

IR Imaging of SN1987A

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Abstract. We present IR imaging observations obtained at various phases in the evolution of SN1987A. They have been obtained with ground-based telescopes in Chile. Some of the early and late ones have not been shown before. Particular emphasis is placed on the recently resolved mid-IR images showing dust in the inner ring being heated by the interaction with the ejecta. Some of its properties are elaborated as well as the importance of such observations now and in the future. Attention is also drawn to the IR emission from the central ejecta and its behaviour. Temporal variations are highlighted.

Keywords: infrared, imaging, dust, light curves, interaction

PACS: 97.60.Bw, 98.38.Jw, 98.38.Mz, 98.55.Mj

INTRODUCTION

Since the main thrust of this talk concerns dust in SNe, it is appropriate to summarize questions relating to this subject. They are as follows:

1. Do SNe produce most of the dust in our Galaxy and in IR galaxies at high redshifts.
2. Is most of the dust formed in the SN envelope or in the CSM formed before the explosion.
3. What is the composition of the dust.
4. Do all core-collapse SNe produce dust. There are now a handful of bona fide cases.
5. Why are there differences in phase after explosion for dust production.
6. Why are there apparent differences in concentration of dust in SN envelopes.
7. Do predicted blackouts occur as a result of dust production.
8. Does dust survive the SN environment.

Some of these questions can be addressed and possibly answered by studying SN1987A.

In the following we show results from ESO, CTIO and Gemini South covering a wide range of epochs and confined to the near-IR and mid-IR spectral regions. There is added importance to this if solely because only a little space-based IR imaging has been obtained and not extending over a wide temporal base-line.

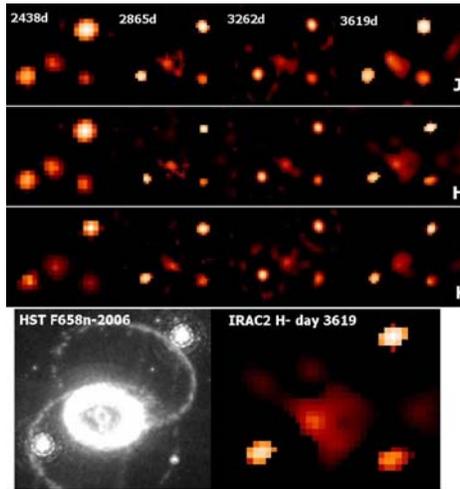


FIGURE 1. Early near-IR imaging of SN1987A at 4 epochs and 3 filters with IRAC2. The recent HST image provides scale and orientation by comparison with IRAC2-H - day 3619.

EARLIER NEAR-IR IMAGING

On such an anniversary occasion it is worth showing as yet unpublished ground-based observations, even if the resolution in the near-IR is less than optimum. We show in Figure 1 a montage of images in the J, H, and K bands taken at 4 epochs in the time interval 2438 - 3619 days. An enlarged image at 3619 days in the H-band (and to a lesser extent the J-band) are the only images to show evidence of resolution of the inner ring from the ejecta, a fact which is made clearer by comparison with a recent HST image. Spectra would be necessary to show why at this epoch the south-west part of the ring would dominate in J and H. When we look at Figure 2 the pattern seems to have changed somewhat. The OSIRIS images at day 5379 show the ring clearly resolved in the HeI $1.083\mu\text{m}$ line with some resolution in the J-band but not in H or K. In the H-band this may simply reflect a lower s/n compared to day 3619.

When one inspects images taken at day 6535 in the 3 near-IR filters one clearly sees the ring resolved in the J and K images but not in H. An understanding of this is apparent by comparison with HST images through similar filters which clearly show that the central asymmetric ejecta dominates more in H than in other filters. Stronger line emission in the ring is the obvious cause of the ring brightness although one should not overlook the possibility also of synchrotron emission in the K-band as suggested for Cas A [1].

