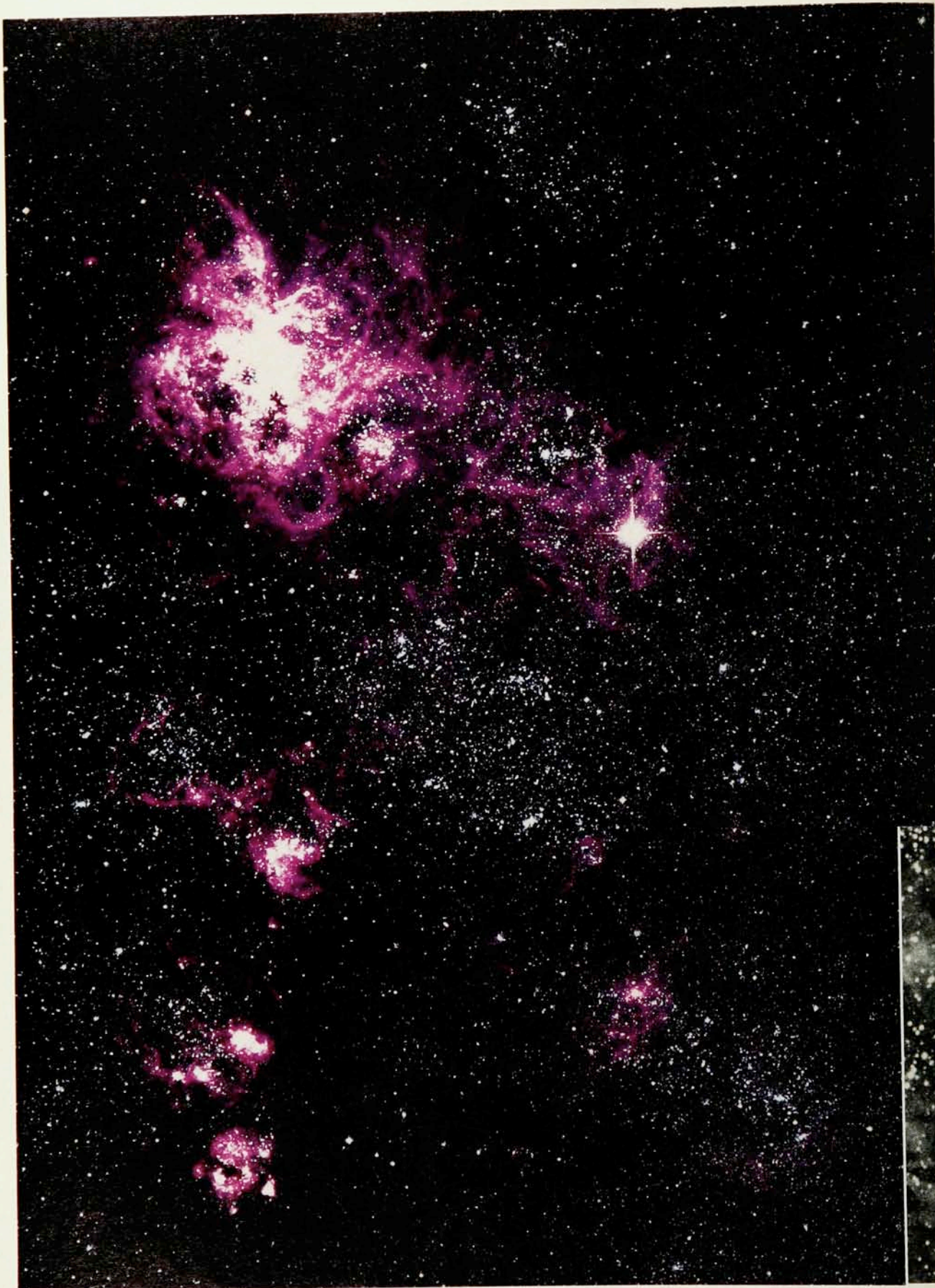




Bang: The supernova of 1987

A stellar explosion in the Large Magellanic Cloud has ended a four-century-long vigil for a nearby event and started the new field of neutrino astronomy.

David Helfand

February was a great month for physics. The subject of high- T_c superconductors exploded as labs around the world pushed the transition temperature for a variety of compounds above 77 K. The Reagan Administration announced its support for the Superconducting Super Collider as a major investment to push back the frontiers of particle physics. And on 23 February, astronomers ended a 383-year vigil as a naked-eye supernova blazed forth in the southern sky. (See figure 1.)

Telegram number 4316 of the International Astronomical Union flashed the news to astronomers around the

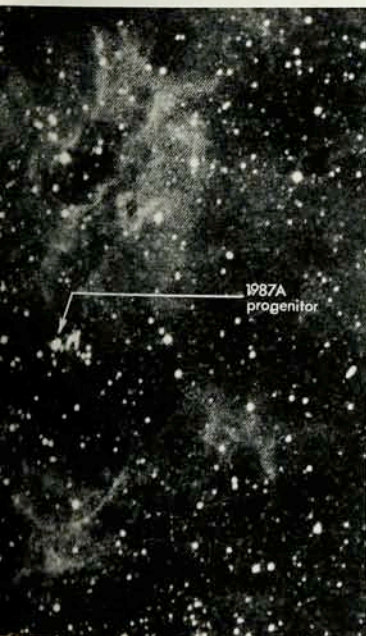
world:

W. Kunkel and B. Madore, Las Campanas Observatory, report the discovery by Ian Shelton, University of Toronto, of a mag 5 object, ostensibly a supernova, in the Large Magellanic Cloud. . . .

By the next evening, nearly all major radio and optical telescopes south of the Equator were observing the supernova, which, as the first such event discovered in the year, was designated SN1987a. Within 14 hours of the initial optical sighting, the International Ultraviolet Explorer satellite was obtaining short-wavelength spec-

tra of the exploded star. Within two weeks, physicists operating proton-decay detectors in Japan and Ohio announced the birth of a new field, neutrino astronomy, having recorded simultaneous bursts of high-energy particles hours before the optical sighting. One month after the event, the supernova story graced the cover of *Time* magazine with one word: "BANG!"

