Research News

Supernova 1987A: Facts and Fancies

Even though the supernova is fading now, the data continue to pour in; indeed, there are new installments yet to come

ELEVEN months after its light reached Earth on 23 February 1987, Supernova 1987A is still one of the astronomers' favorite topics of discussion. Not only has it provided them with a direct confirmation of their standard supernova theory, but it has provided a superabundance of data to deepen and enrich that theory. At the recent winter meeting of the American Astronomical Society in Austin, Texas,* 1987A was the subject of three special sessions, two press conferences, and dozens of papers. Some highlights:

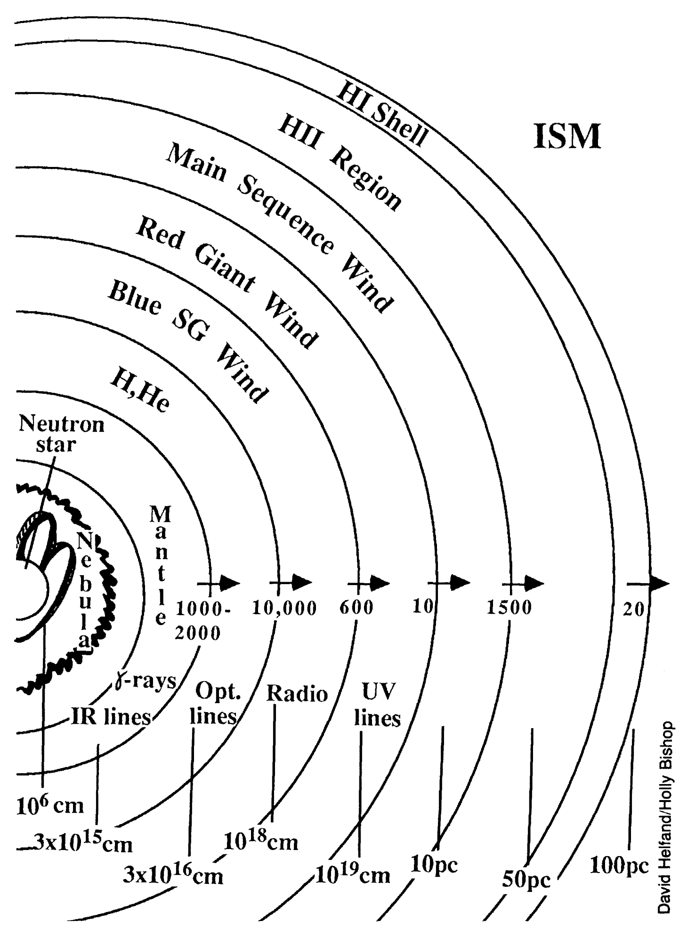
■ *Gamma rays and the light curve.* Supernova watchers were particularly jubilant over the recent observation of gamma rays from 1987A. Just a month before the Austin meeting, in December 1987, University of New Hampshire astronomer Edward L. Chupp and his colleagues announced that their gamma-ray instrument aboard the Solar Maximum Mission satellite had been detecting 847- and 1238-kiloelectron-volt emission lines since August. Also in December, William G. Sandie of the Lockheed Palo Alto Research laboratory and his colleagues announced a confirming observation of the 847-kiloelectron-volt line, obtained during an October balloon flight from Alice Springs, Australia.

The two emission lines, which are just barely visible above a noisy background, mark the decay of cobalt-56 into iron-56. Their detection was hardly unexpected, of course. Not only is cobalt-56 thought to be the most copious radioactive by-product of a supernova explosion, but cobalt decay has apparently been the dominant source of thermal energy in the supernova's expanding shell of debris since mid-summer. Indeed, 1987A has been fading since then at a rate that exactly matches cobalt-56's 78-day half-life.

Nonetheless, the gamma-ray observations have provided the first direct confirmation of explosive nucleosynthesis in supernovas, a development that the astronomers find gratifying to say the least. "Supernova 1987A produced a quantity of cobalt-56 that has 70 times the mass of Jupiter," said Rice University astronomer Donald D. Clayton, one of the originators of the standard model. "If every supernova did this, they could have made all the iron in the universe."

One mystery, however, is that the gamma rays appeared as early as August. Most theorists had not expected them until several months later, when the expanding shell of debris would have thinned enough to let the high-energy photons get out without being scattered and thermalized. On the other hand, the shell may very well be turbulent, which means that some of the cobalt may have been brought up from the deeper layers and mixed into the surface where we can see it. And although this idea has hardly been proved, it is supported by several lines of circumstantial evidence.

