Bull. Astr. Soc. India (1988) **16**, 57–66

# Supernova 1987A—a review

Dipankar Bhattacharya *Raman Research Institute, Bangalore 560 080*

Received 1988 March 2

**Abstract.** Supernova 1987A, the first supernova since the time of Kepler to reach naked-eye visibility, was discovered on 1987 February 24 in the Large Magellanic Cloud. This has naturally been of great interest to astronomers. The proximity and the brightness of this supernova has made possible a very detailed study of its properties. Its behaviour in course of time has been quite unique, unlike all other supernovae known so far. In this review the results of various observations of SN 1987A are summarized and their implications discussed.

*Key words* : supernova—Large Magellanic Cloud—SN 1987A

## 1. Introduction

The most important astronomical event of this year has undoubtedly been supernova 1987A. On February 24 this supernova in the Large Magellanic Cloud was noticed first by Ian Shelton of the University of Toronto southern observatory at Las Campanas, closely followed by several others in different parts of the world. This is the first supernova since the time of Kepler to reach naked-eye brightness, and the first such after the discovery of the telescope. The vicinity and brightness of this supernova has provided us with an unique opportunity to study this event in detail, and therefore it is hardly surprising that it has generated unprecedented excitement and enthusiasm among astronomers the world over. All possible instruments, including orbiting satellites, are being used for regular observations of the supernova. I shall summarize here some of the important results of these observations and their possible interpretations.

## 2. Neutrinos

Perhaps the most exciting observation connected with SN1987A has been the detection of neutrinos from the event. Among the results reported by several

Invited talk at the 12th meeting of the Astronomical Society of India, Raipur, 1987 December.

groups the most convincing one is from the Kamioka water Cerenkov detector in Japan (Hirata *et al.* 1987). They found a burst of 12 neutrino events of energies ranging from 6 to 35 MeV, in a span of about 12s. This is the very first detection of neutrinos from outside the solar system. Using the energies of the detected events one can estimate the total energy emitted by the supernova in the form of neutrinos, and it works out to be $\sim 10^{53}$ erg. This is a very important result, because it indicates the formation of a compact object. Let us recall that according to our present understanding, a supernova may occur because of two possible reasons—one of them is a catastrophic release of energy due to a runaway thermonuclear reaction, and the other is the release of the gravitational binding energy in the formation of a compact object like a neutron star or a black hole. The total energy emitted in neutrinos by the former process is only about $10^{51}$ erg, while in the latter neutrinos carry away $\sim 10^{53}$ erg. It is almost certain, therefore, that SN 1987A has been caused by the formation of a compact object. Whether it is a neutron star or a black hole we do not yet know, but we hope future observations will tell us what really had happened.

One important fact is that the detection of neutrinos actually took place before the light from the supernova was seen. This is to be expected, since the neutrinos are released soon after the core collapse, while the optical display has to wait till the resultant shock reaches the stellar surface. The neutrino burst therefore marks the epoch of the collapse. However, it is to be noted that while the Kamioka experiment, and the Irvine-Michigan-Brookhaven collaboration in the United States (Bionta *et al.* 1987) reported neutrino detection at the same time, the European experiment at Mont Blanc reported a detection four and a half hours prior to this (Castagloni 1987). The reality of this detection is being hotly debated. If this signal does correspond to neutrinos from the supernova, then the only way to explain both neutrino bursts would be through a two stage collapse, first to a neutron star, and then to a black hole (Hillebrandt *et al.* 1987b).

## 3. The progenitor star

In this supernova we also have had the unique opportunity of identifying the progenitor star. It is an early B-type star, Sanduleak-69° 202, and it was identified as the supernova progenitor almost immediately after the event. For some time afterwards, however, a state of confusion followed, thanks to some hasty interpretation of ultraviolet observations from the international ultraviolet explorer (IUE) satellite. When the IUE satellite first looked at the supernova, about 14 hours after the optical discovery, its UV flux was already fading very rapidly. Within a few days the short wavelength flux dropped by a factor of 1000 and then remained steady. This level of residual flux, in fact, happens to be the same as what would be expected from an early B star in the LMC. The IUE team therefore concluded that Sanduleak-69° 202 is still intact. In the meantime, a closer inspection of the optical image of Sanduleak-69° 202 revealed that the stellar image consisted of three components (Walborn *et al.* 1987). The position of the supernova was found to be in very close agreement with that of the brightest among the three (West *et al.* 1987; White & Malin 1987). Once this was known, the IUE observers went back, and found from position-resolved IUE spectra that the survivors are in fact the two fainter components; the brightest star had indeed disappeared (Gilmozzi 1987).