RECENT MID-IR IMAGING

Mid-IR imaging has been obtained at 3 epochs with T-ReCS on Gemini South. The epochs are 6067, 6552 and 7241 days. The day 6552 image at $11.7\mu\text{m}$ can be safely compared to the other N-band images because SPITZER observations have shown that emission lines are too weak to significantly contaminate the continuum emission from

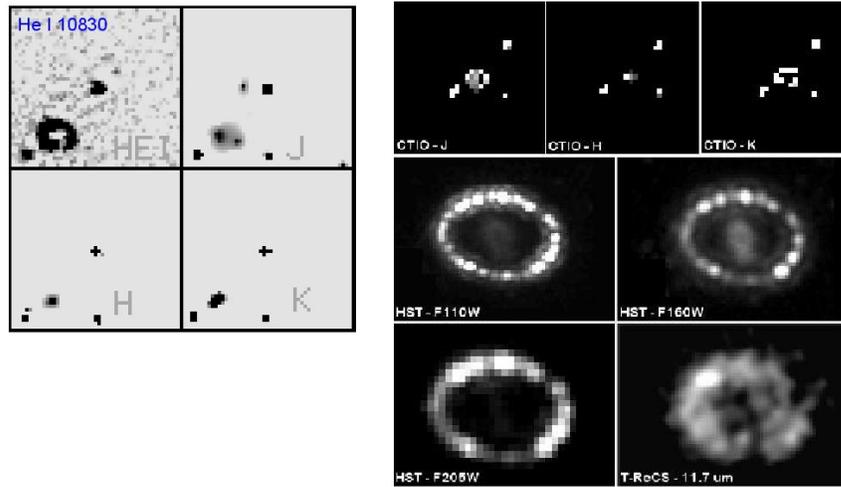


FIGURE 2. Left hand panels show imaging at day 5379 with OSIRIS (CTIO) with J,H,K filters. The ring is resolved in the HeI 10830 filter. Right hand panels shows J, H, K images with OSIRIS at day 6535. A comparison with equivalent HST images plus the TReCS $11.7\mu\text{m}$ reveals the strength of the H-band central source.

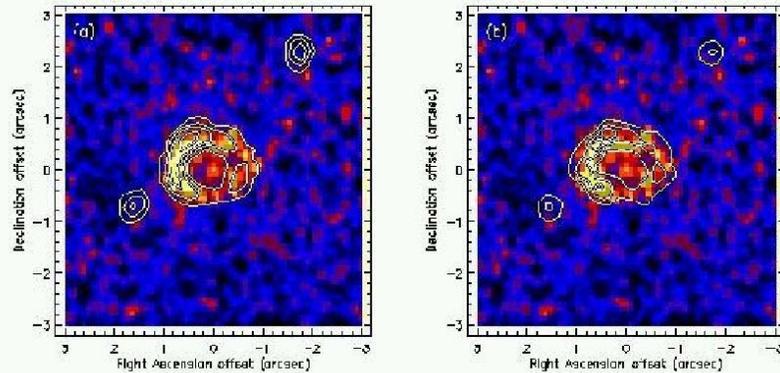


FIGURE 3. Left hand panel shows N-band image at day 6067 overlaid with contours of HeI $1.083\mu\text{m}$ (OSIRIS) contours from day 5749. Right hand shows N-band day 6067 image overlaid with HST $H\alpha+[NII]$ contours from day 5555.

the dust present in the ring and also in the ejecta. Observations in the Q-band were also made at day 6067 and 6552 [2, 3]. These will be illustrated in Figure 4. But first we show Figure 3 which demonstrates that the ring detected and resolved in the mid-IR is, to within the observational errors, coincident with the ring detected in the HeI $1.083\mu\text{m}$ line and in the HST $H\alpha$ filter. The panels show the N-band day 6067 image overlaid

