SN 1987A: AN AUSTRALIAN VIEW.

Michael A. Dopita
Mt. Stromlo and Siding Spring Observatories
The Australian National University

1. Introduction.

The explosion of SN 1987A in the LMC during the early hours of February 23 1987, has presented southern observers opportunity, unique in our lifetime, to gain a new insight into the supernova phenomenon. Fortunately, SN1987A has risen to the challenge, and has shown us that many of our comfortable pre-conceptions about Type II events will have to be revised in fascinating and sometimes unexpected ways. This paper is an attempt to describe what has been learnt so far wth an emphasis on the research being carried out in Australia. All references are dated 1987 unless otherwise specified.

2. The Nature and Evolution of the Precursor Star.

There is now no doubt that SN 1987A is positionally coincident with the B3 I star, Sk-69 202. This has been established by astrometry with a positional accuracy of 0.1 arc sec, or less (White and Malin a,b; West *et al.*). This star had the following parameters (Rousseau *et al.* 1978):

$V= 12.24 \quad (B - V) = 0.04 \quad (U - B) = -0.65.$

The reddening is somewat uncertain. From a measurement of the Balmer Decrement of the surrounding HII region, Danziger *et al.* find $A_V = 0.66 \pm 0.2$. Wampler *et al.* use the observed absolute strength of the λ5780Å diffuse interstellar band (Vladilo) to estimate $A_V = 0.45$. On the other hand, the diffuse interstellar band at λ6613Å shows the LMC feature to be only about 75% as strong as the Galactic component (Vidal-Majar *et al.*). Since the LMC line of sight Galactic reddening has been fairly accurately measured at E(B-V)= 0.034 (McNamara and Feltz, 1980), we can estimate an A_V of order 0.22 on this basis. We adopt a value of $A_V = 0.44$, $E(B - V) = 0.14$, being the average of these estimates. Wood and Faulkner estimate the following parameters of Sk -69 202: $M_{bol} = -7.71 \quad \log (L/L_{\odot}) = 4.98 \quad \log T_{eff} = 4.11$

These parameters define an entirely unremarkable blue supergiant. Conventional wisdom had it that Supernovae of Type II occur either in red supergiants, or perhaps, in the Wolf-Rayet phase of evolution. The central problem for the evolutionary models is therefore, how can the moment of core collapse be contrived to occur in a blue supergiant star? There have already been many attempts made to address this question, and from these it is apparent that the main sequence mass must have been in the range 15-20 $M_{\odot}$. These models teach us that the end-point of evolution is remarkably sensitive to the assumptions and approximations made. The major parameters that determine the outcome are, in no particular order, the opacity, the treatment of convection and the treatment of mass loss.

In general, the decrease in opacity obtained with the lower abundances characteristic of the LMC tends to help to confine the evolutionary tracks to the blue side of the H-R Diagram. However, most models are computed with the an abundance set taken as solar divided by, say, four. In practice, the LMC abundance distribution is not this simple.Dopita (1986) and Russell, Bessell and Dopita have shown that, in the LMC, the underabundance of various elements with respect to solar is dependent upon their atomic number. For example, Cand N are depleted by about 0.8 dex, O and Ne by about 0.5 dex, Ca by anbout 0.3 dex and the heavy elements from Ti through Fe to Ba by about 0.2 dex. This pattern is similar to that produced in models of deflagration supernovae, and may indicate that these have been relatively more important in enriching the interstellar medium in the LMC.

An important constraint in the evolutionary models is that they should correctly describe the observed ratio of red to blue supergiants in the LMC (Wood and Faulkner; Maeder; Miyaji and Saio, all this conference). Many models without mass loss are unsuccessful in this, since they fail to evolve to the red supergiant phase at all (Arnett, Hillebrandt *et al.*). However, this problem is code dependent, and others do evolve to the red and then return (Woosley *et al.* ; Wood and Faulkner; Woosley, this conference).

Models involving mass loss are more successful in reproducing the observed ratio of blue to red supergiants. Those which include convective overshooting (Maeder, this conference) have a somewhat higher core mass, and a larger residual hydrogen envelope than those which do not. The Wood and Faulkner model for a 17.5 $M_\odot$precursor star is in many respects a fully self-consistent model. It contains the correct opacity for the observed LMC abundances, and uses Waldron (1985) mass-loss rates which correctly reproduce the blue to red supergiant ratio.The supernova occurs in these models when the helium core mass is 5.2 $M_\odot$ and only 0.2-0.6 $M_\odot$ of hydrogen is left on the star. Hydrogen shell burning has been extinguished before the supernova explosion.