As of this writing, four months after the bang, the impact of the supernova on astrophysics and particle physics is already enormous. Some theoretical predictions, such as the neutrino lumi-



Supernova 1987a in the Large Magellanic Cloud, a satellite of the Milky Way about 170 000 light years away. The supernova is the bright star just to the right of center in the color photo opposite. The bright patch is 30 Doradus, a giant star-forming region. The image is a composite of three black and white photos taken with the the European Southern Observatory's 1-m Schmidt Telescope at La Silla in Chile. The picture shows a region of the LMC roughly 1° across, with east to the left and north at the top. The black and white photos at left show the immediate neighborhood (about 9' across) of the supernova before (1977) and after the explosion. In the "before" photo the progenitor star appears elongated, indicating the presence of a faint companion 2"6 away. (Photographs courtesy of ESO.) Figure 1

osity of the event, have been spectacularly confirmed; others, such as the expected nature of the progenitor star, have required revision. Despite over a dozen supernova meetings already organized and more than one hundred preprints in circulation, the story is far from complete. Nonetheless a coherent picture of the event is beginning to take shape and plans for future observations are in place. Here are some highlights of these chaotic four months.

Defining supernovae

The first "ostensible" supernova in the historical record was reported by Chinese astronomers in 532 BC. Since that time, roughly ten other such reports have been cited by one or another modern author as representing observations of supernovae in the Galaxy, although only the most recent four—the supernova in 1006 AD; SN1054, which created the Crab Nebula and its central pulsar; SN1572, observed by Tycho Brahe; and SN1604, reported by Johannes Kepler—are universally accepted as genuine. The first supernova detected outside the Milky Way was seen in the neighboring Andromeda galaxy in 1885, and since then roughly 600 extra-Galactic supernovae have been reported. From the beginning of the space age in the early 1960s, however, the nearest of these events was at a distance of roughly 15 million light years. SN1987a in the Milky Way's satellite galaxy, the Large Magellanic Cloud, was closer by 100-fold.

In a classic 1934 paper, Walter Baade and Fritz Zwicky suggested that supernovae are a class of phenomena distinct from ordinary novae—the sudden brightening by a factor of roughly 1000 of faint galactic stars, now known to result from surface thermonuclear flashes of material accreted from a nearby binary companion. Adopting the newly recognized notion that the spiral nebulae were in fact galactic systems at vast distances from the Milky Way, Baade and Zwicky noted that the energy involved in the Andromeda event of 1885 was sufficient to disrupt an entire star. Only 18 months after James Chadwick's discovery of the neutron, they went on to speculate, "With all reserve, we advance the view that a supernova represents the transition of an ordinary star into a neutron star." Their prescience was confirmed a third of a century later with the discovery of a rapidly rotating magnetized neutron star—a pulsar—at the center of the Crab Nebula.

Supernovae are now recognized as

the driving force behind the chemical evolution of the universe, distributing to interstellar space the elements synthesized from primordial hydrogen and helium in stellar cores and producing in the explosions themselves most of the elements heavier than iron. Energy from the explosions dominates the physical and thermal structure of the interstellar medium, with the shock waves from events near dense clouds of gas directly stimulating star formation. Supernovae mark the birthplaces of neutron stars and black holes. Their remnants are among the brightest sources in the sky at radio and x-ray wavelengths, and are probably dominant contributors to the flux of Galactic cosmic rays. Over the past 20 years, intensive efforts have been under way to determine supernova explosion mechanisms, nucleosynthetic yields, progenitor populations and patterns of remnant evolution. SN1987a is providing a stringent, critical test for much of this vast body of work.

Supernova types

The first question to be answered in the days following the discovery of SN1987a was that of the supernova's "type." Until about two years ago, two general classes of supernova were recognized: those whose optical spectra were dominated by hydrogen Balmer lines (Type II) and those in which no spectroscopic evidence for hydrogen was present (Type I). The two classes were also distinguished by the following characteristics:

- ▶ Type II events are confined to galaxies that show strong evidence for ongoing star formation; they have relatively broad light-curve peaks and slow expansion velocities (roughly 5000 km/sec); they have widely differing peak luminosities—ranging over a factor of 30—and several months after explosion they become luminous radio emitters at centimeter wavelengths.

- ▶ Type I supernovae occur in all galaxy types, have a more rapid rise to a fixed maximum luminosity followed by an exponential decay with a roughly 55-day half-life, show expansion velocities up to four times that of Type II events, and are undetectable at radio wavelengths.

The standard view was that Type II events arose from the explosion of short-lived, massive stars whose cores had collapsed after they had exhausted their supplies of nuclear fuel, while Type I supernovae arose from thermonuclear explosions in low-mass binary systems where accretion had pushed a white dwarf over the maximum mass it could support via electron degeneracy pressure.

