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SN 1987a : LIGHT CURVES AND INFERENCES

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Abstract. The UBVRI light curves of SN 1987a are described. The inferences one can draw from these data, such as the colour evolution, evolution of photospheric radius and temperature, and the bolometric light curve, are discussed. Theoretical explanation for different portions of the light curves is also given. The blue light curve is compared with the mean light curves of other supernovae. SN 1987a appears to be a low-luminosity member of type II-P supernovae, its lower luminosity being associated with a low value of envelope mass.

1. Introduction

The visual light curve of SN 1987a during the first year is characterized by an initial rapid rise, subsequent slow rise to a round maximum, followed by a decline that remained linear for a long time before falling below the linear extrapolation. The shape of the light curve contrasts well with the light curves of other well-observed supernovae (SN). However, it appears likely that the curve forms the low-luminosity envelope of the family of type II-P SN light curves. Similar events in other galaxies might have gone unnoticed in the past, or were very poorly observed, due to their under-luminosity.

Following an SN outburst, most of the electromagnetic radiation is emitted by the expanding and cooling photosphere at the optical wavelengths. The line emission does not contribute significantly to the broad band fluxes which can hence be used to infer the blackbody temperature, radius, and luminosity of the source. These quantities help setting constraints on the theoretical models of explosion.

We summarize here the broadband photometric information on SN 1987a during the first year following the outburst, and also inferences drawn from these data.

2. UBVRI light curves

The precursor of SN 1987a was Sanduleak -69°202, a B3I star with V=12.24, B-V=0.04, and U-B=-0.65 (Rousseau et al. 1978). Following the discovery of its outburst on 1987 February 24, it was photometrically monitored extensively, mainly at the South African Astronomical (SAAO), Cerro Tololo Inter-American, and European Southern Observatories. A few prediscovery observations of the region containing the SN have helped in obtaining magnitude estimates closer to the outburst. We reproduce in Fig.1, the Johnson UBV and Cousins RI light curves during the first 365 days, based on the observations from SAAO (Menzies et al. 1987; Catchpole et al. 1987, 1988; Whitelock et al. 1988. Hereinafter referred to as SAAO I-IV, respectively). The peak in V band reached approximately 80 days since outburst, at 2.75 mag.

