Supernova 1987A

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Lessons and Enigmas

1. The Large Magellanic Cloud Awakes

The first supernova discovered in 1987 turned out to be the most spectacular supernova since the invention of the telescope. SN 1987A was the first supernova easily observable with the naked eye since the one recorded by Kepler in 1604. This event also brought the first direct confirmation that our basic picture of the exotic processes that mark the death of a massive star is correct. SN 1987A is the best-studied supernova ever, but the story is still unfolding, and there is much to learn.

SN 1987A did not explode in our Galaxy, but in a nearby satellite galaxy to our own Milky Way galaxy. This satellite galaxy cannot be seen from the northern hemisphere. The first European to record it was Magellan during his epic attempt to sail around the world. In English, it carries the name the Large Magellanic Cloud for this reason. People native to the southern hemisphere were undoubtedly familiar with it before that. The Aborigines living around Sydney had long had another name for it: Calgalleon, which had to do with a woolly sheep. The Large Magellanic Cloud has a somewhat smaller companion that has picked up the unimaginative name Small Magellanic Cloud. In the same Aboriginal dialect, it was rendered Gnarrangalleon. There is poetry!

The Large Magellanic Cloud is only 150,000 light years away, as shown in Figure 7.1. This is not much farther than the span across the Milky Way itself, about 50,000 light years. By contrast, the Andromeda galaxy, Messier 31, the great sister spiral galaxy to the Milky Way in our local group of galaxies, is about 2 million light years away. The nearest rich cluster of galaxies that has provided many well-studied supernovae in the last several decades is about 50 million light years away. The most distant supernovae ever found are more than a billion light years away. The nearness of the Magellanic Cloud was responsible for the great apparent brightness of SN 1987A. Intrinsically, it was relatively dim as supernovae go.

The known distance to the Large Magellanic Cloud gives us another perspective. The supernova actually exploded about 150,000 years ago, before modern *Homo sapiens* walked the Earth. By an incredible piece of luck, the light arrived at Earth just as our science had developed to the point where we could read many of its most important messages. We had to crawl out of our caves, invent fire and the wheel, develop agriculture and writing, and witness the flowering of Greece, the Middle Ages, the Renaissance, and the Industrial Revolution. We had to develop modern science, quantum theory, Einstein's theory, an understanding of the way stars work, and the techniques for detecting neutrinos and get all this done before the light arrived! Whew!

On the other hand, if the supernova had been a mere 100 light years farther away, technology would have advanced, and we might have learned vastly more from it. On a personal note, if I had known that the light from the supernova were encroaching on the orbit of Pluto in September of 1986, I might not have agreed to be the Chair of my department that fall. By the next spring, I felt as if I were trying to drink from two fire hoses at once.

The Large Magellanic Cloud is neither a spiral nor an elliptical galaxy. Rather it is classified as an irregular galaxy. It has a large central band of rather young, newly formed stars, but then a more distended array of older stars. Off to one side of the central band, there is a region of especially intense recent star formation. The highlight of this region is called 30 Doradus by astronomers, or the Tarantula nebula by star gazers for the “hairy” arms of gas that extend from the center. The 30 Doradus region contains a very young cluster of very massive stars, perhaps 100 solar masses apiece. Surrounding the middle of 30 Doradus are large patches of gas and dust and other young massive stars, somewhat older than the core cluster of 30 Doradus. By careful study of the stellar ages, astronomers have been able to track propagating swaths of star formation in the region. One of the stars left behind in a prior wave of star formation became SN 1987A. Despite the obvious evidence for ongoing star formation, the Large Magellanic Cloud is relatively immature in the sense that it has not processed as much of its gas through stars as has the Milky Way. The amount of heavy elements in the Large Magellanic Cloud is only about one-quarter of that in our Sun.