After the establishment of the identity of the supernova progenitor the next obvious thing to do was to look closely at the existing pre-outburst data to learn about the nature of the progenitor. Sanduleak-69° 202 was assigned the spectral type B3 supergiant by Rousseau *et al.* (1978). The subtraction of the contributions of the two fainter components did not appreciably alter the spectral classification of the supernova progenitor (West *et al.* 1987; Blanco 1987). So here was a blue supergiant star that exploded. This was surprising, since it is usually believed that at the presupernova stage a star should be a red supergiant and not blue. It now appears, however, that a blue supergiant presupernova star may be expected under several circumstances. One of the reasons may be a low metal content of the star (Arnett 1987; Hillebrandt *et al.* 1987a). The average metallicity of the LMC is about one-fourth the solar value; and the computed stellar models with such low metallicity never evolve to the red giant branch. These stellar models require a mass of about $15M_\odot$ to fit the progenitor's description.

The other possibility is evolution with heavy mass loss (Woosley *et al.* 1987; Maeder 1987). In this case the star first becomes a red supergiant, and then as the mass loss reduces the hydrogen content in the envelope, the star becomes hotter and moves towards the blue. The evolution of the core is not much affected by this mass loss. Therefore the explosion may occur as a blue supergiant if the mass loss rate had been high enough. Such a mass-losing stellar model which would fit the description of the progenitor has a main sequence mass of $\sim 20M_\odot$, which is reduced to about $9M_\odot$ prior to the outburst.

Which of these two routes did the star take? This question can be answered if we know whether it did go through a red giant phase or not. One possible way to check this is to find the abundances of processed elements at the stellar surface. In the case of heavy mass loss, the photosphere of the presupernova star is an exposed inner layer of the original star which would have undergone convective mixing with CNO processed elements from the deep interior during the red-giant phase. Gonzales *et al.* (1987) have carried out a comparison of the pre-outburst spectrum of Sk-69° 202 and that of Sk-69° 78, another LMC star very similar in spectral type to the SN progenitor. The spectra appear to be very similar, except for the larger strength of the 3995Å N II line in the spectrum of Sk-69° 202. This would indicate an overabundance of nitrogen in its atmosphere. Such enhancement of nitrogen and helium has been found in two other LMC B supergiants studied by Kudritzki *et al.* (1987).

Evidence of an overabundance of nitrogen in the spectrum of SN1987A was pointed out first by Ashoka *et al.* (1987). Recent IUE spectra (Cassatella 1987) show narrow emission lines which presumably originate in the circumstellar wind matter; and the relative strength of these lines indicate a nitrogen-to-carbon abundance ratio about 60 times the cosmic value, and nitrogen-to-oxygen ratio about 6 times the cosmic value. All this may be indicating that the SN progenitor *was* a post-red giant object. However, as pointed out by Ramadurai & Wiita (1987), if the SN progenitor had significant rotation then CNO processed elements can be brought out to the surface by meridional circulations, even if the star has not gone through a red giant phase. Evidently we shall have to wait some more to know the final answer. If there has been a heavy mass loss during the red giant phase, then the high density wind material must be existing around the supernova; may be at a distance of a light year or so. This may become a powerful source of radio radiation when the supernova shock overruns it.

## 4. Optical observations

Since the occurrence of the outburst, the supernova has been extensively monitored at optical wavelengths. Detailed spectroscopic and photometric data have been obtained. It has also been possible to do polarimetry and speckle interferometry of this bright object. The optical emission of the supernova consists of both line and continuum. The continuum comes from a photosphere inside which the SN envelope is optically thick. The line emission originates above the photosphere.

