Dead Stars Do Tell Tales:

The Intriguing Case of Supernova 1987A

Stephen S. Lawrence

Assistant Professor
Department of Physics

When a massive star dies, it really goes out with a bang. In fact, such an explosion, known as a *supernova*, is one of the most energetic events in the entire Universe. During a supernova the dying star, referred to as the *progenitor*, can increase its brightness by 10 billion times, outshining the combined light of the billions of other stars in its home galaxy. The nuclear fusion reactions that take place during the star's lifetime and during the supernova explosion itself are responsible for creating all of the elements heavier than hydrogen and helium. The oxygen we breathe, the calcium in our bones, the iron in our blood, the gold in our fillings – all of these elements are products of supernova explosions. There is even evidence that the formation of the sun and the Earth may have been triggered by the shockwave from a nearby supernova explosion.

Unfortunately, these exciting and momentous explosions are extremely rare, happening on the average of one per century in any given galaxy. Modern searches now discover more than 100 supernovae each year, but they are all in distant galaxies. This makes them very faint and difficult to study in any great detail. Here in our home galaxy, the Milky Way, we are long overdue: Johannes Kepler sighted the last "local" supernova in 1604. This rarity of supernovae is what makes the night of February 23, 1987, one of the most significant dates in modern astronomy.

A shot seen 'round (and through) the world

The nearest supernova in nearly four centuries was discovered that night by two astronomers working in Chile and an amateur astrophotographer from New Zealand. All three were independently observing the Large Magellanic Cloud (LMC), a small companion galaxy that orbits as a satellite around the Milky Way. (The LMC is visible only from the Southern Hemisphere and lies at a distance of 160,000 light years from Earth, meaning that it has taken light 160,000 years to reach us.) They each noticed that a bright new star had appeared in the LMC, where there had been nothing remarkable just the night before. Realizing the significance of a supernova so close to home, the Chilean astronomers used a telegraph service run by the International Astronomical Union (IAU) to broadcast the news of the discovery of Supernova 1987A (so named as it was the first supernova discovered in 1987) to every observatory and astronomy department worldwide. As the Earth turned, astronomers in Australia and South Africa scrambled to find the appropriate filters that would allow them to observe such a bright, naked-eye star with large research telescopes.

During the first few weeks there was practically round-the-clock coverage of the supernova, with observations taken from every southern continent (including Antarctica), using telescopes on mountaintops, weather balloons, high-altitude aircraft and satellites. Observations of the aftermath are still ongoing, making Supernova 1987A the most intensively studied object outside of the solar system. It has been detected at all wavelengths of light, from high-energy gamma rays to low-frequency radio waves. In early March 1987, physicists in Ohio and Japan announced that they had even detected a burst of neutrinos from Supernova 1987A on the night of the explosion. Neutrinos are ghostly subatomic particles produced in nuclear reactions that rarely interact with normal matter. The 12-second burst of neutrinos from Supernova 1987A had arrived from a direction over the South Pacific Ocean near Antarctica and had actually passed *through* the Earth itself to arrive at the underground neutrino detectors *from below*. Generated during the first few instants of the supernova and traveling at the speed of light, the neutrinos tell us the exact time of the explosion. Supernova 1987A is the only astronomical object besides the sun that has been detected through its neutrino emissions.

A three-ring circus

After several years, Supernova 1987A had cooled and faded such that it could be observed only with the largest ground-based telescopes, or with astronomers' newest tool, the Hubble Space Telescope (HST). Figure 1 shows a composite image of the aftermath of Supernova 1987A taken in wavelengths of red light. Multiple images taken between 1994 and 1996 have been combined digitally to improve the resolution and sensitivity to the faintest emission. A number of interesting features can be seen:

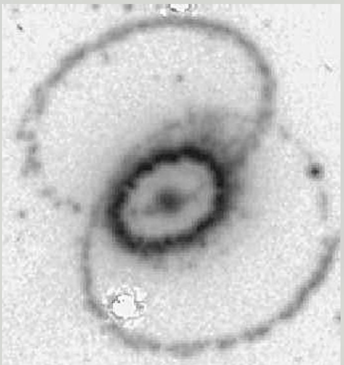

Figure 1. A Hubble Space Telescope image of Supernova 1987A, taken in red light roughly eight years after the explosion. The last glowing embers of the star (center) are surrounded by three mysterious rings of gas. For scale, the brighter, inner ellipse has the same apparent diameter as that of a quarter viewed two miles away.