2. The Onset

SN 1987A was discovered and first formally reported on February 23, 1987, by Ian Shelton, a graduate student from the University of Toronto who was using a small telescope at the Las Campanas Observatory high in the Chilean Andes. The first person to notice it may have been one of the night assistants, Oscar Duhalde, a Chilean of Basque extraction (Figure 7.2). Oscar had worked on the mountain for years and was justifiably proud of his familiarity with the southern sky. He stepped out of the dome for a cigarette and looked at the Large Magellanic Cloud. He noticed that there was a new light in 30 Doradus but did not remark to anyone at the time about it. The supernova was still faint at the time, only hours old, and Duhalde's note of it remains one of the remarkable parts of the story. Half a world away in Australia, Rob McNaught was working on his routine survey of the sky for asteroids. He was especially tired that evening and went to bed without developing his plates. He awoke the next day with the astronomical world full of news of Shelton's announcement and found, when he did develop his image, that he had the first permanent recording of the light from the supernova. Who knows how many other people might have seen something and not mentioned it. There were rumors, but none were confirmed. Figure 7.3 shows a series of photos taken by McNaught with his patrol camera as SN 1987A appeared, brightened, and dimmed over the course of several months.

SEEING SN 1987A

[rfI was one of the first people to hear about the supernova in the northern hemisphere. One of our ex-graduate students, Marshall McCall, was at the University of Toronto when the news came in from Ian Shelton. Marshall promptly called me. I called Nino Panagia who had used the *International Ultraviolet Explorer* satellite to study previous supernovae. Then I called Bob Kirshner at Harvard, perhaps the preeminent supernova observer of the time. I think Bob has never quite forgiven me for calling him second. Bob was also suspicious because I had been around at a meeting in Sicily in 1978 when a wonderful prank was played on him, pretending to bring news of a supernova in Andromeda. I was completely uninvolved in that prank, but guilty by association. Bob's first reaction was that I was pulling his leg. After my call, he went down the hall to the Center for Astronomical Telegrams and found their teletype spewing news of the supernova, although no one had bothered to tell him. I think he was irritated at that, too.

One of my first reactions to the supernova was to try to think of a way to go see it. This was reinforced by one of my colleagues, Don Winget, who said, “Craig, you will die a bitter old man if you don't see this supernova for yourself.” Upon more reflection, I decided that I could be of more use by staying in Austin and trying to contact as many people as possible in the southern hemisphere to alert them to the event and helping to guide observations. I am not an observer myself. I did have some experience in trying to coordinate observations of supernovae at McDonald Observatory and few observatories at the time had any experience in observing supernovae.

One of the first things I did was to consult with Brian Warner, an astronomer visiting Austin from South Africa. We communicated with his colleagues who were beginning to make observations. One of the things I had learned was that if one looked at crude data when it first comes off the telescope, there was some danger of mistaking the strong spectral line of hydrogen that is prominent in Type II supernovae with the strong silicon line that is characteristic of Type Ia supernovae. Some people had mistaken Type Ia for Type II on this basis. I tried to issue this caution to my South African colleagues. They had data showing excess emission in this tricky region of the spectrum. I merely meant to be careful in the identification when they said they thought it was hydrogen. Somehow this came across in the tense rush of those first few hours as a statement that their feature was not hydrogen, but silicon, and that they were looking at a Type Ia. They announced that. Meanwhile other astronomers had done a quick and dirty analysis and recognized that they were, indeed, looking at hydrogen and announced, correctly, that SN 1987A was a variety of Type II super

nova. I think some of the South Africans still hold a mild grudge against me for that.

I also thought that the supernova might emit X-rays. A few supernovae had done so, but there was no clear understanding of the mechanisms

and timing of the X-rays. It did seem that if there were going to be X-rays, it was important to look very early in the explosion when the ejected matter was hot and bright. I called Walter Lewin, an X-ray astronomer

at MIT. Walter pointed out that the Japanese had just launched a new X-ray satellite called *Ginga*, meaning galaxy in Japanese. Walter said that I should call Prof. Minoru Oda, the scientist who was the head of the *Ginga* team. I looked at my watch and we did a quick calculation. It was one in the morning in Tokyo. Walter said, “If I were you, I would call him.” I noticed that Walter did not volunteer himself to make the call. I decided, what the heck, once in 400 years, it was worth the disruption. I got Oda's home number from Walter and rang him up. His wife answered, very sleepy, but very polite. I have the feeling she had handled emergencies before, if not one quite like this. She put Prof. Oda on the phone, and I tried to explain the circumstances as best I could. No one could be sure the supernova was producing X-rays, but looking at it with *Ginga* was the only way to find out. Prof. Oda thanked me and hung up. I heard years later that Prof. Oda had his own version of this story of “some crazy American calling him in the middle of the night.” Fortunately, he did not remember who it was. As it turned out, there were no X-rays to be seen in those first few days, so I could have waited until it was a civilized time in Tokyo to call. *Ginga* did see X-rays a few months later, a detection that revolutionized some of our ideas about the supernova.