### *4.1. Spectral evolution*

Figure 1 shows the evolution of the spectrum of the supernova from February 24 to April 10. We notice two features very distinctly : the spectral lines are becoming more and more prominent with time, and their width is also decreasing. Both these are due to the fact that more and more matter is passing through the photosphere, cooling and accumulating above it. The line optical depth is increasing with time, resulting in the lines becoming more prominent. The narrowing takes place because of the fact that inner parts of the ejecta are moving with smaller velocities. With the expansion of the ejecta and the recession of the photosphere, more and more low velocity material is being uncovered. P-Cygni profiles of hydrogen lines dominate the spectrum, suggesting that this is a supernova of type II.

The velocities seen in the blueshifted absorption of the P-Cygni profile yield the expansion velocity in the line forming region. From the earliest spectra the velocity of the $H_\alpha$ absorption trough is found to be about $-19000$ km s$^{-1}$, and the maximum observable velocity in the $H_\alpha$ profile, that is the blue edge of the line, is about $-31000$ km s$^{-1}$ on February 25. In the ultraviolet, the early spectrum was dominated by a strong P-Cygni profile of ionized magnesium 2800Å line, with its blue edge extending up to $-40000$ km s$^{-1}$, the highest velocity ever seen in a supernova spectrum. This provides a lower limit to the velocity of the shock front.

As a whole, the spectral characteristics of SN 1987A had few surprises, and most features could be fitted well by synthetic spectra (Branch 1987; Lucy 1987). The only major difference compared to other type II supernovae is its rather fast time evolution. This behaviour can be attributed to larger expansion velocities, which in turn could be understood if the presupernova star in this case was a blue supergiant. I shall come to this presently.

