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Evolution of the Optical Spectrum of SN 1987A

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The initial reaction to the spectroscopic behaviour of SN 1987A was that it is a very untypical SN II but after a year, it is said that it is not peculiar after all. Only it went through various stages very fast and that is because it is a blue supergiant that too with metals down by a factor of 4!

The main events in the evolution of the UV and optical spectrum have been presented in a review paper by Dopita (1988). Some aspects which need to be highlighted are illustrated with respect to the light changes. I would base my discussion mostly on spectroscopic observations made at Vainu Bappu Observatory, Kavalur.

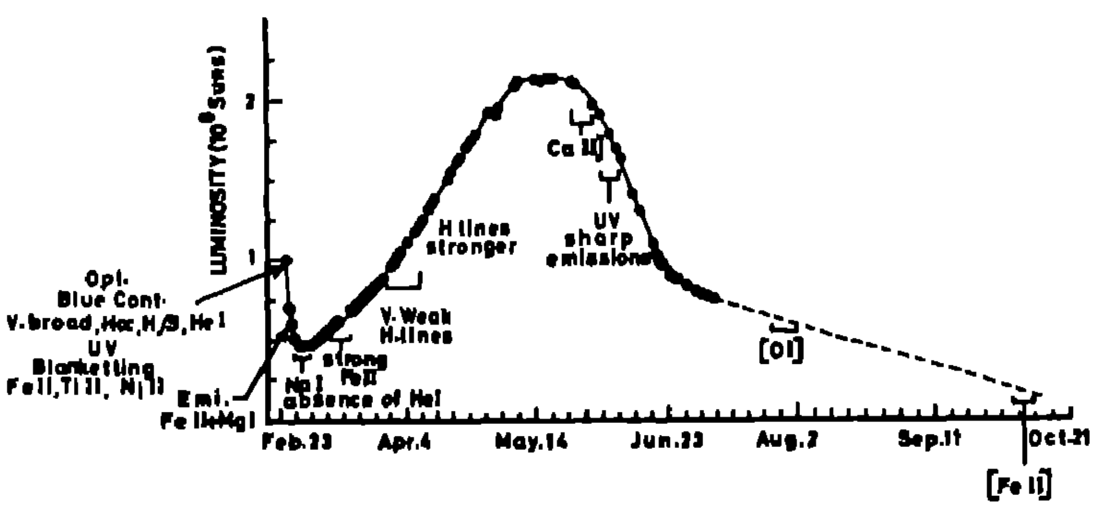

Fig. 1 Light curve prominent spectroscopic changes an indicated.

Early Observations

The initial optical and UV spectra just after the discovery of outburst showed very blue continuum. Only by February 25, 1987 the P Cygni type structure could be discerned in Balmer lines and the expansion velocities measured. The expansion velocity deduced from H α profile was initially as high as 30,000 kms^{-1} which declined very rapidly by about 800 kms^{-1} a day (Ashoka et al. 1987, Danziger et al. 1987). This radial velocity is about twice as large of a typical type II supernova as the rate of decline is about 11 times faster than the typical value of 69 kms^{-1} per day. After 5-7 days the metal lines started to appear, lines of FeII, MgI, NaI etc., which showed much smaller radial velocity conforming with the picture that the velocity is proportional with the radius. The correspondence of radial velocities derived from the metal lines and the photospheric velocity inferred from photometry does confirm that the metal lines form close to the photosphere. The polarization measurements of selected spectral lines and H α (obtained at AAT) does show that the scattering is responsible for the spectral lines (Cropper et al. 1987). As the photospheric temperature lessened, the metal lines started getting stronger and the hydrogen lines, particularly the Balmer lines became weaker during late March and beginning of April. 35-41 days after the explosion, H β, Hγ etc., cannot even be identified either as absorption or emission features. The H α profile shows several asymmetries particularly a hump occurred at λ 6640A around March 23 roughly at the same time as the appearance of the so called mystry spot and did disappear at about the same time as the fading of the spot in April. If this is attributed to H α emission of the spot, then the radial velocity is about 5360 kms^{-1}.

In addition, around March 30, the Hα profile showed interesting structure particularly the two emission peaks on either side of the expected line centre in Hα . These might be identifications of deviations from a symmetric gasflow or asymmetric clumps in the ejecta.

The CaII triplet line at λ 8600 is of particular interest. Strong emission (P-Cygni type) blend appears from Feb 25, 1987 and gains strength with time. Obviously it is blended with other lines. Particularly the central wavelength of the blend is shifted towards red by an amount much larger than expected (at λ8780). For the spectra obtained on March 30, 1987 (at the time when hydrogen Balmer and Paschen line emission is very weak or absent) Ashoka et al. (1987) suggested from the anology with the spectra of supergiants that NI lines are the dominant blends for the CaII triplet. These lines being of high excitation potential implied that nitrogen might be enhanced in outer envelope of the presupernova star. This in turn indicates that it might have gone through CNO processing. Also the fact that this material been brought out indicates extensive mixing (probably due to a deep convection zone) implying the star has passed through a red supergiant stage.