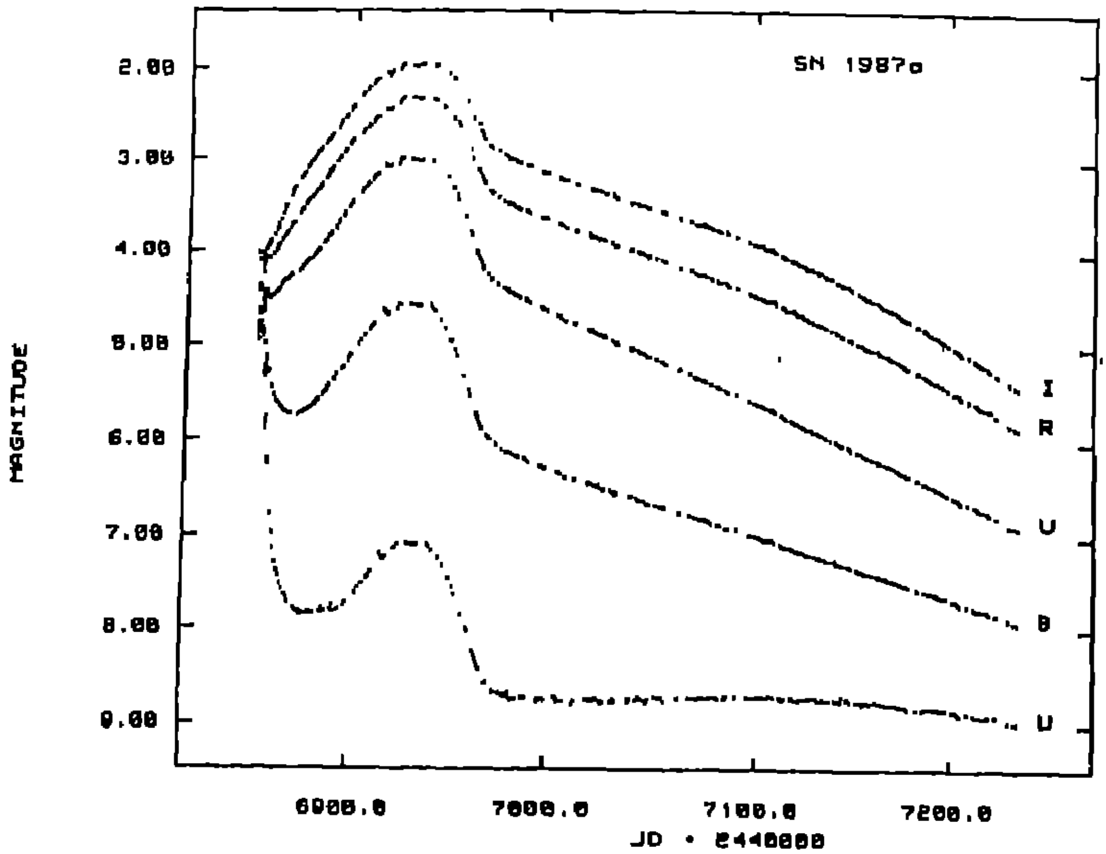

Fig.1 The UBV $(RI)_C$ light curves of SN 1987a during the first 365 days

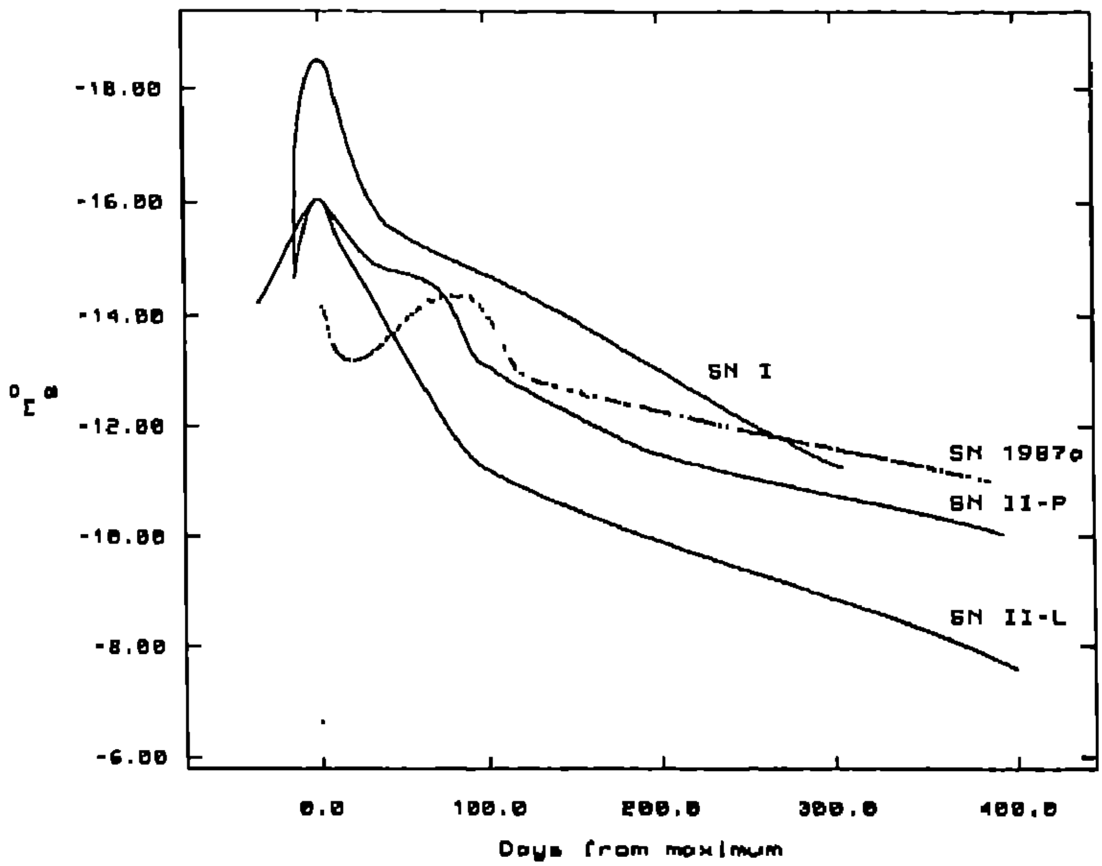

Fig.2 The B light curve of SN 1987a compared with the mean curves for different types of SN on an absolute scale. The zero of time is taken to be the light maximum for mean curves, but as the outburst time for SN 1987a.