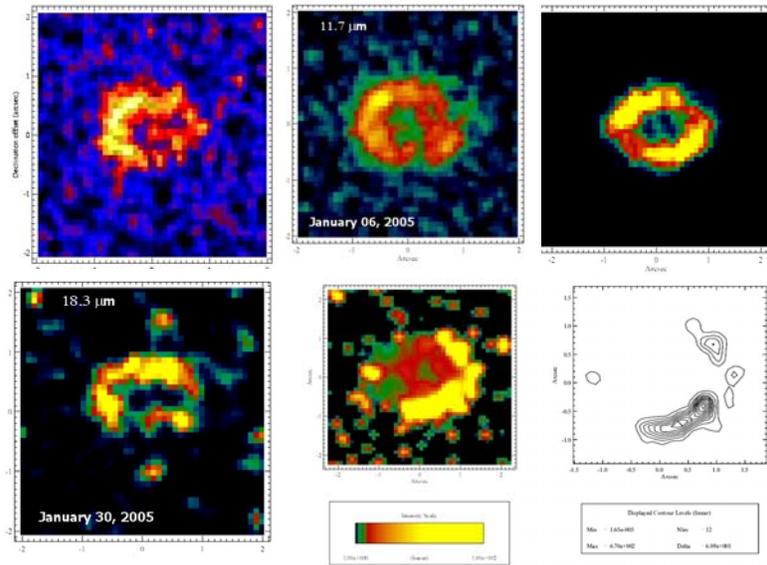


FIGURE 4. A montage of mid-IR images at different epochs. Top row left to right: N-band at day 6067, 11.7 μm band at day 6526, N-band at day 7241. Bottom row left to right: Q-band at day 6526, ratio of N-bands day 7241/6067, and this ratio contoured.

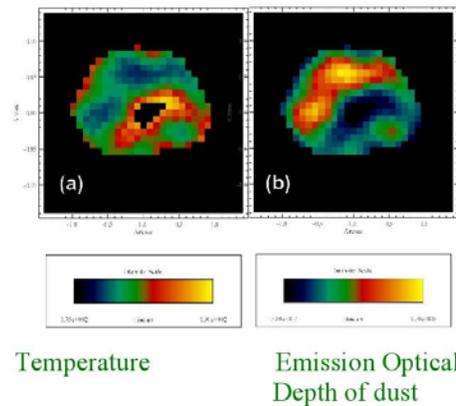


FIGURE 5. Temperature and emission optical depth maps using the 11.7 μm and Q-band (18.3 μm) images at day 6526 and silicate composition [3]

with those respective contours. This mid-IR emission has been ascribed to dust already present in the ring and heated in some way by the ejecta-ring interaction.

We draw attention in Fig 4 to the fact that at 6067 and 7241 days the ejecta was detected in the N-bands. Higher sky background emission at day 6552 prevented this detection. There is also a difference in intensity distribution between the images at 11.7 and 18.3 μm at day 6552 which is a result of the variation of temperature over the ring shown in Figure 5. A temporal change of intensity in the N-bands is evident by inspection and is shown quantitatively by the ratios of images at 7241 and 6067 days shown in colour and as a contour plot in Figure 4.

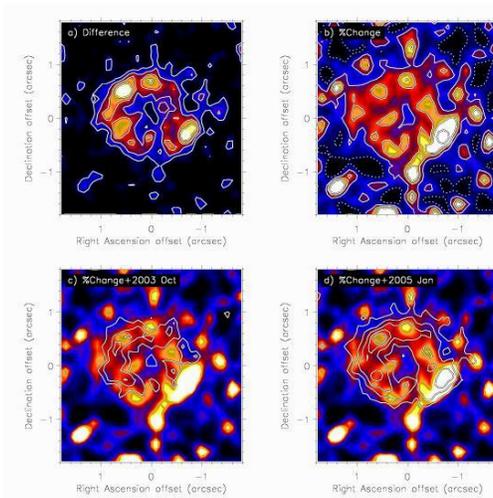


FIGURE 6. A comparison of 10-11.7 μm images at days 6067 and 6526 [3]. a. Top left - difference 6526-6067. b Top right - percentage change 6526-6067/6067. c. Bottom left - (b) overlaid with 6067 contours. d. Bottom right - (b) overlaid with 6526 contours.

