Supernova 1987A!

S. E. Woosley and M. M. Phillips

Light from the brightest supernova in almost 400 years arrived at Earth on 23 February 1987. Although located 160,000 light years away in a satellite galaxy of our own known as the Large Magellanic Cloud, this supernova's relative proximity compared to all others that have been observed in modern times has allowed observations, which were never possible before, to be made from space, from detectors on the ground and carried by balloons and airplanes, and from neutrino detectors deep underground. What emerges is a greater understanding of one of the most violent events in the universe, the death of a massive star. For the most part, theoretical expectations have been borne out, but some major surprises have made the event all the more fascinating.

No event in nature is more violent and powerful than the death of a massive star in the form of a type II supernova. For the star it is the end of a comparatively brief but brilliant life, or at least the transition to a more exotic state. For astronomers it provides not only spectacular fireworks but a unique testing ground for theories of stellar evolution and explosion (*1*).

Throughout history the occurrence of over 620 supernovae had been recorded prior to February of 1987 (12 more were detected by December). Almost all have occurred at vast distances because it is only at such great distances that astronomers can sample a sufficient number of galaxies to compensate for the fact that each produces no more than a few supernovae per century. For example, our own galaxy is believed to produce a type II supernova about once every 40 years, but most go undetected because, bright as they are, their optical emissions are totally obscured by dust. This is especially so for type II supernovae because they involve stars situated very close to the plane of the Milky Way Galaxy. Thus although several dozen supernovae have likely occurred in our galaxy, only five have been visible to the naked eye in the last 1000 years. The brightest of these, SN 1006, was as bright as the quarter moon; allegedly one could read by its light. Of these five historical supernovae perhaps two or three were of type II. The last supernova clearly visible to the naked eye, a type I, occurred in 1604, 4 years before the invention of the telescope, and was observed extensively by Johannes Kepler (a much fainter one, marginally visible to those having good vision occurred in 1885 in a relatively nearby galaxy, Andromeda).

Imagine then the joy and amazement of the world astronomical community when the announcement went out on 24 February 1987 that a bright type II supernova, clearly visible to the unaided eye, was occurring in a galaxy, "just next door" (160,000 light-years), the Large Magellanic Cloud (LMC). Ever the optimists, astronomers refer to this spectacular event, which was discovered by Ian Shelton at the Las Campanas Observatory in Chile, as simply "Supernova 1987A," the first supernova discovered in 1987. Though one in a lengthy series of supernovae that have been detected, by virtue of its proximity and brightness, this one has proved unique in many ways.

It is the first supernova for which an ordinary stellar progenitor has been identified. As we shall discuss, knowing the properties of the star that exploded gives theoreticians a great advantage in understanding the behavior of the supernova. The supernova occurred in an irregular galaxy, the Large Magellanic Cloud. Although not unique in this regard, it is very rare to find a type II supernova in a galaxy of this type. The light curve, (that is, how bright the supernova is as a function of time), was initially fainter by a factor of 10 compared to other type II's. Perhaps the type of galaxy and type of supernova are related—irregular galaxies produce fainter supernovae, which makes them harder to detect. Supernova 1987A was also unique in being observed as a neutrino source. The enormous binding energy of the neutron star that was produced at the center of the explosion came out almost entirely in neutrinos emitted during the first 10 seconds of the explosion. These were detected in deep underground experiments in both the United States and Japan. The first optical detection came only 3 hours after the neutrinos, 1 hour after the shock wave from the exploding core broke through the surface of the star. Such an early detection is again unique in the annals of supernovae and severely constrains the models. More unique properties of 1987A include a light curve powered at peak entirely by radioactive decay (a universal property of type I supernovae, but unique hitherto for type II's); an accurate determination of the iron produced by explosive nucleosynthesis, 0.07 solar masses;

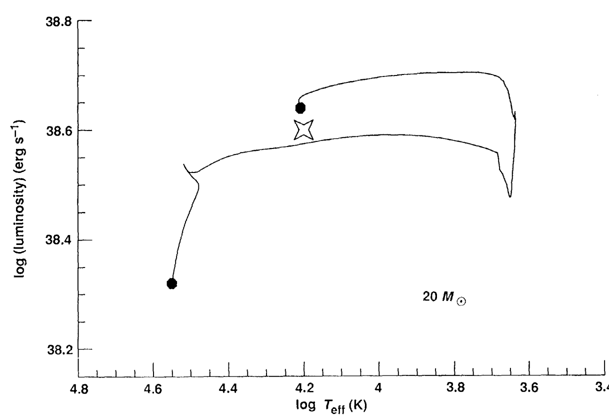

Fig. 1. Hertzsprung-Russell diagram for a star of 20 $M_\odot$ and composition appropriate to the LMC. The logarithm of the luminosity is plotted against the logarithm of the surface temperature of the star. Points to the right of log $T_{eff} = 4$ are generally regarded as red stars and those to the left are blue. The 20 $M_\odot$ star modeled here (*2*) spends most of its life burning hydrogen to helium at the point in the lower left. It then burns helium as a red star of large radius on the right hand side of the figure and evolves back to the blue following helium depletion just in time to explode. The location of the presupernova star is indicated and agrees well with the observed properties of Sk −69°202 (four pointed star).

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the detection, in mid-August, of x-radiation, the scattered photons liberated by the radioactive decay of ^{56}Co to ^{56}Fe; the detection, in late fall 1987, of the γ-rays themselves; the observation in November of an infrared spectrum dominated by heavy elements, seemingly produced in the explosion; the observation beginning about 150 days after the explosion of ultraviolet emission lines from nitrogen-rich circumstellar material believed to be ejected by the supernova progenitor thousands of years before it exploded; and the identification of an unusual "companion" source that, at least early on, was about 10% as bright as the supernova itself. Finally, it should not be overlooked that 1987A was the first (and perhaps last) supernova to appear on the cover of *Time* magazine and to have its own TV show (an episode of NOVA, which was broadcast in October 1987).

These unique results and many more that will surely follow have come about because, for the first time, astronomers have been able to study a bright supernova at all wavelengths on a frequent basis. In the southern hemisphere, radio, infrared, and optical telescopes in Chile, Australia, New Zealand, and South Africa have monitored the supernova on an almost daily basis. From an airplane in New Zealand the Kuiper airborne infrared telescope has obtained spectra of the supernova. From space the International Ultraviolet Explorer (IUE) has studied the optical brightness and ultraviolet spectrum of the supernova; the Japanese x-ray satellite, Ginga, and instruments on the Soviet space station, Mir, have studied the x-ray emission; and the Solar Maximum Mission (SMM) complemented by balloon flights in Australia and in Antarctica have observed the γ-rays. Finally from deep underground, the only detectors in the Northern Hemisphere to see the supernova have witnessed the neutrino burst as it propagated through Earth from the other side. As members who participated in this global effort we offer a personal observation. Especially during the first few weeks following the supernova, observers and observatories of all nations and from all continents shared data, speculations, and the shear exhilaration of the moment. Little was held back. In the process some mistakes were made, but were quickly subjected to test and the errors freely admitted and corrected. It was science as its best. The data we have now will occupy theoreticians for at least a decade, but the memory of the shared experience will last even longer.

The Star That Exploded

As soon as an accurate location for the supernova had been determined, astronomers (we among them) rushed to their charts to see what star had exploded. What we found initially came as a surprise. As expected there was a very bright star, hence a very massive star, situated on plates taken before the supernova at just the location (now determined to 0.05 of a second of arc) of the supernova. The star's name was Sanduleak (Sk) $-69°202$. That it was a massive star came as no surprise. It is believed that only stars more than about eight times the mass of the sun ($M_\odot = 1.989 \times 10^{33}$ g) can become type II supernovae. Lighter stars do not experience the more advanced nuclear-burning stages: carbon, neon, oxygen, and silicon burning required to produce an unstable iron core. The surprise was the color of the star. It was blue, not red.

