SN1987A at 18 Years: Ejecta-Ring Interaction

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Abstract. After 18 years the outer parts of the ejecta of SNl 987A are interacting with the inner ring. This ejecta-ring interaction is the source of most of the activity associated with the supernova. The physical effects are detectable at all accessible wavelengths. Some of these are described with particular focus on IR radiation associated with dust.

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INTRODUCTION

The present physical situation (to first order) with SN1987A is as follows: The ejecta, with its inherent density gradient, is expanding into the circumstellar medium (CSM) which consists of an ambient interstellar medium (ISM) overlaid with the remnants of both a red and blue supergiant wind both of which must have structural inhomogeneities as well as departures from 3-dimensional symmetry. The associated forward and reverse shocks are generating radiation at various wavelengths by various mechanisms. The presence of dust in the ejecta and in the CSM further complicates the picture. The ultimate aim is to decode all the observed effects. Here we concentrate on the dust and how it manifests itself. We note that at the time of this meeting SN1987A was about 7050 days from the time of explosion. We will be discussing IR observations made with Gemini South, CTIO 4m, Spitzer, optical observations with HST and also referring to Xray observations from Chandra, and radio observations from ATNF and MOST.

MORPHOLOGY OF THE RING STRUCTURE

In he past 3 years ground-based imaging observations have been successful in resolving the inner ring structure.

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Mid-IR Imaging

Mid-IR imaging observations were made near day 6067 [1] and days 6526, 6552 with T-ReCS on Gemini South. All these observations clearly resolved the inner ring thus providing spatial information. The latter set of images with the SiII 11.7 and Qa 18.3μm band filters allow one to map the colour temperature (assuming, for simplicity, black body emission) and the optical depth. There appear to be systematic changes of this temperature over the ring, with a range of 130-180K with the hotter regions tending to lie closer to the centre. There also appears to be a systematic variation in the optical depth but all optical depths are extremely small. The two sets of observations also allow one to see that temporal variations in the morphology have occurred over the interval of approximately 470 days. The changes have been quantified by overlaying flux calibrated images.

It would seem that the overall size of the ring has not changed, but there are significant changes in the brightness distribution. In particular there has been a noticeable brightening in the south west sector of the ring. Since these later observations were made with the SiII 11.7μm filter and the earlier with an N-band filter there was concern that the former filter was transmitting [NeII]12.8μm line radiation while the N-band did not. Observations with Spitzer discussed later showed however that this was not the case. Overlays of almost coeval images obtained with ACIS (Chandra) and the 11.7 and 18.3μm images reveal a general correlation with shape and size and even to some extent with brightness distribution, although higher spatial resolution in both sets of images would be desirable in order to draw significant conclusions from the images alone. A comparison with ATNF imaging at 12mm suffers again from lack of sufficient resolution of detail which might also hide small temporal changes. Nevertheless a tendency for enhanced brightening on the eastern side is apparent.

Near IR Imaging

Imaging observations through J,H,K band filters were made at day 6524 with IPSI on the Blanco 4m telescope at CTIO. They may be compared with HST images through similar filters taken on day 6836. Both sets of images show the ring. However the H-band clearly shows a central condensation stronger relative to the ring emission. The HST image shows that this resolved central condensation is asymmetric elongated roughly north-south.

Lacking IR spectroscopy we would conjecture that the emission from this central part is due to line emission from low excitation ions in the ejecta for example from FeII. The ring emission is surely also from line emission from more highly excited ions including H and He and perhaps even coronal lines. The dust does not have a high enough temperature to be emitting continuous radiation at these wavelengths. Nevertheless one should not overlook the possibility of a contribution from synchrotron radiation particularly in the K-band as has been suggested for CasA [3].