Theoretical estimates of the residual mass of the hydrogen envelope at the time of the explosion thus range from about 0.3 $M_\odot$ all the way up to about 10 $M_\odot$. However, some observational data tends to support the lower values. The strength of the nitrogen lines in the precursor (Walborn), and the appearance of narrow NV, NIV] and NIII] lines in the UV some weeks after the explosion (Kirshner) all suggest that CN processed material was not only abundant in the surface layers, but indeed, had been ejected in a previous red-giant phase. The appearance of X-ray emission at early epochs and the early appearance of lines of s-process elements in the spectra (Williams) (He-burnt material at the photosphere) also tends to support lower values for the total mass of the pre-supernova star unless substantial post-SN mixing has occured. However, the energy arguments presented at this conference by Woosley; Wheeler Harkness and Barkat; and Nomoto Shigeyama, and Hashimoto would suggest high residual hydrogen mass, since in the low-mass scenario the hydrogen layers would be ejected at too high a velocity.

3. The Light and Colour Evolution

Monitoring at U, B, V, R and I has been carried out on the 76 cm telescope at MSO by Flynn and Meatheringham, and by a larger group of observers, using the 40 cm and 60 cm telescopes at SSO (Achilleos, Dawe, Rawlings, Mc Naught and Shobbrock). This data (partly reported in Dopita *et al.*) is in no sense as accurate or complete as that collected in South Africa (Menzies *et al.*; Catchpole *et. al.*) or at Cerro Tololo (Gregory *et al.* ; Hamuy *et al.*).In the following analysis, therefore, the Australian data has been combined with the above material.

The compact initial state of the supernova ensured that the initial colour evolution is about five times faster than a normal Type II. At five to seven days the (B - V) colour evolution accelerated as line blanketing, initially from higher members of the Balmer series, but later from metal lines, mainly from the iron group, becomes important. The climb towards maximum was accomplished at an almost constant temperature as measured by the (V - I) colour, but a further decline in temperature was seen in the post-maximum phase as the luminosity collapsed towards the radioactive tail. An increse in (U - B) occurred at 40 - 50 days, but this does not correspond to any change in photospheric temperature. This is presumably the result of a composition change working its way out to the photosphere.

The reduction of these colours and the V magnitude to physical quantities is of necessity rather approximate and has been described in detail elsewhere (Dopita *et al.*). Suffice it to say that the Bolometric luminosities are obtained on the assumption that the apparent distance modulus of the supernova is 18.8, corresponding to a visual absorption $A_V = 0.44$, and using the Bolometric Corrections of Carney (1980). The derived Bolometric luminosity is given in Figure 1.

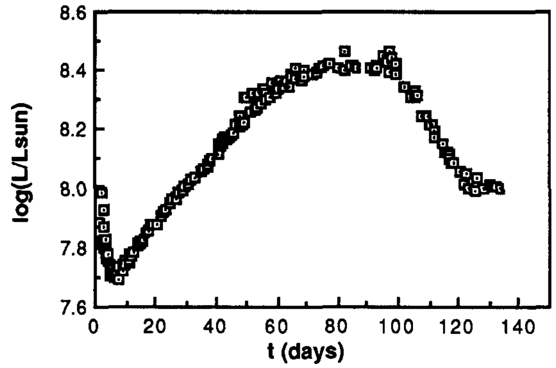
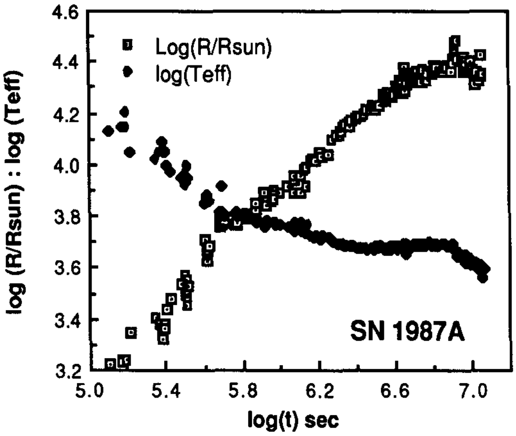


Fig 1: The evolution of the absolute luminosity of SN 1987A. Note the initial "flash", the slow climb to maximum, and the rapid decine to the radioactive powered tail. The maximum corresponds to the "plateau" phase of of normal Type II, provided that Ho ~ 100 km/s/Mpc.