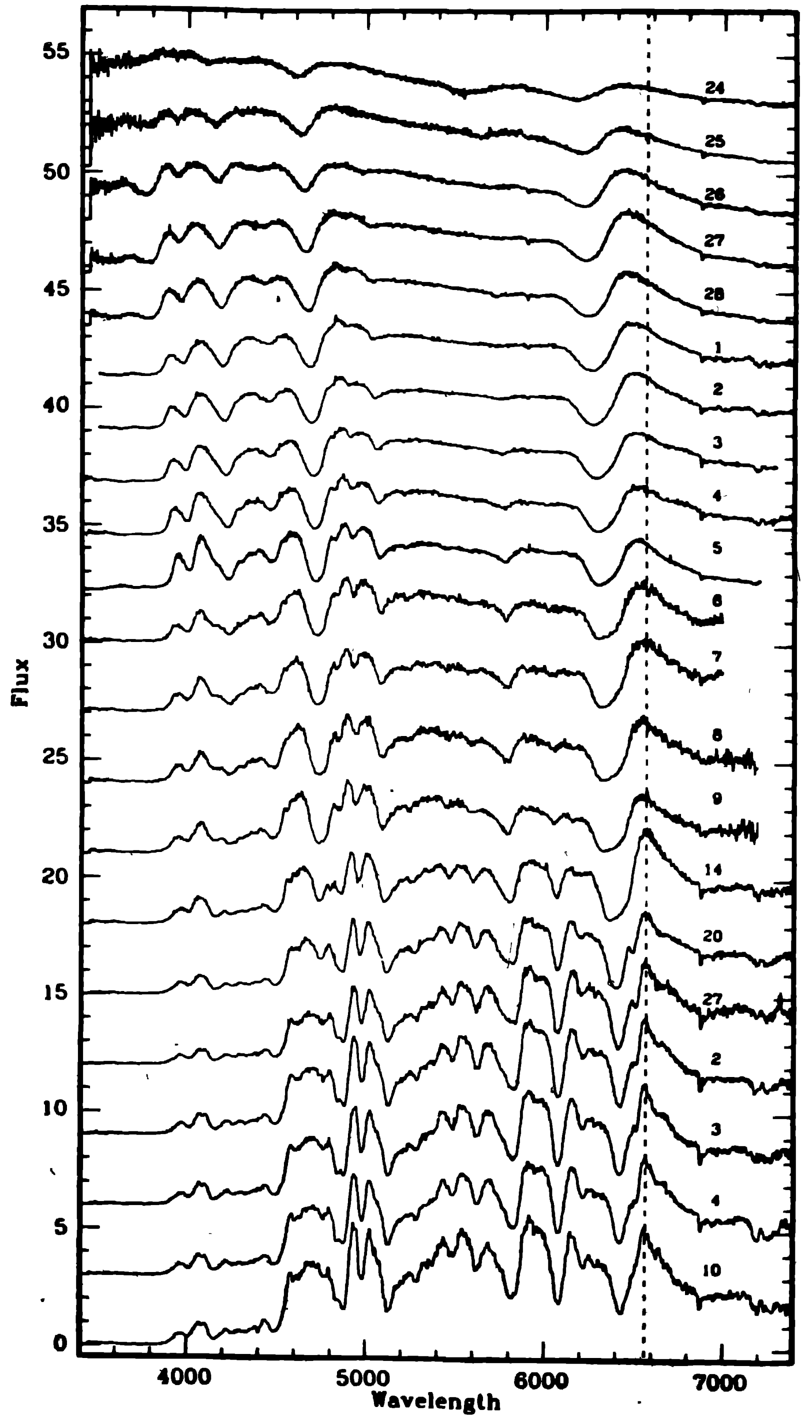


**Figure 1.** Evolution of the optical spectrum of SN 1987A from February 24 (top) to April 10 (bottom). Reproduced from Menzies *et al.* (1987).

The elements Ba II and Sr II, identified by Williams (1987) in the spectrum of SN 1987A, have been seen for the first time in a supernova spectrum. Though the initial analysis required a slight overabundance of barium to produce the Ba II features, it now appears that within the uncertainties its abundance could be normal (Branch 1987). It is also possible that the presumed barium features may be produced by iron lines (N. K. Rao, personal communication).

By mid-June, forbidden lines of Ca II had appeared as relatively narrow emission lines centred near zero velocity, probably indicating the initial stages of interaction between the expanding envelope and the surrounding medium.

Most of the complex structure in the blue and the green is due predominantly to blends of Fe II and Ti II lines arising from low lying metastable levels in these ions. Very recent spectra show several forbidden lines indicating a rather low density in the emitting region (Anupama *et al.* 1987). The computed synthetic spectra should in principle be able to give an estimate of the total mass above the photosphere as a function of time and also the density structure of the SN envelope. However, all the analyses done so far have been rather preliminary and one has to wait for better modelling to give us reliable answers.

### *4.2. The light curve*

The light curve of this supernova (figure 2) has been a most peculiar one. The luminosity of the supernova increased for about 3 months before finally reaching a maximum around May 24. Compared to the light curve of an average type II supernova, the major differences have been the following :

(i) SN 1987A has been quite subluminous. The peak luminosity reached by this supernova was about an order of magnitude below the other SNIIs.

(ii) Initially, the luminosity rose much faster than for a type II supernova, which was followed by a very slow rise to the maximum.

In the ultraviolet, the short wavelength flux decreased very rapidly from a very high initial value. The U-band photometry also showed a similar behaviour. Evidently the photosphere cooled from a very high initial temperature to about 5000–6000 K within a few days.

The subluminous nature of the SN 1987A light curve can again be attributed to the blue supergiant nature of its progenitor. The radius of the SN progenitor was about $2 \times 10^{12}$ cm, as opposed to about $10^{14}$ cm for a red supergiant star. In an expansion from such a small initial radius, the shock deposited energy undergoes heavy adiabatic loss, resulting in a low radiative luminosity and a higher expansion velocity, as we have indeed observed.

The initial high luminosity of the supernova has been associated with the shock breaking out at the stellar surface, following which it cooled very rapidly.

The low rise to the maximum light about 84 days after the explosion would have required some energy to be continuously fed into the supernova envelope, since the thermal energy stored initially would go on decreasing. Several sources for this energy have been proposed, but none can fit the full light curve very well. Among these are :

(i) The radioactive decay of $Ni^{56}$ and subsequently $Co^{56}$ (Woosley *et al.* 1987; Arnett 1987; Shigeyama *et al.* 1987).