SN 1987a is spectroscopically classified as type II. Type II SN are further classified as P(plateau) and L(linear) depending on whether or not the light curve exhibits a halt during the decline. The B light curve of SN 1987a is compared with mean curves of type I, II-P, and II-L in Fig.2. The shapes of the mean curves are taken from Doggett & Branch (1985). The mean brightness at maxima have been taken from de Vaucouleurs (1979) as M_B = -18.5 (type I) and -16.05 (type II) with no distinction between subtypes P and L. A distance modulus of 18.5 for LMC and absorption of A_B = 0.46 towards SN 1987a were assumed. At first sight, the light curve of SN 1987a appears totally different from the mean curve. The maximum brightness of M_B = -14.5 attained by SN 1987a renders it 1.5 mag fainter than mean type II light curves.

If one makes the mean type II-P curves 0.8 mag brighter and shifts the zero time of SN 1987a to day 20 (Fig.3), some similarities between SN 1987a and mean type II-P curve become evident. First, the two curves match well at the late phases. Secondly, the peak of SN 1987a coincides

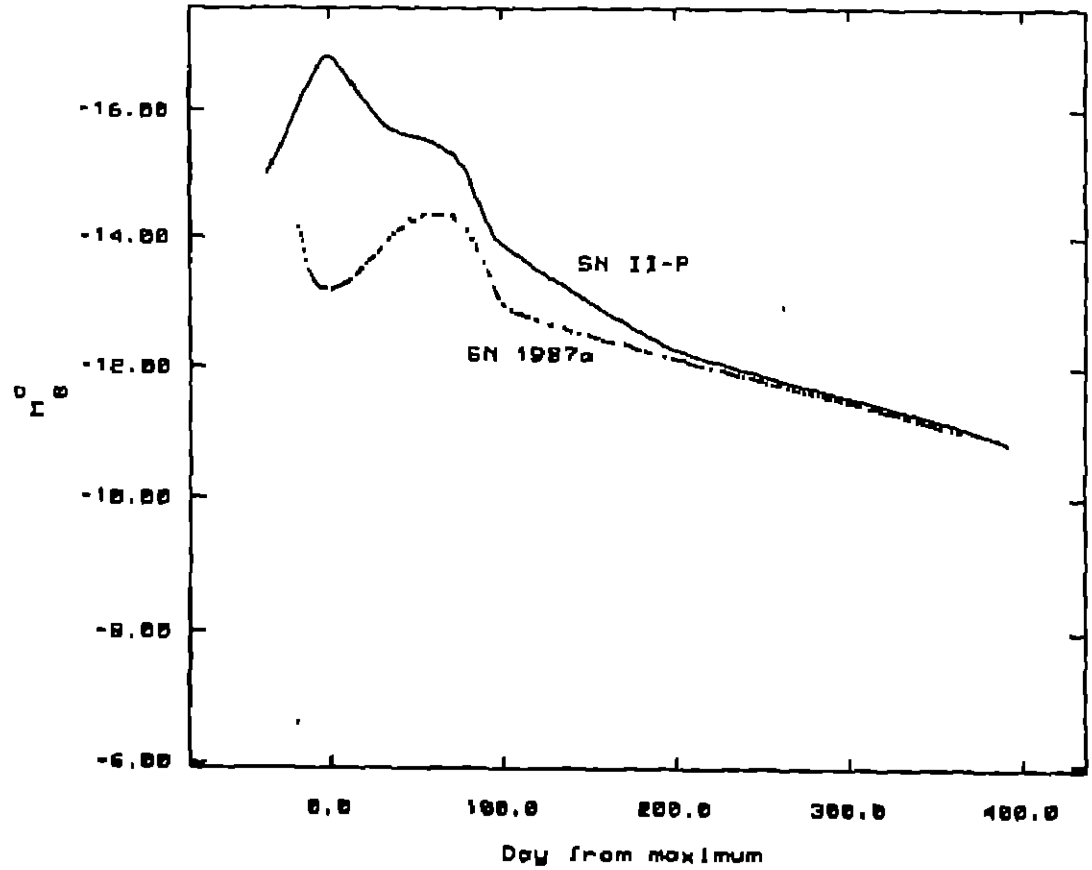

Fig.3 A comparison of mean type II-P light curve (made brighter by 0.8 mag.) and the light curve of SN 1987a (day 20 reckoned as zero)

