Eur. J. Phys. 9 (1988) 168–178. Printed in the UK

## Astrophysics '88

# SN 1987A: a bright supernova in the Large Magellanic Cloud

**Jean Surdej**

Institut d'Astrophysique, Université de Liège, Belgium

Received 22 January 1988

**Abstract** Since the discovery, on 24 February 1987, of the explosion of a bright supernova in the Large Magellanic Cloud, a real euphoria has developed in the astronomical community. Indeed, such a cataclysmic event, visible with the naked eye, is likely to occur no more than once every two hundred and fifty years and it has provided particle physicists with the first detection of the extragalactic neutrinos emitted during the core collapse of a massive star. SN 1987A has also given astronomers the unique opportunity to probe spectroscopically the interstellar and intergalactic media over a distance of 165 000 light years. Furthermore, theoreticians are now trying to reconcile the multi-wavelength observations ($\gamma$-ray, x-ray, visible, IR, radio) presently available for SN 1987A with their models of stellar evolution just before and after the fatal explosion. We present in this article an overview of the main observations and results obtained so far and we discuss the plans for future observations.

**Résumé** La découverte, le 24 février 1987, de l'explosion d'une supernova très brillante dans le Grand Nuage de Magellan a suscité une agitation euphorique sans précédent au sein de la communauté astronomique. En effet, un tel événement cataclysmique, visible à l'oeil nu, ne se produit qu' environ une fois tous les 250 ans et celui du mois de février 1987 a conduit à la première détection de neutrinos extragalactiques émis au cours de l'effondrement du noyau d'une étoile massive. De plus, SN 1987A a fourni aux astronomes une occasion unique de sonder spectroscopiquement les milieux interstellaire et intergalactique sur une distance de 165 000 années lumière. Actuellement, les théoriciens tentent de concilier les nombreuses observations réalisées dans les divers domaines spectraux ($\gamma$, x, visible, IR, radio) avec les modèles d'évolution d'étoiles massives juste avant et après l'explosion fatale. Nous présentons ci-après un résumé des observations et des résultats déjà obtenus et nous décrivons les projets d'observations futures.

## 1. SN 1987A – a very unexpected event

From the statistics of supernova events that have been observed in a large sample of external galaxies we know that, within a period of 1000 years, approximately four galactic supernovae should become visible to a terrestrial naked-eye observer. It was therefore a great surprise for the astronomical community to receive on 24 February 1987 a telegram from the International Astronomical Union (hereafter IAU), directly followed by the IAU astronomical circular no 4316, announcing that a naked-eye supernova of apparent visual magnitude $m_V \sim 4.5$ had been discovered in the Large Magellanic Cloud (LMC) (see figures 1 and 2) during the night of 23–24 February.

Three independent discoveries of the first supernova of the year 1987 (therefore designated SN 1987A) are reported in the circular no 4316. The supernova has been identified by Ian Shelton (astronomer at the University of Toronto station located at the Las Campanas observatory in Chile) on 24 February at 5.5 h UT (universal time) on a 3 h exposure photographic plate taken with a 25 cm astrograph. SN 1987A was visually sighted on the same night by Oscar Duhalde (night assistant at the American Observatory of Las Campanas) and by Albert Jones (an amateur astronomer in Nelson, New Zealand) at 4.8 h and 7.9 h UT, respectively. The appearance of SN 1987A constitutes a unique event since it is the brightest supernova to be observed since 1604 and because the supernova rate in the LMC has been estimated to be about 1 per 500 years. The supernova that was seen 384 years ago appeared in the constellation Ophiuchus, towards the centre of our Galaxy, at an approximate distance

0143-0807/88/030168 + 11 $02.50

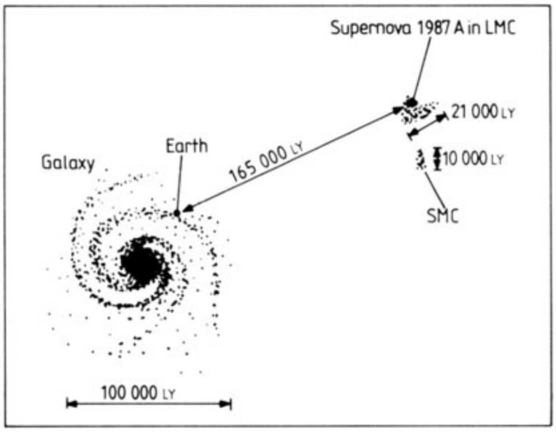


**Figure 1** Schematic position of supernova 1987A in the Large Magellanic Cloud (LMC). The star explosion that led to the sighting of SN 1987A in the LMC took place during the night of 23–24 February 1987. The LMC and the Small Magellanic Cloud (SMC) are two dwarf satellite galaxies of our Milky Way, located at an approximate distance of 165 000 light years. Since the light emitted by the supernova travelled during 165 000 years, we see this cataclysmic event in the LMC as it happened well before the appearance of *homo sapiens* on Earth. Both the LMC and SMC are naked-eye visible galaxies in the sky of the southern hemisphere.

of 30 000 light years. Observations of SN 1604 have been described by Kepler and other contemporary astronomers who, at that time, did not possess any optical telescopes.

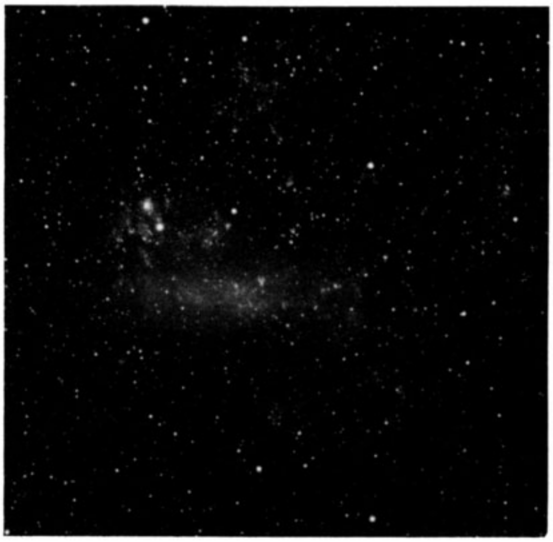
Immediately after the discovery of SN 1987A, most of the radio and optical telescopes located south of the equator started monitoring this rapidly evolving object. By chance, several photographs of the LMC had been taken at various observatories just before and after the supernova event. The location of this bright supernova in the LMC may be very well seen in figure 2. Figure 3 illustrates in more detail the region of the sky near 30 Doradus as it appeared ten years before and three days after the explosion of SN 1987A. These photographs were taken at the European Southern Observatory (ESO, see Appendix) in Chile.

## 2. The progenitor of SN 1987A

We are very fortunate that SN 1987A exploded in the LMC. Since we may reasonably assume that all stars belonging to the LMC, and which are receding from us with an average velocity of 260 km s$^{-1}$, are located at a same distance $d = 165\,000 \pm 10\,000$ light years, we can conclude that SN 1987A is located at that same distance from our Solar System.