1) The grayish spot at the very center of the image is the faintly glowing remains of the densest gaseous debris thrown off during the explosion, called “ejecta.” These ejecta represent the innermost layers of the original star, contaminated by the products of the runaway nuclear reactions that powered the explosion. This gas is kept hot and glowing by the decay of radioactive isotopes of nickel, cobalt and titanium.
2) Three clumpy, elliptical rings of circumstellar gas are centered on the former location of the progenitor. These mysterious rings were shed by the progenitor roughly 20,000 years before it exploded, and are drifting outward at the astronomically leisurely pace of 30,000 miles per hour. The rings are like huge fluorescent lamps, glowing as a result of a strong burst of X-rays and ultraviolet light produced during the first few hours of the supernova; they have been slowly fading ever since. Observations show that the rings are three parallel circles stacked one above the other and tipped toward us by about 45 degrees. (Imagine taking an hourglass and tracing out three circles on it with glow-in-the-dark paint: one around the narrow waist and one each around the widest portions of the upper and lower balls. Now turn out the lights and tilt the top of the hourglass away from you by 45 degrees. This is a reasonable model for the shape and relative positions of the three rings.) One can even see a faint glow from some very low-density gas in the “walls” of the hourglass, as a faint fringe of emission just outside the brighter inner ring. Astronomers have a basic understanding of how the star may have blown off this gas into a general hourglass-like configuration, but it is still a mystery as to exactly why the gas is concentrated into three denser rings, with the walls and end caps at much lower, effectively invisible concentrations.
3) Significant quantities of transparent ejecta are also between the central visible debris and the inner circum stellar rings. The outermost layers of this material were launched from the explosion at approximately 10 percent the speed of light, or roughly 600 million miles per hour! These layers have already cooled and faded to near invisibility, producing the slight grayish glow filling the inner ring.

Seeing spots with Hubble

Based on measurements taken during the first few nights of the explosion, astronomers calculated that the outermost layers of ejecta would reach the bright inner ring in approximately 10 years. Their models showed that these fast-moving, low-density ejecta would drive a massive shockwave into higher-density, slow-moving gas in the ring. This shockwave would suddenly compress the ring gas, briefly heating it to millions of degrees and accelerating it to high velocities. Because the near side of the ring is about a light year closer to us than the far side, we see events and changes there a year earlier than on the far side of the ring. Assuming that the inner ring was truly circular and that the ejecta were thrown off symmetrically with similar velocity in all directions, it was predicted that we would see the impact begin on the near side and then take a year to spread around to the far side of the ring.

As if on cue, in April 1997 astronomers using the Hubble Space Telescope detected a small region on the slowly fading inner ring that was actually brightening and had the signature of newly accelerated, high-velocity gas. This “hot spot” was even on the near side, as predicted. But here the simple predictions broke down. For nearly three years following the discovery this first hot spot grew brighter, but didn’t spread out along the ring. And no other new hot spots were detected.

Then in January 2000 my colleagues at Columbia University and I discovered evidence that a second hot spot was forming, in ground-based data taken at the Cerro-Tololo Inter-American Observatory in Chile. We used an infrared instrument designed to rapidly compensate for the blurriness of the Earth’s atmosphere, and special image processing techniques designed to detect subtle changes in a source by subtracting images taken at different times. Surprisingly, the second spot was located not on the near side of the ring, but most of the way around to the back. Announced in another IAU telegram (now distributed via e-mail), the new hot spot activity was quickly confirmed by other astronomers in HST images taken almost simultaneously with our announcement. Using precious HST orbits held in reserve for such late-breaking discoveries, we developed an innovative method of observing Supernova 1987A that allows us, in combination with our difference imaging techniques, to monitor the entire inner ring for either the brightness changes or high-velocity signatures that indicate the formation of a new hot spot.

Pictured above: Supernova 1987A ring

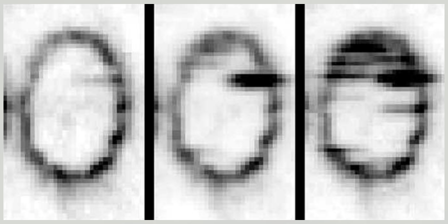

Figure 2. HST spectral images of the inner circumstellar ring of Supernova 1987A, showing emissions from hydrogen gas in April 1997 (left), May 2000 (center) and April 2001 (right).