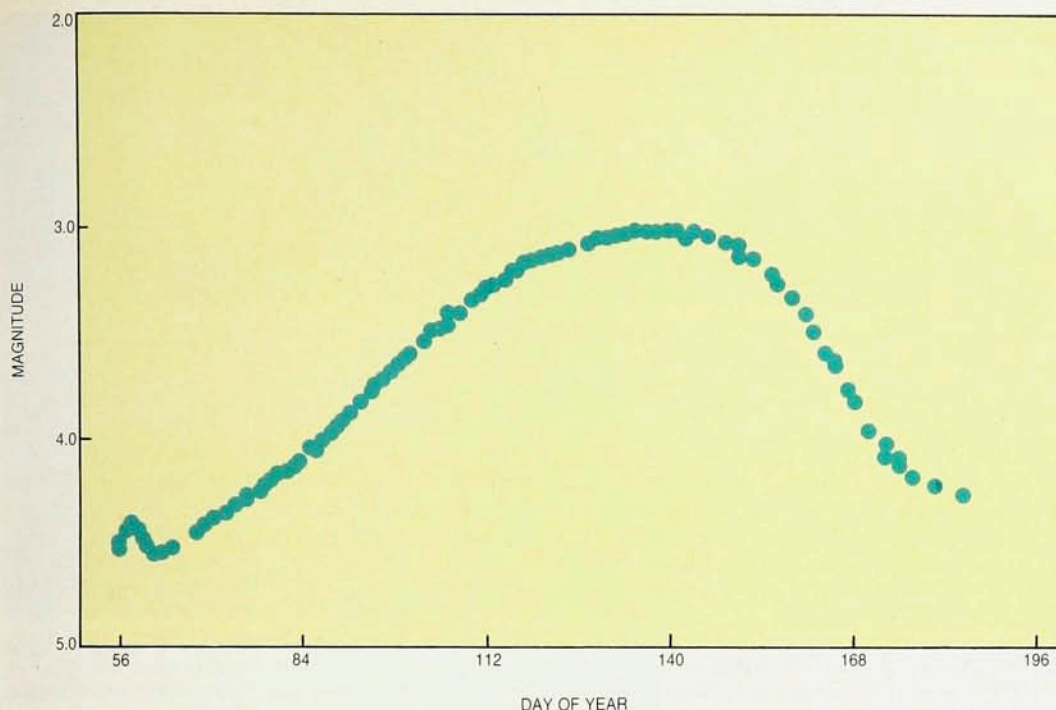
Although the spectroscopic distinc-

tion between the two classes remains clear, several recent supernovae have scrambled the other distinguishing characteristics. Two Type I events were found to be radio emitters and, along with several other hydrogen-deficient supernovae, had peak luminosities a factor of roughly five below the nominal Type I value. Nearly all of these discrepant supernovae (now called Type Ib) occurred near star-forming regions, suggesting massive progenitor stars. At the same time, evidence accumulated for a distinction, based on light-curve morphology, between two subclasses of Type II; in addition, the late-time light from at least one Type II event showed exponential decay with a Type I's 55-day half-life. Thus, as Craig Wheeler (University of Texas, Austin) recently recalled, "At the time of SN1987a's appearance, a consensus was forming that the classification scheme needed revision and that a matrix of at least four types of explosions should be considered."

It is clear that a star can be disrupted by one of two very distinct physical mechanisms: the release of gravitational potential energy by an imploding core, and the release of nuclear potential energy throughout a star as it suddenly burns a significant fraction of its total mass to nuclear statistical equilibrium. Both of these mechanisms could, in principle, occur either in a star with a hydrogen-rich envelope or in one that had lost its envelope via a stellar wind or through accretion onto a binary companion. In the new classification scheme, the Type Ib's come from massive stars that have lost their hydrogen envelopes before undergoing core-collapse explosions, while the normal Type I's are thermonuclear events in hydrogen-deficient white dwarfs; the two subclasses of Type II might likewise represent occurrence of the two different explosion mechanisms in stars that had retained at least part of their envelope material.

This new picture was developed just in time, for SN1987a most certainly did not fit either of the two simple supernova classes. Within the first few days it became clear that its spectrum was indeed that of a hydrogen-rich event, although expansion velocities in the photosphere as measured from the Doppler widths of the Balmer lines exceeded 20 000 km/sec. Though the supernova occurred in an active star-forming region of the Large Magellanic Cloud, its short-lived radio emission was 1000 times weaker than that of a typical Type II event. And the light curve (figure 2) was similar to that of only one previous event: the oddball SN1961v, for which Zwicky had created a new class (Type III). After a small

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Light curve of SN1987a, obtained with the optical star sensor on the International Ultraviolet Explorer satellite between 24 February and 2 July 1987 (day 183). The intensity is given in magnitudes, a logarithmic scale in which an increase of 2.5 magnitudes corresponds to a factor-of-10 loss in brightness. (Courtesy of George Sonneborn and Robert Kirshner.)

Figure 2

decline at the end of the first week, the supernova began to brighten, slowly increasing in luminosity for an unprecedented 80 days after the explosion. By 20 May, it had finally leveled off at a luminosity a factor of five below that of a typical Type II and over 70 times less than the canonical Type I peak. Although initially puzzling, this diverse behavior is now well understood in light of the nature of the progenitor star.

The progenitor star

Since all supernovae recorded in modern times have occurred in distant galaxies, the properties of a pre-supernova star have never been observed directly. The chance to identify the SN1987a progenitor was one of the most exciting aspects of this event for observers and theorists alike. At first, however, confusion reigned. Examination of archival plates initially showed two stars at the approximate position of the supernova, separated by roughly 3 arcseconds. They had luminosities of roughly 10^4 and 10^3 times that of the Sun, and both were blue; the brighter of the two was included as Sk - 69°202 in a catalog by Nicholas Sanduleak (Case Western Reserve University) published in 1969 and had a spectral classification of B3I, indicating a supergiant star with an effective tem-

perature of roughly 12 000 K.

The first problem with these progenitor candidates was that according to most stellar evolution calculations, it is red, not blue, supergiants that explode (although a few models involving extensive pre-explosion mass loss had suggested that blue progenitors could exist). Two weeks later, the situation grew even worse when Robert Kirshner (Harvard University) reported, at a NASA workshop convened to discuss the supernova, on observations made with the International Ultraviolet Explorer. As noted above, that satellite began observing SN1987a as soon as news of the event reached the Goddard Space Flight Center control room. The initial observations showed extremely luminous emission in the 1200–3200-Å band, although it immediately became clear that the uv maximum had already passed. The source intensity declined by a factor of 1000 in less than three days, indicating extremely rapid cooling of the expanding photosphere. By the end of the first week, the supernova could no longer be detected below 1800 Å, but much to the consternation of the observers, the short-wavelength spectra revealed the presence of two blue stars with the approximate separation and intensity ratio of the two blue stars on the archival photographs. It appeared that both

“progenitors” were still there!