The structure of Supernova 1987A



In this schematic diagram, which is not at all to scale, Columbia University astronomer David Helfand has provided a guide to all the concentric shells of material that surround the supernova. The approximate radius of each shell is indicated along the bottom ("pc" stands for parsec, which is a distance of about 3.2 light-years), and the approximate origin of the various spectral features are shown just above. The rightward-pointing arrows indicate expansion velocities in kilometers per second. Reading off the shells from the outside in is like following the Sanduleak star from birth to death. The interstellar medium (ISM) is the tenuous hydrogen gas that exists between the stars. "Main sequence" refers to the object's brief life as a normal, hydrogen-burning star. During that time it was so fiercely hot that it ionized the interstellar medium for hundreds of light-years around (H II region). This ionized hydrogen in turn expanded and swept up a shock wave of neutral hydrogen (H I shell). Meanwhile, the star was emitting a "main sequence wind" analogous to the solar wind. During the star's subsequent red giant phase it emitted a dense, slow-moving "red giant wind." And just before the end, when it had shrunk back to a hotter, more compact blue supergiant phase, it emitted a faster "blue supergiant wind." The explosion itself blew the upper layers of the star (H, He) outward at nearly one-tenth the speed of light. The deeper mantle of the star followed more slowly. And in the center, all that was left was the furiously rotating neutron star, roiling the surrounding plasma (nebula) with its magnetic field.

*The 171st Meeting of the American Astronomical Society, 10 to 14 January 1988, Austin, Texas.

First, the observed gamma-ray lines are quite weak, and represent only a few percent of the total amount of cobalt needed to light up the rest of the supernova shell. This is exactly what one would expect if most of the cobalt were still trapped inside. Second, continuous monitoring by the Solar Maximum satellite shows that the lines have slowly been getting stronger. In August the emitting fraction was barely 1%; now it is roughly 6%. Again, this is exactly what one would expect if the expanding shell were thinning out and letting more and more of the gamma rays shine through.

And finally, as pointed out by George Sonneborn of the Goddard Space Flight Center in Greenbelt, Maryland, 1987A's optical brightness has begun to show a subtle, but undeniable falloff from the straight exponential decay it would have if all the cobalt energy were still being converted into light. Moreover, the magnitude of the effect is roughly what one would expect from the conservation of energy. According to the light curve recorded by the International Ultraviolet Explorer satellite, he said, the energy being lost at visible wavelengths is approximately equal (within experimental errors) to the ever-increasing energy seen in the x-ray and gamma-ray bands.

■ *Peeling back the onion.* In a series of flights out of New Zealand this past November, four different groups of researchers on the National Aeronautics and Space Administration's Kuiper Airborne Observatory (KAO) were able to obtain the best infrared spectra of the supernova to date. Typical were the data presented at Austin by Goddard's Harvey Moseley.

One of the big advantages of working at infrared wavelengths is that the gas of the expanding shell is relatively transparent there, he said. This means in turn that the KAO spectra come from relatively deep in the shell, from material that once comprised the mantle of the pre-supernova star.

Most strikingly, Moseley said, the KAO spectra show emission lines from a variety of heavy elements. Cobalt is there, as expected. But so are iron and sulfur, two elements that play a prominent role in the chain of nucleosynthesis that leads to element creation in stars. Indeed, he said, "There is considerably more iron than you would expect to find in the mantle of such a star, which suggests that we are seeing stuff that formed in the core, either at or near the explosion itself." The sulfur was likewise formed in the explosion, although there is a possibility that it was excavated from still deeper layers of the star where it had formed during the years just prior to the explosion.

As for the future, said Moseley, he and his colleagues hope to start mapping out the structure of these inner regions of the shell, using careful analyses of the Doppler shifts of the lines. "[The infrared spectra] give us an excellent diagnostic," he said. "it lets us peel back the onion and look at the details of how the core exploded."

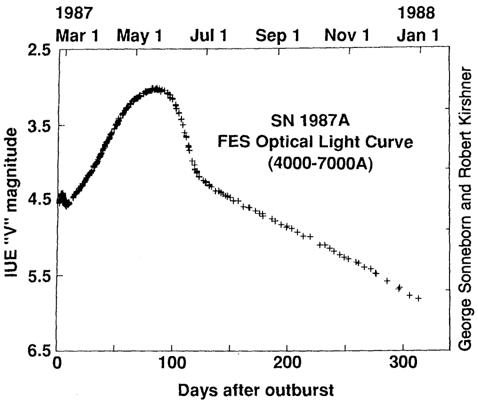
■ *Ultrahigh energy gamma rays.* Astronomers will be monitoring supernova 1987A for decades, if not centuries. So predictions were in ample supply at Austin. Goddard's Alice K. Harding, for example, suggested that the supernova will soon be sending us still more gamma rays—except that these photons will be roughly a thousand to a million times more energetic than anything produced by cobalt.