We can therefore include in a diagram representing the absolute magnitude plotted against temperature (or spectral class), the famous Hertzsprung–Russell (HR) diagram, each individual star of the LMC, including SN 1987A and its progenitor. We recall that in such an HR diagram, the stars are not distributed at random but follow distinct evolutionary tracks that are essentially a function of the initial conditions (mass, chemical composition etc). If we could identify the progenitor of SN 1987A, we would therefore have a unique opportunity to understand what are the late stages of evolution of a massive star. A very good progenitor candidate has soon been identified with a 12.2 magnitude hot supergiant star known as Sk – 69°202. Close examination of earlier photographs revealed that this star had two close companions located at respectively 3.0″ and 1.5″ (see figure 4). Very accurate astrometric measurements of SN 1987A and Sk – 69°202 indicate that their positions coincide to an accuracy better than 0.1″. Furthermore, spectroscopic data obtained in early April with the International Ultraviolet Explorer (IUE) satellite clearly show that the two nearby companions are still there but that Sk – 69°202 has in fact disappeared. After several hesitations, there is now a general consensus that it must have been Sk – 69°202 that exploded.

**Figure 2** The Large Magellanic Cloud (LMC) and SN 1987A. This picture (originally in colour) of the LMC was obtained on 25 February 1987 at 1.0 h UT, i.e. approximately two days after the supernova explosion. It was taken by Claus Madsen at the European Southern Observatory with a Hasselblad camera and 6 × 6 cm Agfachrome 1000 RS emulsion. The exposure time was 20 min. The supernova is clearly seen at a magnitude $m_p \sim 4.5$ to the left of centre and above the LMC main body, as the lower right of the two bright objects. The second bright and diffuse object is the Tarantula nebula (30 Doradus), a giant region of hydrogen that is ionised by a cluster of stars in formation. (*Photograph courtesy ESO*).



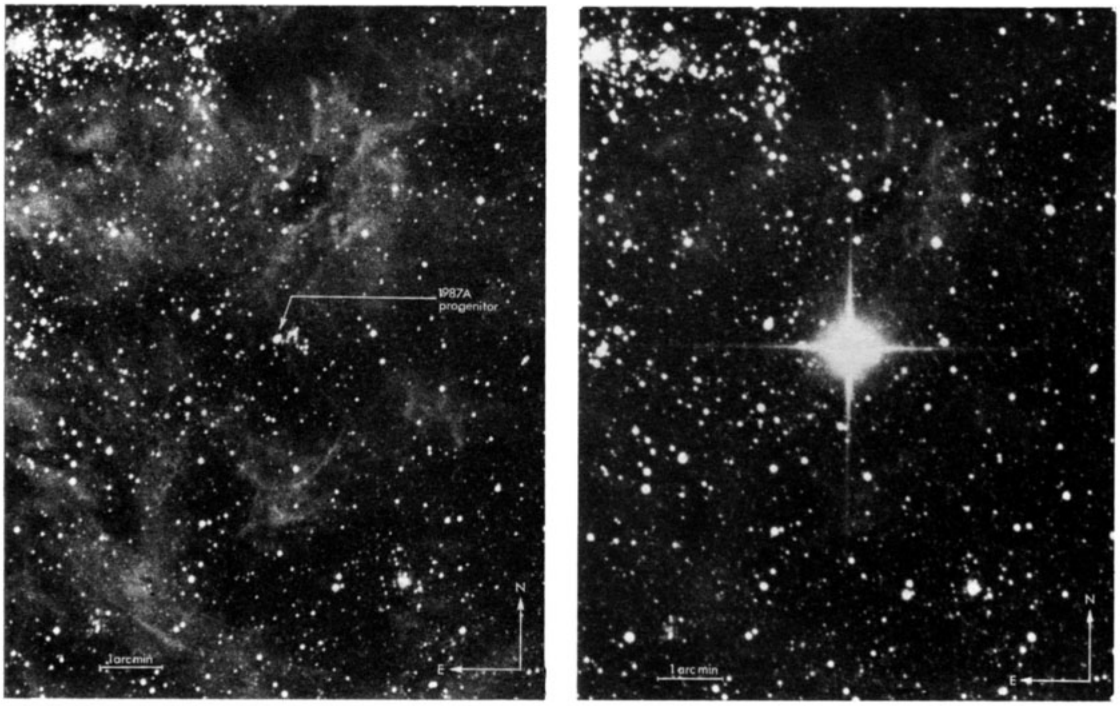


**Figure 3** Immediate surroundings of SN 1987A before and after the explosion. This pair of photographic plates obtained with the ESO Schmidt telescope illustrates the sudden appearance of SN 1987A in the LMC. The left (and right) plates were taken by H E Schuster and O Pizarro (G Pizarro) on a IIa–O emulsion plus UG1 (GG385) filters during 60 (15) min on 9 December 1977 (26 February 1987 at 1h25m UT). The exact position of the progenitor of SN 1987A is indicated by an arrow on the left-hand picture. Between the two epochs when these photographs were made, the brightness of SN 1987A has increased by a factor of more than 1500. It has also been possible to find that this abrupt change in luminosity took place in less than 24 h. Note that the cross seen around the bright star image on the right-hand picture arises because of diffraction of light from the supernova by the plateholder support inside the Schmidt telescope. (*Photograph courtesy ESO*.)

However, this confronted astronomers with the surprising fact that the progenitor of SN 1987A was a blue supergiant. Indeed, according to standard models of stellar evolution most theoretical astrophysicists had predicted that massive star progenitors of supernovae like SN 1987A should evolve to red supergiants prior to the ignition of core carbon burning, and thus should subsequently explode as red supergiants. Theoreticians are therefore left with the puzzle of how to explain that a blue supergiant star could explode into a supernova.

## 3. The birth of a supernova or the death of a massive star

Supernovae are generally divided into two main classes, I and II. Type I supernovae are observed in spiral, elliptical and irregular galaxies (cf the LMC). They are thought to relate to the thermonuclear explosion of a white dwarf in a close binary system (see figure 5). It is important to note that no hydrogen lines are seen in the spectrum of a type I supernova. However, strong hydrogen Balmer lines were soon detected in the spectrum of SN 1987A and these are typical of type II supernovae. It is generally accepted that a type II event corresponds to the explosion of a very massive, short-lived star whose core collapses after it has completely exhausted its supply of nuclear fuel (see figure 6). Let us now compare the observations of SN 1987A with those expected from a type II supernova.