By simple blackbody radiation theory the color of a star of given distance and brightness determines its radius. According to the theory worked out to explain hundreds of other more distant supernovae observed prior to 1987A the radius of the star that exploded should have been very large, several times the distance from Earth to the sun (150×10^6 km). Instead, the radius of Sk $-69°202$ was determined to be only 1/10 of this, or about 50 times the radius of our own sun (solar radius, $R_\odot = 696{,}000$ km). Indeed, the faintness of the early light curve compared to other type II supernovae (if something 50 million times the luminosity of the sun can be regarded as "faint") is now understood in terms of the smaller radius of the progenitor star. Regardless of its starting radius the supernova must expand to about 10^9 km before light can leak out and the supernova becomes bright at visual wavelengths. Starting with the same amount of energy from shock-wave passage, a blue supergiant, because it is about a factor of 10 smaller in radius than a red supergiant, must expand by a greater factor and in doing so loses more of its internal heat to expansion. Thus less energy is available to provide light.

But why was the presupernova star blue? Two solutions have been advanced (and indeed were discussed as possibilities before 1987A): (i) that the star had lost a great deal of mass prior to exploding and was thus almost a bare helium core, or (ii) that the different composition of LMC, in particular the smaller abundance of heavy elements, especially carbon and oxygen, compared to our own galaxy, changed the evolution of the star so as to make it explode with a smaller radius. The former hypothesis finds support in the existence of a class of stars, Wolf-Rayet stars, that are believed to be massive stars that have lost all their hydrogen envelope. Many such stars are seen in the 30-Doradus region near where Sk $-69°202$ exploded. These stars are not just blue, they are ultraviolet. Could it be that slightly less extreme mass loss could leave just a trace of envelope on the star, enough to make it a blue supergiant? The other explanation, that of decreased metallicity (astronomers call all elements heavier than helium "metals"), would be in accord with the low frequency of bright type II supernovae in irregular galaxies and would offer the possibility of making a blue supergiant out of a star that still retained most of its envelope. Observations of the supernova itself, as opposed to observations of the presupernova star, are much more consistent with a star that retained 5 to 10 $M_\odot$ of envelope (*2, 3*). Thus the low metallicity hypothesis is currently favored by many astronomers as the chief cause of why the star was blue though some mass loss probably occurred as well.

A large body of theory concerning the evolution of massive stars and the production of supernovae was already in place prior to 1987A and many aspects of the progenitor star are now generally agreed upon. Here we follow an evolutionary scenario presented for Sk $-69°202$ by Woosley and co-workers (*2*). Similar descriptions of the presupernova evolution are available (*3, 4*).

The star known for a time as Sk $-69°202$ was born about 10 million years ago having a mass within a few solar masses of 20 $M_\odot$. For 90% of its life it was powered, as are most stars in the sky, including the sun, by the fusion of hydrogen to form helium. Its luminosity during this period was about 60 thousand times that of the sun and its color, an intense blue; indeed most of the radiation of this star (classified by astronomers as an "O" star) came out in the ultraviolet (Fig. 1). The central temperature and density during this period were about 40×10^6 K and 5 g cm^{-3}, respectively, and the star's radius, about 6 $R_\odot$. After exhausting hydrogen and producing an almost pure helium core within its inner 6 $M_\odot$, the central regions of star contracted and heated up. Energy continued to be generated by hydrogen fusion in a thick shell surrounding this helium core. Meanwhile the surface layers of the star expanded while the core contracted and got hotter and denser. When the central temperature reached about 170 million degrees (density 900 g cm^{-3}) a new series of nuclear reactions was ignited in the center of the star as helium began to fuse to form carbon and oxygen. During the time between central hydrogen depletion and helium ignition the surface of the star expanded to more than 10^8 km, about the distance from Earth to the sun, and its luminosity roughly doubled to 100,000 times that of the sun. The star had become a red supergiant (right hand side of Fig. 1).

Now helium burned for another million years producing a central core of carbon and oxygen of about 4 $M_{\odot}$. During this period an unknown amount of mass was lost from the surface of the star in the form of a stellar wind so that, after helium burning, the star was left with a helium core (having an embedded core of carbon and oxygen) of total mass about six times that of the sun, capped by an unknown mass of low density envelope where hydrogen had still not burned to helium. When the helium was exhausted in the center of the star, the process of contraction began anew, but this time the surface of the star also participated in the shrinking. A slight decrease in the luminosity coming out of the core made the star incapable of continued support of its red giant envelope so that it contracted by a factor of 10 and once again became blue (moving to the left on Fig. 1). When the central temperature reached 700 million degrees (150,000 g cm^{-3}), carbon began to burn in a new series of reactions that produced neon, sodium, and magnesium and powered the star for about 1000 years. The evolution of the star was becoming extremely rapid by this time. The nuclear burning of heavy fuels that have large electrical charges, and hence great Coulomb repulsion barriers to overcome, requires increasingly extreme values of temperature. But at temperatures above about 500 million degrees, just when fuel is already running short, a new and increasingly efficient process begins to radiate away energy. Copious high energy radiation (γ-rays) present in the plasma produces electron-positron pairs. Most of the time these pairs just annihilate to give back the γ-rays from which they were formed. But occasionally an electron and a positron will annihilate to produce a neutrino-antineutrino pair. The neutrinos easily escape the star and, beginning with carbon burning, carry away more energy than does radiation from the star's surface. The neutrino emission rate is very temperature sensitive (scaling approximately as its ninth power), thus the burning of heavier fuels can power the star for an ever decreasing period. Beyond carbon ignition the evolution in the inner few solar masses of the star proceeds so rapidly that the envelope does not have time to readjust. The star remains as it was, a blue supergiant of about 50 $R_{\odot}$, and that is the configuration in which it dies.

The core continues to evolve, however. After carbon burning, it contracts, heats up, and undergoes a brief period of nuclear readjustment in which neon converts to (more) oxygen and magnesium. This process, which takes place at 1.5 billion degrees and 10^7 g cm^{-3} over a period of several years, releases energy and is called "neon burning." Oxygen burning, chiefly to silicon and sulfur, follows, again lasting several years at a temperature of 2.1 billion degrees. By now the neutrino losses from pair annihilation have become prodigious, amounting to 10 billion times the luminosity of the sun and 100,000 times the (photon) luminosity of the star. One final nuclear-burning stage remains and it is a complicated one. The most abundant nuclei in the center of the star are now isotopes of silicon and sulfur, chiefly ^{28}Si, ^{30}Si, ^{32}S, and ^{34}S in comparable amounts. Direct fusion of any of these isotopes to form nuclei of the iron group is impossible. The temperature required is so great that the radiation bath would tear apart the silicon and sulfur first, and indeed that is what happens. At a temperature of about 3.5 billion degrees and a density near 10^8 g cm^{-3}, in a process that lasts only a few days, a portion of the silicon "melts" into a sea of free helium nuclei (α-particles), neutrons, and protons that add onto residual silicon and sulfur nuclei, ultimately producing elements of the iron group (^{54}Fe and ^{56}Fe are most abundant).

