

## SUPERNOVA 1987A IN LMC : INFRARED OBSERVATIONS

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### ABSTRACT

Results obtained from infrared observations of SN 1987A have been summarized. The supernova developed near-infrared excesses with a characteristic temperature  $\sim 1250$  K beginning around March 15, 1987. Infrared speckle interferometry began to partially resolve the supernova from mid-June, and on August 6 a fully resolved structure ( $\sim 0.42$  arc second) was observed, consistent only with a light echo. Infrared spectroscopy in early October showed that all the lines and the molecular CO bands were redshifted with respect to the LMC by  $\sim 400$ - $1500$  Km/sec. . The dust responsible for the infrared light echo is expected to thermally reemit at far-infrared wavelengths ( $\sim 30 \mu\text{m}$ ) which should be looked for.

### 1. Introduction

Since its discovery by Ian Shelton on February 24, 1987 the supernova (SN) in the Large Magellanic Cloud (LMC) SN 1987A has been subjected to measurement with every possible instrument in all parts of the electromagnetic spectrum. Observations in the infrared (IR) are of particular importance for the possible detection of excess radiation at these wavelengths ( $\lambda \sim 1 - 100 \mu\text{m}$ ) coming from the circumstellar dust that might exist surrounding the supernova progenitor. Dust may also form in the supernova ejecta. Free-free emission from the

ionised gases and infrared emission lines and bands can also contribute to the infrared excesses. Important information about the mass loss from the progenitor star and about the ejecta can be derived from the infrared measurements. The following is a summary of the principal results that have become known by January, 1988.

## 2. Pre-outburst IR measurements

Astrometry of SN 1987A and Sanduleak - 69° 202 (West et al., 1987, White and Malin, 1987) has confirmed the positional near-coincidence between the SN and star 1 of Sk- 69° 202, strongly suggesting that the B3Ia type star Sk-69° 202 (star 1) was the SN progenitor. The only information available about the pre-outburst infrared characteristics of Sk- 69 202 consists of :

- (i) The red (R) and infrared (I) magnitudes determined from photographic images (Blanco, 1987) :  $R = 12.02 \pm 0.01$ ,  $I = 12.06 \pm 0.03$ . These are consistent with the UBV magnitudes and reddening  $E(B-V) = 0.17$  for a B3Ia star after removing the contributions of stars 2 and 3 in the Sk- 69° 202 system. The presence, in the system Sk- 69° 202, of any cool luminous star of type MI-III can be ruled out.
- (ii) IRAS (Infrared Astronomical Satellite) scans of the region around Sk- 69° 202 in 1983 did not show any signal (in the range  $\lambda \sim 10-100 \mu\text{m}$ ) indicating that the progenitor was not a bright dust-shrouded object.

Thus the pre-outburst infrared characteristics of the SN progenitor suggest that it was not a cool luminous star with extensive circumstellar envelope and that the blue star Sk- 69° 202 (star 1) of B3Ia type exploded in the LMC to produce SN 1987A.

## 3. Postoutburst IR observations

A large number of IR measurements have been made since the announcement of the SN outburst on February 24, 1987. These include: photometry, spectrophotometry, spectroscopy, polarimetry and speckle-interferometry.

### 3.1. IR photometry and spectrophotometry

Results from broad-band (J,H,K,L,L',M,N,Q bands at 1.2, 1.6, 2.2,

3.6, 3.8, 4.8, 10, 20  $\mu\text{m}$ ) infrared photometry (Bouchet et al., 1987a, Menzies et al., 1987, Catchpole et al., 1987) can be summarized as follows.

### 3.2 IR light curve

In the near-infrared ( $\lambda \sim 1\text{-}5 \mu\text{m}$ ) the SN light curve showed a behaviour similar to that in the visual (V band at  $0.55 \mu\text{m}$ ). The SN brightness increased in all the bands (J H K L M) monotonically until the end of May, 1987 when maximum brightness was reached around day 90 from the outburst. The bolometric luminosity also reached peak at about the same time. In fact, as the SN cooled, the IR radiation contributed more and more to the bolometric luminosity. The post-maximum brightness declined with a decay time similar to the radioactive decay time (111 days) of  $^{56}\text{Co}$ . The colours have been progressively becoming redder as a consequence of cooling and the appearance of infrared excesses at longer wavelengths as discussed below.