In Figure 5 we show the temperature and emission optical depth maps of the ring using the silicate composition unequivocally identified with SPITZER observations and the T-ReCS images at 11.7 and 18.3 μm at day 6526. The temperature has a range of 135-190K, with higher temperatures concentrating towards the center, while the optical depths are quite small but higher in the north-east sector [3]. The mass of the dust in the ring has been calculated to be: $M_{dust} = 1 - 8 \cdot 10^{-5} M_{\odot}$ which is an order of magnitude lower than that in the ejecta viz. $10^{-4} - 10^{-3} M_{\odot}$ at day 6067 obtained using an uncertain temperature of the dust 90-100K. We note that this latter dust mass is similar to that obtained much closer to the time of dust condensation in the ejecta [4].

To complete the picture of temporal variation of the intensities we reproduce in Figure 6 a quantitative analysis of changes between days 6067 and 6526. This mosaic shows maximum changes of the order of 700 percent with the most obvious occurring in the south-west sector. As we saw from Figure 4 this pattern of brightening continued through day 7241 when the ring seemed almost full of mid-IR emission [3]. It is probably true that the large scale effects involving whole sectors are due to light travel time effects.

LOCATION OF DUST

It is of obvious interest to know how the dust in the ring is distributed and therefore the heating mechanism. Does the dust exist in the hot X-ray emitting gas or in the optical knots in the ring. Although the ring shape and size is similar at all wavelengths, X-ray, optical, IR and radio, the spatial resolution for all but the optical region with HST is not good enough to give a clear one-to-one correlation of brightness [3]. In Figure 7 we attempt to better compare the mid-IR images with HST images. By comparing the day 6526 images at 11.7 and 18.3 μm with HST images convolved to the equivalent resolution we see in the upper mosaic that the result still does not convey much new in-

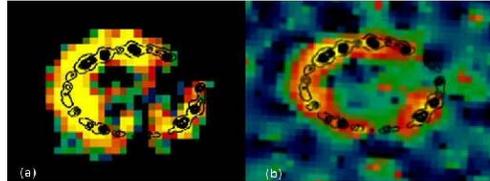
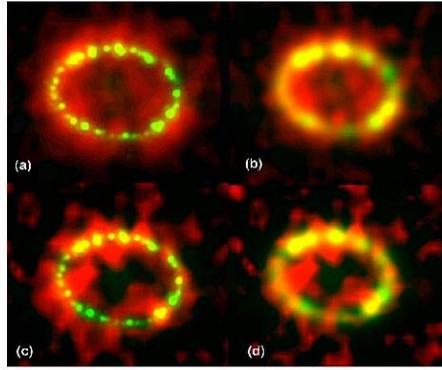


FIGURE 7. Effects of filtering. Top panels. (a) $11.7\mu\text{m}$ overlaid with HST F625W image.(b).The same with HST convolved to resolution of TReCS image. (c) Q-band ($18.3\mu\text{m}$) overlaid with HST image. (d) Same as (c) but with HST convolved as in (b). Bottom panels. (a) $11.7\mu\text{m}$ overlaid with HST UVO (day 6502) contours. (b) $11.7\mu\text{m}$ image deconvolved using the Maximum Entropy Method and overlaid with HST image above.

formation at the level required. However when the T-ReCS $11.7\mu\text{m}$ image is deconvolved using the Maximum Entropy Method the image is sharpened to the point where an overlay of HST contours from a day 6502 UVO image is much more suggestive pointing to a correlation of IR brightness with the blobs and shown in the bottom mosaic. Clearly higher s/n in the IR would be even more advantageous.

LIGHT CURVES

It has been clear for some time that the luminosity at all wavelengths has been increasing as a result of the ejecta - ring interaction and that this tempo of increase has itself dramatically increased between 5000 and 6000 days. These temporal changes also occur in the mid-IR as can be seen in Figure 8 where only mid-IR light curves are presented for clarity. Although the mid-IR data points are much sparser there is clear evidence that radiation from the ring began to dominate the IR emission from SN1987A starting at about 3800 days. The most recent points for the $10\mu\text{m}$ emission suggest that this dust emission is beginning to slow down. This should be compared now with what is happening at other wavelengths. This and the fact that the IR/X-ray emission ratio has been noted to be unusually low in SN1987A [3] might be taken as evidence that dust is being destroyed in the ring. Other interpretations however seem possible. Clearly future monitoring of the emitting dust mass in the ring is an important project.