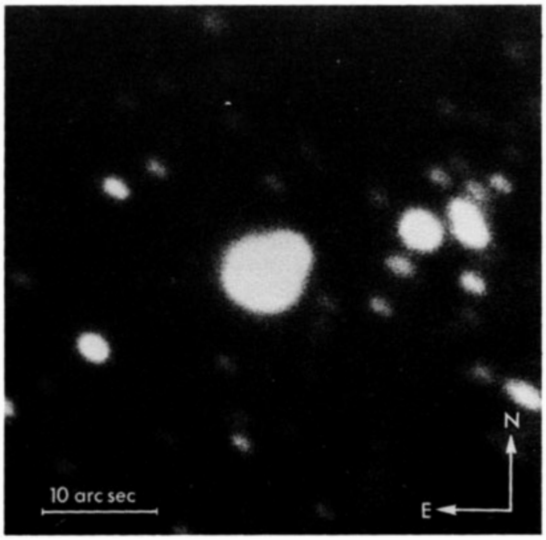
## 4. Photometric and spectroscopic observations of SN 1987A

Because of the very rapid evolution of both its lightcurve and its spectrum, SN 1987A appears to be a very peculiar type II supernova. Figure 7 illustrates the visual lightcurve of SN 1987A during approximately one year since its discovery. From these as well as from additional published data, the following anomalies are noted.

(i) Following the core collapse that occurred on 23 February at 7 h35 m UT (a neutrino signal was detected at that time), the rise in brightness of SN 1987A was extremely steep. A first visual light maximum was reached on 28 February when the shock wave hit the photosphere of the star. However, the luminosity of this peak is found to be approximately seven times fainter than that expected from a standard type II supernova. Furthermore, the ultraviolet radiation of SN 1987A decreased by a factor of more than 1000 in less than three days; during that time, the object was brightening in the red and infrared.

(ii) As early as two days after the explosion of Sk $-69°202$, very broad P Cygni profiles were detected for the hydrogen lines of the Balmer series in the spectrum of SN 1987A (see figure 8). As mentioned previously, unusually large expansion velocities of stellar material up to 30 000 km s$^{-1}$ were measured.

**Figure 4** The progenitor of SN 1987A. The star that exploded on 23 February 1987 in the LMC is well identified on this photograph, obtained in red light with the ESO 3.6 m telescope on 6 December 1979. It was catalogued by Sanduleak in 1969 as an OB star of 12th magnitude and given the designation $-69°202$. Observations at the European Southern Observatory in the mid-1970s allowed it to be classified as being of spectral type B3I, that is a star having an effective temperature $T_{\rm eff}\sim 15\,000$ K, a radius $R\sim 3\times 10^{12}$ cm, a luminosity $L\sim 1.3\times 10^5\,L_\odot$ and a mass $M\sim 15\,M_\odot$, where $L_\odot$ and $M_\odot$ represent the luminosity and the mass of the Sun, respectively. Closer inspection of this star image has however revealed that two stellar companions were located very nearby. On this photograph, the image of Sanduleak $-69°202$ is somewhat elongated towards the northwest, since one of the companions ($m_V\sim 15.3$) lies in that direction at a distance of 3.0″. A third star ($m_V\sim 15.7$) was also found to be present at only 1.5″ southeast of Sk $-69°202$. Note that the stellar images seen on this picture are very close to the edge of the plate and are therefore somewhat elongated, due to less than perfect corrections of optical aberrations. (*Photograph courtesy ESO.*)



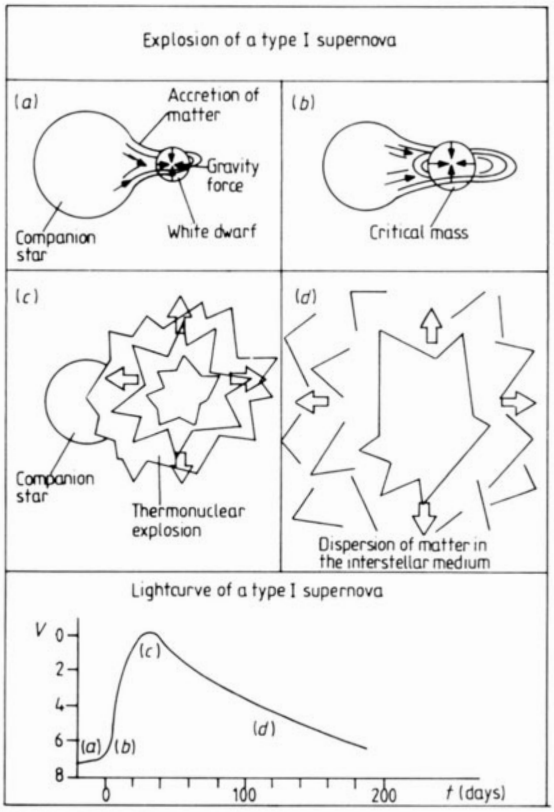


**Figure 5** The different phases in a type I supernova explosion. Astrophysicists believe that type I events relate to close binary systems in which a white dwarf gradually strips off matter from the giant atmosphere of a companion star (*a*). A white dwarf is a fossil star whose radius is comparable to that of the Earth and its mass similar to that of the Sun. There result extremely high densities, of the order of 1 t cm$^{-3}$. It is the electron degeneracy pressure which prevents such an object from being further compressed. However, when the mass of the white dwarf reaches the critical value of about 1.4 $M_\odot$, the whole star collapses (*b*), igniting its core in a thermonuclear explosion (*c*), which completely disrupts the white dwarf and disperses it in the surrounding interstellar medium (*d*).

The enormous amount of energy radiated in such an explosion accounts for the observed lightcurve of a type I supernova. The absolute visual magnitude of the light maximum is typically $-18.7$, i.e. 2 billion times intrinsically brighter than our Sun. After maximum, the lightcurve of a type I supernova exhibits a rapid decline in luminosity.

In order to account for the rapid development of the lightcurve of SN 1987A, theoreticians proposed that the progenitor had to be an object much more compact than a canonical red supergiant star. In addition, a progenitor with a high-density atmosphere akin to that of a blue supergiant would ensure that a larger fraction of the energy released by the explosion went into expansion of its atmosphere,

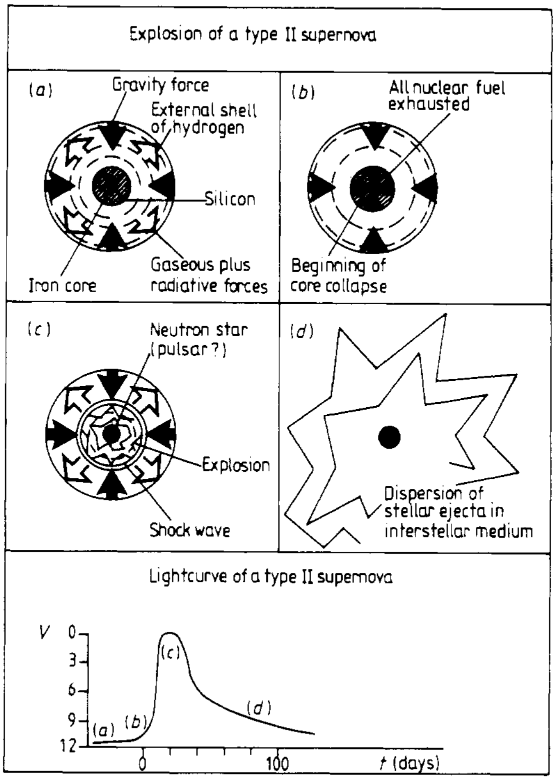


**Figure 6** The different phases in a type II supernova explosion. It is well known that during the evolution of a star, light elements are transformed into heavier ones in its central core. These nuclear reactions actually supply the energy radiated by the star and they also provide the radiative and gaseous pressures needed to balance the inward force of gravity. At the end of its evolution, the stellar core has exhausted most of its supply of nuclear fuel: all hydrogen atoms have been transformed into helium ones, followed by the transmutation of helium into carbon and oxygen etc, until a last chain of nuclear reactions fuse (in less than one day) the silicon atoms into iron ones. At this stage, the star looks like a stratified ball (*a*) made of a central iron core surrounded by various shells of elements whose atomic weight decreases outwards (silicon, ..., aluminium, ..., hydrogen).