Note the increasing number and brightness of the hot spots (horizontal smears) with time, sites where a shockwave from the explosion is beginning to destroy the ring.

Figure 2 presents three epochs of HST data on the inner ring (rotated about 135 degrees with respect to the orientation of Figure 1). These images show the inner ring in a specific wavelength of red light emitted by hot hydrogen gas. The slow-moving gas of the inner ring forms a simple undistorted image, but emission from the turbulent high-velocity gas within a hot spot is broadened by the Doppler effect from a single point in the image into a horizontal smear. The leftmost image, from April 1997, shows the discovery "smear" of the first hot spot (at the 2 o'clock position on the ring). The center image shows the inner ring three years later, in May 2000. The first hot spot is now much brighter, and five new faint spots have appeared (at 7 o'clock and between 10 and 12 o'clock). The rightmost image shows the ring in April 2001. The first hot spot has slowed its rate of brightening, the other spots from May 2000 have increased dramatically, and other new spots have appeared in the space of just one year (at the 3, 5 and 9 o'clock positions). It is very unusual in astronomy to be able to see such rapid changes in an object this large. Our latest difference imaging analysis have shown that there are now 13 hot spots spread around the entire circumference of the inner ring.

We now believe that the hot spots actually represent the innermost peninsulas and protrusions of the clumpy inner ring that have been struck by the blast wave first. The order of appearance and the rate of brightening of the hot spots may provide us with information about the degree of asymmetry in the ejecta velocities and details about the shapes of the ring protrusions too small to resolve even with HST. And we expect that the real fireworks are yet to come, when the ejecta actually reach the full inner surface of the ring. Observations of Supernova 1987A over the next several decades will provide us with an unprecedented amount of detailed information on how supernova shock waves deposit energy into interstellar gas, and how newly synthesized heavy elements get spread throughout a galaxy.

Is there an echo out there?

In addition to being an once-in-a-lifetime opportunity to study a supernova up close, Supernova 1987A has also provided us with a unique probe of the LMC galaxy. For just a few months the supernova was billions of times of brighter than the progenitor had been previously, and then it faded quickly to near invisibility. On astronomical scales of time and distance, this is like an immense flashbulb going off in the galaxy. Much as the burst from a fireworks shell during the grand finale will light up the smoke from earlier shells, photons from the brief maximum of Supernova 1987A are sweeping outward through interstellar space and illuminating clouds of gas and dust in the LMC. The grains of dust scatter and reflect those photons in random directions, with some fraction redirected towards the Earth. Astronomers refer to these scattered photons as "light echoes."

Much as an air traffic controller uses the timing and direction of the reflection of a pulse of radar to determine the location of an airplane, we can use a series of images of these light echoes to map out the three-dimensional distribution of dust clouds in the neighborhood of Supernova 1987A. Consider taking an image of an area of the sky centered on Supernova 1987A (as my colleagues at Columbia University and Las Campanas Observatory in Chile have been doing for the last 13 years), 10 years after explosion. Any photons reaching the Earth on that night have obviously traveled along a path that is 10 light years longer in distance than the photons that arrived here directly on the night of the explosion. By measuring the angle between the echo and the supernova in our images, and combining this with the light-travel delay, we can use simple geometry to calculate the position of the dust cloud relative to the supernova. It is very unusual in astronomy to obtain such three-dimensional information on targets within our own galaxy, let alone at even greater distances.