If we can assume that the shocked SN ejecta expands homologously, and that locally, the density structure can be represented by a power law with index α, then, for a atmosphere with constant ionisation fraction, it follows that $R \propto [t / t_0]^{(\alpha-3)/(\alpha-1)}$. Therefore, the evolution of the radius with time follows a power law with an index which is directly related to the index of the density gradient at the photosphere. An analysis of the photometrically defined temperature and radius shows at least four such power-law segments (fig. 2). The initial expansion is effectively ballistic, with a slope corresponding to an $\alpha \geq 11$. In this phase adiabatic cooling is reducing the

Fig 2: The Logarithmic variation of temperature and radius. Note the discontinuous change of slope at log(t) = 5.7. This corresponds with the onset of hydrogen recombination in the photosphere (see text).



effective temperature. Eventually, the temperature falls to the point at which a recombination wave starts to propagate inwards (log(t) = 5.7). Since in the early phase, electron scattering is the dominant continuous opacity source, the photosphere is locked to the recombination front, and follows it as it sweeps inward. However, the recombination front moves in so rapidly that it eventually leaves the photosphere behind. The α determined by the radius-time relationship should then be an accurate measure of the true α, or about 11 ($6.2 < \log(t) < 6.7$).

The decline from the peak is relatively rapid, since the opacity of the core is determined by electron scattering. As the heavy elements recombine, this declines precipitately and the diffusion timescale rapidly becomes shorter than the dynamical timescale (see, for example, Shaeffer, Cassé and Cahen). In the radioactive tail, the luminosity can be set equal to the rate of energy generation in radioactivity (Weaver, Axelrod and Woosley, 1980):

$$L = 3.9\text{x}10^9 \exp[-t/\tau_{Ni}] + 7.03\text{x}10^9 \{\exp[-t/\tau_{Co}] - \exp[-t/\tau_{Ni}]\} \text{ erg.g}^{-1}\text{.s}^{-1}.$$

where τ_{Ni} and τ_{Co} are the respective decay times on radioacive Nickel and Cobalt. Since $L = 10^8$ L at $t = 1.12\text{x}10^7$ sec, the total amount of radioactive nickel produced in the explosion can be fairly accurately estimated at 0.087±0.015 M .

4. The Shock Breakout Phase

The discovery of a prompt radio burst is related to the epoch of shock break-out was an important Australian contribution to the studies of SN1987A. The burst lasted for only about a week, (Turtle *et al.*), and can be understood in terms of free-free absorption of synchrotron emission (Storey and Manchester). The location of this radio emission was probably in the shocked stellar wind region of the star, with the free-free absorption arising from within this layer. The thickness of the emitting layer was estimated at only 4.8% of the radius, which would be consistent with a power law density distribution of matter with an index of 11.8. Since the first week, the radio emission continued to fade (despite some other reports to the contrary), becoming effectively unobservable at 843MHz after about 50 days.

The epoch of shock breakout from the photosphere certainly resulted in a "flash" of UV photons, although probably not a very intense one. From the early data we find;

$$\log (T_{eff}) = (7.47 \pm 0.23) - (0.64 \pm 0.04)\log(t)$$

Shock breakout occured at about log(t) = 3.6, and at this time the above regression gives a photospheric temperature, $T_{eff} \sim 150000$K. This should be compared with the estimate derived on the assumption that, at the time of shock breakout, the shock is driven by radiation pressure, which gives $T_{eff} \sim 230000$K. The UV flash can therefore be characterised by a temperature of order 10^5 K, a luminosity of $2 \times 10^8 L_O$ and a duration of 2-4 hr. These parameters are consistent with the absence of any detectable effect on the earth's ionisosphere (Edwards). Dopita *et al.* proposed that this flash would ionise the precursor stellar wind (see also Chevalier and Fransson). Fluorescent ionisation of a dense blob of gas lost to the star in the red giant phase may give an explanation of the "mystery spot" discovered by speckle interferometry (Karosova *et al.*; Marcher, Meikle and Morgan), and is certainly the cause of the narrow emission lines which have developed in the UV (Kirshner, this conference).

5. Spectral Monitoring of the Supernova

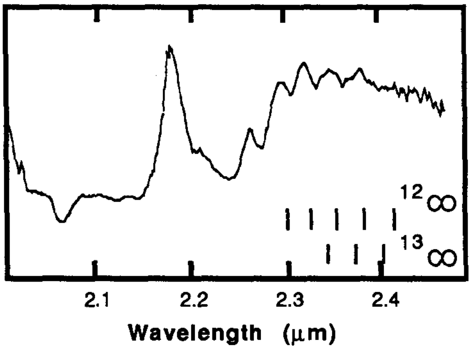
Observations have been obtained in the 3100-7500Å with the Anglo-Australian telescope, generally at fairly low resolution, although a few higher resolution observations exist. These have been reduced by Raylee Stathakis, and a data base is being built up. The FORS spectra which cover the range 5500-10000Å are particulary useful for monitoring the development of the Ca II triplet feature, and the relative intensity of the. A more extensive spectral library has been accumulated using the MSSSO 1.8m telescope at Coudé with its 32 inch camera and the Photon Counting Array as a detector. This data has a typical spectral coverage of 3200-7400Å, a resolution of 40km/s, and a signal to noise of up to 100 per resolution element. Of complete spectra, the data collected at MSSSO has the highest resolution, but is difficult to reduce to absolute flux.

