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SUPERNOVA 1987a IN THE LARGE MAGELLANIC CLOUD: AN OBSERVATIONAL OVERVIEW

Jean Surdej

Institut d'Astrophysique, Université de Liège

Abstract

Since the discovery, last February 24th, of the explosion of a bright supernova in the Large Magellanic Cloud, a real euphory 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 fifty years and it has provided particle physicists with the first detection of extragalactic neutrinos that were 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 recqncile the multi-wavelength observations (visible, I-R, radio, X-ray, γ-ray) 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.

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 lapse of 1000 years, approximately four galactic supernovae should become visible to a naked eye terrestrial 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 *n*° 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 Figs. 1 and 2) during the night of 23-24 February.

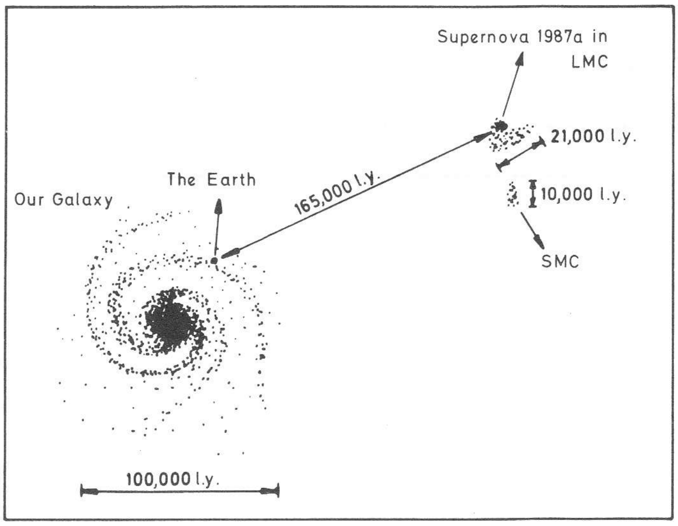


Figure 1: Schematic position of supernova 1987a in the Large Magellanic Cloud (LMC)

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 apparition of the Homo Sapiens on Earth. Both the LMC and SMC are naked eye visible galaxies in the sky of the southern hemisphere.

Three independent discoveries of the first supernova of the year 1987 (therefore designated SN 1987a) are reported in the circular n^{o} 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 5.5h UT (Universal Time) on a 3hr-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 (amateur astronomer in Nelson, New Zealand) at 4.8h and 7.9h UT, respectively. The apparition of SN 1987a constitutes a very 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 383 years ago appeared in the constellation Ophiuchus, towards the center of our Galaxy, at an approximate distance of 30,000 light years. Observations of SN 1604 have been described by Kepler and other contemporary astronomers who did not dispose yet at that time of any telescope.

Figure 2: The Large Magellanic Cloud (LMC) and SN 1987a

This picture (originally in color) of the LMC was obtained on 25 February 1987 at 1.0h 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 6X6 cm Agfachrome 1000 RS emulsion. The exposure time was 20 min. The supernova is clearly seen at a magnitude $m_V \sim 4.5$ to the left of the centre and above the LMC main body, as the lower right of the two bright objects. The second bright and diffuse object is the Tarentula nebula, a giant region of hydrogen that is ionized by a cluster of stars in formation. (ESO Courtesy)

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 Fig. 2. Fig. 3 illustrates with more details 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 the appendix at the end) in Chile.