Figure 3 presents an example of the light echo phenomenon. Containing an area of the sky hundreds of times larger than Figure 1, it displays the results of carefully aligning and subtracting two images taken from Chile in 1995 and 1996. As noted earlier, most astronomical objects remain constant over the timescale of a year, so the vast majority of the thousands of LMC stars that clutter the two original images are precisely canceled out by the subtraction. (A relatively small number of rapidly varying and bright, saturated stars do leave small artifacts). The large, faint, clumpy arcs and rings that remain are the light echoes, whose faint signals would normally be lost in the overwhelming background of the LMC stars. Due to the order of subtraction, the locations of the echoes in 1995 are presented as white, positive values, and in 1996 as black, negative values. Across the space of a year, the light echoes appear to expand radially outward from a point centered on the supernova, like ripples in the surface of a pond. The big "bull's-eye" ring feature represents two large sheets of dust and gas, each hundreds of light-years wide. The brighter clumps scattered along each arc represent small substructures within the sheets where the dust density is much higher. Another interesting structure that the echoes have illuminated is the edge of a huge “superbubble” of gas and dust that was swept up by the combined blue supergiant winds of hundreds of massive stars located in a star cluster at its center. With improvements in telescope technology and our image subtraction techniques, we should be able to monitor the progress of the light echoes for decades to come, mapping out the dust distribution over an immense volume of space within our neighbor galaxy.

This region of the LMC has been a site of intense star-forming activity for the last hundred million years. It is filled with a variety of energetic star clusters, nebulae and the remnants of ancient supernovae and, as such, has attracted the attention of numerous HST programs, focused on a broad variety of objects. My colleagues and I have recently been awarded a grant from the Space Telescope Science Institute to search through the public archive of many hundreds of these HST images, searching for light echoes from Supernova 1987A that just happened to fall in the field of view of an unrelated target. At the superb resolution of HST, any such serendipitous echo images could provide us with detailed information on the internal structure of LMC dust clouds on extremely small spatial scales.

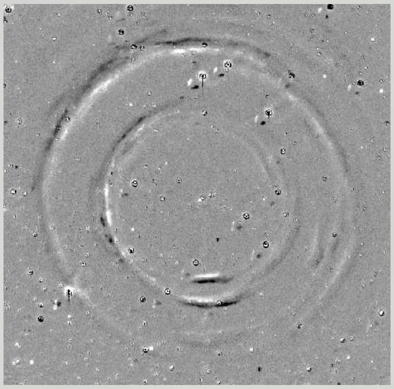

Figure 3. A subtraction of two ground-based images, revealing the light echoes of Supernova 1987A. Analogous to a sound echo, the large “bull’s-eye” pattern displays the reflection of the supernova from two neighboring clouds of interstellar dust, delayed by several years as a result of the enormous extra distance the light had to travel. (Courtesy of Ben Sugerman)

The research projects described here are being conducted in collaboration with Professor Arlin Crotts and Ben Sugerman of Columbia University, Dr. Patrice Bouchet and Dr. Steve Heathcote of Cerro Tololo Inter-American Observatories and Dr. William Kunkel of Las Campanas Observatory. They are being supported through grants from the National Science Foundation, NASA and the Space Telescope Science Institute.

Stephen Lawrence remembers the excitement that swept the astronomy and physics communities when Supernova 1987A exploded during his junior year as an undergraduate. The intense activity triggered by this once-in-a-lifetime event was a factor in his decision to study astronomy, rather than physics, in graduate school. He is particularly pleased that his career has come full circle and allowed him "to study one of the most exciting astronomical events of our time with the Hubble Space Telescope, astronomy’s most powerful research tool."

Professor Lawrence earned a B.A. in physics from the University of Chicago and an M.S. and Ph.D. in astronomy from the University of Michigan. He is a member of Phi Beta Kappa and recipient of the Ralph Baldwin Thesis Prize in Astrophysics and Space Science for his dissertation, "Fabry-Perot Imaging Spectroscopy of the Crab Nebula, Cassiopeia A, and Nova GK Persei."

Prior to joining the Hofstra faculty earlier this year, Professor Lawrence held teaching positions as lecturer at the University of Michigan and visiting assistant professor at Bowling Green State University. He also held research positions as resident astronomer at the Observatorio Astronómico Nacional in Mexico and, most recently, postdoctoral research scientist at Columbia University.

Professor Lawrence’s research interests include supernovae and supernova remnants, light echo phenomena and interstellar dust, and low surface brightness galaxies. He has authored a number of journal articles as well as circulars and conference proceedings relating to his research findings. He has used a variety of large telescopes in Arizona, Mexico and Chile, as well as the orbiting Hubble Space Telescope, to conduct his research.

As pointed out in his article, Professor Lawrence has received funding from the National Science Foundation, National Aeronautics and Space Administration, and the Space Telescope Science Institute in support of his research. - SK