Supernova's gamma rays unveil continuing creation

Scientists continue to study the first explosion of a nearby star since the telescope was invented. Feb. 23 marked the anniversary of its first light. David Cherry reports.

For those who believe in the Big Bang theory of how the universe began, a supernova is principally the death of a star—in the last analysis, a minor contributing drama in the inexorable running down of the universe. But, in the actual universe, a supernova is like a flower. Its brilliance is extinguished as it releases the seeds by which life is developed ever further.

A supernova explosion both creates and scatters into the interstellar medium numerous elements necessary to life—some of them elements for which no other genesis is known.

This feature of Supernova 1987A came to the fore last Dec. 14, when two teams of astrophysicists reported the hoped-for detection of gamma-rays at predicted wavelengths. These gamma rays are our first direct confirmation of "explosive nucleosynthesis"—the creation of new nuclei as part of the supernova explosion process. Even though our understanding of the fundamental processes of supernovae is still very imperfect, the detection is an important milestone.

The detection

The astrophysicists reported their results to the Workshop on Nuclear Spectroscopy of Astrophysical Sources in Washington, D.C., sponsored by NASA and the Office of Naval Research.

The supernova shockwave, according to the theory they have just confirmed, produces radioactive nickel-56 which quickly decays (half-life 6.1 days) to cobalt-56. The cobalt then decays (half-life 77 days) to stable iron-56. This sequence leads to the prediction of gamma-ray emission lines at a dozen different energies, and there are still other nucleosynthesis processes entailing their own gamma-ray emissions. Low-energy gamma rays are the form of energy characteristic of changes of energy levels in the nucleus; hence they are called nuclear gamma rays.

Each of the two experiments detected gamma rays at 847 kiloelectronvolts (keV) and 1,238 keV. These are the strongest of all the predicted lines, and both arise from the decay of cobalt-56 to stable iron. Donald Clayton of Rice University, an old hand in the supernova business, commented that Supernova 1987A had produced cobalt-56 equal to 20,000 times the mass of the Earth. If every supernova did this, he added, they would make all the iron in the universe. His comment was not facetious, since iron and the iron family of elements are thought to be created exclusively by explosive nucleosynthesis, rather than in the humdrum, daily activities of stars. Since nickel-56 and cobalt-56 are both short-lived, the appearance of the gamma-ray signature for cobalt-56 decay is proof that new nuclei have been brought into being by the supernova explosion itself.

The missions

The results reported in December were those of the German-American Gamma-Ray Spectrometer (GRS, Edward Chupp, University of New Hampshire, principal investigator) aboard NASA's Solar Maximum Mission, a spacecraft in Earth orbit for several years now; and from a gamma-ray telescope (Thomas Prince, Caltech, principal investigator) lofted by a NASA high-altitude balloon from Alice Springs, Australia in November.

The first of these results has now appeared in print (*Na-*

ture, Feb. 4). The 847 keV line was detected as a flux of 1 photon per 1,000 seconds per square centimeter, at 843 ± 5 keV, after subtracting the abundant background noise. There are no other gamma-ray sources in the neighborhood of the supernova, and the emissions peak very nicely at the position of the supernova itself. Comparing the observation with the preceding years of data, the experimenters write, "This feature [the observed 847 keV line] cannot be explained by any statistical or systematic fluctuations observed in the seven previous years of GRS data." They calculate a statistical

Why a star explodes

The life of a star begins typically with the condensation of a ball of gas—most of it hydrogen—in a spiral arm of a galaxy. Gravitation induces densification and heating until nuclear fusion begins. The fusion process uses up hydrogen, produces helium, and results in denser, hotter conditions in the core, until helium itself begins to undergo fusion.