Under the normal conditions of temperature and pressure prevailing in stellar interiors, the physical structure of the iron atoms prevents these from fusing into heavier elements. The supply of nuclear energy is therefore totally exhausted and the star can no longer support its own weight. In less than a second, the stellar core collapses (*b*). If the initial mass of the star is not too large – of the order of one solar mass – this cataclysm leads to the formation of a planetary nebula with a white dwarf in its centre. It is very probably along these lines that our Sun will end its evolution in approximately 5 billion years. If, however, the mass of the progenitor is as large as $7\,M_\odot$ or more, the collapse of the iron core will be so violent that even the electron degeneracy pressure will not be able to stop the rapid implosion. Very suddenly the protons in the stellar core capture electrons to form neutrons, very energetic neutrinos and antineutrinos are emitted at this same time, ... a neutron star has been formed. The radius of such a star does not exceed a few tens of kilometres but its volume density is as high as $10\,\mathrm{Mt\,cm^{-3}}$.

Thanks to the strong mutual repulsion of the neutrons, this star cannot be further compressed (for progenitor masses greater than $30\,M_\odot$, the ongoing implosion would lead to the formation of a black hole). A tremendous shock wave then rebounds from the neutron core in a huge explosion that sweeps out all external shells of stellar material (*c*). Expansion velocities up to $30\,000\,\mathrm{km\,s^{-1}}$ have been measured from the so called P Cygni profiles observed for the hydrogen Balmer lines in the spectrum of SN 1987A. Let us note here that in the early phase of the explosion, the temperature and pressure are so extremely high that elements heavier than iron (e.g. uranium, nickel etc) may be synthesised. It is even generally thought that all such heavy elements found on Earth must have been synthesised during the explosion of one or more nearby supernovae. In this context, our Sun appears to be a second or even third generation star, born from the dispersed ashes of a supernova (*d*). The absolute visual magnitude characterising the light maximum of a type II supernova is about $-16.3$, i.e. about ten times less luminous than a type I maximum. The post-maximum decline of a type II lightcurve is however not so steep.

rather than being radiated in the electromagnetic spectrum. This is exactly what has been observed for SN 1987A. Evaluation of the kinetic energy of the expanding envelope amounts to $\sim 10^{44}$ J whereas the light output radiated so far has been estimated to be $\sim 10^{41}$ in the visible and $\sim 10^{40}$ in the ultraviolet. Such a scenario also accounts for the low luminosity of the visual maximum observed five days after the explosion of Sk – 69°202. Let us note here that the rapid decline of the ultraviolet radiation and brightening at longer wavelengths were caused by the fast cooling – and associated line blocking – of the rapidly expanding atmosphere (see figure 9).

Meanwhile, analysis of pre-outburst direct photographs and objective prism spectra of Sk – 69°202 have brought interesting new results. First of all, no evidence was found for significant photometric variability or spectroscopic activity (no emission lines were detected) of this star during the last few decades. A conspicuous nitrogen absorption line has however been identified in the spectrum of the progenitor. Spectral analysis of other blue supergiants in the LMC also indicates that some of these have abnormally high abundances of heavy elements (He, N etc), as in highly evolved post-red-giant objects. It therefore seems plausible, on observational grounds, that Sk – 69°202 became a red supergiant before evolving into a blue one. Independently, theoreticians have recently shown that models of a massive star ($\sim$15–20 $M_\odot$) with

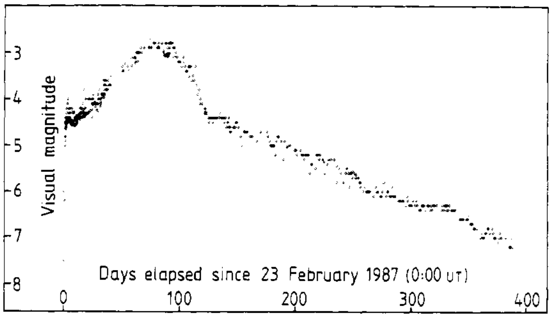


**Figure 7** Lightcurve of SN 1987A. This figure represents the apparent visual magnitude of the supernova against the observing time. Most of the measurements were taken from the IAU astronomical circulars published between 23 February 1987 and March 1988.

reasonable mass loss and a low metallicity†, such as the one characterising the LMC (about one-quarter of the solar value), naturally lead to a blue supergiant as the progenitor of a type II supernova, possibly following a red giant phase associated with the end of the central helium burning and with the onset of helium burning in an external layer. These models also predict that the frequency of red supergiant stars should be higher in the LMC than in our Galaxy, in good agreement with existing observations.

Another very unexpected feature of the visual lightcurve of SN 1987A is that after reaching a first

---

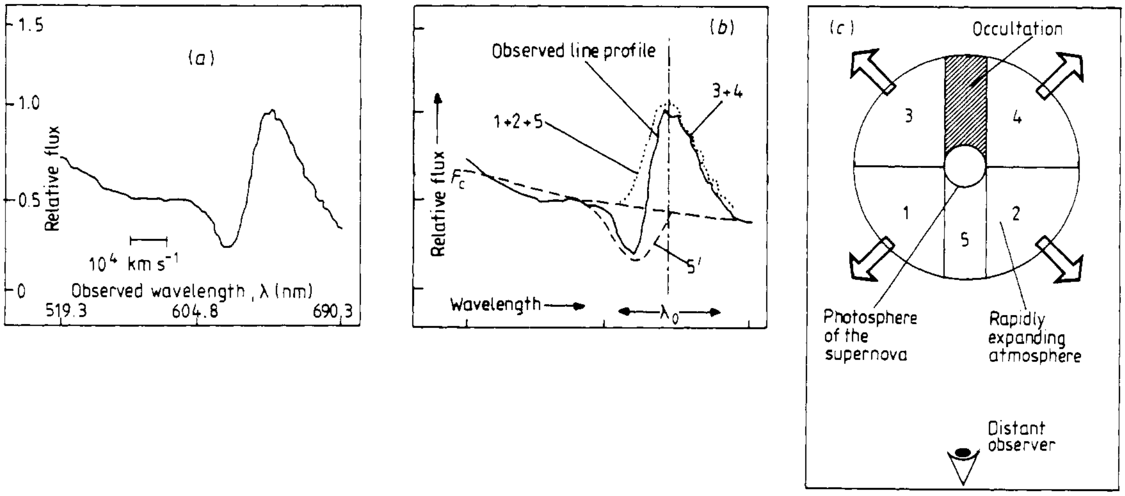
† The metallicity is defined as the mass fraction of all elements heavier than helium.

