades, if not centuries.

Furthermore, as was apparent at a recent supernova workshop at George Mason University,* 1987A has given the astronomers ample reason to keep watching. Not only has it provided a much needed confirmation of their theoretical models about supernovas, it has also provided them with a vivid reminder that theory is not everything. In observations ranging from the detection of neutrinos to the long-term falloff in luminosity, 1987A has so far been right on the mark. And yet its oddball details—the blue color of its progenitor star, for example, and the fact that the explosion was dimmer than expected by a factor of 10—have led the astronomers into a detailed reexamination of what they thought they knew about such stars.

"It's an irony," says theorist W. David Arnett of the University of Chicago. "We started out looking at the most dramatic event in the universe, and now we're arguing about what seemed like the most pedestrian things"—hydrogen burning and stellar evolution.

It should be said at the outset that there are actually two different kinds of supernovas. The brightest and most common variety, often denoted "Type I," are thought to arise in double star systems when one star pulls material off its companion and becomes unstable. The group to which supernova 1987A belongs, often denoted "Type II," are thought to occur only in very massive stars.

*"Supernova 1987A in the Large Magellanic Cloud," The Fourth George Mason Fall Workshop in Astrophysics, George Mason University, 12–14 October 1987.

The general picture of Type II supernovas was not in serious question before 1987A. Indeed, the essential ideas go back to a classic paper by Walter Baade and Fritz Zwicky in 1934. Computer simulations of the process have grown increasingly sophisticated over the years, especially with the advent of modern supercomputers. And the results are in good accord with supernovas seen in other galaxies. (About a dozen are seen each year.) Nonetheless, as pointed out by theorist Stanford E. Woosley of the University of California at Santa Cruz, "It was a theory in dire need of confirming."

The resemblance to radioactive decay is no accident: since June the supernova has been shining by the light of cobalt-56

Supernova 1987A provided that confirmation in the form of three key observations: the progenitor star, the neutrino detection, and the evolution of luminosity with time—the "light curve."

■ *The progenitor star.* Supernovas are actually rather common as cosmic happenings go. The best current estimates are that a large spiral galaxy such as the Milky Way should experience at least one supernova every few decades on the average. Even allowing for the fact that much of the Milky Way is hidden from view by clouds of interstellar gas and dust, one would still expect nearby supernovas to be fairly frequent, even on a human time scale. Unfortunately for astronomers, however, they have not been; by a statistical fluke, the last known supernova in the Milky Way was the one observed by Johannes Kepler in 1604, just before the invention of the telescope. Supernova 1987A therefore marks the first time that astronomers have had any reliable data on the preexplosion star.

Despite some initial confusion, that star has now been definitely identified as Sanduleak −69° 202, a 12th-magnitude blue supergiant of spectral class B3 that was first studied in 1969 by Nicholas Sanduleak of Case Western Reserve University. The object's blue color corresponded to a surface temperature of some 15,000 to 18,000 K, or about three times the 5,800 K of our own sun. Its luminosity was about 100,000 times that of the sun. Taken together these data are consistent with an object having a mass about 20 times that of our sun; the latter figure is also consistent with the subsequent behavior of the explosion itself.

Thus, if one leaves aside the progenitor's blue color for the moment—most observers had assumed that a presupernova star would be red—the Sanduleak star was essentially what the supernova models call for: a very massive object well above the threshold for eventual explosion.

According to the standard theory, that explosion, more properly known as a "core collapse," was the end point of the Sanduleak star's long, losing battle against gravity. In a nutshell, it could no longer support its own weight. The energy source that had sustained it before—thermonuclear fusion—had already gone as far as it could go. Hydrogen had been converted into helium and, as the temperature and pressure in the star's core continued to mount, into carbon, oxygen, silicon, and finally iron, the most tightly bound of all elements. The fusion of iron with iron would have actually subtracted energy from the core, not released it. And more new-made iron kept drifting down.

The situation became critical on the morning of 23 February, as the Sanduleak star's steadily growing core passed a threshold of about 1.5 solar masses and the multibillion-degree iron plasma underwent a phase transition. The iron nuclei suddenly began to "boil" and disintegrate into helium nuclei, thus robbing the core of support: every photon that went into knocking off an alpha particle was one less photon to help maintain the pressure. Meanwhile, electrons began to enter the nuclei and merge with the protons to make neutrons. The pressure fell still more. And at 7:35 a.m. universal time the core gave way.