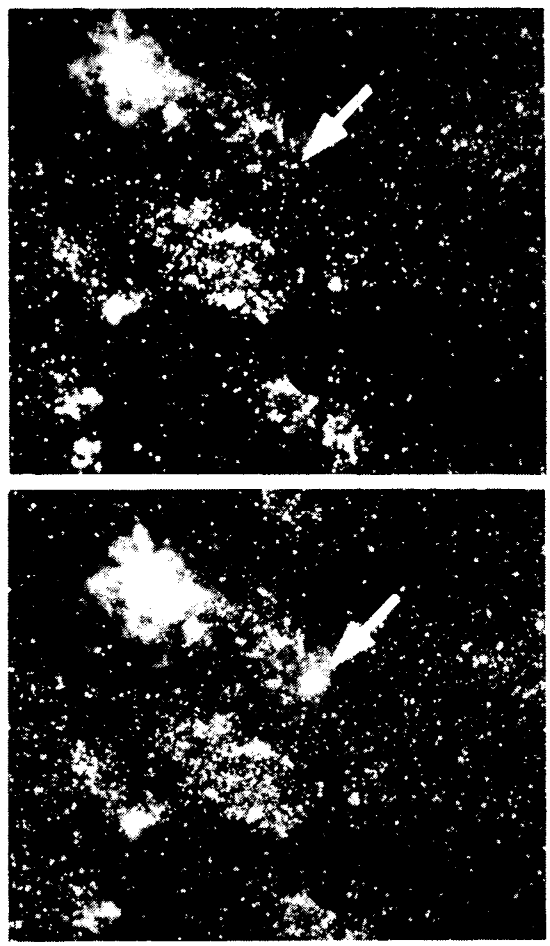
Helium burning produces carbon, and results in even more intense conditions until carbon fuses to produce magnesium, sodium, neon, oxygen, and other elements. And so the process continues until iron is formed. The nucleus of iron is uniquely stable. It will not fuse under the available conditions. What then happens? The following explanation of core collapse is the prevailing theory, but doubtless requires revision in light of what is known today about the nonlinear, nonthermal aspects of plasma behavior.

At all times, the theory goes, the radiation streaming outward from the fusion furnace at the star's core is actually "holding the star up"—it counterbalances the gravitational pull on the outer layers. As more and more iron is formed, the outward flow of radiation dwindles, and suddenly—in a fraction of a second—the star suffers gravitational collapse of its core. This is called "the iron catastrophe," one of the causes of supernovae, and the cause of Supernova 1987A.

Gravitation is now so great at the core that electrons fuse with protons to form neutrons—the iron is no more—and the process entails a prodigious burst of neutrinos. The neutrons, having no charge, pack densely. A neutron star of unimaginable density has come into being. A pocket matchbox of neutronic matter would weigh hundreds of millions of tons.

The collapse is followed by an explosion that creates the visible supernova. One theory holds that the collapse causes the core to momentarily reach greater-than-nuclear densities, and the explosion is driven by the resulting bounce. Another holds that the explosion is driven by the neutrino burst. The shockwave slams into the star's outer layers. It slams into the silicon-28 layer, inducing the creation of nickel-56 by fusion.

The outer layers are blown off with inconceivable force at a velocity 250 times greater than the shockwave of a hydrogen bomb. The diameter of the shock front expands by one Earth diameter every second. The light emitted is as luminous as half a billion suns!



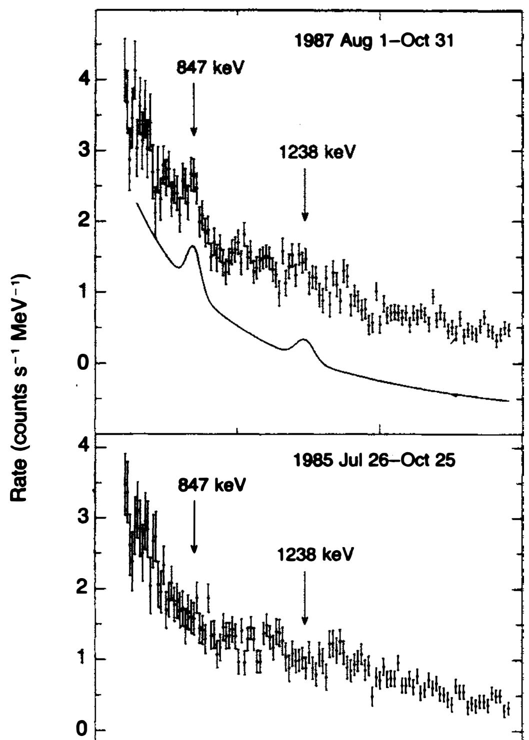
Supernova 1987A in the Large Magellanic Cloud—before and after below, the "discovery plate" exposed by Ian Shelton February 23, 1987 at 11:48 p.m. EST with a small, 10-inch refracting telescope. Above, the same star field taken by Shelton with the same telescope February 22 at 10:36 p.m. Shelton is the resident astronomer for the University of Toronto Southern Observatory at Las Campanas, Chile. The supernova was visible to the naked eye in the southern hemisphere for many weeks, but always beyond the horizon in the northern hemisphere.