When this "silicon burning" has been completed in the inner 1.4 $M_{\odot}$ of the star, no more nuclear energy can be obtained by the rearrangement of neutrons and protons into heavier (or lighter) species. It is the end of the star's evolution. Gravity has not diminished, indeed, it has only become stronger with each successive stage of contraction and burning. Having no other source of energy to support itself, the core does again what it has done ever since the star was born. It contracts and heats up. Two processes accelerate this contraction; both are important. First there is the process of electron capture. Most of the pressure supporting the star comes from the electrons. Removing electrons thus removes pressure. Electrons are removed by merging with protons inside heavy iron group nuclei to produce species that are even more neutron-rich. Second is the process of photodisintegration, the tearing down of nuclei by the high energy radiation into α-particles, neutrons, and protons. This process, which begins during silicon burning, proceeds with increasing efficiency as the temperature gets higher. But this is essentially undoing all the reactions that went into building heavy elements out of hydrogen and helium in the first place; it takes a great deal of energy. Because energy is being spent on photodisintegration rather than in providing heat and pressure, a slight contraction will make gravity stronger without providing a corre-

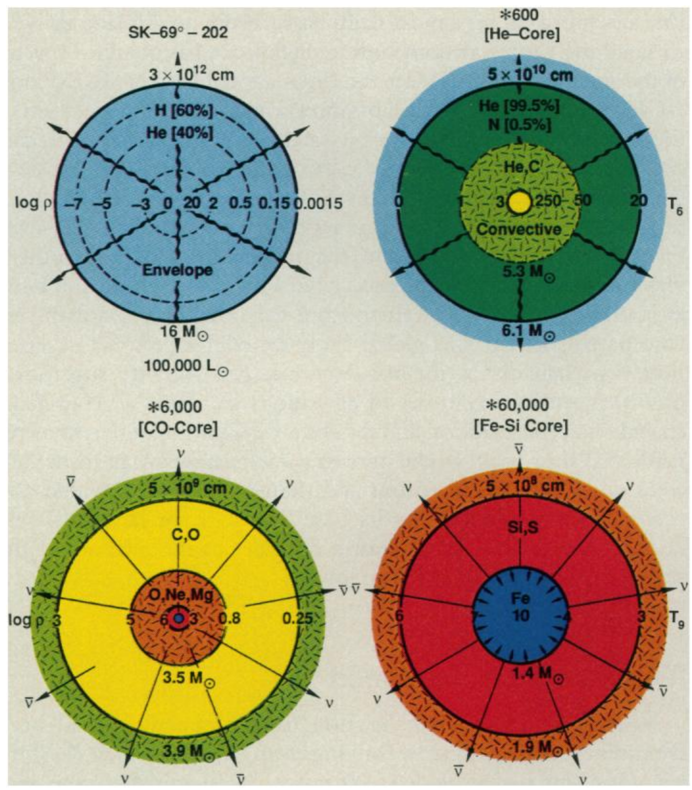

Fig. 2. The structure and composition of a theoretical model (*2*) for the presupernova star Sk −69°202 drawn to scale, in a progressive series of enlargements of indicated magnification. Beginning as a 20 $M_{\odot}$ star burning hydrogen on the main sequence, the star is presumed to have lost 4 $M_{\odot}$ as a red supergiant (Fig. 1) prior to exploding. (**Upper left**) Almost all of the volume of the star is contained in its low density envelope of hydrogen and helium. Radiation produced in the helium core (an unresolved point in the center of the first frame) diffuses out through regions of progressively decreasing density and temperature (dashed contours). Temperature in millions of degrees (T_6) and the log of the density in g cm^{-3} are indicated. (**Upper right**) Magnifying the central regions by a factor of 600, one finds the outer inert core of helium surrounding a region where helium is burning to carbon and energy is being transported by convection. The entire core of helium and heavier elements contains a mass equal to 6.1 times that of the sun. (**Lower left**) Magnified again by ten, one finds a shell of carbon and oxygen inside of which oxygen and neon are burning convectively. Energy is lost mainly to electron neutrinos and antineutrinos that stream out without interaction. Temperature in both lower panels is in billions of degrees (T_9). (**Lower right**) Enlarged by a final factor of 10, a shell of silicon, sulfur, and traces of heavier elements surround a critical mass (1.4 $M_{\odot}$) of iron that is emitting a vast flux of neutrinos and beginning to collapse. At the time sampled the central density and temperature are 10^{10} g cm^{-3} and 10^{10} K respectively and the collapse velocity has reached 1000 km s^{-1}.

sponding increase in the pressure. Because of electron capture and photodisintegration, the core now collapses very rapidly. The composition and structure of the star at this point are summarized in Fig. 2.

The Explosion Mechanism

Once the collapse has commenced in earnest, it continues until the central density in the star has risen by a factor of about one million. This takes only a few tenths of a second as a configuration initially about the size of Earth collapses to a radius of only about 50 km. The velocity during the collapse reaches about 70,000 km s^{-1} (one-fourth the speed of light!) in the outer portion of the iron core. However, because of the weaker gravity experienced by layers further out and because the information that the core has collapsed must propagate outwards as a sound wave of finite speed, the neon, carbon, and helium shells as well as the hydrogenic envelope do not participate in this collapse. Although pressure support has essentially disappeared in the center of the star, the outer layers hang suspended with inadequate time to respond.

The central density rises to several times that of the atomic nucleus (2.4×10^{14} g cm^{-3}) at which point the nuclear force, ordinarily attractive and responsible for holding nuclei together, changes sign and becomes repulsive. Once this occurs the resistance to further collapse is very great. The nuclear pressure, plus that of a (by now) highly relativistic gas of electrons, causes the inner part of the core to halt and spring back. The inner region that rebounds as a unit consists of about 0.7 $M_{\odot}$, (that is, about one-half of the collapsing iron core). Outside, matter is falling supersonically and continues, whereas further down the collapse has halted. As it runs abruptly into the "brick wall" of the rebounding inner core, a shock wave forms, a surface where matter meets matter at supersonic speed. For a time the expansion of the inner core, plus the energy that the infalling matter gets by bouncing off of that core, pushes the shock out. If all goes well (unfortunately it rarely does in the computer models of 20 $M_{\odot}$ stars), the shock continues on out, finally exiting the collapsed core with enough energy (about 10^{51} erg) to eject the rest of the star into space with high velocity. This phenomenon of a "superelastic bounce," which runs so contrary to common intuition, can be well demonstrated by dropping two balls, one a mushy beach ball, the other a hard tennis ball, in contact with each other along the vertical axis. The lower (mushy) ball rebounds a short distance and communicates much of its energy to the upper ball that continues to a much greater altitude than the point where the ensemble was released.

This is called a "prompt hydrodynamical explosion" (*5*). When it works the shock is out of the core and the explosion is under way in only about 20 ms. The difficulty, however, is that the expanding shock wave loses a great deal of energy as it beats its way upstream against the infalling outer core. Momentum is not the problem one might imagine because the falling material simply bounces off of the shock, changing direction but preserving speed and energy. The problem is energy dissipation—neutrinos lost because of the high temperature interior to the shock and, again, photodisintegration. For every 0.1 $M_{\odot}$ that the shock disintegrates to neutrons and protons it loses 1.7×10^{51} erg, roughly equal to the final kinetic energy of a successful supernova explosion like 1987A. If the shock always starts at about the same place then its success or failure will obviously depend in a sensitive manner upon how large the iron core is. Larger iron cores will experience more losses due to photodisintegration and are less likely to explode by this mechanism. It has proved difficult in practice to cause the explosion of iron cores larger than about 1.35 $M_{\odot}$ by the unaided prompt mechanism.