Within 1 second, a ball of degenerate iron plasma the size of Mars found itself crumpling inward at an appreciable fraction of the speed of light. Densities skyrocketed, approaching those of an atomic nucleus. Temperatures exceeded 100 billion degrees. The nuclei touched, merged, and melted together. The gravitational potential energy of the collapsing core started to radiate away as a firestorm of neutrinos—the weakly interacting neutrinos being the only particles that could get out.

And then the collapse slammed to a halt. The core, having transformed itself into a ball of nuclear matter only about 70 kilometers in diameter, suddenly stiffened: the nucleons were now close enough to feel the mutual repulsion of the nuclear force. The result was an abrupt reversal of the infall: a shock wave generated by the stiffening of the core came blasting back upward through surrounding mantle of gas at thousands of kilometers per second. Some 2 hours later the shock wave reached the surface, erupting in a flash of ultraviolet light that briefly rivaled the output of the Milky Way galaxy itself—and in the process destroying the star. All that remained was a spherical pulse of neutrinos fanning out across the galaxy, a rapidly cooling shell of debris expanding into interstellar space, and in the center, a newborn neutron star.

■ *The neutrinos*. The gravitational potential energy given up by the supernova's collapsing core was approximately 3×10^{53} ergs, which is roughly equivalent to converting a tenth of the mass of the sun into energy. It was also about 100 times the kinetic energy contained in the shock wave, and about 10,000 times the radiant energy emitted as light.

According to the standard model virtually all of this potential energy comes out in the form of neutrinos, which are primarily produced by the annihilation of electron-positron pairs in the 500-billion-kelvin core. Indeed, the core of a collapsing supernova is one of the few places in the universe where the weak interactions can have an impact on macroscopic events. And conversely, that pulse of neutrinos is the one signal that can prove to external observers that a core really did collapse inside the supernova; everything else is hidden from view and has to be inferred. Thus the astronomers' jubilation when the neutrino pulse from 1987A was actually seen. At 7:35 universal time on 23 February, a burst of eight neutrino events was recorded at the giant IMB proton-decay detector near Cleveland. Simultaneously, the similar Kamiokande II detector in Japan recorded a burst of 11 events. Subsequent analysis has left little doubt that the neutrinos did indeed come from the supernova. (A burst of neutrino events seen some 4 hours earlier at the Mount Blanc proton decay detector in Europe is now generally believed to be spurious.) "We predicted a core collapse and we saw a core collapse," says theorist J. Craig Wheeler of the University of Texas. "It's the grandest thing to come out of 1987A."

Once the neutrino pulses were found, the theorists were quick to model the details. For example, the precise timing of the IMB and Kamiokande events turns out to fit in very nicely with the subsequent evolution of the supernova's optical brightness. (The Mount Blanc events do not fit in well at all.) The energies of the individual neutrinos, which fall between 6.3 million and 40 million electron volts, correspond reasonably well to the predicted core temperature: 500 billion kelvin. The number of events, taking account of the distance to the supernova and the low probability of detecting neutrinos, works out to a total energy release roughly in line with the predicted 3×10^{53} ergs. And the width of the pulse, a few seconds, is exactly what one would expect from the collapse of a core into a neutron star. "To first order," says Wheeler, "it's all consistent."

If the astrophysicists were elated by the neutrino signal, however, the physicists had to be a bit disappointed. At first, the several second spread in the signal seemed to offer them a handle on the much hypothesized mass of the neutrino (or more precisely, the electron neutrino, which is the only kind that IMB and Kamiokande detect). The idea was that zero-mass neutrinos would all move at the speed of light and would all arrive together. But massive neutrinos would move more slowly than light, and the less energetic ones would lag. A simple plot of arrival time versus energy would thus give a measure of the mass.

Despite the theorists' best efforts, however, the effects of neutrino mass seem inextricably tangled with the smearing of the pulse inside the supernova core itself. "The upper limit is less than 20 electron volts, and probably less than 10 electron volts," says Santa Cruz' Woosley. "But anything else is overinterpretation."

■ *The light curve*. In the first few weeks after any Type II supernova explosion the shell of ejecta continues to glow brightly. In part this is because the deeper, warmer layers of the shell are coming into view as the outer layers expand and become more tenuous. And in part it is because radioactive elements synthesized in the explosion are constantly dumping in new energy. At the same time, however, the shell is also radiating away its thermal energy and cooling off, so it eventually has to grow dimmer. The challenge for the theorists is to understand when.