(ii) The energy released due to recombination of ionized matter in the envelope (Schaeffer *et al.* 1987).

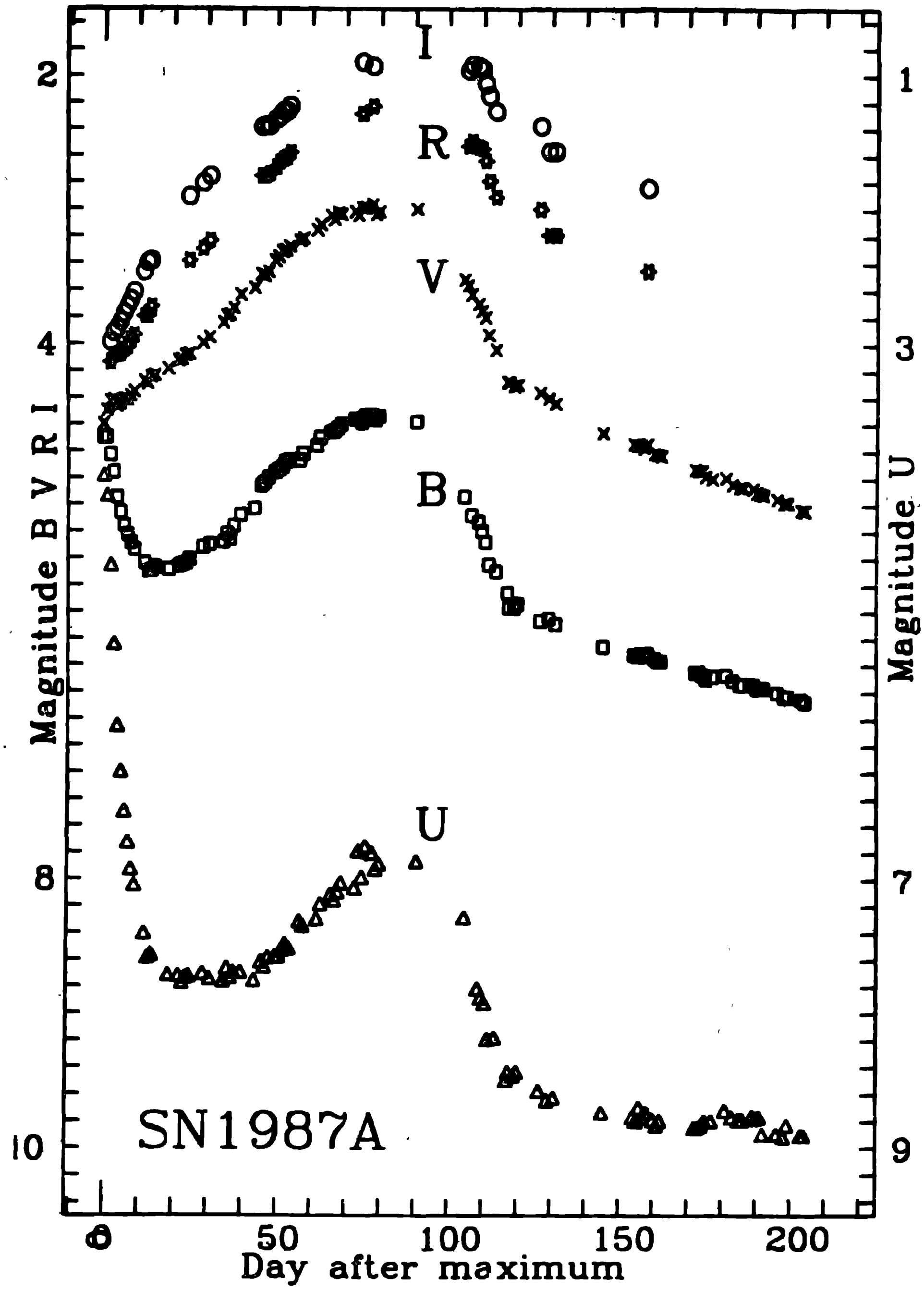


**Figure 2.** The light curve of SN 1987A in U B V and Cousins system R I bands. Reproduced from Cristiani *et al.* (1987).