I did get a chance to see the supernova myself. Our Japanese colleagues added the topic of SN 1987A to a previously scheduled meeting in Tokyo in August of 1987, which was 6 months after the discovery. The reasonable thing to do seemed to be to go to Tokyo by way of Australia. I went with my colleague, Robert Harkness, an expert on the theoretical supercomputer calculations of radiation from supernovae. Robert is also an expert on airplanes. He knew all about the Qantas stretch 747 that we flew from Los Angeles to Sydney. He had also learned from Brian Warner that Brian had been able to see SN 1987A from the window of the upper-level, first-class lounge for which 747s were so famous.

On the other hand, Robert cannot sleep on airplanes. I can. I had a nap while Robert sat in his seat. I woke up for a meal and then slept again. Robert ate little and sat some more. I awoke feeling great while we were in the middle of our 14-hour flight to Sydney. Although Robert was a bit out of sorts by this time, I asked the flight attendant if we could venture up into the upstairs lounge to try to get a peek at the supernova. She asked the captain and he, in turn, invited us, not into the lounge, but onto the flight deck.

So up we scrambled to meet the crew of relatively young Australians, the pilot Jeff Chandler, the co-pilot, and the navigator. I'm sure this would not have happened on an American airline, and I'm not sure it was strictly legal on Quantas. In any case, the crew were fairly bored from the long flight and keen on the distraction we provided. We asked whether they knew where the Large Magellanic Cloud was. The navigator laughed and replied he had no idea. They flew by computer and never looked at the stars. Robert, no observational astronomer himself, then leaned down and peeked out the window next to Captain Chandler and announced, "There it is!"

Indeed, our flight path was such that the Large Magellanic Cloud was at about 10 o'clock from the nose of the aircraft, easily seen out the captain's left window. It was not trivial to see the supernova. Although it was still fairly bright, it had faded from maximum. My admiration for Oscar Duhalde and what he noted in those first few hours went up. I had brought along some binoculars. With them, I could make out the bright dot of light next to 30 Doradus.

Then Captain Chandler had an idea. He said that fresh oxygen helps visual acuity. He pulled his oxygen mask from its holder. This was not a full-face mask, but tubing that was more reminiscent of the oxygen lines for patients in hospitals. There was a framework that supported the thing over your ears. We spent the next 10 minutes passing around the mask and binoculars. The drill was to take the mask, snort a few deep drafts of oxygen, then rip off the mask (and in my case eye glasses), hold up the binoculars, and peer at the supernova. Frankly, I could not tell that it made any difference, but it sure was amusing! These were not, perhaps, ideal circumstances, but I can say that a few optical photons from the degraded gamma rays from the radioactive decay of supernova-created cobalt made it into my very own retinas. I may die a bitter old man, but it won't be for lack of seeing this remarkable event.

Robert and I spent a couple of days in Sydney among the city lights where viewing the supernova was not practical. We then proceeded to Canberra, site of Mount Stromlo Observatory and the location of the small meeting that was our excuse for this Australian junket. I gave a public talk that first night. I mentioned my curiosity about the native names for the Magellanic

Clouds and the next day got a call from a gentleman by the name of Edward Wheeler, no relation that we could identify. He provided me with the names for the Large and Small Magellanic Clouds according to one of the dialects spoken around Sydney when the first British settlers arrived in 1798. The Aborigines speak some 500 languages, so possibilities for other wonderful names like Calgalleon and Gnarrangalleon are enticing. Afterward, there was a clear night, but Robert and I were still exhausted from our trip (and a couple of late nights in Sydney), so we made no attempt to see the supernova that evening. That would have required

staying awake until 2 [small]a.m[/small]. We had a beer with our host, Mike Dopita, and went to bed.