The very earliest spectra were nearly featureless, but there was a very rapid development of strong Balmer lines with very broad P-Cygni profiles. Initially, the maximum expansion velocity in the absorbing material was as high as 30000km/s, with the absorption maximum in Hα at about 17000km/s. This was almost twice as large as in "normal" Type II supernova events, and is certainly associated with the compact nature of the precursor star. Like Danziger *et al.*, we found that the radial velocity of the hydrogen absorption features rapidly decreased, initially by about 800km/s each day. This corresponds to the fastest-moving material expanding, and becoming optically thin. The development of a CaII P-Cygni feature occured very early, but by about March 3 as the photospheric temperature falls below 6000K, and the recombination wave developed, many absorption features corresponding to FeII, NaI and Mg I lines appeared and deepened. The appearance and strength reached by the s-process element lines of Ba and Sc are particulary interesting, and may show real enhancements of these elements, which are produced in the He-burning layers (Williams). However, non LTE effects are certainly important in the formation of the hydrogen lines after only a couple of days, and so abundance estimates should be treated with caution.

Throughout the second half of March and through April, the rate of spectral evolution slowed considerably. Line blanketing below 4400Å became almost total, and the depth and width of the absorption lines continued to decrease slowly. The Hβ line showed a particulary interesting behaviour, almost dissapearing by the end of April, before returning as a prominent and almost saturated absorption line in late June. This may have been the effect of veiling by the FeII features according to Chugaj (prive communication). An alternative explanation is that hard X-rays started to heat the layers above the photosphere leading to an increase in the excitation temperature of the hydrogen. The re-emergence of the Hβ lines corresponds to the onset of the nebular phase, with Hα and CaII developing in emission and with the appearance of [CaII] emission near 7400Å. The ratio of the CaII to [CaII] emission will provide a very useful density diagnostic. The OI 7774Å feature also appeared in absorption for the first time at this epoch, suggesting that oxygen-rich material may now be reaching the photosphere.

Spectral monitoring has also been carried out in the IR, between 1.0-1.4μm, 1.45-1.85μm, 1.9-2.5μm and 2.9-4.1μm (by Mc Gregor, Hyland and Ashley at MSSSO and by Allen at the AAO) and at 8-13μm (by Aitken and collaborators using the AAO). The spectrum has evolved from a relatively featureless continuum with a few broad lines of hydrogen with P-Cygni profiles, to a rich emission-line spectrum with features reminiscent of a Nova. The continuum distribution in the 8-13μm band is consistent with the opacity being dominated by the free-free contribution. A particulary interesting discovery was the development of the 1st overtone band of CO in emission after about 120 days (see figure 3). The lines are broad, and the emission is almost certainly produced by collisional excitation near the photosphere.

Fig 3: IR Spectrum taken on Sept 1 by P. Mc Gregor, showing prominent CO emission. The bright isolated emission feature is the hydrogen Brackett - Gamma line.



Spectropolarimetric monitoring is being carried out on the Anglo-Australian telescope by Cropper *et al.* (1987). The initial continuum polarisation was about 0.8%, but this subsequently decreased. However, the polarisation in the lines, particulary in the absorption component of Hα has increased sharply. Since the polarisation is determined by the interstellar dust, the shape of the supernova fireball and the scattering processes in the photosphere, these results are difficult to interpret. However, they can provide us with very useful modelling constraints.

6. Interstellar Absorption Line Studies.

The rich interstellar absorption spectrum of SN1987A has already been well described by Vidal-Majar *et al.*. Using the Parkes radio telescope Wayte (in prep) has shown that the clouds at 64, 125 and 167 km.s^{-1} can be identified with very faint HI features. If these clouds in fact fill the 15 arc min.beam, then the HI column densities are 1.1x10^{18} cm^{-2}, 5.6x10^{18} cm^{-2} and 0.6x10^{18} cm^{-2}, respectively. The total Galactic and LMC column densities in the direction of SN 1987A are 5.1x10^{20} cm^{-2} and 2.6x10^{21} cm^{-2}, respectively. Using a special set-up at the Coudé focus of the AAT, Pettini and Gillingham (1988) have been able to measure the hyperfine splitting for a number of clouds along the line of sight at a resolution of about 10^{6}. However, perhaps the most remarkable result has been the discovery of [FeX] in absorption in the LMC (Pettini *et al.*.1987; D'Odorico *et al.* 1987). This extends from 205 to 380 km.s^{-1}, and has an equivalent width of 16.4mÅ, implying a column density N(FeX) = 2.1x10^{17} cm^{-2}. If this is global to the LMC it would require an ionised hydrogen column density of order 10^{22} cm^{2}. It seems more likely that SN1987A is sitting in a local bubble of hot gas, possibly produced by the precursor star.

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