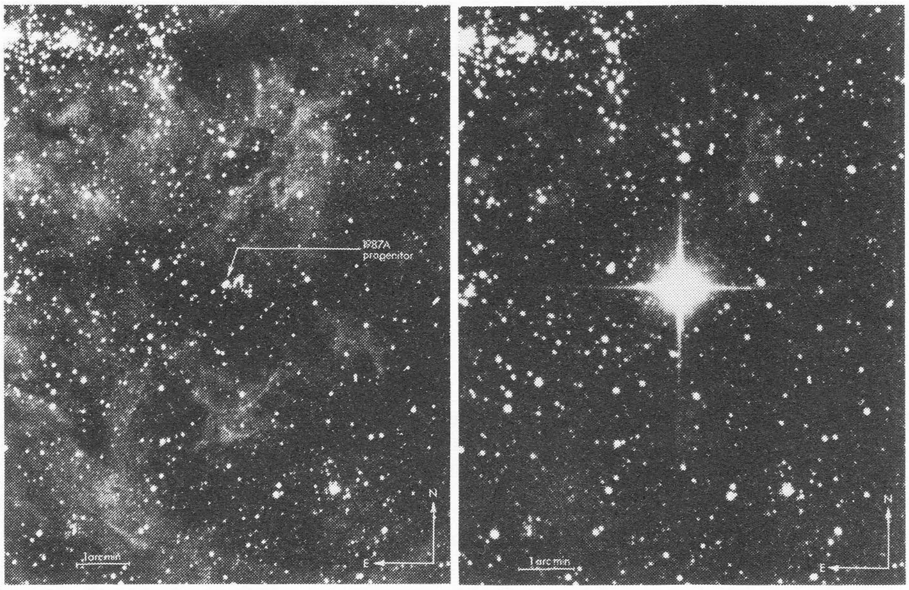


Figure 3: Immediate surroundings of SN 1987a before and after the explosion

This pair of photographic plates obtained with the ESO schmidt telescope illustrates the sudden apparition 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 side picture. Between the two epochs when these photographs were made, the brightness of SN 1987a has increased by more than a factor 1500. It has also been possible to find that this abrupt change in luminosity took place in less than 24 hours. Note that the cross seen around the bright star image on the right hand side picture arises because of diffraction of light from the supernova by the plateholder support inside the Schmidt telescope. (ESO Courtesy)

2. The progenitor of SN 1987a

We are very fortunate that SN 1987a exploded in the LMC. Indeed, 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/sec, are located at a same distance d = 165,000 ± 10,000 light years, we conclude that SN 1987a is located at that same distance of our Solar System.