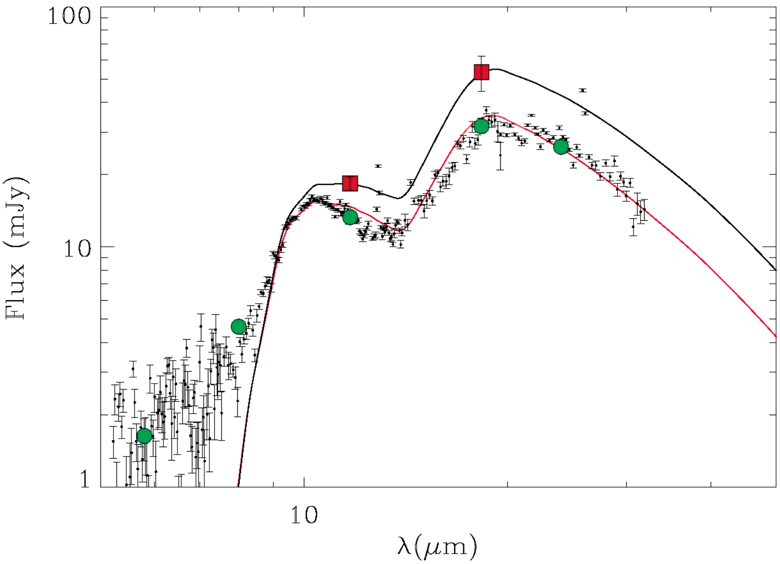

FIGURE 1. The spectrum from Spitzer is overlaid with the best fit model for silicate grains. The squares are the broad-band data from T-ReCS and the circles are the broad-band data from Spitzer. The Spitzer observations were made earlier (6190 days) than T-ReCS, thus an increase in IR luminosity has occurred.

SPITZER OBSERVATIONS

Spectra and photometry of SN1987A were obtained with Spitzer prior to the most recent T-ReCS data [2]. The IR spectra were essential in identifying the composition of the dust in the ring. This is because the 2 broad band points measured near 10 and 18 microns can be made to fit emission from graphite, silicon or carbon.

However the mass absorption coefficient for silicates has the well known peaks near 10 and 18 microns. This has resulted in the observed Spitzer spectrum of Figure 1 together with a best model fit to silicate grain emission. The quality of this fit precludes virtually no emission component from other grain types. The figure also shows that the grain emission was increasing with time. The temperature for the integrated spectrum is 180K with uncertainy of 20K. The dust mass is M(dust) = 1.1+0.8-0.5 $\times 10^{-6} M_{\odot}$. These results are quantitatively consistent with those obtained using only T-ReCS data. The Spitzer spectra also revealed relatively narrow emission lines of [OIV], [NeII], [NeIII], [NeV], [FIV], [SiII] and [FeII] the presence of none of these affecting the above conclusions. Improved s/n for some of these lines will provide diagnostic criteria for the gas near the SN.

THE DUST HEATING MECHANISM

The heating mechanism for the dust must depend on the location of the dust. We have considered: 1. dust located in the X-ray emitting gas, and 2. dust in the optical knots. In both cases one can estimate the dominant cooling mechanism, dust temperature and dust mass to be consistent with observations.

X-Ray emitting gas

In this environment one can show that dust heating is dominated by electron collisions. A computed series of contours of dust temperature as a function of plasma tempeature and density reveals the following important results. Dust temperature T(dust) is independent of grain size. For T(plasma) > 3×10^6, T(dust) is independent of T(plasma) but an indicator of density Ne. Using values of T(plasma) $> 3 \times 10^6$ indicative from Chandra, and T(dust) 150-200K from our IR observations, one obtains Ne in the range 300-1400cm^{-3} consistent with a Chandra 2-component (0.23-2.2 keV) analysis [4].

There is however a useful diagnostic ratio of IR/X-ray flux which theoretically should be in the range 10-400 for T(plasma) in the range $10^6 - 10^8$K. In fact for galactic SNRs this ratio is » 1, but for SN1987A it is $\sim$ 1. This apparent lower dust/gas mass ratio might be caused by: a. lower grain condensation in the ring. or b. grain destruction by thermal sputtering. It can therefore be inferred that IR radiation is not the dominant cooling mechanism of the shocked gas. It can also be shown that the dust probably maintains an equilibrium temperature.

Optical knots

One can first overlay both the 11.7μm and the 18.3μm images with an HST F625W image. Even when the HST image is convolved to match the resolution of the T-ReCS images a good point by point correlation is not apparent. However when the T-ReCS 11.7μm image is deconvolved using a maximum entropy algorithm there is a noticeably improved point by point correlation of most features.This therefore encourages the belief that most of the IR radiation is in fact coming from the knots.

Therefore we have used a published [5] model of Spot 1 to argue that most dust resides in unshocked gas heated by radiation from the cooling shocked gas. A compression of the radiation field in a knot leads to T(dust) $\sim$ 125K reasonably consistent with the observed average. Here the dust/gas mass ratio is 10 times lower than the local ISM. Furthermore destruction of grains by transmitted shocks would predict higher IR emission in the past, contrary to observation.