It clouded up that night. The patch of clouds did not cover all of Australia, but only that fraction we were destined to visit: Canberra, Sydney, and the other major observatory, the Anglo-Australian Observatory at Coonabarabran in the north. By the time we got to Coonabarabran, we were aware that our chances were slipping away. Both Robert and I awoke on the mountain top and watched fog blow over, opening occasional “sucker holes,” but never giving a good view of the sky, never mind the Large Magellanic Cloud. We talked a little desperately of getting a car and driving down off the mountain because there was some thinking that the fog might be a localized, mountain-top phenomenon. The bottom line was that we left Australia the next day, having never seen the supernova from the ground. Thank goodness for that Qantas crew.

3. Lessons from the Progenitor

SN 1987A is one of a very few supernovae for which there is any evidence of the star that existed before it exploded. The star was seen in photographs taken for other purposes. It was listed in a catalog of hot stars in the Magellanic Clouds compiled by Norman Sanduleak. The star that exploded was listed by its position in the sky and known as Sk-69 202. You can make it out if you know where to look in Figure 7.4.

Sk-69 202 was not well studied. It was on a list of stars that German astronomer Rolf Kudritzky was investigating intensively, one by one, but it blew up just before Rolf got to it. There is some scientific import to the lack of attention drawn to the star. As Peter Conti, a hot star expert from the University of Colorado, remarked, there was nothing special about Sk-69 202. It did not vary in light output. It did not have any anomalous emission lines. It did not seem to be shedding mass at an especially noticeable rate or in a special way. There was simply no hint at all that Sk-69 202 was special until it disappeared in a violent flash of light. We still do not know why that was so.

A blown-up photographic image of Sk-69 202 is shown in Figure 7.5. The original, larger-scale photo was taken for other reasons, part of a study of star formation in the vicinity of the 30 Doradus nebula, by You-Hua Chu of the University of Illinois. The big dark patch in the center of Figure 7.5 is Sk-69 202. It is just a point of light, but it looks big because the photographic process smears out the image. The brighter the star, the more intense and the larger the image. This also became known as Star 1, the star that blew up. To the upper right in this image is what is known as Star 2. This is another star in the Large Magellanic Cloud. It is somewhat less massive than Sk-69 202 was. It is not physically or gravitationally close to Sk-69 202, it is several light years away, but it was probably born in the same burst of star formation that gave rise to Sk-69 202 and other fainter stars in this image. Dr. Chu gave me this slide when I went to Champaign-Urbana to present an already-scheduled colloquium on another topic about a week after SN 1987A erupted. She saw something in the photo that was part of a story that played out over the next few months.

When SN 1987A first went off, the vicinity of the supernova shown in Figure 7.5 was lost in the intense glare of the explosion. SN 1987A faded first in the ultraviolet. As it did, Star 2 in Figure 7.5 could be identified. The surprise was that something was also left behind at the location of Star 1 in the images from the *International Ultraviolet Explorer* satellite, the only ultraviolet instrument available at the time of the explosion. The lingering ultraviolet image left some people wondering whether the wrong progenitor star had been identified. What You-Hua Chu had recognized was that the lower left part of the image in Figure 7.5 was somewhat blurry. She was sure there was a third star there, Star 3, that was obscured by the brighter, smeared image of Sk-69 202 in Figure 7.5. As SN 1987A continued to fade, careful positions were measured, and it was determined that the lingering image was not at the location of Star 1, but slightly offset. There was, indeed, a third star, Star 3. Both Star 2 and Star 3 show up clearly in later images taken with the *Hubble Space Telescope* after the supernova faded (see Figure 7.6). Other people got more credit for resolving this mystery at the time, but there is no question in my mind that Chu knew of the existence of Star 3 within days of the explosion. She scored another coup a decade later at a meeting in Chile to celebrate the tenth anniversary of the discovery of the supernova when she reported that she had discovered the first star to have rings around it like the progenitor of SN 1987A (Section 8).

From preexplosion observations such as Figure 7.5, we know that Sk-69 202 had a mass of about 20 solar masses. This follows from knowing the luminosity. The luminosity is a clue to the mass of the evolved helium core even though that core was buried in a surrounding hydrogen layer. From our knowledge of stellar structure and evolution, we can then estimate the mass that the star originally must have had to make such a massive core. The luminosity suggests that the core was about 6 solar masses, and such a core arises in a main sequence star of about 20 solar masses. The star shed some mass while evolving. The best estimates are that the star retained about 15–18 solar masses by the time it exploded.