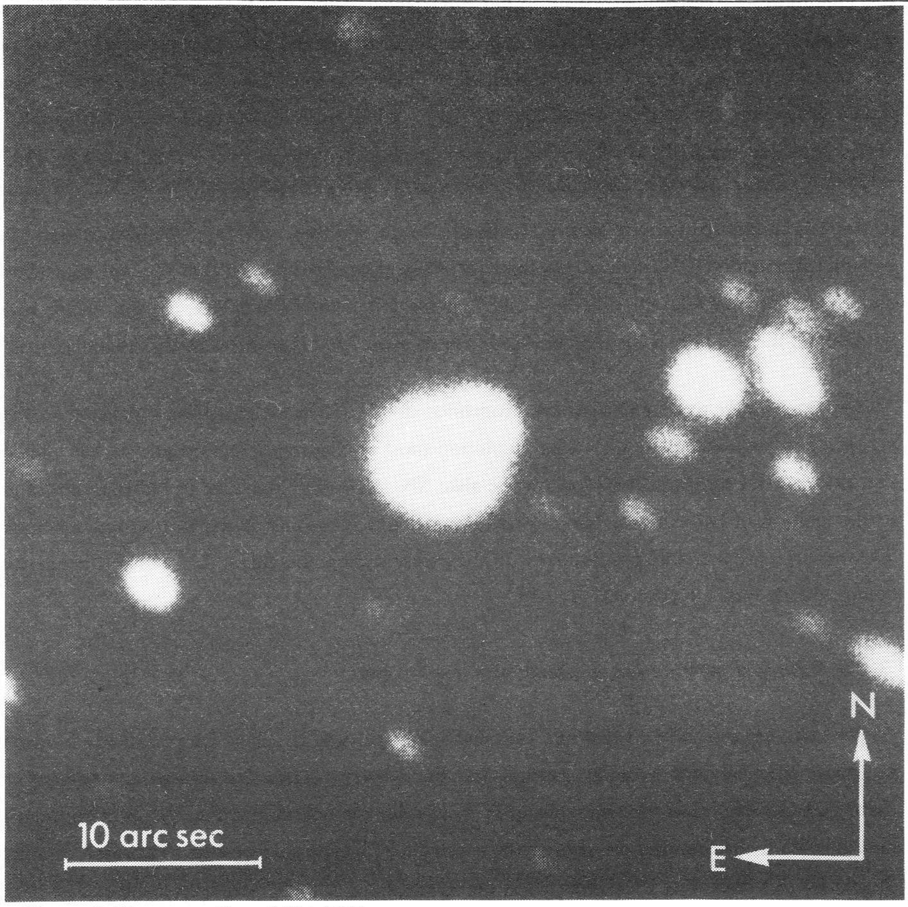


Figure 4: The progenitor of SN 1987a

The star that exploded on 23 February 1987 in the LMC is well identified on this photograph obtained in red light with the ESO 3.6m 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-1970's allowed to classify it as of spectral type B3I, that is a star having an effective temperature $T_{eff} \sim 15{,}000°K$, a radius $R \sim 3 10^{12}$ cm, a luminosity $L \sim 1.3 10^5 L_{\odot}$ and a mass $M \sim 15 M_{\odot}$. 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 2.6″. A third star ($m_V \sim 15.7$) was also found to be present at only 1.4″ 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 optimal optical adjustment. (ESO Courtesy)

We can therefore plot in a diagram representing the absolute magnitude versus temperature (or spectral class), also known as the famous Hertzsprung-Russel diagram, each individual star of the LMC, including SN 1987a and its progenitor. We recall that in such an H-R diagram, the stars are not distributed at random but follow distinct evolutionary tracks that are just a function of the initial conditions (mass, chemical composition, etc.). If we could identify the progenitor of SN 1987a, we would therefore have a very unique opportunity to understand what the late stages of evolution of a massive star are. 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 2.6″ and 1.4″ (see Fig. 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 of $Sk\ -69°202$ are still there and that the latter has in fact disappeared. After several hesitations, there is now a general consensus that it must have been $Sk\ -69°202$ that exploded.

However, nobody really expected the progenitor of SN 1987a to be a blue supergiant. Indeed, according to standard models of stellar evolution most of theoretical astrophysicists had predicted that massive star progenitors of supernovae alike 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 confronted 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

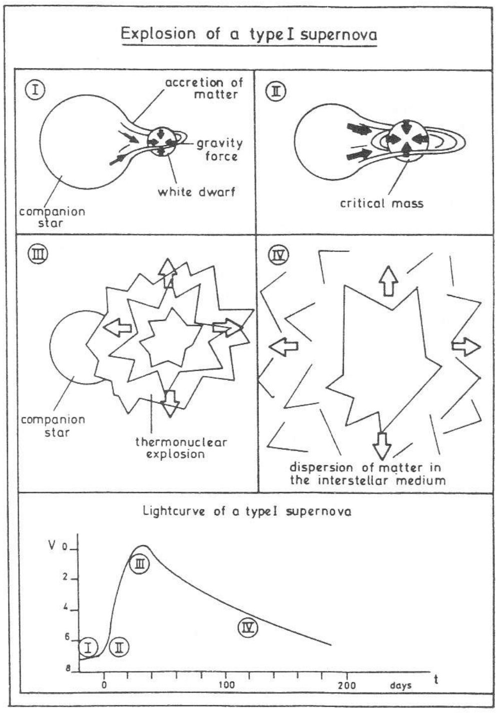
Supernovae are generally divided into two main classes, I and II. Type I supernovae are observed in spiral, elliptical and irregular galaxies (cf. the LMC). They are thought to relate to the thermonuclear explosion of a white dwarf in a close binary system (see Fig. 5). It is important to note that no 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 Fig. 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. Fig. 7 illustrates the visual lightcurve of SN 1987a during approximately half a year since its discovery.

Figure 5: The different phases in a type I supernova explosion

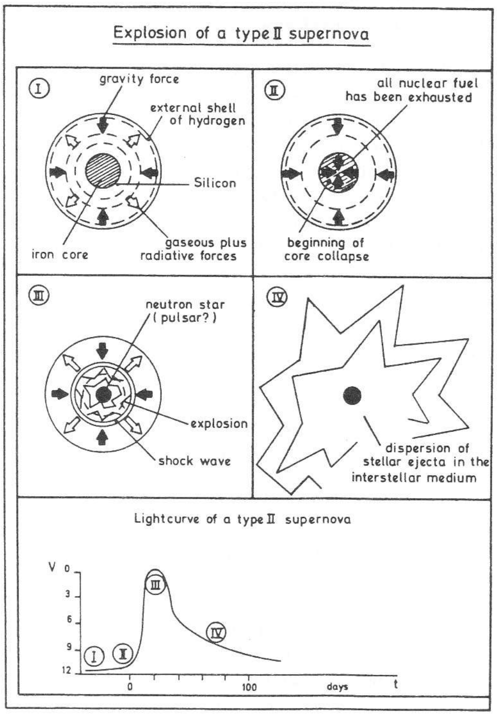
Astrophysicists believe that type I events relate to close binary systems in which a white dwarf gradually strips off matter from the giant atmosphere of a companion star I . A white dwarf is a fossil star whose radius is comparable to that of the Earth and its mass similar to that of the Sun. There results extremely high densities, of the order of 1 ton per cm^3. It is the electron degeneracy pressure which prevents such an object to be further compressed. However, when the mass of the white dwarf reaches the critical value of about 1.4 $M_{\odot}$, the whole star collapses II igniting its core in a thermonuclear explosion III which completely disrupts the white dwarf and disperses it in the surrounding interstellar medium IV . 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.