Indeed, the light curve is one of the most complex things about a supernova. It is also one of the most informative, which is why the modelers have always had such a preoccupation with untangling it. In one sense, however, the light curve of 1987A is remarkably simple: since June, it has been following a perfect exponential decay with a half-life of 78 days. Moreover, its resemblance to radioactive decay is no accident: since June the supernova has been shining by the light of cobalt-56, which decays into iron-56 with precisely that half-life.

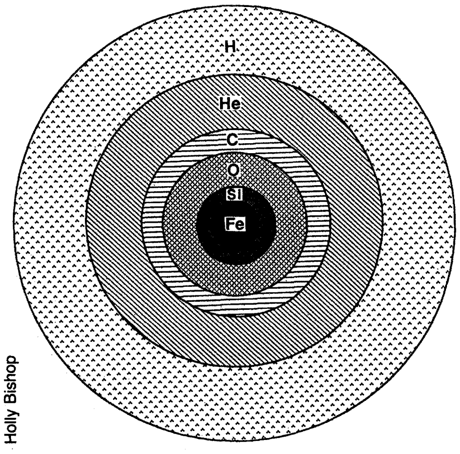
The emergence of cobalt-56 is yet another confirmation of the standard theory, says Woosley. It had been predicted, of course, and hints of it had been seen in other supernovas in other galaxies. "But it's hard to measure the tail of the light curve in other galaxies because it gets too faint," he says. "And in any case, people don't usually stick with a supernova for 200 days and more." With 1987A, however, the data are there in abundance.

Supernova 1987A in the Large Magellanic Cloud

The exploding star shines forth in a photograph taken shortly after its discovery. The bright, diffuse area to the left is the Tarantula Nebula, a region of interstellar gas and dust that is actively producing newborn stars.

National Optical Astronomy Observatories

In broad outline the story goes like this, says Woosley: on the morning of 23 February, as the shock wave came surging out of the supernova core, it immediately slammed into the overlying layers. The resulting spike of temperature and density was enough to trigger a new round of fusion. Nuclei that had been produced in the star's earlier waves of fusion—primarily silicon and oxygen—all began moving inexorably up the periodic table toward iron. Indeed, by the time the outer layers of the star had been blown clear and the fusion reactions had slowed to a stop, some 0.07 solar mass of this material had burned to completion. The inside of the ejecta shell was saturated with it.



The cosmic onion. *By the time the Sanduleak star had reached the threshold of core collapse, thermonuclear fusion was taking place in many concentric shells. The "ash" from the reactions in each shell would rain down and ignite in the shell below. At the center, hottest and densest of all, was iron. (This diagram is not to scale.)*

As it happens, however, the primary reaction product was not iron itself but nickel-56, the closest isotope to iron that has equal numbers of protons and neutrons; the fusion reactions had happened so fast that they preserved the one-to-one ratio found in silicon and all the other light isotopes around the core. On the other hand, nickel-56 decays into cobalt-56 with a half-life of only 6.1 days. By June it was completely gone, as was the shell's original reservoir of thermal energy from the explosion itself. All that was left to keep the supernova alight was the heat being generated by the slow decay of cobalt-56 into iron. Thus the latter-day simplicity of the light curve. And thus the theorists' elation.

"We've never had such an accurate fix on nucleosynthesis in a supernova," says Woosley. "For the first time we know for sure that a supernova makes iron." If nothing else, this observation verifies the astronomers' long-held belief in a corollary to the standard model: that virtually all the iron in the universe, virtually all the other heavy elements in the universe, and indeed virtually all the material in the earth itself, are the products of long-ago supernovas.

Two major predictions of the standard model remain to be tested. First, the ever-expanding ejecta shell should eventually become tenuous enough for a direct observation of cobalt-56's 847,000-electron-volt (keV) gamma-ray line. (At the moment the gamma-rays are being absorbed and thermalized inside the shell material.) In fact there are already hints that this is beginning to happen. In mid-August, x-rays from 1987A were detected by the Japanese Ginga satellite and simultaneously by the Kvant astrophysics module aboard the Soviet Union's Mir space station. Moreover, the x-ray flux seems strongest in the 18-keV to 100-keV range, which is about what one would expect from 847-keV gamma rays that had only suffered a few collisions on their way out. True, there were some surprises in these results, most notably that the x-rays had appeared about 75 days earlier than predicted. On the other hand, it may be that the expanding shell is breaking up into clumps and filaments, which then let the x-rays leak through.