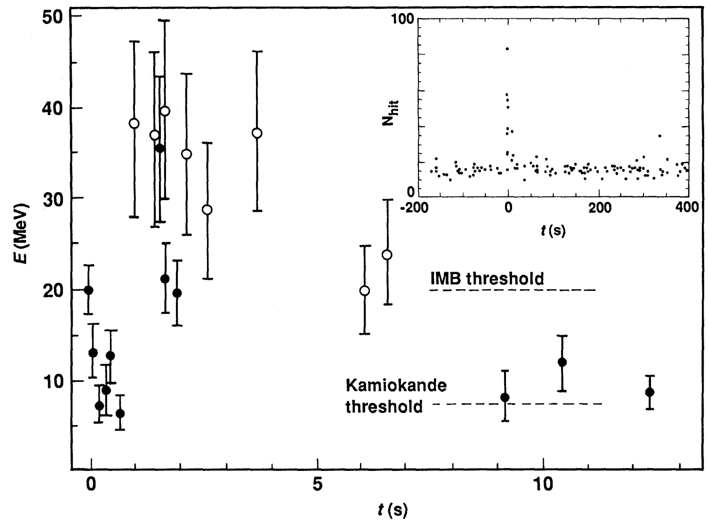

Fig. 3. A combined display of the IMB (open points) and Kamiokande (filled points) neutrino data. Energy of the arriving neutrino is shown plotted against its arrival time with zero equal to 7:35:40 UT on 23 February 1987. Shown as an inset is replication of the laser printer output of the raw data from Kamiokande at the time the supernova was detected. Note the very high signal to noise ratio.

If the prompt mechanism fails, as it must for some critical mass of iron core, another means must be found to explain stellar explosion. Otherwise, for all our effort, we have just created a big black hole. The shock would halt its outward motion; the core would grow to several solar masses by accretion; and then, suddenly, the core would collapse inside its event horizon to be followed within a few hours by the rest of the star. This might be an exciting event to some, but it would also be dim and definitely not a supernova. In recent years a second mechanism has been called upon (*6*) to avoid this dismal prospect. In some ways a return to earlier notions (*7*) of the 1960s, this mechanism draws upon the enormous energy in the neutrinos released by the collapsing core during its first one second. At least 99% of the binding energy of the neutron star that forms, roughly 2×10^{53} to 3×10^{53} erg, comes out in neutrinos. These neutrinos, being neutral and massless (or nearly massless) have great penetrating power. Once they escape the core, they stream freely through the rest of the star. But the energy in these neutrinos is 100 times that needed for a shock wave to give a powerful supernova. The problem then is channeling some small fraction of the neutrino energy to the proper place and at the proper time to help the shock along and get the explosion going again. The proper place is right underneath the shock that still exists where matter is accreting onto the dense iron core. Here electron neutrinos and antineutrinos deposit energy as they are captured by neutrons and protons and scatter off of electrons. This provides heat and pressure so that, after a few tenths of a second, the shock wave starts moving out again. Some theoreticians have referred to this as "the pause that refreshes." Because of its longer time scale this mechanism has also come to be known as the "delayed explosion mechanism."

It was initially hoped that observations of SN 1987A would resolve a controversy over which mechanism dominates in the explosion of 20 $M_{\odot}$ stars—prompt or delayed. Unfortunately, most of the observable properties of the supernova: velocities, spectra, light curve and so on, are not sensitive to how the star explodes, but only the fact that about 10^{51} erg is somehow deposited in the central regions of the star. As mentioned before, delayed explosions tend to be favored if the iron core mass exceeds 1.35 times that of the sun. Model calculations (see discussion above) and the energy of the neutrino signal (see discussion below) suggest that the iron core in

Sk $-69°202$ was slightly larger than this, perhaps 1.4 $M_{\odot}$. On the other hand, delayed explosions tend to have less kinetic energy ($\lesssim 10^{51}$ erg) than prompt ones ($\gtrsim 10^{51}$ erg). Thus astronomers are keen to measure the energy associated with the expansion of SN 1987A. For the time being, such estimates are mired in uncertainty concerning the mass of the hydrogen envelope at the time Sk $-69°202$ exploded, that is, how much mass was lost to the stellar wind during the red supergiant stage. Smaller envelope masses slow down the expanding helium core less and, for a given observed velocity, imply less expansion energy. Larger envelopes on the other hand require more energy. For now the best estimate of the explosion energy, based upon light curve and velocity, is 1×10^{51} erg, within a factor of 2. Clearly this does not resolve the debate on mechanism. Also one must realize that the arguments relating explosion energy and iron core mass to mechanism are based upon theoretical estimates of arguable precision.

However it was born, it is clear that a powerful shock did propagate through Sk $-69°202$, leading to its explosion. To state the obvious, we saw a supernova. Moreover, the very high emission temperature observed on the first day of the supernova was characteristic of a shock wave breaking through the surface of a star. We also know that the core collapsed to a neutron star or black hole because, for the first time, we saw the neutrino burst. The known radius of Sk $-69°202$ and the timing between the arrival of the neutrinos and the first optical observations are consistent with the supersonic propagation of a signal originating at the center of the star. Finally, as we shall discuss later, the light curve of SN 1987A has, since the end of the first month, been powered by the decay of a radioactive nuclide, ^{56}Co. This short-lived species could only have been synthesized and ejected from a massive star by a strong shock.

The Neutrino Burst

When all is said and done, the most exciting and unique aspect of SN 1987A will remain the detection of the neutrino burst that signaled the collapse of its iron core to a neutron star. The numbers are awesome. The luminosity of the supernova in all flavors of neutrinos was, during the first second, about 10^{53} erg s^{-1}. Adopting for the luminous matter in galaxies a universal function (*8*) of $\sim 4 \times 10^{41}$ erg s^{-1} Mpc^{-3} and a radius for the observable universe (all that matter from which we could have received light since the Big Bang) of about 10 billion light-years, one finds that the luminosity of the "universe" is about 5×10^{52} erg s^{-1}. The supernova exceeds this and generates all its energy in a region less than 30 miles across. Expressed another way the sun lives for 10 billion years radiating at 3.9×10^{33} erg s^{-1}. Thus the total output of the sun in its life will be about 10^{51} erg. The supernova radiates 100 times this in less than one second. All the nuclear weapons in the world, on the other hand, could only power the sun for a few millionths of a second. Supernovae are by far the most violent events in the universe. For comparison, an energetic quasar, 3C$-$273, emits only 10^{47} erg s^{-1} (one-millionth of the supernova neutrino luminosity at peak), though it does so for a much longer period of time.

By the time the neutrino signal, currently estimated to have been 2×10^{53} to 3×10^{53} erg, has traveled the 160,000 light-years to Earth it has been reduced by geometry to a flux (proportional to $1/r^2$) of a modest 50 billion neutrinos per square centimeter. Because they interact with matter so weakly most of these neutrinos stream right through Earth with no interaction. But because there are so many of them, a sufficiently large detector might hope to snag a few. Indeed, we estimate that one neutrino of approximately 10 million electron volts (MeV) coming from SN 1987A was stopped in the bodies of each of roughly one million people worldwide on 23 February 1987. This is small, however, compared to the neutrino flux received over a lifetime from the sun and neither is of any biological consequence whatsoever.