From these as well as from additional published data, the following anomalies are noted:

(i) Following the core collapse that occured on 23 February at 7h35m UT (a neutrino signal was detected at that time), the rise in brightness of SN 1987a has been extremely steep. A first visual light maximum was already 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 7 times fainter than that expected from a standard type II supernova. Furthermore, the ultraviolet radiation of SN 1987a has decreased by more than a factor 1000 in less than three days; during that time, the object was brightening in the red and infrared.

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 made of a central iron core surrounded by various shells of elements whose atomic weight decreases outwards (silicon, ..., aluminium, ..., hydrogen) I . 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 totally exhausted and the star cannot support any longer its own weight. In less than a second, the stellar core collapses II. 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 center. 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 kilometers but its volume density is as high as ten million tons per cubic centimeter. Due to the strong mutual repulsion of the neutrons, this star cannot be further compressed [for progenitor masses greater than 30 $M_{\odot}$, the on-going implosion would lead to the formation of a black hole]. A tremendous shock wave rebounds then from the neutron core in a huge explosion that sweeps out all external shells of stellar material III . Expansion velocities up to 30,000 km/sec have been measured from the 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 synthesized. It is even generally thought that all such heavy elements found on Earth must have been synthesized 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 IV . The absolute visual magnitude characterizing the light maximum of a type II supernova is about -16.3, i.e. ~ 10 times less luminous than a type I maximum. The post-maximum decline of a type II lightcurve is however not so steep.

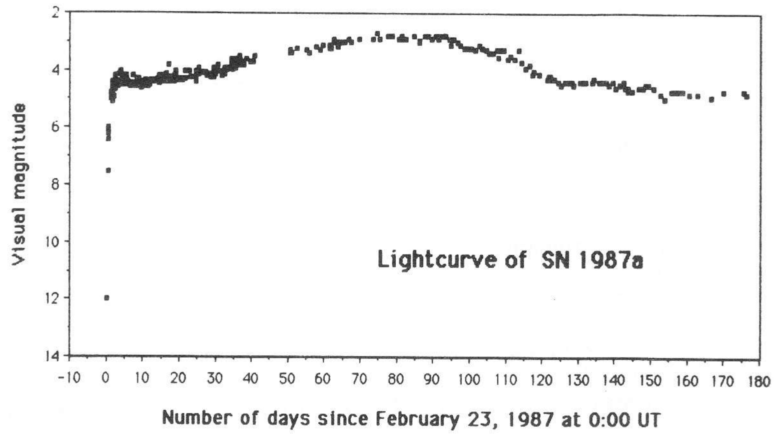


Figure 7: Lightcurve of SN 1987a

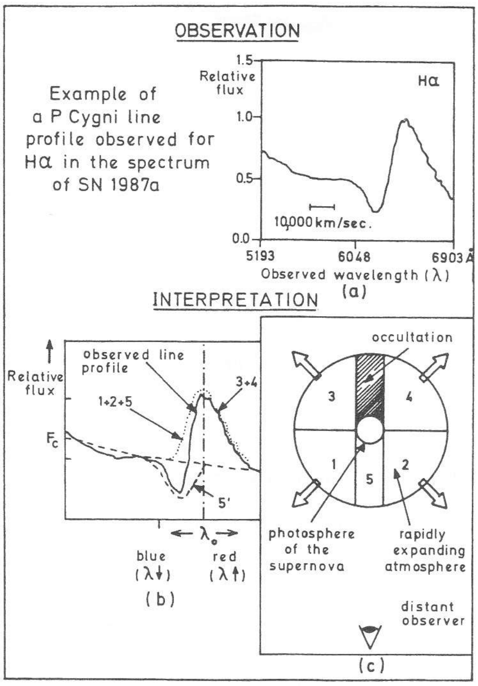
This figure represents the apparent visual magnitude of the supernova against the observing time. Most of the measurements were taken from the IAU astronomical circulars published between 24 February and 17 August 1987.