Somewhat surprisingly, the star that exploded was not a red supergiant, as might have been expected given the basic theory of stellar evolution and the observation that there are many red giants of 20 solar masses in the Large Magellanic Cloud. Instead, the star was relatively compact and blue. The reasons for this are still not fully understood. The relatively small size produced an unorthodox and somewhat dim light curve. The light curve is by now well understood, given the starting conditions of the star when the explosion erupted. A legion of computer models based on single stars has been calculated in the attempt to understand the compact starting conditions, none of them entirely satisfactory. These models based on single stars may be wrong. The current hot idea is that Sk-69 202 might have been in a binary in which the companion was engulfed in a common envelope and dissolved, leaving only one star to explode. This process might have caused the envelope of the progenitor to contract to a smaller radius and produced some of the other special features of SN 1987A that we will discuss in Section 8. There is no definite sign of any current companion, but that is consistent with none ever having existed, or the companion having been consumed by the supernova progenitor.

4. Neutrinos!

SN 1987A brought us a wealth of new understanding, but the single most important aspect was the burst of neutrinos that were detected from Earth. SN 1987A generated about 10^{57} neutrinos. Most of these went off in directions away from the Earth. Only a tiny fraction arrived at the Earth, and of this number only a tiny fraction interacted with the detectors so that their presence could be recorded. In the case of the neutrinos, the fact that the "observatories" were in the northern hemisphere was irrelevant. The neutrinos, with their ability to interact weakly and hence penetrate matter easily, raced up through the Earth. The same property meant that most of the neutrinos that passed through the detectors also did so without any interaction. Of the original 10^{57}, only nineteen neutrinos interacted with atoms of water in the detectors generating recorded flashes of light. Neutrinos were first detected by the Kamioka experiment in Japan, mentioned in Chapter 1 in the context of the solar neutrinos. Some neutrinos were also seen by a similar experiment in a salt mine near Cleveland and in a special site under a mountain in the Caucasus, what was then the Soviet Union. Those nineteen detected neutrinos were sufficient, however, to show that the basic picture of core collapse was correct. SN 1987A gave birth to extragalactic neutrino astronomy. Unfortunately, with the scant evidence of the nineteen neutrinos, we cannot determine whether the mechanism of the explosion was a core bounce, neutrino heating, or some other related process.

Putting the story together after the fact, astronomers realized that the neutrinos arrived at the Earth before the light. The reason is that the neutrinos are generated in the core collapse, or shortly thereafter, for about 10 seconds. The neutrinos that escape from the newly formed neutron star race outward at very nearly the speed of light. If neutrinos have a small mass as current theories suggest, then they will not travel at quite the speed of light, but so close to it that the difference is negligible. The shock wave that causes the star to explode propagates very rapidly, about one-thirtieth the speed of light. This is faster than the speed of sound in the star, but not at the speed of the departing neutrinos. It took the shock wave about an hour to propagate to the edge of the blue supergiant and generate the first intense burst of light seen by Oscar Duhalde and recorded by Ian Shelton and Rob McNaught. Those first photons were thus a light hour behind the neutrinos, a lag of about 10 million kilometers, about the radius of Jupiter's orbit. The pulse of neutrinos and that first pulse of light raced each other for 150,000 years, but the light could not catch up. The neutrinos arrived an hour ahead of the optical photons. At this moment, more than 10 light years beyond the Earth, the pulse of neutrinos is still ahead of the leading edge of the pulse of light.

5. Neutron Star?

The detection of the neutrinos was dramatic confirmation that a very compact object formed in SN 1987A by the process of core collapse. This result is completely consistent with stellar evolution theory for a star of initial mass about twenty times that of the Sun. The icing on the cake would be the direct detection of the neutron star.

We know that the supernova of 1054 that made the Crab nebula did leave behind a neutron star. This knowledge does not help us to reach general conclusions about how stars explode and make neutron stars because the Crab nebula is peculiar in many respects. It has a large helium content and slower expansion motions than are characteristic of most supernova remnants. Despite the useful observations of the Chinese, we do not know whether it was a Type I of some flavor, a Type II, or perhaps a transition event like SN 1993J. Astronomers of that era could not obtain spectra.