with the plateau of type II-P curves, being only 0.2 mag fainter (on the scale of deVaucouleurs 1979). Finally, the peak of type II-P curve coincides with the dip in B curve of SN 1987a. No dip appears at corresponding time in the VRI and bolometric light curves. One may hence assume that SN 1987a is a type II-P in which the light curve directly reaches plateau without going through a normal maximum.

The evolution of different colour indices of SN 1987a is shown in Fig.4. The colours become progressively redder during the early days at a rate several times faster than for other SN. This can be understood as an effect of lower envelope mass, and consequent increase in the cooling efficiency. Line blanketing, initially by Balmer lines and later also by metallic lines, contributes to the reddening of U-B and B-V colours. This is also a consequence of cooling. The reduced envelope mass may thus explain the anomalous light curves of SN 1987a.

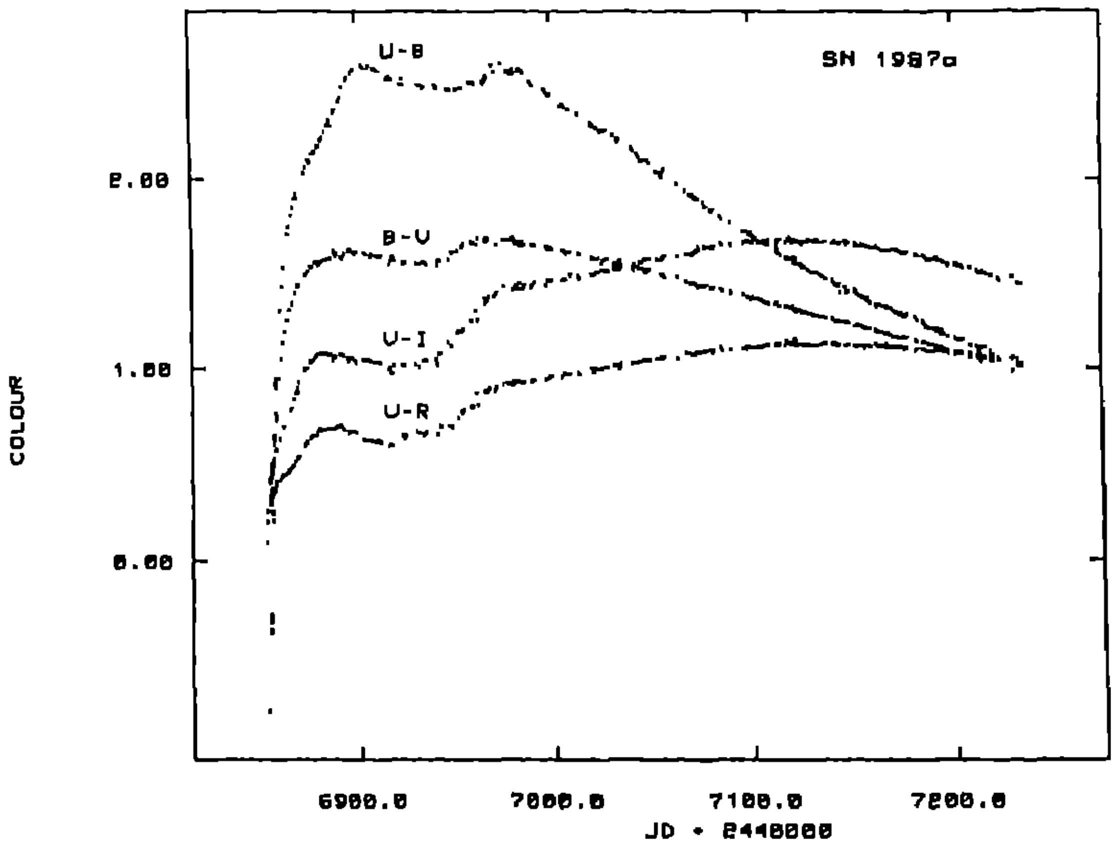

Fig.4 The evolution of broadband colours of SN 1987a.