(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 Fig. 8). As mentioned previously, unusually large expansion velocities of stellar material up to 30,000 km/sec were measured.

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 a larger fraction of the energy released by the explosion to go into expansion of its atmosphere, 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 $\sim 10^{51}$ erg, whereas the light output radiated so far has been estimated to be $\sim 10^{48}$ erg in the visible and $\sim 10^{47}$ erg 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 Fig. 9).

Figure 8: Example of a P Cygni line profile in the spectrum of SN 1987a

We have reproduced in this diagram (a) 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 3.6m telescope. The selected spectral range shows a P Cygni profile due to the $H\alpha$ hydrogen Balmer line. This type of profile has been 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 (λ) of photons emitted in a radiative line transition (cf. the rest wavelength λ_o = 6563 Å for $H\alpha$) because of important Doppler effects caused by the rapid expansion of an envelope around a central object (see diagram (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 component. Finally, the absorption of the photospheric continuum of the supernova by atoms located between the stellar disk and the observer (see region 5 in (c)) leads to the formation of a blueshifted absorption component.

We have also indicated with a bar in diagram (a) the spectral interval corresponding to a Doppler shift of 10,000 km/sec. 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/sec 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.

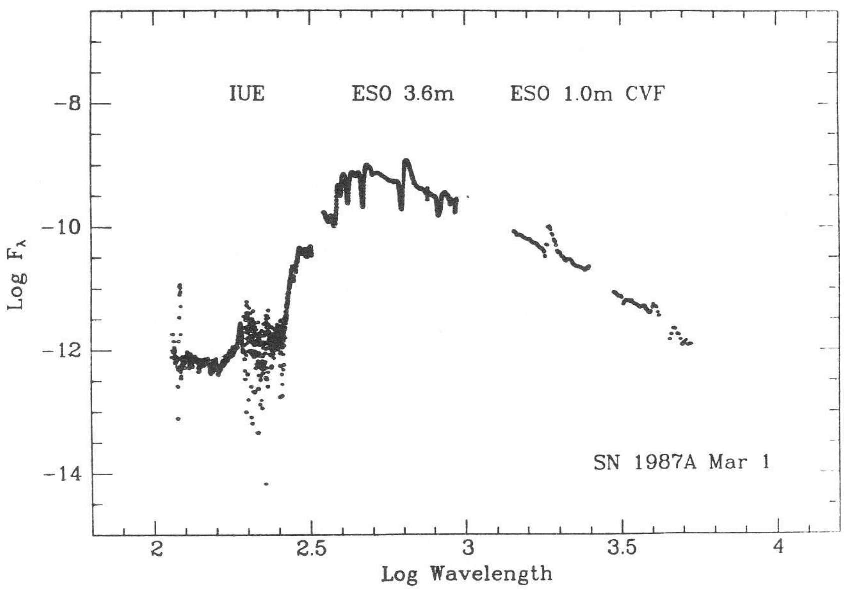


Figure 9: The composite spectrum of SN 1987a

This figure illustrates the composite spectrum of SN 1987a as observed in the far ultraviolet with the IUE satellite, in the visual with the ESO 3.6m telescope and in the infrared with the ESO 1m 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 ionized elements (FeII, SiII, 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 far infrared ($T \sim 1200°K$). It is not clear whether this IR excess is due to free-free emission from an ionized envelope or to an infrared echo resulting from the reprocessing of the initial burst of optical and UV light by circumstellar dust grains located several light months away from the supernova. Note that in this figure both the wavelength scale, in nm, and the ordinate axis, in units of $ergcm^{-2}s^{-1}nm^{-1}$, are logarithmic (from a paper by Danziger et al. 1987, Astronomy and Astrophysics, 177, L13).