Careful astrometric measurements of the supernova and the progenitor field clarified the IUE results: Within weeks, astrometrists at Yale and the European Southern Observatory had determined that Sk - 69°202 and SN1987a were coincident to better than 0".1. This result from classical positional astronomy, an often unappreciated but fundamental subject, virtually ruled out other potential candidates for the progenitor star.

Careful examination of pre-explosion plates of the field then cleared up the mystery of the IUE spectra. The supernova field lies near the great star-forming region 30 Doradus, so it was well covered on 4-meter plates taken at Cerro Tololo Interamerican Observatory for other programs; from inspection of 32 of these plates and detailed analysis of 8 of them, Nolan Walborn, Barry Lasker and Victoria Laidler (Space Telescope Science Institute) and You-Hua Chu (University of Illinois, Urbana-Champaign) determined that the progenitor field in fact contains three stars: the B3I star, the companion at 3" separation, and a third star only 1.5" away.¹ (See figure 3.) Because the separation between the B3I star and the third star is comparable to the image size in the 4-m plates, the interpretation of the data is delicate; qual-



Pre-explosion image of the precursor star Sk - 69°202 and an analysis demonstrating the presence of two companions. At center is a photo of the precursor star. At right is an image of a control star. At left is a synthetic image of the control star and two companions with locations and magnitudes adjusted to produce the best fit to the center photo. The resulting parameters for the companions match those seen in the IUE spectra. (From reference 1.)

Figure 3

itatively, however, the three-star description of the field is clear. As Lasker put it, "Although measuring the exact brightness of star 3 is a can of worms, it's definitely there and it's definitely not red." New IUE data analyzed by George Sonneborn (NASA Goddard Space Flight Center) and his colleagues confirmed that the separation and intensities of the two objects remaining in the satellite's spectrograph are consistent with those expected for the two fainter companions, strongly suggesting that the B3I star is now gone. While direct confirmation must await the launch of the Hubble Space Telescope with its superior angular resolution, Kirshner and his colleagues conclude in a recent preprint that the blue supergiant was indeed the supernova's progenitor.²

A quiet supernova

Although initially very unsettling to the community of stellar evolution theorists who had expected only red supergiants to explode, the characteristics of the progenitor explain a number of the anomalous properties of SN1987a: the weak and rapidly declining radio flux, the absence of x-ray emission, and the extremely short interval between the time of core collapse (as indicated by the neutrino signal) and the first optical sighting.

Within a day of the first supernova reports, radiotelescopes at Parkes, Molonglo and Fleurs in Australia were observing the event; a report by Anthony Turtle (University of Sydney) and collaborators summarizes the results.³ By the time of the first observation, 2.1 days after the neutrino burst, the flux was already declining at the highest frequency observed (2.3 GHz). The flux peak continued to move to lower frequencies, as expected for a radio-emitting plasma in an ionized gas cloud, until by the end of the first week, the radio output of SN1987a was declining at all frequencies. Ten weeks later, it was undetectable even at 800 MHz. By

contrast two recent extragalactic Type II supernovae reached maxima 200 days and 1000 days, respectively, after the outbursts, and both were 1000 times more luminous than the LMC event.

SN1987a has also been notably unspectacular at x-ray frequencies. There has been only one previous detection of prompt x rays from a supernova: Claude Canizares (MIT) and his collaborators used NASA's Einstein Observatory to record 0.5-4-keV x rays from SN1980k 45 days after optical maximum; the observations yielded a luminosity of 2×10^{39} ergs/sec. A month later, the source had declined by at least a factor of two in intensity and was below the telescope's sensitivity threshold thereafter. Canizares and his colleagues⁴ attributed the emission to inverse Compton scattering of optical photons by the relativistic electrons responsible for the radio emission from the event; some of the x rays may also be synchrotron radiation from the high-energy electrons in the tail of this distribution, or thermal x rays from shock-heated gas outside the photosphere. Like the radio emission, the x-ray flux from a supernova provides important constraints on shock dynamics and on the surroundings of the progenitor star.

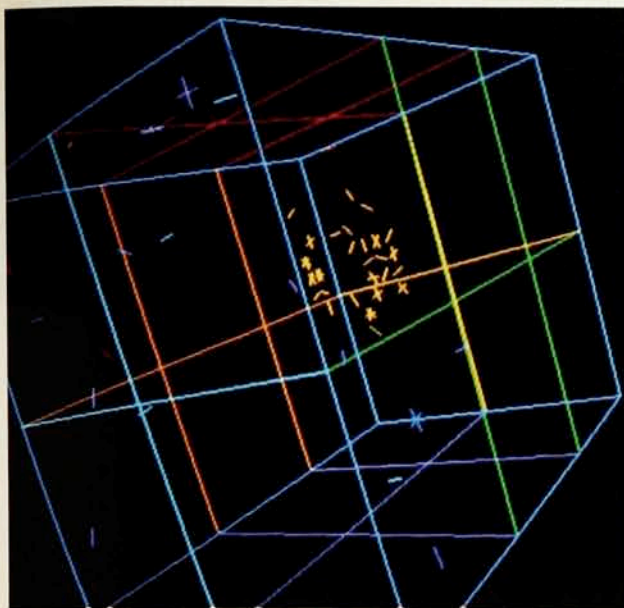
Unfortunately, the Einstein mission ended in 1981 and no US x-ray satellite will replace it until well into the next decade; the European Space Agency's Exosat x-ray mission terminated over a year ago. With the shuttle fleet grounded, Western astronomers thus have no way to observe SN1987a in the four decades of the spectrum from 0.1 keV to 1 MeV. Fortunately, however, the Japanese had launched the third in their series of x-ray satellites, Ginga, just three weeks before the supernova exploded. As soon as the instrument was checked out, they began observing SN1987a in early March in the 2-30-keV band. Yasuo Tanaka (Institute of Space and Astronautical Science) re-

ports that weekly observations have revealed no x rays to date; the upper limit to the luminosity is roughly 5×10^{36} ergs/sec, nearly three orders of magnitude below that of SN1980k. Rashid Sunyaev (Institute of Space Research, Moscow) reports that x-ray instruments aboard the Soviet Mir space station will soon give stringent limits in the 20-800-keV band.