Ultimately, she said, the source of these gamma rays is the furiously rotating neutron star that presumably formed at the center of the supernova at the instant of the explosion. The neutron star is actually the subject of a prediction all its own: since it almost certainly has a strong magnetic field, then sometime in the next few years it will start to shine through the ever-expanding ejecta shell as a pulsar. But in the meantime, said Harding, the pulsar's fast-moving magnetic field is whipping up the plasma inside the shell and flinging high-energy protons outward. As these protons slam into the material on the underside of the shell they produce a spray of collision products, among which are neutral pions. These pions then decay into ultrahigh energy gamma rays of roughly 10^{12} to 10^{15} electron volts.

Sometime in the next few months, said Harding, gamma rays that have begun to leak through the expanding shell will start arriving at the top of Earth's atmosphere, where they will produce air showers detectable by a number of existing cosmic ray detectors. "If we see these gamma rays," she said, "that tells us there is an accelerator [inside the supernova] with a million times the luminosity of the sun. And that's very good evidence for a central pulsar."

■ *The light echo.* While Harding waits for the gamma rays, her Goddard colleague Bradley Schaefer is looking forward to a much milder phenomenon: the so-called light echo.

As Schaefer explained it, a light echo from the supernova would work in basically the same way that sound echoes do on Earth. Light moving outward from the explosion would encounter an obstacle, such as an interstellar cloud of gas and dust, and would scatter in all directions; the portion that scattered in our direction would then reach terrestrial telescopes at some time after the flash that arrived along a straight-line path last February. The difference is that the delay would be measured not in seconds but in years, given the magnitude of interstellar



The rise and fall. *This plot of data obtained from the International Ultraviolet Explorer satellite shows the evolution of 1987A's optical brightness over time. The magnitude scale on the left is logarithmic; thus, the linear falloff after 1 July corresponds to exponential decay. The half-life is 78 days, corresponding to the half-life of cobalt-56. The slightly steeper falloff after 1 November seems to correspond to the energy lost as gamma rays from cobalt-56 decay escape to the outside.*

distances. Moreover, the echo would appear not as a single pulse, but as what Schaefer called a "phantom nebula": a slowly expanding circle of reflected light centered on the location of the supernova.

The light echo is one prediction that will almost certainly come true, said Schaefer. The phantom nebula phenomenon was first observed in the aftermath of Nova Persei in 1901, and since then has been found in a number of other stellar eruptions. At the moment, 1987A's phantom nebula is hidden by the glare of the supernova itself. But as the supernova fades, said Schaefer, the nebula should emerge with a brightness of about tenth magnitude, which will make it easily visible in amateur telescopes. Indeed, he said, it promises to be an endlessly fascinating target, one that is constantly evolving over the decades as 1987A's light pulse is reflected from ever more distant objects. "The big question now," he said, "is the location of the interstellar dust clouds."

■ *The formation of dust grains.* The subject of dust was also much on the mind of the University of Minnesota's Robert D. Gehrz. In the interstellar context, "dust" refers to the fine, smoke-like grains of carbon and silicate minerals that seem to be ubiquitously mixed in with the galaxy's giant gas clouds. When stars form in such clouds, dust grains presumably supply the material to make any planets, asteroids, or other solid bodies. The question is, What makes the grains?

Although no one knows for sure, said Gehrz, supernovas are considered a very likely source. In their preexplosion phase the stars accumulate elements such as carbon, silicon, and oxygen through nucleosynthesis—exactly the elements needed to make the dust. And in their postexplosion phase, as most of the stars' material goes flying outward, the rapid expansion of the debris causes equally rapid cooling—exactly the conditions needed to condense the vaporized elements into solid grains.

On the other hand, said Gehrz, one can also argue that other factors in the debris shell—radioactivity, say—will stop the grains from growing. Thus the importance of 1987A as a test case. If the scenario is correct, he said, then grains should start to form there sometime in the next year or so, and the observational signature will be dramatic. The supernova will suddenly fade by 90% to 98% in the visible band as the dust begins to absorb light. Simultaneously, it will brighten in the infrared band as the dust reradiates that energy at longer wavelengths. This condition will last a year or two, said Gehrz, or until the expanding shell is so tenuous that the dust is no longer an effective shield.

■ *Do supernovas reexplode?* Moving from the 1- or 2-year time scale to the decadal timescale, Kenneth Brecher of Boston University predicted that 1987A will undergo a "reexplosion" within 10 to 50 years.

Part of the argument is historical, he said: supernovas seem to have reexploded before. One example is the very bright supernova of 1006, which was noted both in Europe and in China. (This was *not* the famous supernova that created the Crab Nebula in Taurus; that event took place in 1054.) In a recently discovered Chinese manuscript, said Brecher, an observer who had seen the new star of 1006 wrote that he saw another new star appear in the same place 10 years later, in 1016.