SN 1987A is the best-studied supernova ever, and we know it underwent core collapse, so the potential to learn about neutron star formation is great. As of this writing, however, SN 1987A is 12 years old, and there is still no concrete evidence for a neutron star. This is important because there is just the smallest possibility that the collapse could have generated an explosion and the observed neutrinos, but still ultimately have crushed the nascent neutron star to make a black hole. SN 1987A seems to be a close cousin to the supernova that produced Cas A in about 1680. Both were dimmer than usual, both seem to have occurred in massive stars, and until very recently, neither had obvious evidence for a neutron star. See Chapter 8 for an update on Cas A.

This does not prove that a neutron star is absent in either SN 1987A or Cas A. The neutron star in SN 1987A could be slowly rotating or not very magnetized and therefore not radiating very much. There is also a question of whether the neutron star could be "beaming" its radiation away from Earth as some pulsars are known to do (see Chapter 8). The argument against that is based on the fact that the expanding gas of SN 1987A must surround any pulsar. This gas should absorb any emitted pulsar energy and reemit the energy in all directions. What is certain is that if there is a neutron star in SN 1987A, that 12-year-old neutron star is dimmer, by about a factor of 10, than the nearly 1,000-year-old neutron star in the Crab nebula.

6. The Light Curve

SN 1987A also provided the most direct evidence that radioactive decay of nickel-56 and cobalt-56 can power supernova light curves. Because it was a relatively compact star, Sk-69 202 had to expand farther before it could leak the heat from the original shock. It did not have to expand as far as a Type I, but about ten times farther than a normal Type II exploding in a red-giant state. Thus SN 1987A cooled more than a normal Type II and had less shock heat to radiate by the time it could radiate. This made it dimmer than a normal Type II supernovae. The fact that it was a blue supergiant with a smaller initial radius made SN 1987A naturally dimmer than a normal Type II explosion in a red giant.

Models of the explosion of SN 1987A show that the shock energy dissipated in the expansion about a week after the explosion, yet the supernova did not attain maximum light for 2 months more. That power came from radioactive decay of nickel to cobalt to iron. Models show that the peak light in SN 1987A is produced solely by decay of nickel and cobalt. After the peak light, the light curve declined at a well-defined rate, showing the precise half-life of decay of cobalt-56. From the brightness of the tail, one can read off precisely how much nickel was originally ejected and how much iron will eventually expand into space. The answer is 0.07 solar mass. This is a little on the low side compared to prior expectations but in the range expected for a star of 20 solar mass. In addition, there is direct spectroscopic evidence for the cobalt, and satellites rigged to measure gamma rays detected the gamma rays that were predicted to come from the decay of cobalt. The direct evidence for nickel and cobalt decay in SN 1987A gives us increased confidence that the same process accompanies core collapse in other explosions in massive stars. Understanding these processes in SN 1987A also gives us more confidence to use them in the rather different environment of the thermonuclear explosions of Type Ia supernovae.

7. This Cow's Not Spherical

There is an old joke, one version of which has a scientist hired to study the efficiency of a dairy. He begins his report with the statement, "First we assume all cows are spherically symmetric."

This is an in-joke that carries a lot of weight with astronomers. Stars are almost perfectly spherically symmetric because gravity pulls in on them in all directions. Stars are not exactly spherically symmetric, however, if they rotate rapidly or have a strong magnetic field. Still, to make headway in understanding new phenomena, physicists and astronomers have learned that it is often fruitful to make simplifying assumptions to block out the rough truth. Details, out-of-roundness, can be added later as needed. For SN 1987A, it was needed.

The first computer models of SN 1987A assumed that the cow was spherically symmetric. That simplifies the analysis, making minimal computational demands on what are already complex computer calculations. Such simplified models were the obvious place to start. The first clue that they were substantially wrong came from the detection of X-rays. At a meeting in Tokyo (see sidebar) 6 months after the first detection of the explosion, in August of 1987, several theorists presented their predictions that the expansion should lead to the free streaming of X-rays and gamma rays from the radioactive decay in about another year. Japanese astronomers had recently launched a new X-ray satellite. They calmly stood up and reported that they had already detected the X-rays!