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 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 very plausible, on observational grounds, that $Sk - 69°202$ has become 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 reasonable mass loss and a low metallicity, such as the one characterizing the LMC (about one quarter of the solar value), naturally lead to a blue supergiant as the progenitor of a type II supernova. 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 maximum on 28 February, its brightness dropped slightly but rose again after 5 March during almost three months. The brightest apparent visual magnitude of SN 1987a reached a maximum around 24 May; it was then a bright 2.8 mag. object in the southern sky. Since the radiative energy powered by the explosive shock wave has 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 proposed that this excess of light radiation could be due to the energy liberated by the radioactivity of unstable isotopes synthesized in the early phase of the explosion. It has been estimated that the production of less than 0.1 $M_{\odot}$ of Ni^{56}, decaying to Co^{56} which in turn decays to the stable isotope Fe^{56} , would suffice to reproduce the observed lightcurve of SN 1987a. This in turn is found to be in good agreement with current models of explosive nucleosynthesis. γ -ray astronomers are constantly monitoring SN 1987a with the aim of detecting the first escaped energetic γ-rays that should accompany the decays of Ni^{56} and Co^{56} . Until now, all attempts have failed but this is not surprising since the γ-ray opacity of the supernova atmosphere is expected to be high at early times. Others have suggested that the excess of visible light radiation might be caused by the recombination of electrons and ions in the ejecta of the progenitor that are enriched in heavy elements (N, O, etc.). Finally, it has also been proposed that a central energy source powered by a rapidly rotating neutron star with a period as small as about 10 milliseconds could be responsible for the observed behaviour of the lightcurve. Such an 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 very likely that the opaque expanding atmosphere will first become transparent to X-ray and radio pulses. 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 presently available evidence that such a neutron star may exist in the centre of SN 1987a.

5. First detection of extra-solar neutrinos

As already mentioned in Section 3, theoreticians had predicted that a strong emission of neutrinos and antineutrinos should have taken place during the neutronization ($p + e \rightarrow \nu_e + n$) of the iron core of $Sk - 69°202$. It was therefore a great news when a group of italo-sovietic physicists reported in the IAU astronomical circulars $n°$ 4323 (28 February 1987) and $n°$ 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 with very heavy iron slabs from the cosmic ray background. The signal consisted of five pulses, above the 7 MeV energy threshold over an interval of 7 seconds starting at 2h52m37s UT. The european physicists estimated that the probability of a random occurence 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 *n*° 4338 (10 March) that the Kamiokande-II experiment observed an electron neutrino (anti-neutrino) [1] 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 (anti-neutrino)- produced electron (positron) events in an underground water Cerenkov imaging detector located deep in a zinc mine at Kamioka, in Western Japan. The events were observed during an interval of 13 seconds 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 *n*° 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 seconds interval, five of them during the first two seconds. The energy of these events was confined in the 20-40 MeV range. The IMB experiment also consists of an imaging water Cerenkov detector (see Fig. 10). The Kamiokande-II and IMB detections of neutrinos and/or anti-neutrinos from SN 1987a have further been confirmed by the observation of 5 events above a 5 MeV threshold within a lapse of 9.1 seconds at the Physics Laboratory of Baksan in Soviet Union. Though this detection took place some 20 seconds later than those reported in 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 four hours and 43 minutes earlier.

The neutrino observations reported by Kamiokande-II and IMB indicate that SN 1987a must have radiated approximately $3\ 10^{53}$ erg in the form of three different flavors of neutrinos and anti-neutrinos. 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 percent of this released gravitational energy is used for the expansion of the stellar ejecta and that only 0.01 percent will be radiated in the form of visible and ultraviolet light photons (cf. Section 4).

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[1] It is believed that there exists three different flavors of neutrinos (electron, muon and tauon) and that each type has an antiparticle. At the energies of supernova explosions, the terrestrial detectors are however more sensitive to electron antineutrinos, then to electron neutrinos, a.s.o.