3. Radii, temperatures and total luminosities

Beginning with the outburst, and until the spectrum begins to be dominated by emission lines, the broadband magnitudes and colours can be used to estimate the radius, temperature and total luminosity of the SN. Two methods are available: First, the observed colours may be compared with a suitable calibration for effective temperature; the observed colour and magnitude may be compared with a suitable calibration for angular diameter (Ashoka et al. 1987; Hearnshaw, Mc Intyre & Gilmore 1988). Alternatively, blackbody curves may be fitted to the observed UBVRI magnitudes, supplemented by JHKL magnitudes, to derive the effective temperature, angular radius, and the total apparent luminosity (Danziger et al. 1987; SAAO I-IV; Hamuy et al. 1988). The quantities derived from SAAO data are shown in Fig.5. The effective temperature reduces quickly in the early stages and reaches a plateau lasting till about day 100. It then comes to a minimum only to steadily rise thereafter. The radius reaches a maximum about day 100 and reduces thereafter. The total luminosity has a maximum at about days 80-90.

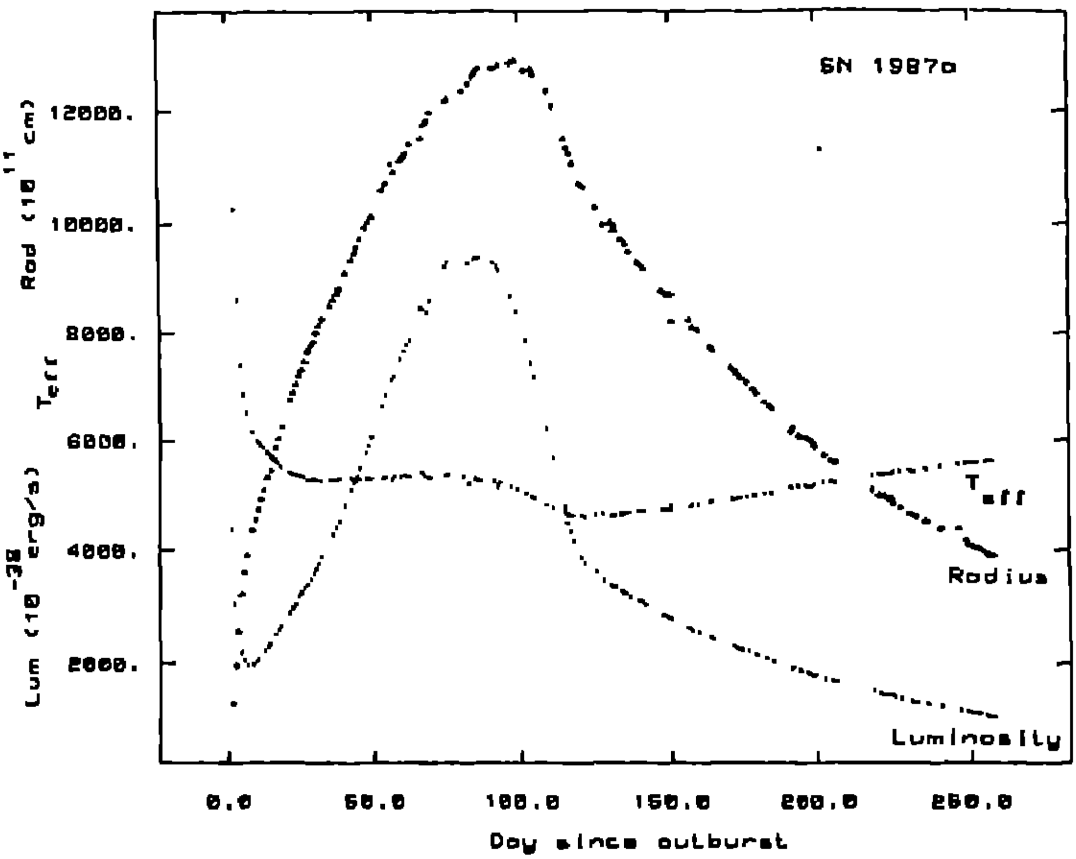

Fig.5 The evolution of the photospheric radius, temperature and total luminosities of SN 1987a.