significance level of greater than 5σ (5 standard deviations—3σ is a 98% level of confidence in the significance of the result). The detection of the 1,238 keV line is less certain, but is seen clearly in others' observations yet to be published (see Woosley interview, below). The GRS detection testifies to the importance of getting telescopes into space—in this case because gamma rays cannot be detected through the atmosphere at all. (See **Figures 1** and **2**.)

Surprisingly, the gamma rays made their appearance in early August. The GRS data reported in December run to Oct. 31, and show an early August onset. It had been generally agreed that it would take several additional months for the supernova envelope to expand and thin out enough for the gamma rays to get out. "Gamma rays by Christmas or Easter," as Stirling Colgate had put it (interview, below). Of course X-rays had escaped from the envelope 75 days ahead of predicted schedule also. It is guessed that the envelope may not be uniform, and that through turbulence a certain amount of cobalt-56 has gotten out beyond most of its depth. That is consistent with the brightness of the two lines as observed by the GRS experimenters. The lines are so faint, they say, as to correspond to only about 1.3% of the cobalt-56 that the light curve indicates is present, this observed amount is completely free of the envelope.

Further observations by these experimenters are under way. Other groups' observations—already accomplished—are now being prepared for publication and we are at the onset of numerous additional gamma-ray experiments that will peak this spring.

FIGURE 1
Gamma-ray spectrum of the supernova



Above, a segment of the gamma-ray spectrum, recorded by the GRS from the direction of the supernova. It was accumulated over the period Aug. 1 to Oct. 31, 1987. Background flux has been subtracted, but residual atmospheric gamma-ray continuum emission remains. The solid curve is based on calculations of what we would expect to see. Below, an equivalent spectrum accumulated in 1985, for comparison.

(S.M. Matz et al., *Nature* Feb. 4, 1988, pp. 416-18.)

History of a breakthrough

The origin of the Solar System and of solar systems in general is one of the most challenging questions that astronomers and space scientists confront, and lies behind the question of the origin of life. It is really a complex of questions. How were the planets formed? What determines their orbits? *What processes determined the relative abundances of the elements and their isotopes?* This last question is the one that leads to the puzzle of nucleosynthesis.

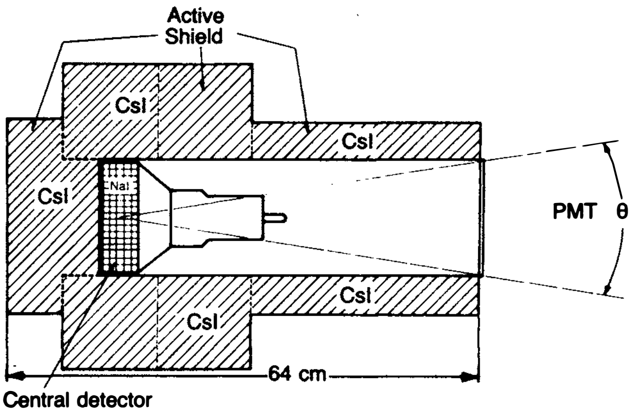
In the 1930s it was finally established that the source of energy by which the Sun and the stars shine is nuclear fusion—the creation of larger nuclei through the fusing of smaller ones. Was it not therefore possible that the range of naturally occurring elements in the universe is created by the steady burning of the stars and was not determined "primordially"? Perhaps, but the conditions then known to exist in these fusion furnaces were not sufficiently intense to account for the abundances of many of the heavier elements. (See **Figures 3** and **4** and Woosley interview, below.)

Meanwhile, it was also in the 1930s that a new astrophysical phenomenon was identified—the "supernova." For some centuries astronomers had studied novae—Latin for "new stars." Novae are not really new stars, but they do increase in brightness very dramatically. They may brighten by as much as 16 magnitudes (an intensity increase of a million times) in just a few hours. After peaking, the nova's light curve slopes gently downward over a period of months. Finally the star settles down and looks much like its former self.