Another good example is the supernova of 1572 in Cassiopeia, which was studied in detail by the great Danish astronomer Tycho Brahe. Forty years later, in the winter of 1612–3, the German astronomer Simon Marius examined the position of the supernova telescopically and noted the reappearance of a star "somewhat dimmer than Jupiter's third moon." (One of the top astronomers of his age, Marius had worked at Tycho's observatory as a young man and had independently begun to use a telescope for astronomy at the same time as Galileo.) In modern terms Marius' estimate translates to a magnitude of five or six, or about 10,000 times dimmer than the 1572 supernova at its brightest. This object faded and was gone after a year.

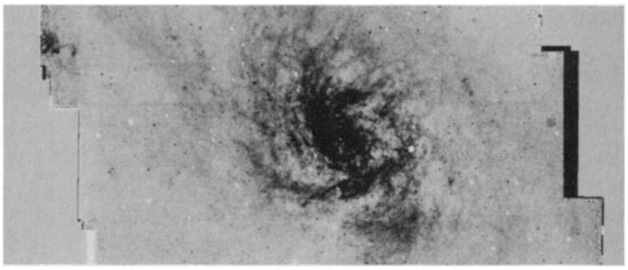
Still another example is Kepler's supernova of 1604, said Brecher. In 1664, Chinese astronomers reported that the star reappeared with "a near red-yellow" color. It faded again, and by May of 1665 it, too, had vanished .

Taken together with other such records, said Brecher, these anecdotes are highly suggestive—which brings us to the second part of the argument: 1987A has revealed a plausible mechanism for reexplosions.

According to spectra taken by the International Ultraviolet Explorer satellite, he said, the supernova is surrounded by a huge shell of material about 1 light-year out. This shell contains about four times times the mass of the sun—mostly in the form of hydrogen, helium, and an admixture of heavier elements such as nitrogen—and it is moving outward relatively sluggishly: only about 10 kilometers per second. Simple arithmetic suggests that the material of the shell was ejected from the vicinity of the precursor star, Sanduleak −69 202, just a few hundred thousand years ago. The presumption is that this epoch corresponded to the Sanduleak star's red giant phase, a period when it briefly swelled to a gargantuan size and began emitting the material from its surface as a dense, slow-moving stellar wind. (Such behavior is not unusual; virtually all stars go through a windy red giant phase as they near the end of their lives.)

Since 23 February 1987, of course, this larger, older shell has found itself surrounding not a star, but a supernova. Moreover, the supernova's ejecta shell is erupting outward at velocities of up to one-tenth the speed of light. Thus the prediction, said Brecher: sometime in the next decade or so the inner shell will catch up with the outer one, merge with it, and flare with dissipated kinetic energy. For about a year the much-faded supernova will brighten again, reaching a magnitude of about ten. It will glow red with the color of ionized hydrogen. And then, inexorably, it will begin to fade once more. ■ M. Mitchell Waldrop

Do You Know This Galaxy?



As unfamiliar as it looks, this is actually an image of the most famous spiral in the sky: M31, the Great Galaxy in Andromeda. It was presented at the recent meeting of the American Astronomical Society in Austin, Texas, by Robin Ciardullo of the Kitt Peak National Observatory. His coauthors were Kitt Peak's George H. Jacoby and Vera C. Rubin of the Carnegie Institution of Washington.

In essence, the image is a mosaic that shows what the central regions of M31 would look like if all its stars and interstellar dust were removed, and only its interstellar gas were left. Ciardullo created the mosaic by digitally adding hundreds of charge-coupled device frames that he had taken over the past 5 years in a search for novas. He was able to suppress the light of the stars and dust because he had taken these particular frames using a narrow-band filter centered on the light of ionized hydrogen. The result provides the most detailed look at the gas in this region ever obtained.

Perhaps the most striking thing is that this tiny gas spiral in the middle of M31 seems much more face-on to us than the galaxy as a whole. The larger spiral is inclined by about 77°, while the small spiral is inclined by no more than 45°. This suggests that the inner structure is dynamically decoupled from the outer disk—which is perhaps not surprising, since it is sitting deep within M31's spheroidal bulge. Indeed, astronomers are turning up these little disks at the center of galaxies more and more often.

Less striking, but more perplexing, are the thin, thread-like structures that seem to plunge into the center from every angle. Neither Ciardullo nor any of his coauthors cared to speculate what these were. The closest analogs are the thread-like structures seen in radio images of the center of our own galaxy. But those threads are only one-tenth the size—and no one understands them, either. ■

M. Mitchell Waldrop