4. Theoretical modelling of the light curve

We discuss below the dominant physical mechanisms responsible for different portions of the light curve of SN 1987a. A comparison of two specific models in literature is reproduced in Fig.6 from Dopita (1988).

4.1 Initial Rise: The Shock Breakout

The intial rise in brightness of SN is attributed to the breakout of shock following the core-bounce. The time of core collapse is reckoned with the neutrino event (1987 February 23.316 UT from Kamiokande detection). The optical outburst, on the other hand, had to wait for the shock to propagate to the surface, and for the surface to cool sufficiently to radiate in the optical. Two pre-discovery observations help in setting limits on the time of optical outburst: a negative observation on February 23.44 UT, and a positive one on 23.54 UT. The time difference between the optical outburst and the neutrino event place constraints on the envelope mass, radius, and explosion energy. Optimum values are 10 $M_{\odot}$, 3×10^{12} cm, and 10^{51} erg,

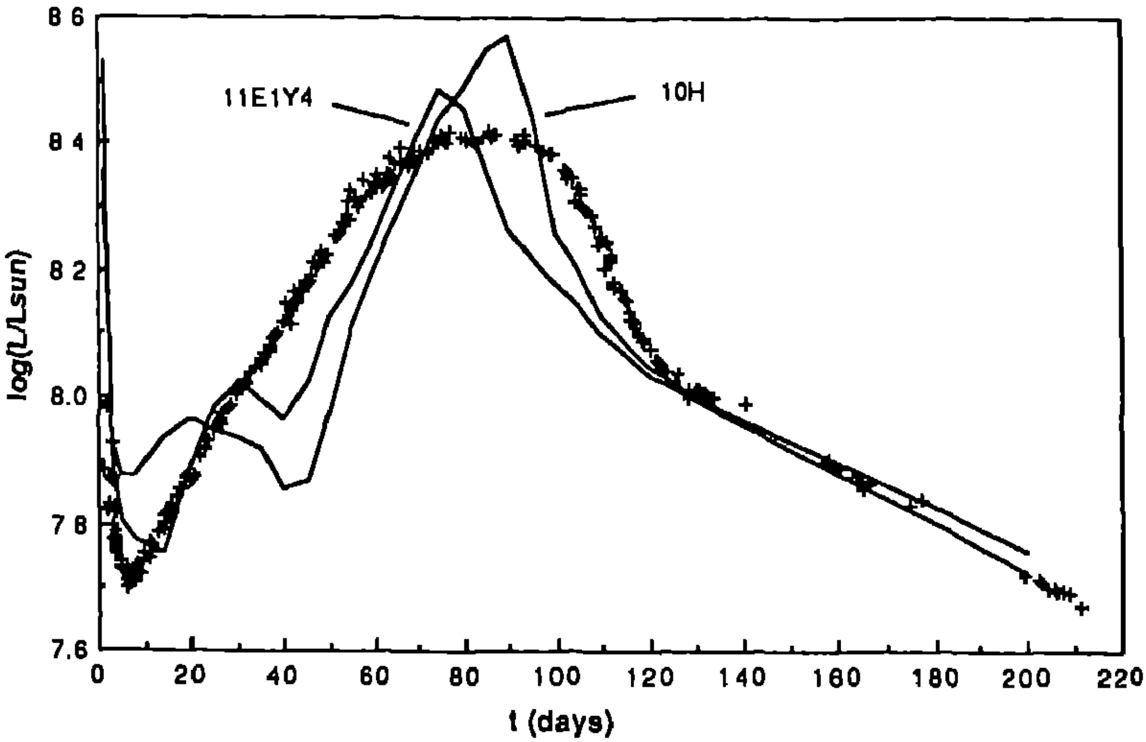

Fig.6 A comparison of observed bolometric light curve of SN 1987a with the 10H model of Woosley (1988) (envelope mass: 10$M_\odot$; Kinetic energy: 1.4 x 10^{51}erg), and 11E 1Y4 of Nomoto, Shige-Yama & Hashimoto (1987) (6.7 $M_\odot$, 10^{51}erg). The figure is reproduced from Dopita (1988). See also Shigeyama, Nomoto & Hashimoto (1988) for more models.

respectively (cf. Dopita 1988). The first two parameters agree with aB3I precursor.