**Figure 8** Example of a P Cygni line profile in the spectrum of SN 1987A. (*a*) shows part of the spectrum of SN 1987A that was observed on 27 February 1987 by European astronomers using a Boller and Chivens spectrograph attached to the Cassegrain focus of the ESO 3.6 m telescope. The selected spectral range shows a P Cygni profile due to the H$\alpha$ hydrogen Balmer line. This type of profile was observed for the first time in the spectrum of the star P Cygni, an old nova of the XVIIth century, still subject today to important mass losses.

A P Cygni line profile is mainly composed of a central emission component (cf the contributions 1 + 2 + 5 and 3 + 4 in diagram (*b*)) bordered on its violet wing by an absorption component (contribution 5′ in (*b*)). The formation of such a line profile essentially results from a redistribution in wavelength ($\lambda$) of photons emitted in a radiative line transition (cf the rest wavelength $\lambda_0 = 656.3$ for H$\alpha$) because of important Doppler effects caused by the rapid expansion of an envelope around a central object (*c*)).

In this model, line photons emitted by atoms of hydrogen moving towards a distant observer (cf the regions 1, 2 and 5 in (*c*)) give rise to the formation of a blue emission component. Similarly, the emission of photons by atoms which recede from a distant observer (cf the regions 3 and 4 in (*c*)) accounts for the red emission wing. Finally, the absorption of the photospheric continuum of the supernova by atoms located between the stellar disc and the observer (see region 5 in (*c*)) leads to the formation of a blue-shifted absorption component.

We have also indicated with a bar in diagram (*a*) the spectral interval corresponding to a Doppler shift of 10 000 km s$^{-1}$. Dividing by two the Doppler width of the observed profile in (*a*), one may derive that the expansion velocity of the envelope around SN 1987A was greater than 18 000 km s$^{-1}$ on 27 February. A more detailed analysis of such line profiles recorded in the spectrum of SN 1987A should allow one to derive the physical conditions (temperature, density) prevailing in the expanding envelope as well as the type of velocity distribution and the mass of the ejected atmosphere.



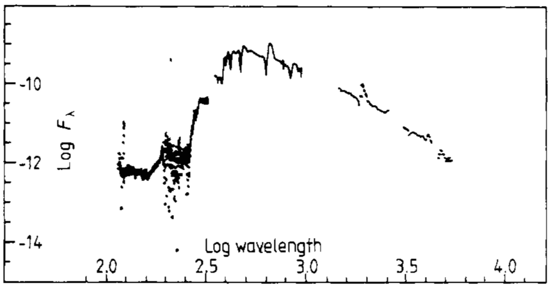


**Figure 9** The composite spectrum of SN 1987A as observed in the ultraviolet with the IUE satellite, in the visual with the ESO 3.6 m telescope and in the infrared with the ESO 1 m telescope plus infrared scanner, on 1 March 1987. Whereas the visual and infrared parts of the spectrum are nicely fitted by a black-body curve at a temperature of 5800 K, there is a significant departure in the ultraviolet due to light absorption by resonance and low excitation lines from singly ionised elements (Fe II, Si II etc). Spectral lines of various elements are seen as peaks or discontinuities in the photospheric continuum. By the end of June 1987, the expanding envelope was getting larger and cooler ($T \sim 5000$ K). There were also signs of an excess of light radiation in the infrared ($T \sim 1200$ K). It seems that this excess is caused by an echo of IR radiation resulting from the reprocessing of the initial burst of visible and UV light by circumstellar dust grains located several light months away from the supernova (see § 7). Note that in this figure both the wavelength scale, originally in nm, and the ordinate axis, originally in units of erg cm $^{-2}$s $^{-1}$nm $^{-1}$, are logarithmic (from Danziger *et al* 1987 *Astron. Astrophys.* **177**, L13).

maximum on 28 February, its brightness dropped slightly but rose again after 5 March during almost three months. The apparent visual magnitude of SN 1987A reached a maximum around 24 May; it was then a bright 2.8 magnitude object in the southern sky. Since the radiative energy powered by the explosive shock wave had been released within the first few days, another source of energy is required in order to produce the increasing light output observed between 5 March and 24 May. Astrophysicists have suggested that the excess of visible light radiation might be cause by the recombination of electrons and ions in the ejecta of the progenitor that are enriched in heavy elements (N, O etc). Others have proposed that a central energy source powered by a rapidly rotating neutron star with a period as small as 10 ms could be responsible for the observed behaviour of the lightcurve. Such a hypothetical pulsar would generate relativistic electrons emitting a powerful synchrotron radiation as they get accelerated in strong magnetic fields. Fast photometry of SN 1987A has already been carried out at various observatories with no positive detection of optical pulses. However, if such an object does really exist, it is likely that the opaque expanding atmosphere will first become transparent to x-ray and radio pulses.

However, it appears more and more likely today that the excess of light radiation is due to the energy liberated by the radioactivity of unstable isotopes synthesised in the early phase of the explosion. It has been estimated that the production of less than $0.1\,M_\odot$ of $^{56}$Ni, decaying to $^{56}$Co which in turn decays to the stable isotope $^{56}$Fe, would suffice to reproduce the observed lightcurve of SN 1987A. This is further supported by the fact that, starting approximately 120 days after the explosion of Sk − 69°202 the luminosity of SN 1987A exhibits an exponential decline with an e-folding time of about 114 days (see figure 7), in good agreement with the 111.3 day e-folding time of $^{56}$Co decaying into $^{56}$Fe.

Since the discovery of the bright supernova, many attempts have been made to detect x- and $\gamma$-rays. Whereas the very first measurements provided negative results, because the x- and $\gamma$-ray opacity of the atmosphere is expected to be high at early times, the GINGA satellite has measured since 15 June 1987 an increasing flux of hard x-rays (10–20 keV) from SN 1987A, reaching a maximum in early September (cf the IAU astronomical circular no 4447). At similar times, detection of $\gamma$-ray line emission at 847 keV and 1238 keV due to the decay of $^{56}$Co has been reported for SN 1987A (cf IAU circulars nos 4510, 4526, 4527). The flux measured for the emission at 847 keV, of the order of $10^{-3}$ photons cm$^{-2}$ s$^{-1}$, is equivalent to the energy liberated by the disintegration of $2.3 \times 10^{-4}\,M_\odot$ of exposed $^{56}$Co, i.e. about 0.3% of the quantity of $^{56}$Co thought to be present in early August 1987 in order to power the observed radiation from SN 1987A. The hard x-rays are similarly thought to originate from the degradation of $\gamma$-rays interacting with supernova ejecta.

Because SN 1987A is a very peculiar type II supernova, it is not easy to predict when we shall be able to see what is left over at the centre of the explosion. The reported detections of neutrinos from the core collapse of Sk − 69°202 probably constitute the best evidence currently available that such a neutron star may exist at the centre of SN 1987A.