For gamma rays the only operating detectors are those on the Solar Maximum Mission and a small instrument aboard the Pioneer Venus Orbiter. The latter detector recorded no anomalous signals either at the time of the neutrino pulse or near the optical turn-on. The SMM team also saw no transient events on 23 February; however, the Large Magellanic Cloud is near the south ecliptic pole and the satellite is normally oriented toward the Sun, so it would only have recorded supernova gamma rays that reached the NaI spectrometer through the side of the spacecraft. The current upper limit on gamma-ray lines from the decay of radioactive species produced in the supernova is roughly 10^{-3} photons/cm²sec, considerably above the level expected this early in the development.

Modeling the supernova

These data from throughout the electromagnetic spectrum impose tight constraints on the nature and evolution of the progenitor star. Despite the early confusion over the apparent survival of the Sanduleak star, W. David Arnett (University of Chicago) reports, "several of us theorists obstinately insisted that the pre-supernova object was something like that star." Arnett has produced an excellent fit to the early-time light curve of the event, including "pre-discovery" sightings from Australia and New Zealand. Ken Nomoto and his collaborators, as well as Stanford Woosley, Philip Pinto and Lisa Ensman⁵ (all at the University of California, Santa Cruz), have also matched models to the light curve; the



Reconstruction of a supernova neutrino event in the IMB detector. The straight lines show the detector walls; the yellow crosses and dashes mark the phototube "hits," showing clearly the intersection of the Čerenkov light cone with the detector walls. (Courtesy of Frederick Reines and John van der Velde, IMB collaboration.) Figure 4

consensus parameters require a deposition of 2×10^{51} ergs (at the time of the neutrino burst) in a star with a mass of roughly 20 solar mass units and a radius of 3×10^{12} cm, all consistent with what we know of the progenitor star. One can even derive the radial density profile of the progenitor by comparing the evolution of the uv and optical line profiles with atmospheric models and simultaneously requiring a match to the light curve. A density profile proportional to r^{-7} fits the data well.

Roger Chevalier (University of Virginia) and Claus Fransson (Stockholm University) have used their standard model for the interaction of a supernova blast wave with the circumstellar material to interpret the radio and x-ray data and to set limits on the pre-explosion behavior of the progenitor.⁶ For the radio emission, synchrotron radiation by electrons accelerated in shock waves in a fully ionized stellar wind gives a good fit with a pre-supernova mass loss rate of $8 \times 10^{-6} M_{\odot}$ /year in a wind with a velocity of roughly 500 km/sec. The model also explains the extremely low x-ray luminosity for SN1987a and, again, is in excellent accord with what one expects for a B3I star.

The light curve between 10 and 100 days is unique among known supernovae, but given the low peak luminosity, this may represent an observational selection effect rather than an indication that SN1987a is a rare type of

explosion. The ten-week rise in optical luminosity beginning seven days after the explosion requires a source of continuing energy input, since the bulk of the energy deposited by the shock wave was radiated away during the first week. Two obvious energy sources suggest themselves: radioactive decay of isotopes produced in the explosion, and radiation from a rapidly rotating neutron star. A third scenario, published recently by R. Schaeffer (Saclay) and collaborators, suggests that the visible output may be powered by the recombination of electrons and ions in the oxygen-rich ejecta of a massive star.⁷ Since the three models predict distinctly different behaviors beginning a few months after the explosion, it should be straightforward to determine which is applicable to SN1987a. A luminosity of roughly 10^{42} ergs/sec over the first 100 days is required to produce the light curve seen to date.

The most abundant radioactive isotope produced in the supernova is Ni^{56} , which undergoes a series of beta-decays: to Co^{56} with a half-life of 5.6 days and then to the stable isotope Fe^{56} with a half-life of 78 days. Earlier calculations by Stirling Colgate and Albert Petschek (Los Alamos) show how the energy deposition from the positrons and resultant gamma rays produced in these decays, coupled with the changing opacity due to expansion of the gas cloud, could produce the observed 55-day decay constant characteristic of

Type I light curves. For SN1987a, Woosley and his collaborators require a mass of $0.1 M_{\odot}$ of Ni^{56} to power the light curve observed to date; this amount is consistent with the stellar evolution and core-collapse models of Woosley and Tom Weaver (Livermore). Observations in the coming months will reveal whether or not such radioactivity is responsible: In 200–600 days, the envelope should become sufficiently transparent to permit balloon-borne spectrometers to observe the 847-keV and 1.2-MeV gamma-ray lines characteristic of the decay $\text{Co}^{56} \rightarrow \text{Fe}^{56}$. We would then have, for the first time, a direct confirmation of the 30-year-old theory of stellar nucleosynthesis.

The second potential source of energy for the light curve—a young, rapidly rotating neutron star—is an equally exciting prospect. A star with a magnetic moment similar to that of the Crab pulsar would require an initial spin period of roughly 5 msec to power all the visible output of the supernova. Although it may be 1–5 years before the expanding remnant is optically thin enough for us to see x-ray pulses and decades before radio pulses can emerge, nearly everyone is convinced that a neutron star does indeed exist at the center of SN1987a. The reason for this conviction is perhaps the most remarkable aspect of the event: the pulse of neutrinos detected by the Kamiokande II and Irvine-Michigan-Brookhaven collaborations.

The neutrino supernova

The integrated optical luminosity of SN1987a over its first year will be perhaps 10^{49} ergs and contributions from the rest of the electromagnetic spectrum may raise this total by a factor of two or three. The radio luminosity is a trivial 10^{41} ergs, and the x-ray and gamma-ray photons, when they ultimately emerge, may approach the optical output. The kinetic energy of $10 M_{\odot}$ of ejecta moving at 10 000 km/sec would be nearly 10^{52} ergs. But explosion models show less than $1 M_{\odot}$ moving at these high speeds, with the bulk of the ejected material moving at only 1–2000 km/sec; typical explosion energies inferred from studying old remnants are 10^{51} ergs.