### 3.3 Spectral energy distribution

For the first two weeks the spectral energy distribution in the infrared could be well fit by a single temperature ( $T_1$ ) blackbody emission. In fact during this early phase the IR continuum is a better indicator of the photosphere temperature than the flux distribution in the optical region which is strongly influenced by spectral features.

Infrared excess radiation first appeared around March 15, 1987. From then on an additional second cool (temperature  $T_2$ ) blackbody component is needed to fit the spectral energy distribution beyond about  $2 \mu\text{m}$ .

The temperature  $T_1$  decreased rapidly from  $\sim 14000 \text{ K}$  (day 1.5) to  $\sim 6000 \text{ K}$  (day 10.5) in the beginning and then settled to  $\sim 5900 \text{ K}$  in about a month where it remained for the next two months. From the beginning of June it further decreased at a slow rate. The temperature  $T_2$ , characterising the infrared excess, on the other hand did not require any significant change from a value  $\sim 1250 \text{ K}$ .

Emission lines and bands could also contribute to the infrared excesses observed in the photometric bands. However, spectrophotometric

measurements (Bouchet et al., 1987b, Aitken et al., 1987) in the range  $\lambda = 1-14 \mu\text{m}$  confirm the existence of excess radiation in the infrared continuum with the colour temperature  $\sim 1200$  K. There is no evidence for the dust emission features at  $3.3 \mu\text{m}$  and  $9.7 \mu\text{m}$  characteristic of dust dominated by carbon or silicates.

Two possible interpretations of the IR excess are: free-free emission from the SN ejecta and thermal emission from heated dust. The free-free emission mechanism requires a high luminosity ( $\sim 5 \times 10^{42}$  erg/sec) of ionising ultraviolet photons, which is much larger than what is available. Electron scattering could lower the required ultraviolet luminosity. If the IR excess is due to thermal emission from heated dust then the dust temperature  $T \sim 1250$  K and the observed IR excess flux implies a dust mass  $M_d \sim 7 \times 10^{-6} (L_{\text{IR}} / 10^7 L_{\odot}) M_{\odot}$  where  $L_{\text{IR}}$  is the excess infrared luminosity (Bouchet et al., 1987a). The IR excess radiation could come either from dust that has condensed in the SN ejecta or from that which pre-existed in the regions surrounding the SN progenitor and is heated by the radiation from the SN (the infrared echo model (e.g. Dwek, 1983)).

If the dust is heated by the SN light, then the observed dust temperature  $T \sim 1250$  K implies, for typical interstellar dust parameters, that the dust is located at radial distances from the SN of  $\sim 10^{16}$  cm. Since the SN progenitor was a blue supergiant (B3Ia) it is unlikely that the dust condensed from the low density, fast wind (expansion speed  $\sim 10^3$  Km/sec) in the evolutionary phase immediately preceding the SN outburst. Dust could have formed in the high density, slow stellar wind (expansion speed  $\sim 10$  Km/sec) during the red supergiant phase (Renzini, 1987). If  $\Delta t$  is the time since the star left the red supergiant phase, the remnant wind would have reached a distance  $\sim 3 \times 10^{18} (v_{\text{exp}} / 10 \text{ Km/sec}) (\Delta t / 10^5 \text{ yr})$  cm. But at such distances the equilibrium dust temperature would be  $\sim 100$  K, much lower than the observed temperature  $\sim 1250$  K which will require  $\Delta t \sim 10^3$  yr. This is a short time indeed!

The IR excess could come from dust that condensed from the SN ejecta. With an outflow speed  $v_{\text{out}} \sim 18000$  Km/sec it would require  $\sim 100$  days to reach the appropriate distances ( $\sim 2 \times 10^{16}$  cm). The IR excess in June, 1987 could be explained thus, but the early appearan-

ce (by March 15, 1987) of IR excess requires that some material was ejected at very high velocities ( $\sim 4-5$  times  $v_{\text{out}}$ ) and dust managed to condense from it.