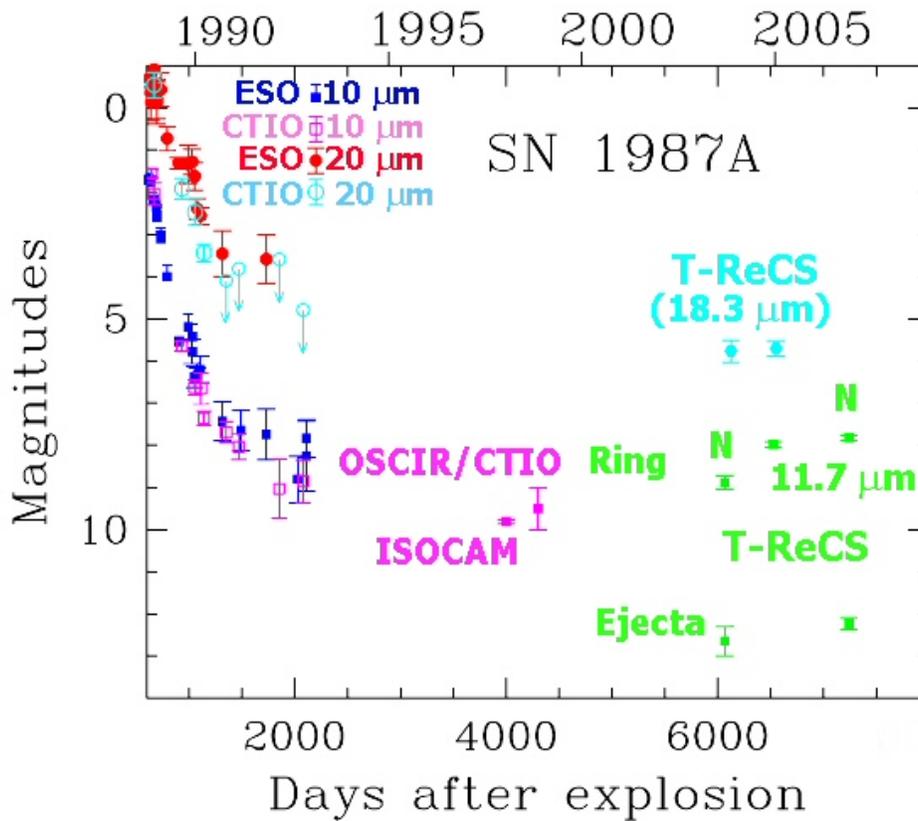


FIGURE 8. IR light curves for ring and ejecta showing most recent results from day 7241.

In Figure 8 we draw attention also to the N-band emission from the central source. The latest point at 7241 days suggests that it is increasing perhaps in parallel with optical HST observations reported by Kirshner at this conference. In the mid-IR this is a delicate measurement because of restrictions imposed by lack of resolution and weather conditions, as well as the fact that this central object extends in the north-south direction almost to the ring. The cause cannot be radioactive heating nor does it seem likely that the reverse shock has propagated back far enough to collisionally heat the central ejecta.

ONGOING

The dust in the ring and in the ejecta is not hot enough to be emitting in the near-IR. However at the ESO VLT there is now NACO an imaging and spectroscopic instrument covering the near-IR region and using an adaptive optics capability for both modes. In fact there now exist both images and long slit spectra in the J, H, K, and L bands accumulating since October, 2006.