Walter Baade and Fritz Zwicky in the early 1930s noticed that an occasional nova seen off in another galaxy was really something else. These were very bright novae that peaked, faded, and left apparently nothing behind. They had simply exploded! Zwicky dubbed these "supernovae." Historical records made it possible to identify as supernovae the spectacular events of 1054 (recorded by Chinese and Japanese

FIGURE 2

Low energy gamma-ray telescope



Gamma rays from astrophysical sources can only be observed from above the atmosphere. Compared to astrophysical X-rays they are sparse, and also much harder to catch.

This is a schematic of one kind of gamma ray telescope, illustrating the principle used by the GRS to detect the supernova's gamma rays. The GRS itself is more complex. The central detector is a disk of a scintillator material, sodium iodide (NaI).

The incoming gamma ray interacts with the field of a nucleus in the central detector, causing an energetic electron to be emitted (Compton scattering) that ionizes other atoms. The gamma ray loses some of its energy and continues on its way. The ionized atoms de-excite by emitting optical photons to which a photomultiplier tube responds (PMT in figure). The end result is an electric current that can be recorded.

How is the direction of the gamma-ray source determined? Unfortunately, the pathway of the electron produced in the central detector does not imply very much about the direction of the incoming low-energy gamma ray. Directionality is achieved by surrounding the central detector with shielding to limit the field of view to angle θ 15° in this case. Passive shielding (e.g., lead) to actually stop gamma rays makes these instruments more massive than they have to be. Active shielding is made of another scintillator material, such as cesium iodide. Gamma rays that pass through the shielding before hitting the central detector can be identified by their time coincidence and eliminated from the count.

The GRS was built to detect gamma rays from the Sun. It always points toward the Sun with rare exceptions, and is therefore pointing away from Supernova 1987A by about 90 degrees, with some variation. Observation of the supernova was achieved by counting the photons entering the shielding and ignoring those entering the aperture! Directionality was achieved by comparing counts accumulated while the supernova was in view with those accumulated while it was occulted (obscured) by the Earth. The latter was then subtracted from the former.

(After Walraven et al., *Astrophys. J.* 1975, p. 503.)

astronomers, its remnant is still visible today as the Crab Nebula), 1572 (recorded by Tycho Brahe), and 1604 (recorded by Johannes Kepler). All three had exploded in our home galaxy, brightening the sky even by day and provoking terror in hardy souls.

Supernova explosions, then, might account for the creation of some heavy elements, making up theoretical deficiencies. Moreover, the explosions would scatter the newly created nuclei into interstellar space, making them available, for example, to our Solar System.

The detailed study of nucleosynthesis began in earnest with a seminal paper by the British cosmologist Fred Hoyle in 1946 and further work over the following decade. The development of the hydrogen or fusion bomb aided the process of understanding supernovae, not least because of the study of bomb-generated shockwaves. The creation of heavy elements in a supernova explosion is a shockwave phenomenon. Stirling Colgate studied both kinds of shocks, and had the advantage of discussions with other bomb scientists at Lawrence Livermore Laboratory such as Tom Weaver, George Chapline, and Edward Teller.

It was Colgate and Chester McKee in 1968 who discovered that supernovae must create nickel-56, which then decayed to stable iron-56 while giving off gamma rays, correcting Hoyle's initiating paper. Hoyle had supposed that the iron abundance peak came about through supernova creation of the iron directly. (See Colgate interview, below.) It was then immediately realized that the gamma rays might well be detectable.

Universal gamma-ray background on agenda

Donald Clayton of Rice University developed the idea of detection, and in "Confirming Explosive Nucleosynthesis with Gamma-Ray Telescopes" (1973) went further to propose the detection of the universal gamma-ray background that must surround us from the totality of supernova nucleosynthetic activity. One might be able to sample historical rates of nucleosynthesis by sampling the background at different distances, he wrote. Because of the expansion of the universe, the background at greater and greater distances (greater red shifts) would reflect conditions ever further in the past. (See Clayton interview, below.) It is this provocative proposal that must now be brought to fruition in the 1990s.

Other aspects of the supernova's development will be covered in a second installment.