LIGHT CURVES AT DIFFERENT FREQUENCIES

We illustrate the more recent ejecta-wind interaction with Figure 2 where radio, X-ray and IR light curves are plotted. A more careful perusal than is possible in this

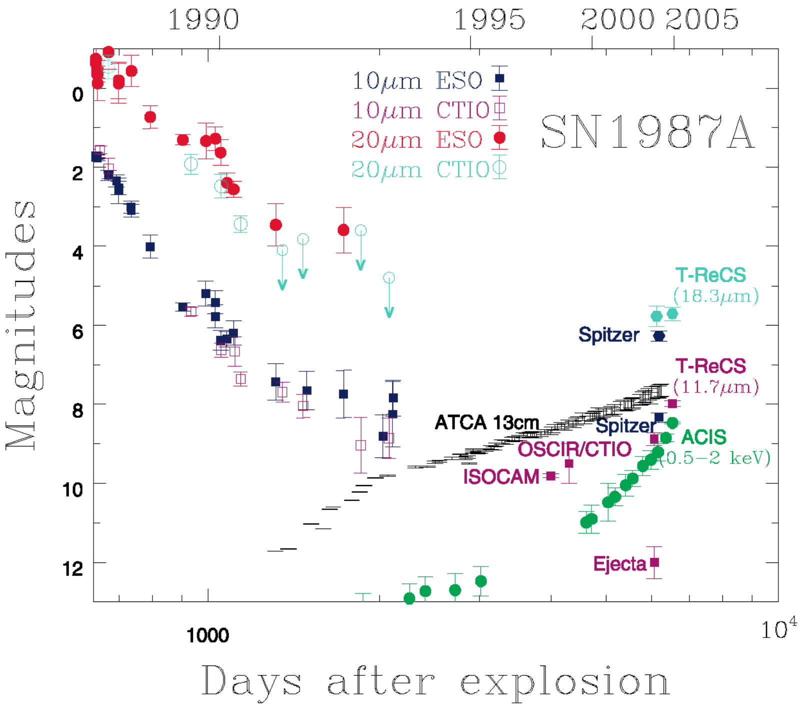

FIGURE 2. Observed light curves at late times. X-ray data is from Rosat < 4000days and ACIS (Chandra) > 4000days. Radio 13cm points are from ATCA. Note the one late point for IR emission from the ejecta.

crowded figure reveals significant changes at all frequencies. Near 3800-4000 days the IR emission starts to increase as a result of heating of dust in the ring. The first brightening of an optical knot occurs at this time. After 4000 days the IR from the ring dominates IR from the ejecta. In fact the last recorded IR detection of the ejecta is seen at the lower right slightly later than 6000days. It results from dust in the ejecta presumably heated by radioactive decay of ^{57}Co and ^{44}Ti. The increasing tempo of brightening, albeit somewhat more subtly, also occurred at radio wavelengths observed with ATCA and MOST.

The more striking increase at all wavelengths has occurred near 6000 days. Observations at all frequencies show not only an increase but an increase in the derivative. The closely spaced X-ray and MOST (843Mhz) observations illustrate this latter fact best. This is surely caused by denser parts of the ejecta penetrating denser parts of the ring. We await further brightening!

SUMMARY

1. Silicate dust is the main source of IR emission from the ring. There is little evidence for the presence of other dust grains.

2. A comparison with Chandra and HST images shows a correlation between the 11.7μm IR and X-ray and UV-optical images. Because of the limited spatial resolution of the IR images we cannot determine the location of the heating mechanism of the dust.

3. The dust could be in a hot $\sim 10^7$K gas and collisionally heated by the X-ray emitting plasma. In this case the dust temperature is a good diagnostic of the electron density yielding values in the range 300 - 1400cm^{-3}.

4. A comparison of IR and X-ray fluxes suggests the dust is depleted by x30 in the X-ray gas compared to the ISM of the LMC. If this is due to destruction by thermal sputtering in the shocked gas, the grain radii must be < 50Å.

5. An alternative is dust residing in the UV-optical knots in the ring and radiatively heated by cooling gas excited by shocks. A comparison with the mass of the knots shows that the dust-to-gas mass ratio is lower by x10 compared to that of the LMC. One might speculate that there has been a lower condensation efficiency in a metal-poor progenitor wind.

CONCLUSIONS

With further work we would like to know or understand the following issues.

1. The heating mechanism of the dust.
2. Why the apparent low dust/gas ratio.
3. A more detailed composition of the dust.
4. Will the dust survive the passage of the shock and being heated.

And more generally:

5. The structure of the red and blue supergiant winds.
6. The origin of the radio, and the hard and soft X-rays.

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