Later appearances of the sharp emission lines of NIII, NIV, NV in ultraviolet spectral region coming from the circumstellar material photoionized due to the UV flux of the supernova also showed that nitrogen is enhanced and the surface layers of the presupernova star has undergone CN processing (Cassetella et al. 1987). It is worthwhile analysing the observations of Ashoka et al. (1987) using the synthetic spectra to confirm and estimate independently the nitrogen abundance.

Some absorption lines have been identified by Williams (1987) for March 1987 spectra as due to s-process elements like Ba II, Sr II etc. Particularly, lines at λ 6070 and the blend to NaI D lines as due to BaII. Although, no quantitative estimates are available, these identifications (if real) might even suggest the over abundance of s-process elements. Although the identification seems to be convincing, the further development of the spectrum does indicate a complex picture and the interpretation is not as straightforward (see Fig.2). The Balmer lines after being weak during March-April 1987, start getting stronger again. The reason for this behaviour is not very clear (however see Dopital 1988). The H β shows more P Cygni structure by June-July and the forbidden lines start making their appearance by the middle of June; the [CaII] feature at λ7300 starts appearing and gains strengths gradually. Also the [OI] lines at λ6300 and λ6363 star appearing. These changes in the spectrum indicate gradual change in the electron density in the ejecta (Anupama et al. 1988) from $>10^9$ to 10^8 by August and 10^7, when lines due to [FeII] λ7155 start appearing.

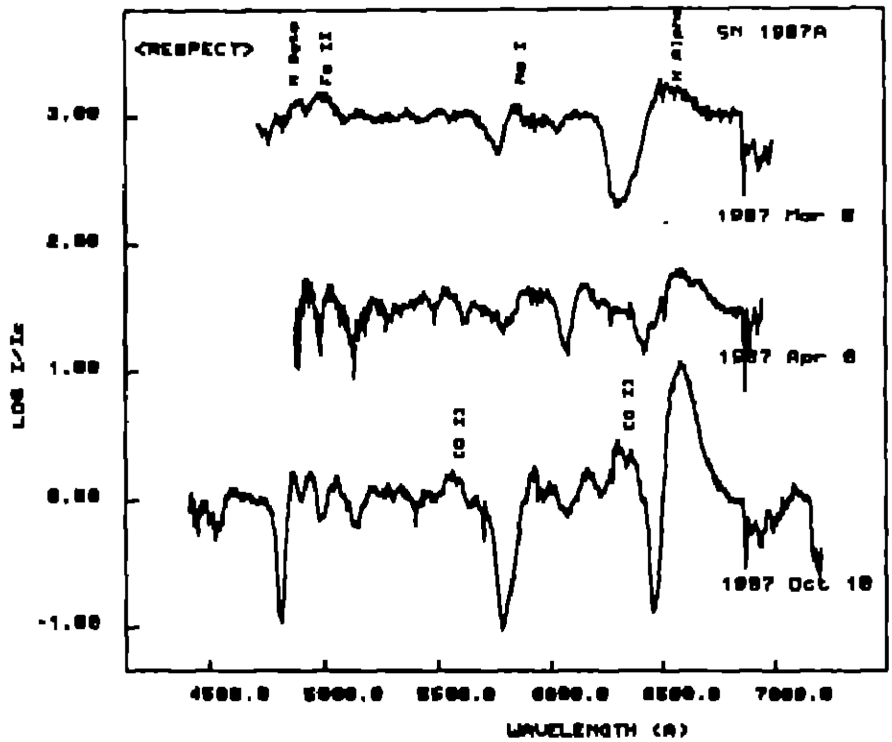

Fig. 2 Sample VBO spectra.

Late time spectrum

The spectrum appears to change very slowly, by mid June [CaII] at 7300A and by July end and beginning of August [OI] λ6300 starts making appearance (Anupama et al. 1988). [OII] has been detected by Hearnshaw et al. (1988) during August 7-September beginning. By September 17, it is quite strong. The simple calculation show the $Ne \sim 10^8$. Slowly the continuum is getting weaker and the emission lines start becoming dominant.

As the forbidden lines are getting stronger the Hα is getting narrower and the P Cygni absorption is getting weaker. Radial velocities however, have not changed much. The Hβ line makes its reappearance from May 1987.

The spectra in IR (Oliva et al. 1987) region shows that most of the hydrogen lines of Paschen, Brackett and higher series follows case B recombination theory. Oliva et al. (1987) could identify [Fe II] in the IR region. There is a strong feature approximately at λ7155 possibly due to [Fe II] blended with atmospheric H_2O. The permitted lines (Hα etc.) show red shifts of 480 kms^{-1}. But the [OI] lines in the optical region show no such shifts, the line centre almost occurs at the expected wavelength. Moreover, the profiles look flat topped (as is expected for optically thin lines).