Whatever the explanation, theorists are now predicting that the gamma rays themselves will be detectable within a few months. The National Aeronautics and Space Administration is searching for them with the gamma-ray detector aboard the Solar Maximum Mission satellite, at the same time that it is sponsoring balloon and sounding-rocket experiments at Alice Springs in central Australia. European observers, meanwhile, are flying similar suborbital searches. "Gamma rays for Christmas or Easter!" says theorist Stirling A. Colgate of the Los Alamos National Laboratory. "That would really be a present to us."

The second prediction is the eventual emergence of the neutron star in the middle of the supernova. If it is like other newborn neutron stars, it will be spinning at nearly 100 revolutions per second, and will be energizing the surrounding plasma with a rotating magnetic field on the order of a trillion gauss. If so, then the energy being generated by the neutron star will eventually come to dominate the heat being generated by the decaying cobalt-56. The observational signature will be a slowing and flattening of the light curve's straight exponential decay. At some time after that—no one knows exactly when—the expanding shell may become thin enough to reveal pulses from the neutron star, thus allowing astronomers to time the object's rotation and measure its magnetic field.

With the standard model seemingly in good shape, and with everyone hopeful that the gamma rays and the neutron star will appear more or less on schedule, the debate and controversy about 1987A now centers on something that might have once seemed quite straightforward: the outer layers of the Sanduleak star and their history in the epochs leading up to the explosion.

In retrospect, of course, the subject is not straightforward at all. Indeed, it turns out that the inner regions and the outer regions of such massive stars lead lives that are remarkably independent of each other.

The inner regions include the concentric shells of iron, silicon, and so forth where thermonuclear fusion is taking place. This is also where all the star's luminosity is produced; the photons created in the release of fusion energy simply diffuse outward from here until they reach the surface. And, of course, this is where the explosion takes place. As the preceding discussion suggests, the evolution of this inner region is well understood. The theorists seem quite confident when they say, for example, that the preexplosion luminosity of the Sanduleak star came from an inner region comprising about 6 solar masses of material.

Surrounding the core of a Sanduleak-type star, however, is roughly a dozen solar masses of unfused hydrogen and helium that comprise its outer region, or envelope. The envelope is responsible for the external appearance of the star, basically because it is heated by the energy welling up from below until its surface is hot enough to radiate at the same rate. In the process, however, the envelope expands like any other hot gas. So if the envelope expands a lot—say to a radius of a few billion kilometers—then its surface becomes paradoxically cool, since the star now has a great deal of surface area from which to radiate. Its emissions peak toward the red end of the visible spectrum, and it is known as a red supergiant. If the envelope remains relatively compact, however, then the surface will be hotter since the same luminosity has to be radiated over a smaller area. The emissions peak at the more energetic, blue end of the spectrum and the star is known as a blue supergiant. Before 1987A, conventional wisdom had it that a presupernova star would spend most of its short life in the blue phase and then expand into red supergianthood just before the end. Indeed, most supernovas seen in other galaxies seem to fit in with this picture. Yet the Sanduleak star, of course, was blue when it exploded.

Although that was undeniably puzzling, astronomers were quick to realize that the odd color of the Sanduleak star did help explain the other odd feature of the supernova: its relative dimness. The argument hinges on two facts. First, blue supergiants are smaller than red supergiants, even if the masses are the same. Second, a supernova's ejecta shell has to reach a certain size before its outer layers become tenuous enough to let the heat radiate efficiently. This means that a shell produced by a blue precursor star will have to travel much further before it can radiate than the shell from a red precursor, which means in turn that the gas deep inside will be at a much lower temperature when the radiation begins. In technical terms, the gas will have cooled by adiabatic expansion. The result is less thermal radiation and a dimmer supernova.

In short, the two mysteries are actually one mystery: if the supernova was dim because the Sanduleak star was blue, then *why* was it blue?

In retrospect, say the modelers, it might have been better to ask the question the other way around: why should supernova precursors only be red? Although it is true that virtually all the supernovas seen in other galaxies had red precursors, those were also the brightest supernovas. Perhaps we just never noticed the dimmer ones. Furthermore, it turns out that the people who model supergiant evolution on the computer have known all along that the star's color is very sensitive to such details as its precise composition, or the extent of thermal convection in its envelope. "It's very delicately balanced," says Chicago's Arnett. "Relatively minor changes can make it tip from one one side to the other."