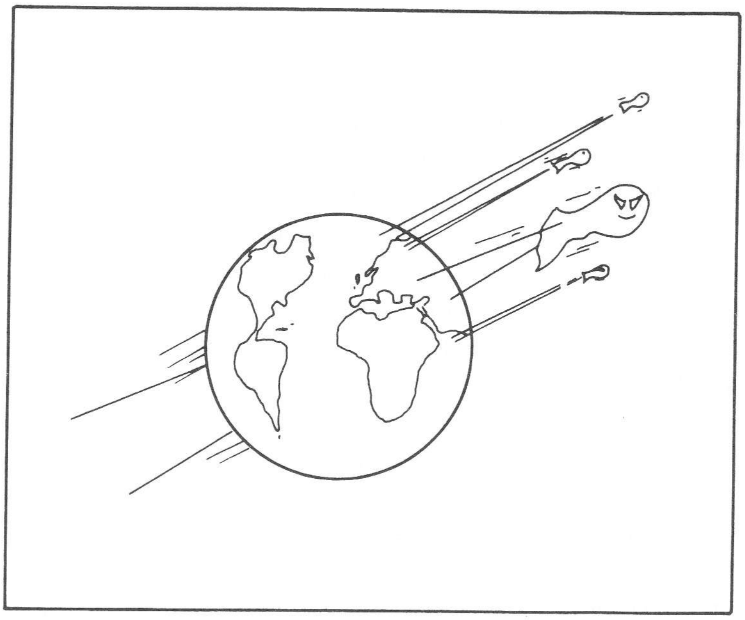

Figure 10: Ghost elementary particles called "neutrinos"

On 23 February 1987, around 7h35m UT, each of us has been crossed by approximately one million of 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 a 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 ghost particles have literally crossed the Earth without noticing its presence. Therefore, Neutrino Observatories consisting of enormous tanks of purified water or liquid scintillator surrounded by thousands of very sensitive detectors of light have been constructed deep in mines. For a terrestrial observer, the flux of neutrinos from SN 1987a was typically 10^{10} electron antineutrinos per cm^2 of which only about two tens have been detected by Neutrino Observatories.

The neutrino observations of SN 1987a therefore indicate that the current standard model of supernova 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 the special relativity of Einstein, this implies that the rest mass of the electron neutrino and antineutrino must be extremely small. Using the expected anti-correlation between the arrival time and energy of the detected neutrinos, upper limits of about 15 eV have been derived for the rest mass of the electron neutrino and antineutrino[2] . 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 years. As a consequence, it results that 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 supernova explosions. This great success has already led to decisions of building up in the near future super-observatories of neutrinos. Neutrino astronomy was really born on 23 February 1987.

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

With a visual magnitude record 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 International Ultraviolet Explorer (IUE) satellite and with the Coudé Echelle Spectrometer (CES) at the 1.4m Coudé Auxiliary Telescope (CAT) of ESO. Six multiple components of a Magnesium line (MgI) and others due to Nickel (NiII), Zinc (ZnII) and Silicon (SiIV) have been identified in the ultraviolet spectrum of SN 1987a. No less than 24 narrow absorption components due to a calcium line (CaII), 13 components associated with Sodium (NaI) and 2 with Potassium (KI) have been measured in the optical spectrum of SN 1987a (see Fig. 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 on the concentration of the tracer isotope Li^7 in the interstellar gas. This result is of great interest since the observed abundance of Li^7 does provide an important constraint on the theories of primordial nucleosynthesis.

7. Latest news from SN 1987a

Adopting a distance to SN 1987a of 165,000 light years and an average velocity of 20,000 km/sec for the expansion of its stellar ejecta, it is easy to estimate that within half a year after the explosion the hydrogen envelope should become observable from Earth under an angular diameter of 80 milliarcsec.

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[2] 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