## 5. First detection of extrasolar neutrinos

As already mentioned in §3, theoreticians had predicted that a strong emission of neutrinos and antineutrinos should have taken place during the neutronisation ($p + e \rightarrow \nu_e + n$) of the iron core of Sk − 69°202. It was therefore great news when a group of Italo–Soviet physicists reported in the IAU astronomical circulars nos 4323 (28 February 1987) and 4332 (6 March) that a signal from the LMC had been detected on 23 February at the Mont Blanc Neutrino Observatory. The neutrino telescope is located in the Mont Blanc tunnel between France and Italy and is made of a liquid scintillator shielded from the cosmic-ray background by very heavy iron slabs. The signal consisted of five pulses, above the 7 MeV energy threshold over an interval of 7 s starting at

2h52m37s UT. The European physicists estimated that the probability of a random occurrence with SN 1987A was 1 such event per 10 000 years.

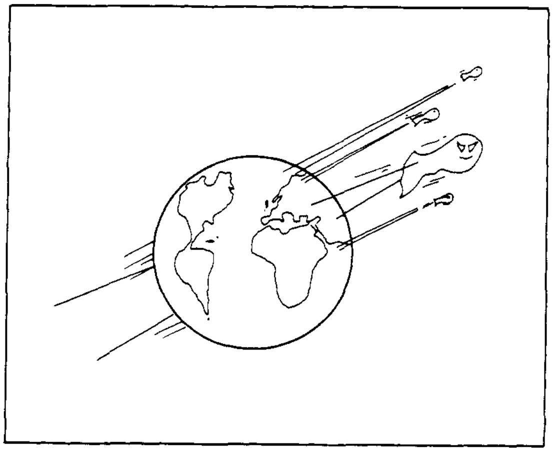
However, a great surprise came when another team of Japano–American particle physicists announced in the IAU astronomical circular no 4338 (10 March) that the Kamiokande-II experiment observed an electron neutrino (antineutrino)† burst from SN 1987A on 23 February at 7h35m35s±1 min; that is more than four hours later than the detection at Mont Blanc. The signal consisted of 11 neutrino (antineutrino)- produced electron (positron) events in an underground water Čerenkov imaging detector located deep in a zinc mine at Kamioka, in Western Japan. The events were observed during an interval of 13 s and the measured electron (positron) energy interval was from the 7.5 MeV threshold to 36 MeV.

Another very important result came from the Irvine–Michigan–Brookhaven (IMB) collaboration who reported in the IAU astronomical circular no 4340 (11 March) that a signal was observed in data from a nuclear decay detector installed in a salt mine under the shore of Lake Erie near Cleveland, Ohio, on 23 February at 7h35m41s UT; i.e. coincident with the Kamiokande-II detection. Eight events were recorded in a 6 s interval, five of them during the first two seconds. The energy of these events was confined to the 20–40 MeV range. The IMB experiment also consists of an imaging water Čerenkov detector (see figure 10). The Kamiokande-II and IMB detections of neutrinos and/or antineutrinos from SN 1987A have further been confirmed by the observation of 5 events above a 5 MeV threshold within a lapse of 9.1 s at the Physics Laboratory of Baksan in the Soviet Union. Though this detection took place some 20 s later than those reported from Kamiokande-II and IMB, Soviet scientists believe that this might be due to a timing problem. Physicists have estimated that the capacity of detecting neutrinos at the Mont Blanc Observatory is about twenty-five times less than that of Kamiokande-II and therefore the non-detection of neutrino events at 7h35m UT with the Mont Blanc experiment is in perfect agreement with the other data. Nevertheless, it cannot be easily understood why the Kamiokande-II and IMB experiments did not confirm the Mont Blanc observation made 4 h 43 min earlier. It cannot, however, be totally ruled out that Sk − 69°202 underwent a two-stage collapse. Two bursts of neutrinos would then have resulted as the progenitor's core first became a neutron star, recollapsing 4 h 35 min later into a black hole.

The neutrino observations reported by Kamiokande-II and IMB indicate that SN 1987A must have radiated approximately $3 \times 10^{46}$ J in the form of three different flavours of neutrinos and antineutrinos. This number is in excellent agreement with the theoretical estimate of the energy that is released from the gravitational binding energy of a 1.6 $M_\odot$ stellar core that is transformed into a neutron star. Let us note here that only about 1% of this released gravitational energy is used for the expansion of the stellar ejecta and that only 0.01% will be radiated in the form of visible and ultraviolet light photons (cf §4).

The neutrino observations of SN 1987A therefore indicate that the current standard model of supernovae explosions involving core collapse is essentially correct. Since the neutrino detections were all reported several hours before the observed rise in light of SN 1987A, these also support the idea that the neutrino particles have necessarily travelled the long distance of 165 000 light years at a speed comparable to that of light. In accordance with special relativity, this implies that the rest mass of the electron neutrino and antineutrino must be extremely small. Using the expected anti-correlation

**Figure 10** On 23 February 1987, around 7h35 min UT, each of us was crossed by approximately one million billion neutrinos and antineutrinos emitted in the explosion of SN 1987A. However, none of us could have noticed it because the probability of interaction of one such particle with the atomic nuclei of our human bodies is exceedingly small. It has been estimated that only one among all neutrinos that have passed through more than one thousand people on Earth had a chance of interaction. Most of these ghostly particles have literally crossed the Earth without noticing its presence. Therefore, neutrino observatories consist of enormous tanks of purified water or liquid scintillator surrounded by thousands of very sensitive detectors of light. These unusual telescopes have been constructed deep in mines to shield them from any other radiation but that of neutrinos. For a terrestrial observer, the flux of neutrinos from SN 1987A was typically $10^{10}$ electron antineutrinos per $cm^2$ of which only about twenty have been detected by neutrino observatories.



---

† It is believed that there exist three different flavours of neutrinos (electron, muon and tauon) and that each type has its antiparticle. At the energies of supernovae explosions, the terrestrial detectors are however more sensitive to electron antineutrinos than to electron neutrinos, etc.

between the arrival time and energy of the detected neutrinos, upper limits of about 15 eV have been derived by various authors for the rest mass of the electron neutrino and antineutrino[†]. Let us remark that a zero rest mass is also consistent with the observations. Furthermore, one can also certify that, in the reference frame of a terrestrial observer, the neutrino lifetime is greater than 165 000 y. In consequence, the deficiency of the flux of solar neutrinos observed on Earth cannot be caused by the decay of these particles on their way from the Sun to the Earth.

We conclude that the detection of neutrinos from SN 1987A constitutes an unprecedented achievement in our understanding of particle physics and supernovae explosions. This great success has already led to decisions to develop in the near future super-observatories for neutrinos. Neutrino astronomy was really born on 23 February 1987.