All of these energies, however, are trivial compared with the 3×10^{53} ergs of gravitational binding energy that must be radiated to turn a $1.5 M_{\odot}$ stellar core into a 10-km neutron star. And on 23 February the proton-decay detectors at Kamioka and Cleveland saw just such a collapse.

The two detectors are of similar design: large volumes of ultrapure water surrounded by thousands of phototubes and located in deep mines to

minimize the background from cosmic rays. High-energy charged particles entering the detectors or originating within the water as a result of a decay or an interaction with a neutral particle are detected as Čerenkov light pulses. The IMB experiment was constructed specifically to test the proton-decay predictions of minimal SU(5); that theory is now ruled out by the 10^{32} -year lower limit on the proton's lifetime. The Kamiokande detector has a smaller fiducial volume than IMB (2140 tons of water versus 5000 tons), but its 20-inch phototubes cover a larger fraction of the surface, resulting in an energy threshold of roughly 8 MeV (IMB's threshold is closer to 20 MeV) and allowing its use in solar neutrino work as well as in setting constraints on grand unified theories. The background rates for particles originating within the detectors, the so-called contained events, are extremely low; in the IMB experiment, for example, the number of contained events induced by 20–100-MeV atmospheric neutrinos is 0.2 per day.

Within three days the first preprint concerning neutrinos from SN1987a was on the streets, with predictions about what these two detectors, as well as others such as Ray Davis's solar neutrino detector in South Dakota, should expect to see. Using only results from the published literature, John Bahcall (Institute for Advanced Study) and his collaborators summarized the expectations from 20 years of astrophysical calculations: a neutrino burst with a temperature of roughly 5 MeV lasting several seconds with a total energy of 3×10^{53} ergs and producing easily detectable signals (10–50 events) in the IMB and Kamiokande II detectors but a signal far below threshold in Davis's Cl³⁷ experiment.⁸

The IMB and Kamiokande teams were, of course, already searching their data for evidence of a neutrino signature from the supernova. On 6 March, K. Hirata and collaborators released a preprint⁹ with a short, simple abstract:

A neutrino burst was observed in the Kamiokande II detector on 23 February, 7:35:35 UT (± 1 minute) during a time interval of 13 seconds. The signal consisted of 11 electron events of energy 7.5 to 36 MeV of which the first 2 point back to the Large Magellanic Cloud with angles $18^\circ \pm 18^\circ$ and $15^\circ \pm 27^\circ$.

The paper went on to describe the spatial, temporal and energy distributions of the neutrinos, noting that a burst of this magnitude would occur as a statistical fluctuation only once in 7×10^7 years. Both scattering ($\nu + e^- \rightarrow \nu + e^-$) and capture ($\nu_e + p \rightarrow n + e^+$) interactions were thought to have

been recorded; only scattering events (which have a cross section more than an order of magnitude smaller than the capture cross section) preserve the direction of the incoming neutrino, so the broad angular distribution observed was not unexpected. The total energy output in ν_e for the supernova was calculated as 8×10^{52} ergs for an assumed average neutrino energy of 15 MeV. Since roughly equal numbers of each of the six neutrino types are expected to emerge, the total implied energy—about 4×10^{53} ergs—is just that predicted for a core-collapse event.

On 9 March, three days after the Japanese preprint was released, the IMB collaboration submitted a paper¹⁰ to *Physical Review Letters* reporting the simultaneous detection of a burst containing eight neutrinos with energies between 20 and 40 MeV in 6 seconds and with a probability of chance occurrence of less than one part in 10^{30} . (See figure 4.) When energy uncertainties of individual events and the differing sensitivities and thresholds of the two detectors are taken into account, the agreement between the two experiments is excellent. Unfortunately, however, the two sets of events cannot be combined to improve the statistics of the received burst time profile. Since it seemed rather unimportant to the Kamiokande collaboration to record the exact time of a proton decay should one ever be observed, the group's absolute timing accuracy, derived by manually entering the phone company's recorded time report into the control computer, is only good to 1 minute. It would have been straightforward to recalibrate the control computer clock after the observation of the neutrino burst, but an abrupt, complete power outage in the Kamioka Mine on 25 February made that impossible. Thus, although we know the absolute time of core collapse to 10 milliseconds from the IMB results, all calculations designed to set limits on the neutrino mass from the correlation of arrival time and energy must use the two data sets separately.

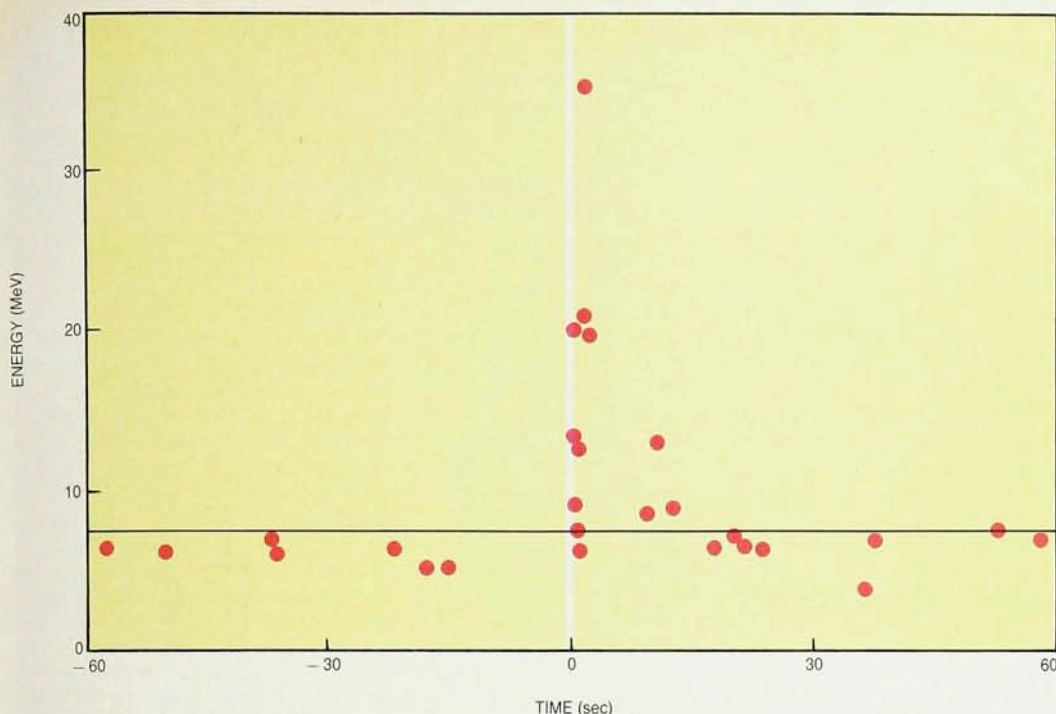
This power failure is not the only example of Murphy's attempt to thwart the detection of the supernova. IMB spokesperson John van der Velde (Michigan) told us that in the middle of the night, a few hours before the neutrino burst, a power supply tripped off, shutting down one-fourth of the detector's 2048 phototubes. This also caused the on-line data-filtering routines to stop functioning in the unattended detector. Fortunately, the raw data could be recovered from the partially malfunctioning detector and suffered no serious biases due to the