More to the point, since no one felt these neutrinos, large detectors had been set up at various points around the world, in Japan, in the United States, in the Soviet Union, and in Italy. These detectors were originally constructed to search for proton decay (the revised Kamiokande II detector was to search for solar neutrinos) but were also well instrumented for detecting neutrinos from supernovae. Indeed, the search for neutrinos from supernovae had been one of the secondary goals of the experiments, but, of course, no one was certain when, or even if, a supernova would happen so nearby in our lifetimes. But neutrinos were indeed detected on 23 February. The Kamiokande II detector in Japan observed 11 events (*9*) on February 23.316 (universal time), and the IMB (Irvine-Michigan-Brookhaven) detector, located in Cleveland, Ohio, saw eight at the same time (*10*). All the neutrino detectors are located in the Northern Hemisphere and the supernova was in the Southern. The neutrinos detected had come through Earth and were on their way back out into space. The 11 neutrinos detected by Kamiokande had a mean energy of 15.4 MeV and arrived over a period of 12 seconds (Fig. 3). The eight events observed by IMB, which has a higher energy threshold for detection (20 MeV versus 7 MeV), had a mean energy of 32.5 MeV and arrived over an interval of 6 seconds. Both sets of detections individually have very high statistical significance (see inset, Fig. 3) and, taken together, it is certain that a cosmic neutrino event was observed. Given the arrival time, within 3 hours of the first optical record of SN 1987A, and the good accord of the signal in neutrino energy, number of neutrinos, and duration with that predicted beforehand for a type II supernova (*11*), it is also certain that this signal came from the supernova. Serendipitously, the near simultaneous arrival of neutrinos of quite dissimilar energy after traveling for 160,000 years places limits on the mass of the electron antineutrino that are better than previous laboratory limits. In particular, the mass of the particle $\bar{\nu}_e$ can be no greater than 14 eV/c^2 at the 90% confidence level (*12*).

Offsetting somewhat the triumph of theory in predicting the properties of the neutrino burst observed by the Kamiokande and IMB detectors is the puzzle of the signal acquired on the same day by another neutrino detector experiment situated in Europe beneath Mt. Blanc (*13*). Five events in the energy range 7 to 11 MeV were recorded in the space of 7 seconds on February 23.12, that is 4.7 hours before the Kamiokande/IMB detection. To have such an occurrence within hours of the known onset of the brightest supernova in four centuries is indeed suggestive of an association. The signals from Kamiokande and IMB are so significant and mutually confirming that there is no doubt that they saw the supernova. Could there have been two signals that day?

Many theorists have attempted to find a way of answering this question in the affirmative. Their models are imaginative, but generally incredible. There are two principal difficulties. First the early light curve, especially the observations of McNaught and the upper limit set by Jones (see discussion below), are consistent with a shock wave starting at the center of a blue supergiant at the time Kamiokande and IMB saw the burst, but not with a shock wave starting at the Mt. Blanc time (*2, 3*). A second neutrino signal could conceivably have been generated later, for example by a phase transition in the neutron star, but then the second signal would follow, not precede Kamiokande/IMB. Second, no strong signal was reported at IMB or Kamiokande at the time of the Mt. Blanc detection (actually one count was seen just above threshold in the Kamiokande detector, but the experimenters themselves claim that this was a background event; there was no increase in the subthreshold counting rate). These other detectors are more sensitive and should have seen the signal if Mt. Blanc did. It is our evaluation that either the detection at Mt. Blanc was a statistical fluke, or something very unusual happened on 23 February (minus 160,000 years) that will take us a long time to understand.

Observations of the Light Curve

When Ian Shelton announced his discovery of SN 1987A on the night of 24 February, astronomers in the Southern Hemisphere immediately began searching recent photographs of the Large Magellanic Cloud to determine when exactly Sk −69°202 had begun to brighten. By good fortune, Shelton had taken a plate of the same field the night before his discovery, which showed that light from the supernova had first arrived within the last 24 hours. Soon word was received that R. H. McNaught, observing from Siding Spring, Australia, had serendipitously recorded the supernova at a visual magnitude of 6.4 (that is, over 200 times brighter than Sk −69°202 had been when it was a blue supergiant) only 8 hours later than Shelton's 23 February plate, which had shown nothing unusual. As it turned out, McNaught's photograph had been taken a mere 3 hours after the detection of the neutrino burst by Kamiokande and IMB. Although McNaught was justifiably disappointed that he had failed to examine his photograph in time to have been the official "discoverer" of SN 1987A, his observation remains of fundamental importance in documenting the extremely rapid rise of this supernova. A second crucial observation (actually a nondetection!) of SN 1987A during the first few hours of 23 February was made by the New Zealand amateur astronomer A. Jones, who independently discovered SN 1987A the next night only a few hours after Shelton. On the night of the 23rd, however, Jones did not notice the supernova while scanning the appropriate region of the sky with a small telescope, suggesting that SN 1987A was at least three times fainter than when McNaught photographed it a scant 78 minutes later. These two early data points in the light curve had proved invaluable in constraining hydrodynamical models of SN 1987A, and serve to dramatically emphasize the important role that amateurs still play in modern astronomy.

Once informed of the discovery of SN 1987A, professional astronomers at observatories in Chile, New Zealand, Australia, and South Africa began to intensively monitor its brightness at optical and infrared wavelengths. After the rapid rise displayed during the first few hours, the visual brightness of SN 1987A leveled off at a value that was roughly a factor of 10 times less than would have been expected for a "normal" type II supernova. Approximately 24 hours after core collapse, the first accurate photometric measurements showed that the temperature of the supernova had already dropped to 15,000 K (compared with a theoretical value of over 300,000 K at the moment the shock broke through the surface of Sk −69°202). This dramatic decrease in temperature continued over the next week as the outer layers of Sk −69°202 underwent rapid adiabatic expansion. Soon, SN 1987A was one of the reddest objects in the sky visible to the naked eye. By the 20th day of observation, the temperature had dropped to a value of approximately 5500 K, where it stayed for the next 70 days (until late May).

As SN 1987A evolved, one of the major challenges for observers was to measure the "bolometric" light curve, which is simply the energy radiated over all wavelengths as a function of time. In practice, this required that frequent brightness measurements be obtained at optical and infrared wavelengths with ground-based telescopes, and (for the first few days) in the ultraviolet with IUE. The resulting light curve as calculated by groups at Cerro Tololo Inter-American Observatory in Chile and the South African Astronomical Observatory (*14*) is shown in Fig. 4. The slight difference between the two curves is not due to observational error, but arises instead from different computational methods and different assumptions of the amount of interstellar dust extinction.

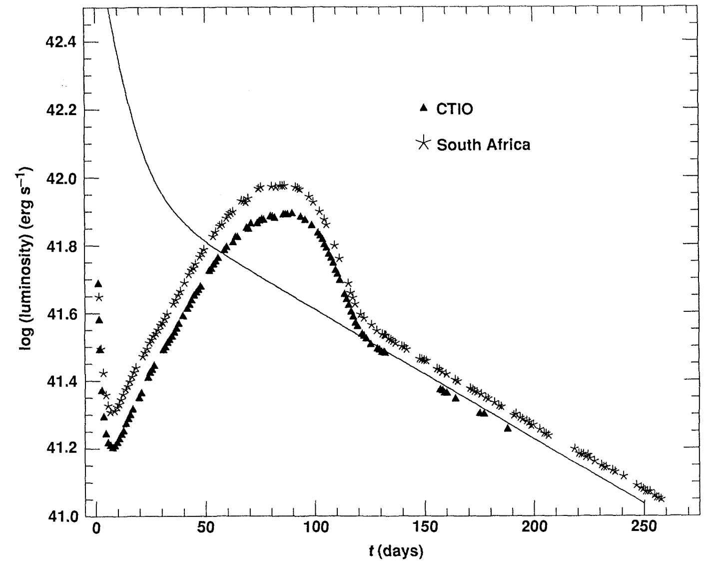

Fig. 4. The observed bolometric light curve (*14*) compared to that which would result from 100% optical conversion and escape of energy from the radioactive decay of 0.07 $M_{\odot}$ ^{56}Ni and ^{56}Co.