The reason for the early onset of X-rays was that SN 1987A was not expanding as a uniform sphere with the hydrogen on the outside, a helium layer deeper in, and the nickel, cobalt, and iron down in the deepest, slowest moving layers. SN 1987A was instead a roiling, turbulent mess that stirred the elements it ejected. Further thought and subsequent computer models showed that fingers of radioactive nickel should, and did, reach out into the outer layers. Streams of hydrogen and helium should plunge inward. The outward mixing of nickel allowed the X-rays and gamma rays to emerge earlier than predicted from the simple models. We learn from our mistakes. By now the understanding of the complicated structure of SN 1987A and how those lessons apply to other types of supernovae has reached a fairly sophisticated level.

8. Other Firsts

Further observations revealed two other "firsts" for SN 1987A. Both were expected at some level, but never before seen. One was the formation of molecules. Molecules of varying complexity fill the interstellar medium. If the density is high enough, single atoms can bind together to form molecules. This apparently happened in SN 1987A. After about 200 days, SN 1987A showed evidence for at least carbon monoxide (CO) and silicon monoxide (SiO). There are other ways of forming molecules, but one cannot help thinking that the first steps toward molecular complexity that lead to life might begin in supernovae like SN 1987A.

The other interesting observation was to see "dust." The interstellar medium is also full of tiny bits of grit that astronomers call dust. Astronomical dust is interstellar dirt, formed of clumps of graphite (carbon) or sand (silicon oxides) or rust (iron oxides). Theories had predicted that the carbon, oxygen, silicon, and iron in supernovae might in some circumstances coalesce into dust. SN 1987A gave the first firm observational evidence for this process when the light curve got dimmer after about 500 days, as it became shaded in a cloud of its own dust. Studies of this process showed that the dust formed in dense patches, again emphasizing that the ejecta of the supernova were not uniform, but very clumpy.

9. Rings and Things

The most dramatic direct evidence that something about SN 1987A was not sedately spherically symmetric is from the amazing pictures of the rings around the supernova. These were first discovered from the ground but were widely illustrated by images from the *Hubble Space Telescope*. As the epic of SN 1987A unfolded, the *Hubble Telescope* was launched, found to be out of focus, and repaired in a dramatic space walk. The focused *Hubble* images revealed a central ring around the supernova that is tilted in its aspect to us. There are also two fainter rings, nearly but not quite concentric with the first. These preexisting ring structures and the central, expanding supernova ejecta are shown in Figure 7.6. The *Hubble* images also show that the ejected matter is not round in profile, but elongated. This can be seen in Figure 7.7.

The origin of these rings is still debated. They must have formed by matter shed by the progenitor star before it exploded. One popular model is that the star blew a slowly moving wind from its equator while it was a red giant and then a faster wind after it contracted to become the blue supergiant that eventually exploded. The fast wind is supposed to have shaped the slow wind to form the bright ring and to have expanded outward to form the other two rings. Unfortunately, computer models show that the inner, bright ring often does not survive the interaction in the form observed. Another hypothesis is that the rings were shed when the progenitor of SN 1987A consumed a smaller mass binary companion.

What has been clear all along is that the inner ring is only a few light years across. The most rapidly moving outer portions of the exploding star are moving at a substantial fraction of the speed of light, at least 10 percent. This implied that in a few years, or perhaps a couple of decades, the ejecta should smash into the ring. The result should be a renaissance for SN 1987A. Astronomers expect a new brightening in the optical, the radio, and the X-rays from the gas heated by the collision. The ring is formed of bits and clumps of gas. Each of those should light up when the shock wave hits it, so the ring should sparkle like fireworks over time scales of months to years.

The first estimates of when the collision should occur were based on the notion that there was no material between the supernova and the inner ring to slow the ejecta down. The answer was about 10 years, or, roughly, 1999. More study showed that the space between the supernova and the ring did contain matter. The time for the collision was put off to about 2005. That is not long in the big scheme of things; however, it is long in the life of an astronomer waiting to check a theory.

Given this new time scale, there was thus a little surprise when the *Hubble Space Telescope* revealed that a small portion of the ring had brightened in 1997, as shown in Figure 7.7. Many people thought that the collision had begun. Others worried that there might be some other unexpected anomaly. Ground-based observations from March 1998 showed that many more clumps were lighting up. The collision has begun. Why it occurred faster than the revised estimates is a puzzle. The image of the ejecta in Figure 7.7 resembles a question mark. That is an appropriate metaphor as we continue to follow this piece of astronomical history as it evolves. What is clear is that the next few years will be exciting ones for SN 1987A. This amazing event has much more to teach us.