missing phototubes. The Kamiokande experimenters had an even narrower escape; they finished a regular calibration sequence only minutes before the event. The bottom line, however, was a monumental success for both experiment teams; the neutrino detection must be regarded as an unqualified triumph of international science and has already stimulated planning for future worldwide efforts in neutrino physics and astronomy.

The statistical improbability of the neutrino bursts in each of the two detectors is extremely impressive, but it is their coincidence that conclusively rules out any unaccounted-for systematic effect: That an intense, extraterrestrial burst of neutrinos arrived on 23 February is incontrovertible, and its association with SN1987a is now unquestioned. However, two other reports of neutrino events on 23 February have met with less than universal acceptance.

Five days after the explosion an IAU telegram announced that the collaboration operating the Underground Neutrino Observatory in the Mont Blanc tunnel had seen a signal. The group's published report¹¹ shows five neutrino-like events with energies less than 10 MeV in an interval of 7 seconds at 2^h 52^m UT, four and a half hours before the coincident Kamiokande and IMB detections. Accepting the reality of both sets of detections has led some authors, including Wolfgang Hillebrandt (Max Planck Institute, Munich) and his collaborators, to speculate that the Mont Blanc event signaled the formation of a neutron star and the IMB–Kamiokande neutrinos represent the subsequent collapse to a black hole. Others have suggested that the Mont Blanc results are just a statistical fluke unrelated to SN1987a, and have disputed the hypothesis of a two-stage collapse. A vigorous discussion of the issue at a workshop in early June organized by the Theoretical Physics Institute at the University of Minnesota was related to us by Thomas Walsh (Minnesota), who said, "The most important problem [with the Mont Blanc results] is the lack of a consistent story on their statistics; background bursts of the magnitude seen on 23 February have been variously reported as occurring once a month, once every five months and once every two years." However, Carlo Castagnoli, spokesperson for the collaboration, countered that "since the very beginning we have reported the same value for the imitation rate of our burst by background: 0.7 per year." It appears that the jury is still out on the significance of the Mont Blanc detection.

In addition, an initial report by O.



Neutrino events observed in the Kamiokande II detector as a function of energy in the 2-minute interval around 7:35:35 on 23 February 1987. The horizontal line is the threshold energy corresponding to fewer than 20 phototube hits. The white vertical line indicates the time of the supernova explosion. (Courtesy of Alfred K. Mann, Kamiokande II collaboration.)

Figure 5

Saavedra of the Baksan experiment in the Soviet Union claims three events occurring in 6 seconds within a minute of the IMB-Kamiokande burst. At the recent IAU colloquium on supernova remnants and the interstellar medium held in Penticton, British Columbia, in mid-June, however, V. Chechetkin (Moscow University) issued a revised report that indicated five events above 10 MeV within a 9-second interval beginning 25 seconds after the IMB burst; Chechetkin called the delay "very difficult to understand." The bulk of the effort in interpreting the neutrino signal, then, has concentrated on the IMB and Kamiokande data.

The neutrino prediction

Colgate and R. White (Los Alamos) recognized in 1966 that neutrinos might be a dynamically important factor in supernova explosion models. Their seminal paper has been followed by a substantial effort to determine how the neutrinos created in the neutronization ($p + e \rightarrow n + \nu_e$) and subsequent collapse of the degenerate stellar core diffuse out of the star.

The energy distribution of the detected neutrinos is consistent with that expected from a thermal, Fermi-Dirac distribution with a temperature of roughly 5 MeV; this spectrum as well as the total luminosity and duration of

the burst is remarkably consistent with recent calculations of the expected properties of neutrinos from a core-collapse supernova. Although the information available is too limited to settle such questions as whether the neutrinos are important in lifting off the mantle of the star, as was recently suggested by James Wilson's (Livermore) calculations, astrophysicists are in general extremely pleased with the degree of agreement between model explosions and the real thing. Bahcall, who has worked on many problems involving neutrinos in astrophysical settings over the past 25 years, called it "a fabulous collective achievement—from Baade and Zwicky to Pauli and Fermi, Fowler and Hoyle, Colgate and White, Wilson, Burrows and Lattimer—a trail of extraordinary insight of which physics should be proud."

Particle physicists were equally excited by the news of the neutrino detection because it offered, in principle, a new method of determining such neutrino properties as masses, lifetimes, mixing angles and magnetic moments. As of this writing, the number of preprints on this subject has already far exceeded the number of neutrinos detected. That the neutrinos from SN1987a hold important implications for neutrino physics is undisputed, but a consensus has yet to be

reached as to what the data really show.