Further evidence for the shock breakout comes from the radio light curve which reached its peak at 843 MHz on day 4. The radio emission is attributed to synchrotron emission from a thin shel near the expanding ejecta (Storey & Manchester 1987).

4.2 To the Maximum and Downhill: The Photospheric Evolution

Beginning with the halt soon after outburst, the evolution of the light curve follows the evolution of the photospheric radius and temperature. The effect of line-blanketing and consequent departure from a blackbody result in initial dips in U and B light curves instead of a halt as in VRI bands.

Though the photosphere keeps increasing till the maximum, it is shrinking with respect to the matter streaming out of it. A comparison of photospheric absorption lines with photospheric radius can hence yield information on the variation of expansion velocity with radius at this stage.

After day 20, the temperature of the photosphere of SN 1987a remained nearly constant. The rate of photospheric expansion at this stage can also yield information on the density law. Assuming the photospheric density falling as $(\text{time})^{-\alpha}$, one derives $\alpha = 10.6$ between days 15-26, 5.1 between days 26-46, and 4.1 between days 46-103 (Dopita 1988). The density and velocity laws too place constraints on the envelope mass and structure, and kinetic energy of explosion.

In SN II-P the photospheric radius remains constant at the 'plateau' of the light curve. Average brightness of the plateau is $M_B = -14.5$ (de Vaucouleurs 1979). This compares well with the maximum of SN 1987a. It thus appears that SN 1987a just reached the 'plateau' at its maximum. This would further suggest that SN II-P may form a family with differing envelope masses, larger envelope masses resulting in brighter maxima.

After the maximum the radius of photosphere begins to shrink isothermally, resulting in the decline of the light curve. Increasing contribution of line emission from outer regions brakes the decline to some extent. A new mechanism then takes over and turns the light curve linear.

4.3 Linear Decline: ^{56}Co decay

Fe-peak element are synthesized by neutron capture during SN explosions. Of these, ^{56}Ni decays radio-actively to ^{56}Co with a mean life of 8.8 days, and the latter decays to ^{56}Fe with a mean life of 111 days. The gamma rays emitted during the decay heat the envelope. When the photospheric radius has shrunk considerably, the radioactive heating brakes the decline and the luminosity falls exponentially. Most of the ^{56}Ni is converted to ^{56}Co by this time (beyond day 120) and the light curve mimics the decay of ^{56}Co. The decline has a 'mean life' of 104-115 days, comparable to the mean life (111 days) of ^{56}Co (SAAO III). Assuming that the energy radiated on day 127 was equal to the energy released by radio-active decay, one deduces that 0.085 $M_\odot$ of ^{56}Ni was produced in the explosion (Dopita 1988). The photosphere continues to shrink during the linear decline revealing hotter and hotter inner layers (Fig.5).

Beginning with day 265 the light curve begins to dip slightly below the extrapolated linear rate. This can be attributed to the leakage of the radio-active energy in other bands of radiation. The x-rays observed by Ginga satellite reached a maximum around day 190 (Dotani et al. 1987). These result from the Compton scattering of the gamma rays. The gamma rays themselves became observable soon after (cf.Mahoney et al. 1988). The leakage is caused by a decrease in the opacity of the envelope, and is expected to increase continuously. Thus the light curve would decline faster and faster.

5. Conclusion

Since SN 1987a is much closer than any SN observed in modern times, it has been observed well in all bands of electromagnetic radiation, and in neutrinos. Though the SN was intrinsically fainter, and presented somewhat peculiar light curve, the light curve is understood fairly well in terms of a low envelope mass of its precursor. The theoretical modelling of this SN would pave way of improving the models of SN with more massive envelopes. Finding a compact star exploding as SN has demanded the refinement of theoretical models of stellar evolution. The SN rates will need to be revised now, since similar SN may have been missed in past SN searches. This fact would motivate detailed observations of fainter extragalactic SN. The revised SN rates will have important implications on the chemical evolution of galaxies. Thus SN 1987a has truly heralded a new era in astronomy and astrophysics.

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