## 6. SN 1987A as a light probe of the intervening medium

With a record visual magnitude of $m_V \sim 2.8$, SN 1987A became the brightest object in the LMC. It was over 10 000 times more luminous than the brightest stars in the Clouds and one can even state that SN 1987A is the brightest object that has ever been observed so near the doorstep of our Galaxy. It therefore turned out to be an ideal light source to probe the physical and dynamical structures of the interstellar and intergalactic media located along a distance as large as 165 000 light years. An impressive number of narrow absorption lines formed in the interstellar medium of the LMC and of the Milky Way, in the halo of our Galaxy, and in clouds of the intergalactic space have been detected in high resolution spectra of SN 1987A. These data were obtained with the IUE satellite and with the Coudé Echelle Spectrometer (CES) connected to the 1.4 m Coudé Auxiliary Telescope (CAT) of ESO. Six components of a magnesium line (Mg I) and others due to nickel (Ni II), zinc (Zn II) and silicon (Si IV) have been identified in the ultraviolet spectrum of SN 1987A. No less than 24 narrow absorption components due to a calcium line (Ca II), 13 components associated with sodium (Na I) and 2 with potassium (K I) have been measured in the optical spectrum of SN 1987A (see figure 11). These observations seem to indicate that a real bridge of matter exists between our Galaxy and the LMC. It is also possible that some of the narrow absorption lines are associated with matter expelled from Sk − 69°202 during a phase of rapid mass loss, prior to the supernova explosion. Finally, the brightness of SN 1987A has allowed astrophysicists to set a very secure upper limit to the concentration of the tracer isotope $^7$Li in the interstellar gas. This result is of great interest since the observed abundance of $^7$Li does provide an important constraint on the theories of primordial nucleosynthesis.

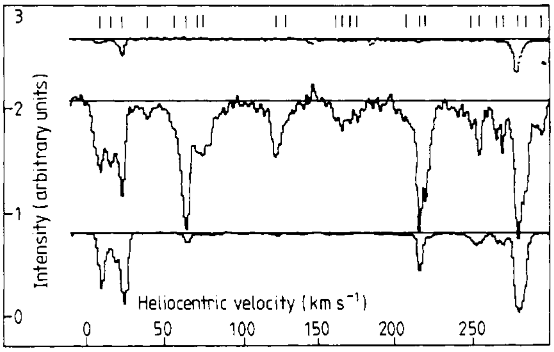


**Figure 11** Interstellar lines in the spectrum of SN 1987A. Very high-resolution spectra of SN 1987A have revealed the presence of numerous interstellar and intergalactic narrow absorption lines due to potassium (K I, upper spectrum), calcium (Ca II, middle) and sodium (Na I, lower). Marks at the top show the locations of the 24 interstellar absorption components detected in Ca II. Their corresponding velocities, as measured along the line of sight, may be derived from the bottom scale. All these narrow lines are due to the absorption of the supernova light when the latter passes through interstellar clouds on its way to us. Depending on the velocity of the cloud, the position of the line appears to be shifted differently in the spectrum because of the Doppler effect. The lines at low velocities (to the left) correspond to clouds in the Milky Way; those to the right, above 250 km s$^{-1}$, to clouds in the LMC. The lines in between are thought to originate in a bridge of matter between our Galaxy and the LMC. These spectra were obtained with the CES Reticon spectrograph fed by the 1.4 m ESO CAT telescope (from Vidal-Madjar *et al* 1987 *Astron. Astrophys.* **177** L17).

## 7. Latest news from SN 1987A

Adopting a distance to SN 1987A of 165 000 light years and a conservative velocity of 10 000 km s$^{-1}$ for the expansion of its stellar ejecta, it is easy to estimate that, three months after the explosion, the supernova envelope should have been observable from Earth under an angular diameter greater than 20 milliarcsec.

It is remarkable that such a small nebulosity, corresponding to a linear diameter of 1000 AU (astronomical unit) at the source, has been successfully measured by means of optical interferometry (see the IAU astronomical circular no 4457).

Furthermore, another interesting result has been announced in the IAU astronomical circular no 4382. Indeed, high-angular-resolution speckle observations of SN 1987A at the end of March have shown a bright unresolved feature at 57 milliarcsec

---

[†] Similar arguments have led particle physicists to state that the electric charge of the detected neutrinos must be smaller than about $10^{-17}$ times the charge of the electron.

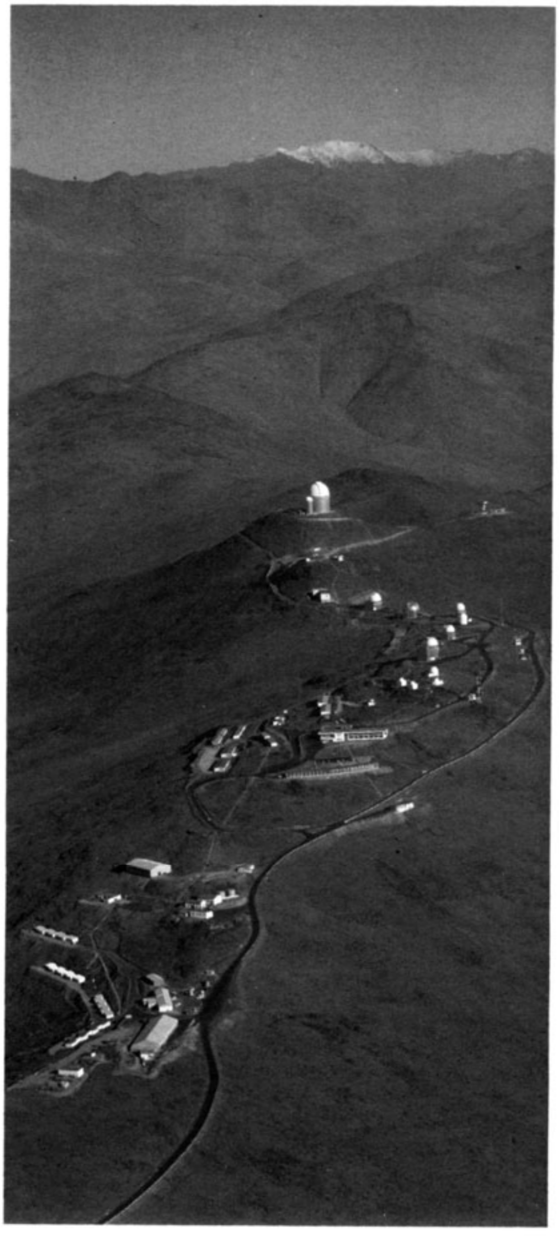
south of the supernova. This feature appeared to be 2.7 magnitudes fainter than SN 1987A in a narrow bandpass centred on the Hα hydrogen Balmer line. The nature of this bright object ($m_{H\alpha}$~6.8) remains unknown and it has therefore been named the 'mystery spot'. Among the various suggested explanations, some astrophysicists have proposed that the 'mystery spot' may reflect the interaction of the early UV–optical burst of the supernova (see below) with a nearby dense and cool protostellar cloud, or be associated with the impact of relativistic jets formed during the collapse of the progenitor of SN 1987A. Whichever is the correct interpretation, there is no doubt that the 'mystery spot' must be physically related to the SN 1987A phenomenon.