Figure 4 shows that over the first 7 days after core collapse, the bolometric luminosity of SN 1987A decreased sharply (as did the temperature) in response to the rapid expansion of the shock-heated surface of the star. Soon thereafter the hydrogen in the envelope, which had been ionized by the initial shock wave, began to slowly recombine in an inward propagating wave. Since the opacity increases steeply between the neutral and ionized zones owing to the scattering off of free electrons, the photosphere (that is, the surface at which the bulk of the observed radiation is emitted) closely tracks the hydrogen recombination wave during this phase. Likewise, the observed temperature levels off at 5000 to 7000 K, which is the value at which hydrogen recombines at the low densities ($\sim 10^{-13}$ g cm^{-3}) prevalent in the envelope. This so-called "plateau" phase lasts until the recombination wave encounters the helium mantle, which the model calculations indicate occurred around the 40th day after core collapse for SN 1987A. The bolometric luminosity during this phase slowly increased, reflecting the fact that the photosphere, although receding in mass coordinates, was still growing in physical size as a result of the continuing expansion of the envelope.

Were there no other source of energy besides the initial shock wave, the bolometric luminosity of SN 1987A would have begun to suddenly drop after about one month as the recombination wave passed through the base of the hydrogen envelope. In fact, as shown in Fig. 4, the luminosity continued to climb at a steady rate and did not reach a maximum until approximately 85 days after core collapse. The question on every astronomer's mind during this period was "What is now powering the light curve?" Two possibilities were suggested early on: (i) radioactivity from ^{56}Co produced in the initial explosion, or (ii) reprocessed energy from a rapidly spinning pulsar buried at the center. Fortunately, the radioactivity hypothesis could be easily checked observationally since shortly after maximum, when the helium mantle began to grow transparent, the bolometric luminosity should start to decline exponentially at a rate dictated by the 77.1 day half-life of ^{56}Co. Thus, in early June when the light curve of SN 1987A finally began to turn down, the theorists anxiously awaited word from the observers. Within a few weeks, a steady decline rate in the bolometric luminosity of 0.010 mag day^{-1} set in, precisely as predicted from the decay of ^{56}Co.

From this "radioactive tail," which has continued at the same slope through late November, it follows that 0.07 $M_\odot$ of ^{56}Ni were produced in the initial explosion (see Fig. 4). The error in this determination (20 to 30%) is set entirely by our knowledge of the distance to the Large Magellanic Cloud and the amount of dust extinction in the line-of-sight. (Note the radioactive decay sequence: ^{56}Ni decays to ^{56}Co with a half-life of 6.1 days; ^{56}Co decays to stable ^{56}Fe.)

SN 1987A was no longer underluminous by the time the bolometric light curve had made the long, slow climb to maximum, and then settled onto its radioactive powered tail. This observation tells us that the basic mechanics of the explosion of Sk $-69°202$ (that is, the collapse of the iron core, and the resulting outward propagation of the shock wave) were essentially identical to those that occur in other type II supernovae. The key difference was the fact that Sk $-69°202$ was a blue instead of a red supergiant, and hence was considerably more compact initially. This means that everything we learn from the remaining evolution of SN 1987A, as the products of explosive nucleosynthesis and, perhaps, the neutron star are revealed, should apply equally well to other type II supernovae with similar mass progenitors.

Information from the Spectrum

The first optical spectra of SN 1987A (see Fig. 5, top) revealed broad "P Cygni" emission lines of hydrogen and helium atop a strong blue continuum (*15*). The term "P Cygni" is used by observers to refer to an emission line that is accompanied by blueshifted absorption. Such line profiles are an unmistakable signature of gas in outflow, and are observed not only in supernovae but also in hot stars that are experiencing substantial mass loss (P Cygni is just such a star). The blueshifted absorption is produced by gas in the line of sight, and hence provides a direct measure of the outflow velocity. In the first spectra of SN 1987A, velocities as great as 30,000 km s^{-1} were deduced from the hydrogen line profiles, offering dramatic testimony of the huge kinetic energy imparted by the shock wave.

As the photospheric temperature of SN 1987A dropped, the appearance of the optical spectrum changed rapidly (see Fig. 5, center). The helium lines, which arise from highly excited energy levels, disappeared within 5 days of outburst. At the same time, absorption lines of lower ionization species such as neutral sodium and doubly-ionized calcium, iron, and scandium began to strengthen. Rather unexpectedly, strong lines of singly ionized barium and strontium were also identified (*16*). It is important to realize that the spectral lines at this stage were still being formed in what had been the hydrogen envelope of the progenitor, Sk $-69°202$. In the atmospheres of most stars (the sun, for example), barium and strontium are trace elements that show up only very weakly in the spectrum. Hence, the unusual strength of these lines in SN 1987A suggests that the barium and strontium abundances in the hydrogen envelope of Sk $-69°202$ were anomalously high. Barium and strontium are produced primarily in the helium burning zones of massive stars by the so-called "s-process" whereby iron nuclei are converted to heavier elements through the slow addition of neutrons. Certainly the s-process must have operated in Sk $-69°202$ before it exploded, but for barium and strontium to have such high abundances in the hydrogen envelope strongly suggests that material from the helium burning zone was mixed close to the surface at some stage either by convective mixing as a red supergiant prior to the explosion or during the supernova outburst itself.

Further evidence that Sk $-69°202$ was once a red supergiant has come from ultraviolet spectra obtained with IUE (*17*). SN 1987A was a strong source in the ultraviolet for only the first few days following core collapse. However, the persistent IUE observers continued to obtain daily spectra on the chance that the supernova might unexpectedly brighten again. Their diligence was rewarded in mid-July (approximately 150 days after outburst) when emission lines of nitrogen began to be detected. The narrowness of the line profiles showed that the emission was not coming from the supernova itself. Instead, the origin was apparently a pre-existing shell of low velocity nitrogen-rich material at a radius of approximately one-half light-year that was ionized by the initial burst of ultraviolet radiation that accompanied shock outbreak from the surface of Sk $-69°202$. The high nitrogen abundance, about 30 times more abundant compared to carbon as in the sun, implies that this gas had initially been processed in the hydrogen burning zone, was mixed to the surface during the red supergiant phase, and then lost as a stellar wind.

Figure 5, bottom, shows the optical spectrum as it appeared in September, nearly seven months after outburst. Note the striking increase in the strengths of the emission lines relative to the continuum as the spectrum slowly evolves from that of a star to a nebula. As the outer layers of SN 1987A continue to expand, the heavy elements synthesized in the explosion become visible. By November the infrared spectrum taken by two groups using the Kuiper Airborne Telescope (*18*) showed that this had happened. An emission line spectrum, qualitatively similar in appearance to Fig. 5,

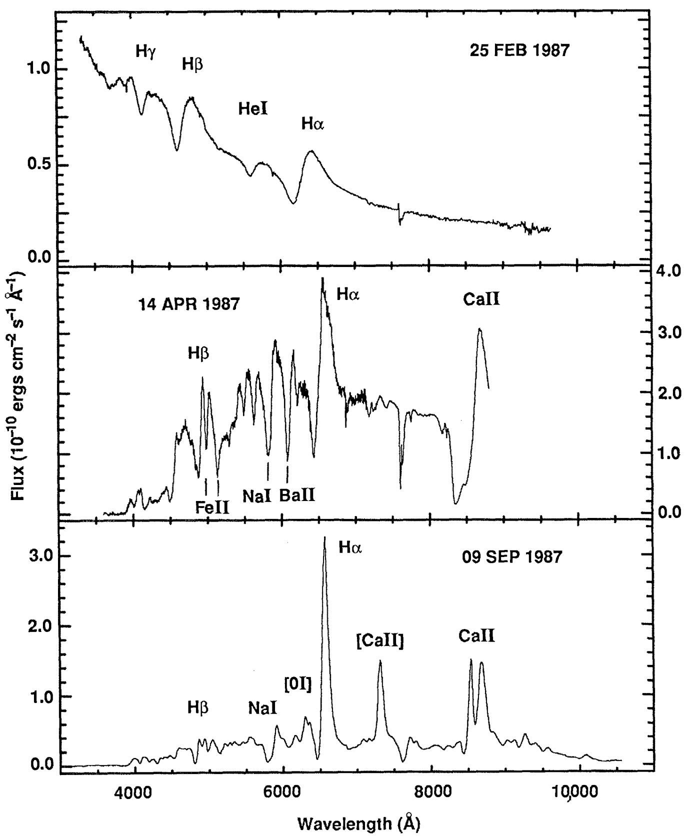

Fig. 5. The optical spectrum of SN 1987A at three different epochs: (**Top**) 25 February 1987—only 40 hours after core collapse. Note broad profiles of the hydrogen and helium lines, and the large blueshifts of the P Cygni absorption components. (**Center**) 14 April 1987—50 days after core collapse. The spectrum is now dominated by lines of low ionization elements. Note the strength of the barium line at 6142 Å. (**Bottom**) 9 September 1987—more than 100 days after the maximum of the bolometric light curve. The spectrum has by this time taken on more of a nebular appearance with strong emission lines of hydrogen, oxygen, calcium, and sodium dominating.