(iii) The energy released by an active pulsar buried inside the ejecta (Ostriker 1987).

The first option fails to reproduce the initial rising part of the light curve properly, but matches perfectly the late linear decline. While the other two may be able to fit the rising part well, they will have difficulty explaining the nice linear decline.

*4.3. Speckle inte. ferometry : the mystery spot*

Another curious feature of SN 1987A showed up in optical speckle interferometry. Meikle *et al.* (1987) found a bright red companion object, only about 3 mag fainter than the supernova, at an angular distance of about 75 milliarcsec from it. This is about 100 times brighter than any star in the same field existing before the outburst. It was therefore caused by the supernova, and the distance of the spot from the supernova implied a minimum velocity of 0.4 times the velocity of light. However, it could not be satisfactorily explained as a light echo, since the observed flux was much too large. Other explanations that have been suggested involve a jet emanating from the supernova, either due to the pressure of relativistic particles trapped inside the ejecta (Rees 1987), or the collapse dynamics of a rapidly rotating object (Piran & Nakamura 1987). In both these cases, it is difficult to understand why the "mystery spot", as it has been called, disappeared after about three months.

## 5. Radio emission

The situation in other wavelengths have been as follows. Weak radio emission from the supernova was detected in the Australian telescopes for about 10 days after the outburst (Turtle *et al.* 1987). According to Manchester (1987) and Chevalier (1987), the observations can be fit by synchrotron emission together with thermal free-free absorption in the same region. The relativistic electrons necessary for the synchrotron process could have been accelerated either by the shock wave, or by turbulence at the ejecta-stellar wind interface. In an interesting alternative proposed by Bisnovatyi-Kogan (1987), particles responsible for the observed radio emission were relativistic positrons generated by the interaction of antineutrinos with the protons in the outer envelope of the supernova. According to him, these positrons generated plasma oscillations, which subsequently were converted into radio radiation.

## 6. Infrared observations

In the infrared, the spectrum appears to have an excess amount of continuum, which might come from newly condensed heated dust in the supernova envelope (Bouchet *et al.* 1987). There have also been recent reports of the detection of an infrared light echo (Chalabaev *et al.* 1987). Another puzzling thing in the infrared spectrum is the appearance of a whole lot of broad emission lines that are redshifted by about 400 to 1500 km $s^{-1}$ (Oliva *et al.* 1987). According to Leon Lucy, this may indicate some asymmetry in the distribution of the ejected matter.

## 7. X-rays

Very hard-spectrum x-rays from SN 1987A have been detected by Mir-Kvant observatory (Sunyaev *et al.* 1987) and the Ginga satellite (Dotani *et al.* 1987). Results from the Ginga satellite showed the x-ray luminosity rising to a maximum of $\sim 1.5 \times 10^{37}$ erg $s^{-1}$ (10–30 KeV) in September. It then dropped a little, and rose again to the maximum by October. These x-rays may come from Comptonization of the gamma radiation from radioactive elements (Grebenev & Sunyaev 1987; Xu *et al.* 1987), or they might also be produced by an embedded pulsar nebula (Bandiera *et al.* 1987). Again we shall have to wait for future observations to clarify the situation.

## 8. Conclusion

To conclude, we have seen how SN 1987A has been rather different from most of the known supernovae. The large amount of data that has been collected is far from well understood, and it will keep theorists busy for quite some time to come. Meanwhile observations will continue, and will perhaps bring more surprises. Among the exciting future observational prospects is the detection of gamma-ray spectral lines of cobalt decay, which will presumably be powering the light curve till the ejecta become transparent to gamma rays. We shall also be anxiously waiting for the ejecta to become optically thin to reveal what kind of compact object has been formed due to the core collapse. Perhaps in this supernova we shall also have the first opportunity to follow its evolution all the way to a supernova remnant in the centuries to come.