Figure 9 shows a recent H-band image of SN1987A where inspection suggests spatial resolution rivalling that of HST. It and the other images and spectra should allow us to separate various regions in what is now a complex supernova environment. The

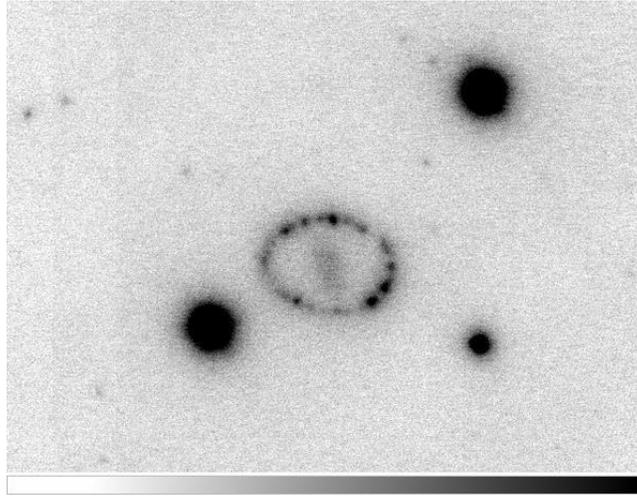


FIGURE 9. NACO (VLT) H-band image taken in October, 2006

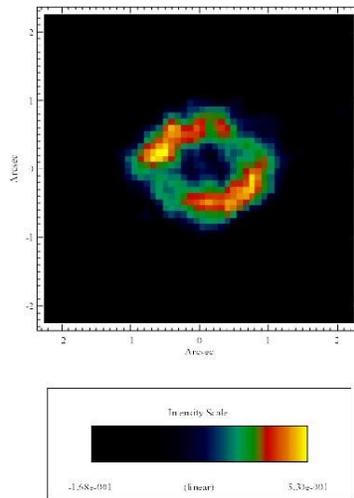


FIGURE 10. Difference between N-band images day 7241-day 6067.

intriguing central condensation shows clearly the form evident in HST images so one could investigate the dynamical behaviour with emphasis on the Fe presumably present as a result of the explosion and concentrated towards the center. The reverse shock propagating inwards from the ring should also be separable spatially if relevant spectra with sufficient s/n are available. Finer structural details around the ring also become accessible.

In Figure 10 we show the difference image of the N-band images day 7241 - day 6067.

Clearly some parts of this difference image are due to propagation time delay effects. These large differences may be smothering a more subtle effect resulting from an apparent increase in the radius of the ring evident in the time series of HST exposures in the optical reported by Kirshner at this conference. Any increase does not of itself

indicate a physical bulk movement of matter but may be simply indicating a shift to regions becoming more luminous as a result of shock propagation outwards. There are some indications that the mid-IR radius has increased over the period of 3.2 years but a more detailed analysis will be forthcoming in order to separate out various effects.

SUMMARY

We summarize briefly conclusions arrived at so far as a result of mostly mid-IR observations, referring back to some of the points raised in the Introduction.

1. The dust in the inner ring consists almost entirely of silicates and is heated by the shock interaction of the ejecta with the ring.

2. The currently observed mass of this dust in the ring is an order of magnitude lower than that of the dust in the envelope. There is some disagreement about the composition of the envelope dust. If it is amorphous carbon then one needs to understand why silicates are in the pre-supernova wind but carbon in the ejecta. Also the dust masses observed in SN1987A are too low to account for most of the dust in our Galaxy being produced by such SNe.

3. The excitation of the ring dust began to be visible near 3800 days, whereupon the luminosity increased rapidly along with emission at all other measurable wavelengths. The most recent mid-IR measures suggest a flattening of this light curve which could suggest grain destruction is now important and would be also consistent with the low IR/X-ray flux ratio..

4. Whereas the mid-IR emission from the envelope until 6000 days appeared to be steadily decreasing possibly as a result of the radioactive decay of the long living radioactive isotope ^{44}Ti , the very last observations suggest an increase similar to that reported for the optical luminosity, even if the IR observations were far less frequent.

ACKNOWLEDGMENTS

We acknowledge Gemini-South, CTIO and ESO for providing the observing time and capabilities on which this talk was based. HST and SPITZER observations have also been necessary to our understanding.

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