bottom, showed prominent features due not only to hydrogen, but singly ionized iron, cobalt, and nickel. Other features were also identified and attributed to silicon, sulfur, and the molecule carbon monoxide. The strengths of the lines were such that they could not have been produced by just the small abundances of these elements present in the star since birth, but require large quantities of the heavy elements to have been synthesized by the star, either before it exploded (probable in the case of carbon and oxygen) or during the supernova itself (silicon and heavier elements). Of particular interest are features attributed to singly ionized cobalt, the strength being such that they must reflect the large abundance of radioactive ^{56}Co known to have been produced in the explosion as ^{56}Ni.

As time passes and more spectra are obtained at all wavelengths and as more accurate calculations of the radiation transport are carried out, it should prove possible to obtain reliable abundance estimates from the relative emission line strengths, which can then be compared with the model predictions. In addition, the line shapes and precise energies can be used to map the compositional structure of the ejected material as a function of its ejected velocity. An important issue—has there been extensive mixing during the first year of the explosion? Are some heavier elements moving faster than lighter ones in contrast to the simple spherically symmetric model (Fig. 2)?

Observations at X-Ray and γ-Ray Wavelengths

From the light curve it is clear that radioactivity has been produced in the supernova; to be precise, 0.07 $M_\odot$ of ^{56}Ni was synthesized as the shock wave went through the innermost layers to be ejected. Within a few weeks this ^{56}Ni had all decayed to ^{56}Co which, owing to its longer half-life, is still present in appreciable amounts. Each time a ^{56}Co nucleus decays to a stable nucleus of ^{56}Fe it emits a number of γ-rays of discrete energy. This is because the cobalt decay leaves iron in a highly excited (nuclear) state and, just like an atom in an excited state, the relaxation to the ground state emits one or more photons of specific energy. If the supernova had become rapidly transparent to these γ-rays owing to expansion, clumping, or jets, they would have been detected early on by SMM. During the first 150 days, at least, they were not detected because the γ-rays produced deep inside the supernova were all trapped. As they diffuse out, collisions of the γ-rays with electrons reduce their energy so that they become first x-rays and finally optical emission. Even now, one year later, 90% of the energy from radioactive decay is still coming out at optical, ultraviolet, and infrared wavelengths. This is why the bolometric light curve tracks the half-life of ^{56}Co so well.

As the supernova expands however, a fraction, and ultimately all of the γ-rays escape unimpeded. First one sees hard x-rays, and then γ-lines of specific energy. Based upon models that fit the optical light curve and were calculated beforehand, it was expected (*2, 19*) that the hard x-radiation would reach a level detectable to Ginga around the end of 1987. In fact x-radiation having the predicted properties appeared several months earlier, which suggests either that there is less matter between us and the center of the supernova than most people thought or that the radioactive ^{56}Co has somehow been mixed out into the overlying ejecta (*20–22*). The alleged mixing could have been due to the hydrodynamics of the shock wave that exploded the star or might have been caused by the expansion of the ^{56}Ni and ^{56}Co region owing to the energy from radioactive decay.

Beginning in early August x-rays were detected by two experiments on board the Russian space station Mir and by the Japanese X-ray satellite Ginga (*23*). The very hard spectrum observed in both cases, peaking around 20 keV with detectable emission extending, for the instruments on Mir, above 100 keV (Fig. 6), is consistent with what was expected from γ-rays from ^{56}Co decay that have been degraded by scattering and that is almost certainly its origin (*19–22, 24*). Since its detection the x-ray signal has increased only about a factor of two and may already have reached its peak. Observations in October and November showed that the hard x-ray emission ($\gtrsim$40 keV) was essentially unchanged since early September. Theory predicts a roughly constant flux of hard x-rays for the first two hundred days after detection (*20*). Surprisingly there is a second, time variable component of x-ray emission in the Japanese measurements though not yet reported at comparable sensitivity by instruments on Mir. This component is soft (4 to 10 keV), but turned on at about the same time as the hard signal. It does not seem a likely consequence of radioactive decay and has been attributed instead to a shock wave interacting with matter around the supernova (*24*). Why two components attributed to distinctly different mechanisms should turn on at the same time is a mystery as is the rapid time variation of the soft component.

Once hard x-ray emission had been detected, the γ-rays themselves could not be far behind (*19–22, 26*). Beginning in fall 1987, a series of experiments, both satellite and balloon borne, began to detect the characteristic 847 keV and 1238 keV lines that accompany ^{56}Co decay to ^{56}Fe. First came SMM, which measured (*27*) during the period August through October a flux for the 847 and 1238 keV lines of about 1×10^{-3} and 0.6×10^{-3} γ-rays cm^{-2} s^{-3}, respectively. During October through January four balloon flights carrying γ-ray detectors, three out of Alice Springs, Australia and one in Antarctica, also detected the supernova at about the same flux level. So far the quality of the data, although convincing in showing that the supernova is indeed emitting γ-rays at the anticipated energies, has not been adequate to provide detailed information on the velocity distribution of the ejected radioactivity. Thus, scientists are eagerly looking forward to the next round of balloon flights occurring March and April 1988 in Australia. At least a half-dozen detectors will be flown, again out of Alice Springs, some of them

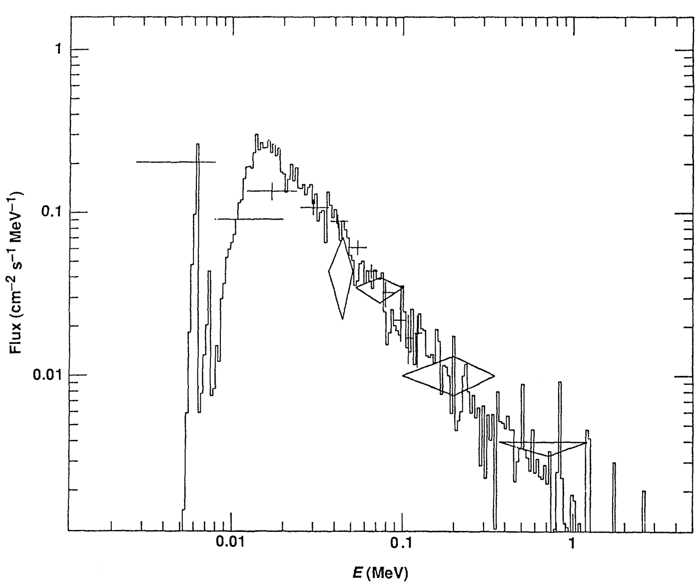

Fig. 6. The x-ray spectrum of SN 1987A as sampled by three instruments (PULSAR, HEXE, and TTM) on the Russian Space Station Mir (*23*) during August 1987. The right-most half-triangle and left-most two horizontal lines are upper bounds. Shown for comparison is the 175 day x-ray spectrum from radioactive decay calculated by Pinto and Woosley (*21*) for a theoretical model supernova (Fig. 2) of 1.4×10^{51} erg in which extensive mixing outwards of the radioactive ^{56}Co was simulated.

having considerably greater sensitivity than any of the previous instruments used to study the supernova.