## References

Anupama, G. C. *et al.* (1987). Paper presented at the 3rd Asia-Pacific Regional Meeting, China.
Arnett, W. D. (1987) *Ap. J.* **319**, 136.
Ashoka, B. N. *et al.* (1987) *J. Ap. Astr.* **8**, 195.
Bandiera, R., Pacini, F. & Salvati, M. (1987) preprint.
Bionta, R. M. *et al.* (1987) *Phys. Rev. Lett.* **58**, 1494.
Bisnovatyi-Kogan, G. S. (1987) in *ESO87**, p. 347.
Blanco, V. M. (1987) in *ESO87*, p. 27.
Bouchet, P. *et al.* (1987) in *ESO87*, p. 79.
Branch, D. (1987) in *ESO87*, p. 407.
Cassatella, A. (1987) in *ESO87*, p. 101.
Castagloni, C. (1987) *IAU Circ. No.* 4323.
Chalabaev, A., Perrier, C. & Mariotti, J. M. (1987) *IAU Circ. No.* 4481.
Chevalier, R. A. (1987) in *ESO87,* p. 481.
Cristiani, S. *et al.* (1987) in *ESO87*, p. 65.
Dotani, T. *et al.* (1987) *Nature* **330**, 230.
Gilmozzi, R. (1987) in *ESO87*, p. 19.
Gonzales, R. *et al.* (1987) in *ESO87*, p. 33.
Grebenev, S. A. & Sunyaev, R. A. (1987) *Sov. Astr. Lett.* **13**, 945.
Hillebrandt, W., Hoflich, P., Truran, J. W. & Weiss, A. (1987a) *Nature* **327**, 597.
Hillebrandt, W. *et al.* (1987b) *Astr. Ap.* **180**, L20.
Hirata, K. *et al.* (1987) *Phys. Rev. Lett.* **58**, 1490.
Kudritzki, R. P. *et al.* (1987) in *ESO87*, p. 39.
Lucy, L. B. (1987) in *ESO87*, p. 419.
Maeder, A. (1987) in *ESO87*, p. 251.

*ESO87 : Proceedings of the ESO workshop on SN 1987A (ed. I. J. Danziger), European Southern Observatory, Munchen, FRG.

Manchester, R. N. (1987) in *ESO87*, p. 177.
Meikle, W. P. S., Matcher, S. J. & Morgan, B. L. (1987) in *ESO87*, p. 197.
Menzies, J. M. *et al.* (1987) *M. N. R. A. S.* **227**, 39p.
Oliva, E., Moorwood, A. F. M. & Danziger, I. J. (1987) *IAU Circ. No.* 4484.
Ostriker, J. P. (1987) *Nature* **327**, 287.
Piran, T. & Nakamura, T. (1987) *Nature* **330**, 28.
Ramadurai, S. & Wiita, P. (1987) preprint.
Rees, M. J. (1987) *Nature* **328**, 207.
Rousseau J. *et al.* (1987) *Astr. Ap. Suppl.* **31**, 243.
Schaeffer, R., Casse, M., Mochkovitch, R. & Cahen, S. (1987) *Astr. Ap.* **184**, L1.
Shigeyama, T., Nomoto, K., Hashimoto, M. & Sugimoto, D. (1987) *Nature* **328**, 320.
Sunyaev, R. *et al.* (1987) *Nature* **330**, 227.
Turtle, A. J. *et al.* (1987) *Nature* **327**, 38.
Walborn, N. R., Lasker, B. M., Laidler, V. G. & Chu Y-H. (1987) *Ap. J.* **318**, 664.
West R. M., Lauberts, A., Jorgensen, H. E. & Schuster, H. E. (1987) *Astr. Ap.* **177**, L1.
White, G. L. & Malin, D. F. (1987) *Nature* **327**, 36.
Williams, R. E. (1987) *Ap. J.* **320**, L117.
Woosley, S. E., Pinto, P. A., Martin, P. G. & Weaver, T. A. (1987) *Ap. J.* **318**, 664.
Xu, Y., Sutherland, P., McCray, R. & Ross, R. R. (1987) *Ap. J.* **327**, 197.