### 3.4 Infrared spectroscopy

Spectroscopic measurements in the infrared (Bouchet et al., 1987b, Larson et al., 1987, Witteborn et al., 1987, Oliva et al., 1987) have resulted in the detection of a large number of emission lines, bands and features. The spectra are dominated by hydrogen lines. Some emission features are yet to be identified.

IR spectroscopy during the period from March 1 to June 27 (Bouchet et al., 1987 b, Larson et al., 1987, Witteborn et al., 1987) showed mainly the hydrogen recombination lines, the strongest being Pa- $\alpha$  (1.88  $\mu\text{m}$ ), Br- $\alpha$  (4.05  $\mu\text{m}$ ), Pf- $\alpha$  (7.46  $\mu\text{m}$ ), Hu - $\alpha$  (12.37  $\mu\text{m}$ ) and other lines of these series. The line intensities increased with time. The relative intensities are close to those expected for a case B recombination spectrum. The  $\lambda = 1.083$   $\mu\text{m}$  line of He was seen in absorption in late May, but its 2.058  $\mu\text{m}$  line remained undetected. All the lines were broad with velocity widths ranging from  $\sim 7000$  Km/sec to  $\sim 3000$  Km/sec. Features at  $\lambda = 1.61, 1.65, 3.11, 3.34, 11.8$   $\mu\text{m}$  could not be identified.

During October 5-8, 1987 the 1-5  $\mu\text{m}$  spectra showed some unique characteristics (Oliva et al., 1987). A strikingly large number of lines are now present. Around 20 hydrogen recombination lines are identified. Helium lines at 1.083  $\mu\text{m}$  and 2.058  $\mu\text{m}$  are detected. The [FeII] lines at 1.257  $\mu\text{m}$  and 1.644  $\mu\text{m}$  are present. Lines of a number of neutral atoms (eg. OI, SI, NaI, MgI) are also present. The fundamental band of molecular CO at 4.6  $\mu\text{m}$  dominates the emission in the M band and its first overtone band dominates emission between 2.3 and 2.5  $\mu\text{m}$ . All the lines are broad with typical FWHM  $\sim 3000$  Km/sec. The emission peaks are redshifted by  $\sim 400-1500$  Km/sec with respect to the systemic velocity of the LMC. The helium lines exhibit P Cygni profiles whereas the hydrogen lines do not. The relative strengths of the resolved CO bands in the 2.3-2.4  $\mu\text{m}$  region lead to crude estimates for the temperature and the CO mass as:  $T \sim 2000\text{K}$  and  $M_{\text{CO}} \sim 2 \times 10^{-4} M_{\odot}$ . The [Fe II] line intensities imply a large

(but uncertain) mass  $\simeq 0.04 M_{\odot}$  of  $\text{Fe}^+$ . Far-infrared observations from Kuiper Airborne Observatory on November 4 and 7, 1987 (Erickson et al., 1987) yielded a probable detection of [Fe II] line at  $25.98 \mu\text{m}$  with FWHM  $\sim 3000\text{-}5000 \text{ Km/sec}$ , whose other possible identifications are: [O IV] ( $25.87 \mu\text{m}$ ) or [Fe V] ( $25.92 \mu\text{m}$ ).

### 3.5 Infrared polarimetry

Polarization measurement in the near-infrared bands (J,H,K) have been reported by Cropper et al., (1987) and Bailey et al., (1987). These, together with their polarization measurements in the visual (V band) are given in Table 1 where the numbers in the parentheses give the errors in the last significant digits. P is percent polarization and  $\Theta$  is the position angle in degrees.