Not only do the theorists find it very easy to get supernovas out of blue supergiants, but they have divided into two contending camps over just how it happened. Arnett's calculations, for example, suggest that the Sanduleak star may have always been blue, that it blew up without ever going into a red supergiant phase. But Woosley and others suggest that the star did go through a red phase before it contracted again and moved back to the blue. Their models show that it could have done this by internal evolution, by shedding some of its distended envelope, or by some combination of both.

For the moment, at least, the evidence seems to favor the latter hypothesis. Red supergiants are known to shed material in much the same way that the sun emits the solar wind, only more vigorously. Moreover, there is spectroscopic evidence from the International Ultraviolet Explorer satellite that 1987A is surrounded by a tenuous shell of material, about 1 light-year in radius, that was shed about 30,000 years ago. On the other hand, the final word is not yet in—which is why the astronomers keep watching, and waiting, and wondering. ■

M. MITCHELL WALDROP

Alzheimer's Drug Trial Put on Hold

Signs of liver damage in test patients brings controversial drug study to temporary halt

WHAT goes up, must come down. And for now, THA, a drug that was widely touted as a treatment for Alzheimer's disease, is down, although perhaps not out. On 23 October, a multicenter clinical trial to test THA (tetrahydroaminoacridine) in patients with the neurological disease was brought to a halt because 8 of the first 41 patients who received the drug showed signs of liver damage. The development is the latest in a year of controversy about THA and its proposed role in treating Alzheimer's disease.

The drug first burst into the public consciousness last November as the result of an article and an accompanying editorial in the 13 November issue of *The New England Journal of Medicine*. William Summers, a physician in private practice in Arcadia, California, and his colleagues reported that THA could alleviate the symptoms of Alzheimer's disease. Their article said, for example, that "One subject was able to resume most of her homemaking tasks, one was able to resume employment on a part-time basis, and one retired subject was able to resume playing golf daily."

For Alzheimer's victims, these were amazing accomplishments, indicating a much greater degree of patient improvement than those produced by previous experimental Alzheimer's treatments. Not surprisingly, Summers' results, which received a great deal of attention in the press, generated in biomedical circles what could be called a firestorm of interest in THA.

Alzheimer's disease now afflicts as many as 3 million people, most of them elderly, and is characterized by a relentlessly progressive neurological degeneration that robs its victims first of their memories and reasoning powers and then of their lives. When Alzheimer's family members heard the news about the Summers article they besieged physicians and the government for access to THA. Summers recollects that his office alone received 1800 telephone inquiries about the drug in the 10 days following the publication of his paper.

The public interest in THA ultimately led to the initiation of the now interrupted clinical trial, which started in September of this year under the sponsorship of the National Institute of Aging (NIA), the Warner-Lambert Company of Morris Plains, New Jersey, and the Alzheimer's Disease and Related Disorders Association. Meanwhile, however, scientific doubts about Summers' results emerged in the 18 June issue of the *New England Journal*, which included five letters that criticized the research on several grounds.

Summers had also taken what would prove to be a controversial action when in June 1986 he formed a for-profit corporation, Solo Research, Inc., to make THA therapy available to Alzheimer's patients at a cost of up to $12,000 for the first full year of treatment. According to Summers, he formed the corporation to obtain the funds necessary to continue his studies of THA.

He had been unsuccessful at getting a research grant, despite several applications, and he was using money generated by his private medical practice to support the Alzheimer's research. "If I hadn't gone to that mode [the corporation] the work would have never been completed," he recently told *Science*. He also says that the money went to pay only expenses for the THA research, including the cost of the drug and of technicians' salaries, but, "None of it ever came to me."

Nevertheless, officials of the Food and Drug Administration (FDA) were concerned that Summers was commercializing an as yet unproven therapy. According to the FDA's Paul Leber, they also did not want to see additional patients exposed to THA until it could be studied more thoroughly. The *New England Journal* paper describes the results of treating only 17 patients, a small number on which to conclude that a drug that might be used by millions of people is safe and effective.

Early this year Leber told Summers that he could take up to a total of 45 patients, including those that had already begun receiving the drug. However, Summers was not to charge for the experimental therapy beyond the "usual and customary" fees for his services. Summers says that he has since put another $18,000 from his private practice into the research.