It is particularly of interest to compare the late time spectrum with other type II supernovae. Usually the strongest emission is H α line and the late time observations showed the exponential decay of radiation around 108 day. The spectrum is dominated by emission lines of hydrogen and strong absorption lines of FeII, MgI, NaI. The light curve shows the radiation is powered by radioactive decay of ^{56}Co. Fransson and Chevalier (1987) made comparison based on the early observations about the nature of the late time spectra powered by the γ-rays generated from the ^{56}Co decay.

We compared the flux obtained from the VBO spectra using the published wide band photometry at 310 days after outburst with the expected line fluxes computed by Fransson and Chevalier (1987) for 300 days after outburst for different models with initial mass of 25 and 15 $M_{\odot}$ on ZAMS. Predicted luminosity relative to [OI] λλ6300 - 6364 Å for strong lines for models of 25 $M_{\odot}$ and 15 $M_{\odot}$ at 300 days are given in the table along with VBO observations.

Predicted luminosities relative to [OI] λλ6300 - 6364 Å for strong lines for models at 25 $m_{\odot}$ and 15 $m_{\odot}$ at 300 days along with VBO observations

Parameter	mass ($m_{\odot}$) 25	ZAMS 15	VBO Observations 30 Dec.87 (310 days)
V_c(Km s^{-1})	2640	1200	
M(^{56}Ni) m_e	0.28	0.10	
L(6300, 64) erg s^{-1}	2.38×10^{40}	3.32×10^{39}	$3.67\text{-}5.54\times10^{39}$
[OI] 6300, 6364	1.0	1.0	1.0
[OI] 5577	0.015	0.42	0.035-0.023
[CaII] 7291-7332	0.11	1.58	2.92-3.1
CaII 8498-8662	0.09	1.27	0.90-0.71
OI 7774	0.09	0.21	0.05
[Mg I] 4571	0.63	1.43	0.05
[Ca] 8727	0.21	0.52	0.1

Assuming the distance of LMC as 55 Kpc and E(B-V) = 0.20

The above comparison indicates a progenitor mass ~18 $m_{\odot}$.

However, the lines fluxes of [MgI] and [CI] are inconsistent. These theoretical results computed by Fransson and Chevalier (1987) are sensitive to the core velocity and the density distributions. At this stage hydrodynamical models predict that oxygen region should be geometrically a thin shell giving a flat topped profile. Observed [OI] lines do show such a profile.

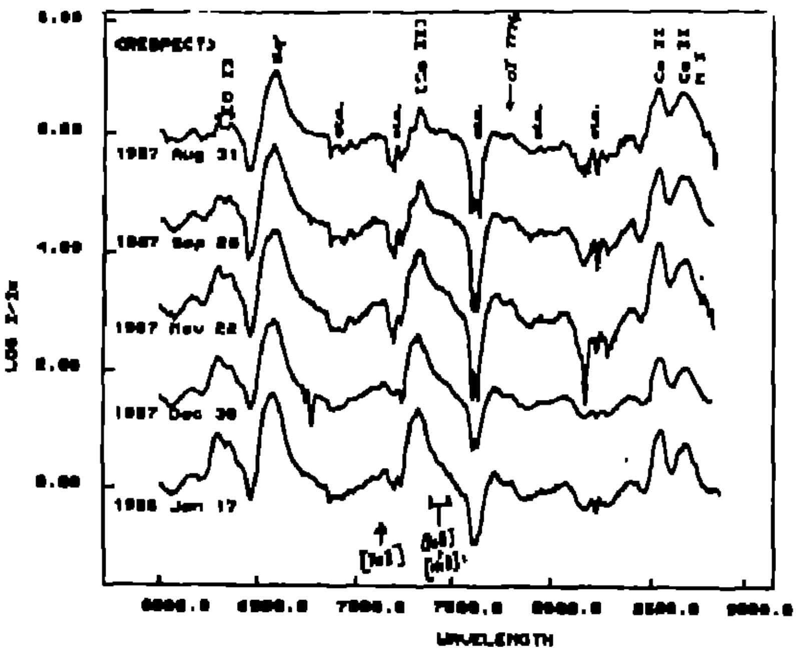

Fig. 3 Sample VBO spectra.

If the emission feature at ~ λ 7774 is mostly due to OI λ 7774, then the attempt can be made at estimating the O^+/H^+ ratio by using the infrared Paschen lines of HI. Oliva et al. (1987) show that Paschen lines intensities on October 3 follow case B recombination theory; assuming that OI λ7774 is purely a recombination line. The O^+/H^+ is estimated as about 0.02 based on spectra obtained between 26 September and 3rd December 1987.

The late time evolution of spectrum would be dictated by the cooling rates and would be interesting to see whether ^{56}Co decay is the only source for the line emission.

Finally we would like to mention about the spectrum of the progenitor star (SK -69° 202) in the optical region. Rao & Vasundhara (in preparation) traced the spectrum on the UK Schmidt objective prism plate at a dispersion of 400 A/mm at Hγ. The spectrum seems to support the conclusion of Gonzales et al. (1987) that NII lines might have been enhanced in SK -69° 202 when compared to other B3Ia supergiants.

I would like to thank many of my colleagues at IIA for allowing me to mention some of our joint work which is in preparation for publication.

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