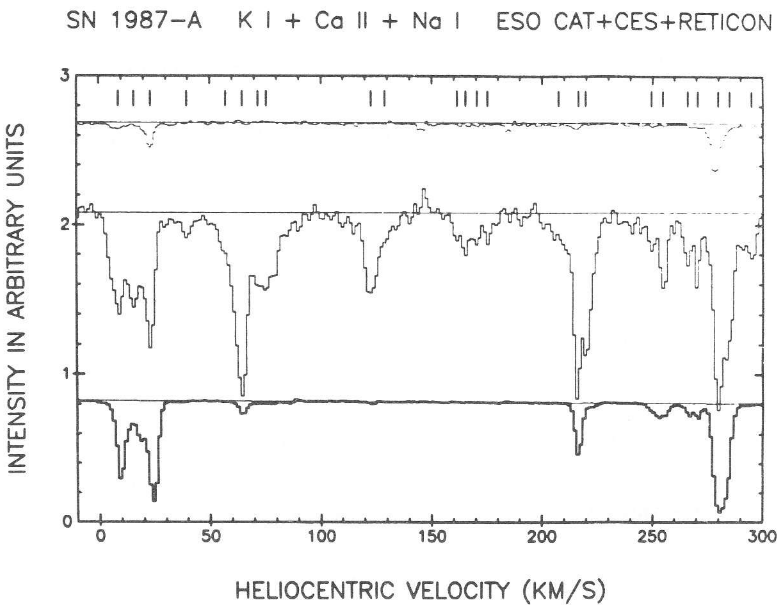

Figure 11: Interstellar lines in the spectrum of SN 1987a

Very high resolution spectra of SN 1987a have revealed the presence of numerous interstellar and intergalactic narrow absorption lines due to Potassium (KI; upper spectrum), Calcium (CaII; middle) and Sodium (NaI; lower). At the top, tick marks show the locations of the 24 interstellar absorption components detected in CaII. Their corresponding velocities may be derived from the bottom scale. All those 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/sec, 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 1.4m ESO CAT telescope (from a paper by Vidal-Madjar et al. 1987, Astronomy and Astrophysics, 177, L17).

Resolving such small separations may only be achieved by means of optical speckle interferometry or radio interferometric techniques.

Although, up to now, optical astronomers have failed to resolve a nebular disk around SN 1987a, a very interesting result has been announced in the IAU astronomical circular $n°$ 4382. Indeed, high angular resolution speckle observations of SN 1987a have shown at the end of March a bright unresolved feature at 57 milliarcsec south of the supernova. This feature appears to be 2.7 mag. fainter than SN 1987a in a narrow bandpass centered on the $H\alpha$ 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". There is however no doubt that it must be physically related to the SN 1987a phenomenon.

Though a prompt but weak radio burst was detected at around 1GHz during the first days after the explosion (cf. IAU astronomical circular *n*° 4321), observations carried out after July with a very sensitive 275 km interferometer in Australia have failed to detect any significant radio signal from SN 1987a (cf. IAU astronomical circular *n*° 4432). The radio burst detected around 25 February was very 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 within about 30 years from now when the shock wave will reach the red giant wind shell at a distance of $\sim 10^{18}$ cm.

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 *n*° 4410 and 4435). They proposed that these spectral changes may be 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 polarization variations of the optical light of SN 1987a, reaching up to 3-4 percent, have been observed, suggesting some patchyness 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 may arise from circumstellar material being photoionized by the strong UV-optical burst ($\sim 10^{48}$ erg) that should have developed when the shock generated by the core collapse reached the photosphere of the progenitor. In the latter case, a future interaction between the expanding debris and this material sould lead to an emission of X-rays and radio waves due to the turbulent acceleration of electrons.

Because of the multitude of predictions that have been made for the future evolution of SN 1987a, it has become very difficult to predict at all how the supernova will develop in the near future. Numerous sensitive X-ray and γ-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 will collide with circumstellar material or when the expanding atmosphere will get sufficiently transparent to unveil either the products and radiation of the explosive nucleosynthesis or the compact object left over at the centre of the explosion. Whereas there is no doubt that the discovery and observational study of SN 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.

Figure 12: Aerial view of the European Southern Observatory

Appendix: The European Southern Observatory

ESO, an intergovernmental European Organization, was founded in 1962 to establish and operate an astronomical observatory in the southern hemisphere and to promote and organize 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 2,400 m altitude, 600 km north of Santiago. Thirteen telescopes are at present in operation, and the largest instrument with a diameter of 3.6m is one of the most powerful telescopes in the world. Moreover, a 15m submillimeter telescope entered into operation in early 1987 and a 3.5m New Technology Telescope (NTT) should be operational in late 1988. A Very Large Telescope (VLT), consisting of four 8m telescopes (equivalent aperture 16m) is being planned for the 1990's. Six hundred astrophysicists make proposals each year for the use of the telescopes at La Silla.

At the European Headquarters near Munich (FRG), 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 there is the scientific and administrative centre of ESO, where extensive facilities enable european scientists to analyze 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. We refer to the recent article in Ciel et Terre (Vol. 103, p. 43, 1987) by Jean-Pierre Swings for more details on the European Southern Observatory.