Though a prompt but weak radio burst was detected at around 1 GHz during the first days after the explosion (cf IAU astronomical circular no 4321), observations carried out after July 1987 with a very sensitive 275 km interferometer in Australia have failed to detect any significant radio signal from SN 1987A (cf IAU astronomical circular no 4432). The radio burst detected around 25 February was probably due to synchrotron emission from a thin shell of circumstellar material that interacted with the outgoing shock wave. The weakness of that observed radio emission supports the idea that the progenitor was not surrounded by a very dense shell of radio-opaque gas, as might have been expected for a red supergiant losing mass. Furthermore, although type II supernovae originating from red supergiant progenitors generally become luminous radio emitters several months after explosion, it is believed that this should happen for SN 1987A only about 30 y from now when the shock wave will reach the red giant wind shell at a distance of $\sim 10^{16}$ m.

From early July onwards, astrophysicists observing with the IUE satellite have reported the appearance of narrow emission lines in the ultraviolet spectrum of SN 1987A (cf IAU astronomical circulars nos 4410 and 4435). They proposed that these spectral changes were due to the thinning out of the ejecta that are exposing the innermost and hottest layers. In this context, it is interesting to note that polarisation variations of the optical light of SN 1987A, reaching up to 3–4%, have been observed, suggesting some patchiness in the expanding shell. The IUE astrophysicists have also proposed, as an alternative, that the presence of narrow lines apparently emitted by a nitrogen-enriched gas were arising from circumstellar material being photoionised by the strong UV–optical burst ($\sim 10^{41}$ J) that should have developed when the shock generated by the core collapse reached the photosphere of the progenitor.

Because of the multitude of predictions that have been made for the future evolution of SN 1987A, it has become very difficult to foresee precisely how the supernova will develop in the near future. Numerous sensitive x-ray and $\gamma$-ray detectors on board satellites, balloons and planned rocket flights as well as ground-based optical, infrared and radio telescopes spread all over the southern hemisphere are on stand-by waiting for the moment when the shock wave collides with the dense regions of the circumstellar material or when the expanding atmosphere gets sufficiently transparent to unveil the characteristics of the compact object left over at the centre of the explosion. Whereas there is no doubt that the discovery and observational study of SN

**Figure 12** Aerial view of the European Southern Observatory. (*Photograph courtesy ESO.*)



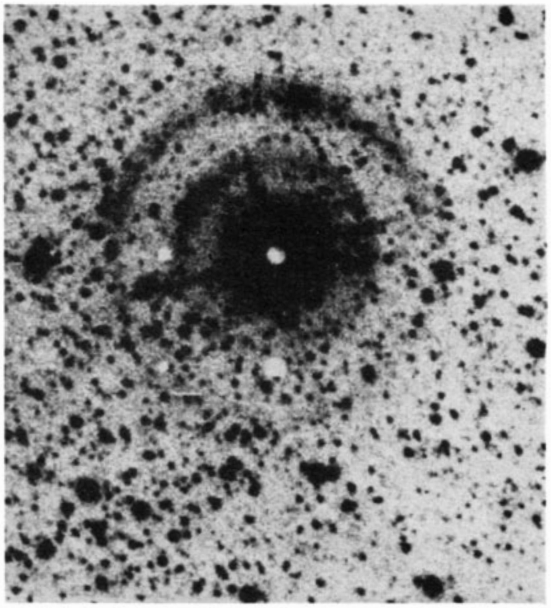


**Figure 13** Light echoes from Supernova 1987A. A double light echo from SN 1987A in the LMC was observed on 13 February 1988 with the ESO 3.6 m telescope and the EFOSC instrument (observer: M Rosa). The light echoes are reflections in interstellar clouds in the LMC of the light from SN 1987A and are seen as two concentric rings around the overexposed image of the supernova itself. The outer ring, which has a radius of 51″, is strongest towards North, but can be followed all the way round. The inner ring has a radius of 32″. Note that the 'cross' extending from the image of the supernova is an artefact from the telescope optics. In order to see the very faint light echoes (about 10 000 times fainter than SN 1987A), the light from the supernova was dimmed by a small obscuring disc (i.e. a coronograph), here seen as a lighter spot at the centre of the image. (The shadows of three other discs are also seen). This computer-enhanced photo was obtained by a CCD detector behind a narrow optical filter at a wavelength near 470 nm, thereby suppressing the light from interstellar nebulae in the LMC in order to improve the visibility of light echoes. For the same reason, the photo is here reproduced as a negative (black stars on a light sky). (*Figure caption and photograph courtesy ESO.*)

1987A have already contributed very much to our understanding of the final evolutionary stage of a short-lived massive star, it is certain now that future observations will make this achievement even greater.

**Acknowledgments**
It is a pleasure to thank Myriam Macours-Houssonloge for typing this article, Armand Kransvelt for the drawings, Carlo Denis for keeping updated the lightcurve of SN 1987A in his personal Macintosh Plus Adoré, and Jean-Pierre Swings and Martin Huber for their comments on the manuscript.

## Appendix: The European Southern Observatory

ESO, an intergovernmental European organisation, was founded in 1962 to establish and operate an astronomical observatory in the southern hemisphere and to promote and organise cooperation in astronomical research in Europe. Its member states are Belgium, Denmark, France, the Federal Republic of Germany, Italy, the Netherlands, Sweden and Switzerland. The observatory is located in Chile, on La Silla, a mountain of 2400 m altitude, 600 km north of Santiago. Thirteen telescopes are at present in operation and the largest instrument with a diameter of 3.6 m, is one of the most powerful telescopes in the world (see figure 12). Moreover, a 15 m submillimetre telescope entered into operation in early 1987 and a 3.5 m New Technology Telescope (NTT) should be operational in late 1988. A Very Large Telescope (VLT), consisting of four 8 m telescopes (equivalent aperture 16 m) is planned for the 1990s. Six hundred astrophysicists make proposals each year for the use of the telescopes at La Silla.

At the European headquarters near Munich, technical development programmes are carried out to provide the La Silla Observatory with the newest instruments. While the design of instruments is made at ESO, their construction is largely contracted to European industry. Also in the headquarters are the scientific and administrative centres of ESO, where extensive facilities enable European scientists to analyse their data. In addition, the European Space Agency (ESA) and ESO jointly operate the Space Telescope European Coordinating Facility. In Europe, ESO employs about 150 international staff members, fellows and associates; at La Silla about 40 and, in addition, 150 local staff members.

## Note added in proof

One of the most spectacular astronomical observations that has recently been reported is the detection of light echoes from SN 1987A (see the IAU circulars nos 4561, 4564 and 4567). These consist of luminous rings centred on SN 1987A with angular radii of about 32″ and 51″ and typical thicknesses of 5–10″ (see figure 13). These arise from the reflection towards the observer of part of the supernova light by interstellar dust clouds surrounding the exploded star. The patchy distribution of clouds in space directly accounts for the non-uniform brightness of the luminous rings. Low-dispersion spectra of the brightest knots in the rings essentially confirm that they originate from the light of SN 1987A emitted at earlier epochs. Combining this chronometric information with the observed steady increase (approximately 2″ per month) of the ring diameters, it will become possible to map the three-dimensional distribution of the interstellar dust around the bright supernova.