Table 1  
Polarization measurements of SN 1987A

Date 1987		V	J	H	K
Feb. 25 Cropper et al. (1987)	P	0.83(8)	0.62(6)	0.52(7)	0.49(12)
	$\Theta$	46(4)	43(3)	50(4)	44(8)
Mar. 21 Bailey et al. (1987)	P	0.49(7)	0.28(6)	0.21(6)	0.21(3)
	$\Theta$	47(5)	78(8)	94(8)	96(4)

Soon after the outburst the polarization in all the bands was much higher than that expected due to interstellar dust in the direction of the supernova. The polarization decreased by about a factor of two from February, 25 to March 21, 1987. The polarization position angle in the IR bands, on February 25, was similar to that in the visual, but on March 21 the IR polarization position angles were very different from that in the visual which did not vary much. It is interesting to note that the IR excesses had begun to appear in the near-infrared by the time the second set of polarization observations were made.

### 3.6 Infrared speckle interferometry

Speckle-interferometry in the infrared could directly resolve any possible infrared emitting dust shell around the progenitor. Results of IR (K, L', M bands) speckle interferometry have been reported by Perrier et al. (1987) and Chalabaev et al. (1987). Observations in early May and June 1987 did not show the mystery spot observed in the visible light. Beginning from mid-June ( $\sim$  day 115) a barely resolved structure appeared in the L' ( $3.8 \mu\text{m}$ ) band. Observations on August 6, 1987 confirm that the SN is definitely resolved in the IR ( $2.2$  to  $4.6 \mu\text{m}$ ) and are consistent with a ring like structure of  $\sim 0.42$  arc second diameter. At the distance of the LMC this corresponds to  $\sim 6 \times 10^{17}$  cm and requires a projected velocity  $\sim 0.4c$ . This is consistent only with a light echo. The resolved structures contribute only about 2.5 to 3% of the total flux in the IR bands. The observed near-infrared excesses therefore do not come from a light echo, but from either the ejecta or regions immediately surrounding the ejecta.

### 4. Discussion and conclusions

Infrared observations of SN 1987A have yielded important information about the nature of the supernova progenitor, the outburst, the ejecta and its circumstellar environs. Infrared photometry has made it possible to construct the bolometric light curve for the SN. The appearance of near-infrared excesses by around March 15, 1987 was recognized. Infrared spectroscopic measurements detected a large number of ionic, atomic and molecular emission features and some peculiar kinematic motions and abundances. Polarimetric measurements show that the SN outburst was not spherically symmetric. Light echo from distant circumstellar matter was detected most directly by infrared speckle-interferometric measurements. Some of the important points that have emerged are the following:

- (1) There is no evidence for significant circumstellar matter pre-existing close to the progenitor star.
- (2) IR measurements detected excess radiation in the near-infrared with a characteristic temperature  $\sim 1200$  K beginning March 15, 1987. This is consistent with the type II nature of the SN as only type II SN have been found to develop IR excesses in the near-infrared (e.g. Bode 1982). However, the IR excesses

developed too early ( $\leq 20$  days) in SN 1987A. In other type II SN IR excesses have never been detected before about 50 days.

- (3) It is not yet clear whether the IR excess is due to free-free emission or due to thermal emission from dust. It is to be noted that spectrophotometry has not shown any of the familiar dust features in the infrared at  $3.3 \mu\text{m}$  and  $9.7 \mu\text{m}$ .
- (4) IR spectroscopy has detected a large number of emission features due to ions, atoms and molecules. The hydrogen lines have relative intensities consistent with case B recombination spectrum. A preliminary estimate for the  $\text{Fe}^+$  abundance gives a large value ; mass of  $\text{Fe}^+ \sim 0.04 M_{\odot}$  in  $\sim 10 M_{\odot}$  ejecta.
- (5) In early October, 1987 all the IR lines and the CO bands were redshifted with respect to the LMC by  $\sim 400$ - $1500$  km/sec. This is a unique feature that is yet to be understood.
- (6) IR speckle interferometry on August 6, 1987 clearly resolved the SN in the near-infrared. The observations are consistent with a ring structure of  $\sim 0.42$  arc second diameter and imply the detection of a light echo from dust at  $\sim 3 \times 10^{17}$  cm from the SN. This, however, does not significantly contribute to the near-infrared excesses. The dust responsible for the light echo would radiate thermal infrared radiation at longer wavelengths ( $\sim 30 \mu\text{m}$ ) that should be looked for.

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