Nearly 20 years ago, G. T. Zatsepin (Moscow) suggested using an anticorrelation of the arrival times and energies of neutrinos from a supernova to set limits on the neutrino mass. For a highly relativistic particle of mass mc^2 and energy E , or γmc^2 , the velocity β is

$$\beta = \frac{\sqrt{1 - \gamma^{-2}}}{\gamma} \approx 1 - \frac{m^2 c^4}{2E^2}$$

The time interval Δt between the creation of the particle and its arrival at a detector a distance D away is

$$\Delta t = D/\beta c \approx (D/c)(1 + m^2 c^4/2E^2)$$

Thus, assuming one knows D , E and the time spread of the emitted pulse, the relationship between each particle's energy and relative arrival time determines the particle mass.

Claims appearing in a flood of circulating preprints range from a detected ν_e mass of roughly 3 eV to an upper limit of greater than 20–25 eV. While the recipe for deriving a neutrino mass from the data is straightforward, Edward Kolb, A. Stebbins and Michael Turner (Fermilab) point out in a recent *Physical Review* paper that the procedure "involves a number of steps, each wrought with uncertainties and subtleties," such as the unknown intrinsic burst profile, which events in each

burst to ignore as background, what the true individual energy uncertainties are and what supernova distance to adopt.¹² Many groups are currently engaged in extensive Monte Carlo calculations to narrow the range of the first-cut estimates; values similar to those found initially by such authors as Bahcall and Sheldon Glashow (Harvard),¹³ Adam Burrows (University of Arizona),¹⁴ and Arnett and Jonathan Rosner (University of Chicago)¹⁵—roughly 10 MeV—may well emerge as the consensus limits.

SN1987a at the APS and NASA

At the spring APS meeting, a post-deadline session on SN1987a was held the evening of Monday, 20 April. Over 600 excited physicists crowded into the ballroom of the Hyatt Regency Hotel in Crystal City, Virginia, to hear Kirshner lead off the program with a review of the optical and uv data, which at that time showed the supernova to be still slowly increasing in optical luminosity. There followed a score of talks and three panel discussions, most of which revolved around the neutrino detections and their implications for both astrophysics and particle physics. Alfred K. Mann (University of Pennsylvania), representing Kamiokande II, showed the remarkable neutrino burst signal from that detector. (See figure 5.)

Frederick Reines (University of California, Irvine) recounted his involvement in the extended labor preceding the birth of neutrino astronomy: from his work with George Cowan on discovering the neutrino in the 1950s, through his Supernova Early Warning System, which he constructed at Case in 1960—a predecessor to the large water Čerenkov detectors of today—to his participation as spokesperson in the IMB collaboration. In that role he reported the group's results and then went on to provide some perspective on the SN1987a neutrinos. Some 170 000 years after the explosion, 3×10^{16} neutrinos passed through the detector volume and 8 were left behind as the only direct trace of a stellar core collapse that we are likely to have until well into the next century.

Although SN1987a occurred at a most inopportune time for space-based observations, NASA's prompt, aggressive, "science first" reaction to the event has been almost as refreshing to the beleaguered space astronomy community as the supernova itself. Within nine days of the explosion, the Astrophysics Division in the Office of Space Science and Applications distributed a "Dear colleague" letter to all rocket and balloon experimenters stating, "If you have a payload which could make

useful observations of the supernova which can be ready for flight on a short schedule... send a brief proposal to this office detailing the justification for your particular observation." Proposals were due 15 March. Four days after the letter was issued, a workshop was held at the Goddard Space Flight Center to review the background and status of SN1987a observations and to explore the prospects for doing supernova science from space.

Near the end of March, the agency administrator, James Fletcher, testified before Congress that NASA would "use [its] unique capabilities—operating satellites, suborbital programs, communication networks and computational facilities—to study this event in some detail at all wavelengths." He pledged an ongoing "campaign utilizing a series of balloons, rockets and airplane observations as the envelope unfolds and the secrets of this colossal and unique event are revealed."

By 7 April a NASA review committee had selected 13 gamma-ray experiments, three x-ray instruments and two uv rocket payloads to participate in a series of campaigns in Australia to occur during the interval from April 1987 until at least April 1989. The Kuiper Airborne Observatory for the far infrared had the supernova added to its scheduled program of April observations flying out of New Zealand, and an announcement of opportunity to propose projects for future southern flights was issued to the community. Efforts were inaugurated to see if there was any way to expedite the launch of the sensitive Broad Band X-Ray Telescope, originally scheduled to fly on the shuttle. All of the scientists involved, while excited by the prospects for directly measuring the radioactive products of explosive nucleosynthesis with the gamma-ray balloon experiments and for probing the composition of the pre-supernova star by observing x-ray and uv absorption and fluorescence lines, were equally impressed with the fast and effective NASA response. "At last," said one participant, "space science has some priority again." By June, four balloon flights carrying gamma-ray detectors had been completed, with the most stringent of the upper limits on the Co⁵⁶ line flux already beginning to constrain models for the explosion.

While at first many aspects of SN1987a were startling, Woosley recently emphasized that "in the end, the supernova is really not all that strange, and it is precisely because it is not strange that we stand to learn much about supernovae in general by studying SN1987a over the coming months and years." Observers using balloons,

rockets, satellites, airplanes and ground-based telescopes have by now largely charted the course of that study, and supercomputers around the world are crunching away on problems ranging from how stellar evolution theories must be modified to yield a blue exploding star (apparently a relatively easy task) to what the "real" neutrino mass limits are (likely to be a source of continuing controversy).

While SN1987a is unlikely to have the wide-ranging impact outside of the sciences that Kepler's supernova occasioned in 1604, one dividend already apparent is improved communication between particle physicists and astrophysicists. At the Minnesota TPI conference Walsh noted that "most of the astrophysicists sat on one side of the room and the particle physicists sat on the other." However, overheard comments such as "Oh, we don't use those cross sections anymore" indicated the value of the exchange. Elsewhere, a slightly weary and well-traveled Kirshner captured the feeling of many of the participants caught up in the excitement of the past few months: "The supernova is very much like having a baby—at first it's great fun, and it becomes ever more rewarding, but it sure is hard work!"

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