Such missions are often quite adventurous. As this article goes to press, one experimental group headed by Jim Matteson and Bob Lin of the University of California has just flown their balloon-borne detector from Australia over Africa to a rough landing on a rooftop just outside Rio de Janeiro, Brazil. Data analysis will commence as soon as the instrument is retrieved from the local fire station.

The Mystery Spot

In late March, just 1 month after Sk $-69°202$ exploded, a team of astronomers from the Harvard-Smithsonian Center for Astrophysics traveled to Cerro Tololo Inter-American Observatory in Chile to obtain high-resolution pictures. Using a complicated image reconstruction technique called "speckle" interferometry, the team hoped to directly observe the expansion of the supernova over the next year or so. At this early date, it seemed rather unlikely that they would be able to resolve anything yet, even with the speckle technique. Nevertheless, the team ignored their prejudices and ended up making one of the most surprising discoveries of all (*28*).

As expected, the images obtained of SN 1987A did not show any measurable extension. Amazingly, however, a second object was clearly visible to the south of the supernova at a projected separation of 18 light days. Even more astounding was the fact that this "mystery spot" was only a factor of 12 times fainter than the supernova, or roughly 150 times brighter than Sk $-69°202$ had been before it exploded. In fact, pre-outburst photographs of the region of the supernova showed clearly that the Sk $-69°202$ had been the brightest star in the field. Thus, the mystery spot was obviously something new associated with the supernova.

The properties of the mystery spot were so unexpected that most theorists were (for once!) at a loss to explain its appearance. If it were gas participating in the explosion, it would have to have been ejected at a velocity of at least 0.6 times the speed of light. On the other hand, it seemed unlikely that the spot was a cloud of gas or dust at rest being illuminated or ionized by radiation since it would have been able to intercept only a tiny fraction of the total luminosity of the supernova. Two of the more interesting suggestions were that the spot was a fragment of the neutron star that had been catapulted away, or that it was material being lit up by a relativistic jet. An obvious test of some of these ideas was to see if the spot was stationary or moving. Hence, results from the Harvard-Smithsonian team's next attempt at speckle imaging in late May and early June were eagerly anticipated. But as fate would have it, the spot was no longer visible, implying that it was at least 40 times fainter than the supernova. Further observations made in July were equally unsuccessful. If the light is the result of a jet it would be difficult to understand why no strong radio or x-ray emission was observed in early April. Where too are the γ-lines (see above) that should be very bright if material were directly ejected from near the core?

So what was the mystery spot? Unfortunately, in the absence of further data, it is very difficult to say. Our best bet at the moment is to look for other observed phenomena that might somehow be related to the existence of the spot. For example, from late March to mid April 1987, two symmetric emission features appeared in the blue and red wings of the hydrogen lines. Was this simply a coincidence? Still more intriguing are the optical polarization observations reported by astronomers at the Anglo-Australian Observatory (*29*). These data show that the intrinsic polarization of the continuum and emission lines of SN 1987A was significant and variable, which necessarily implies that the geometry of the explosion was not perfectly spherical. As it turns out, the axis of symmetry deduced from the polarization observations is identical to within the errors to the angle between the supernova and the mystery spot. Perhaps this is yet another coincidence—or perhaps it is not. In the months and years to come there may be other clues. But for now, at least, the nature of the mystery spot remains just that, a mystery.

The Future

In the immediate future the attention of observers will be focused upon obtaining further information on the composition and distribution of matter in the exploding debris. What elements were made in the explosion and how much of each? Is the material homogeneous or has it begun to clump? Is the supernova spherically symmetric or deformed? Are there jets? Has there been extensive mixing of material created in the deep interior with material further out or has the spherical distribution of Fig. 2 been approximately retained? Further study of the γ-rays from ^{56}Co decay will aid in answering some of these questions. The intensity of the γ-rays as a function of time will tell how much material lies between us and the decaying atoms. How the bolometric light curve deviates from the strict exponential decay of its radioactive power source will give similar information. The shapes of the γ-ray lines may give a handle on the extent to which the supernova has mixed. So too will the shapes of emission lines observed in the infrared and optical from heavy elements like iron, oxygen, silicon, sulfur, and calcium.

But what of the collapsed object that lies at the center? Theory and observation both tell us that either a neutron star or black hole has been born. There was a neutrino signal and the energy can only be explained by gravitational collapse of the stellar core to one of these two objects. Theory predicts that the mass of the collapsed remnant is 1.4 $M_{\odot}$, a value consistent with the properties of the neutrino signal, in which case it is very likely a neutron star. Is it a pulsar? That depends upon the magnetic field strength and rotation rate of the neutron star. It also depends critically upon the density of material surrounding the neutron star. Even a little bit of matter falling back from the expanding debris could choke the pulsar mechanism. The very good agreement of the present rate of decline of the optical light curve with that expected from the decay of ^{56}Co shows that if there is any source of energy other than radioactivity, it must have a small effect on the light curve. This implies that if the neutron star is a pulsar with a magnetic field similar to the one in the Crab Nebula (4 trillion gauss), it cannot be rotating very rapidly. Otherwise it would contribute light at an unacceptable level. Current numbers imply that a pulsar, if present, is rotating slower than about once every 20 ms. This is still fast, but not a millisecond pulsar as some might have expected.

To actually see pulsed emission from a central source the expanding supernova must become transparent. For example, so long as a typical light ray coming from the neutron star scatters along the way we must observe at Earth a hodge podge of signals that have come along paths of varying length. This washes out any regular pulsation that might exist at the source. The optical depth to electron scattering remains large for about two years following the explosion. After that, seeing a possible pulsar depends upon the wavelength at which one observes and the orientation of the system. If there is a pulsar it may make its presence known by its contribution to the bolometric luminosity of the remnant (*30*) long before pulsations are seen, if indeed they are ever seen. On the other hand the radio pulsar mechanism may be shorted out by accretion if just a trace of matter is falling back onto the core from the ejecta. If the neutron star is an accreting x-ray emitter it might make its presence known when the supernova has declined in luminosity to that of the brightest of these sources, about 10^{39} erg s^{-1} 1 year from now.

Farther out, still moving at about 1/10 the speed of light, the shock wave is bound for interstellar space. By now it has gone about one-half trillion miles. In other supernovae in the past this shock wave, by interacting with gas around the supernova, has generated intense radio and x-ray emission. The present supernova is somewhat anomalous in having a lower density in its vicinity, a property attributed to the fact that it originated from a blue supergiant rather than a red one. Blue supergiants have weaker stellar winds. But observations and at least some of the theoretical models suggest that the progenitor star, Sk −69°202, was at some point in its life, perhaps as recently as 20,000 years ago, a red supergiant. Observations from IUE, for example, show spectroscopic evidence for low velocity, nitrogen-rich material surrounding the supernova. As time passes, from one year to several decades, the blast wave should impact this circumstellar shell giving rise to strong radio and x-ray emission.

Whatever occurs from this point on will be new and exciting. The great beauty of this supernova is that, again owing to its proximity, we will be able to observe it at all wavelengths for a long time to come. Direct measurements of radioactive decay in freshly synthesized elements, the birth of a pulsar, the evolution of a young supernova remnant, all are likely spectacles over the next few years. But the most important and exciting events will come unforetold as Supernova 1987A continues to be the answer to an astronomer's prayer—"Surprise me!"

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