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9500 Nights of Mid-Infrared Observations of SN 1987A: the birth of the remnant

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Abstract. The one-in-a-life-time event Supernova SN 1987A, the brightest supernova seen since Kepler's in 1604, has given us a unique opportunity to study the mechanics of a supernova explosion and now to witness the birth of a supernova remnant. A violent encounter is underway between the fastest-moving debris and the circumstellar ring: shocks excite "hotspots". ATCA/ANTF, Gemini, VLT, HST, Spitzer, Chandra, and recently ALMA observations have been so far organized to help understanding the several emission mechanisms at work. In the mid-infrared SN 1987A has transformed from a SN with the bulk of its radiation from the ejecta to a SNR whose emission is dominated by the interaction of the blast wave with the surrounding interstellar medium, a process in which kinetic energy is converted into radiative energy. Currently this remnant emission is dominated by material in or near the inner equatorial ring (ER). We give here a brief history of our mid-infrared observations, and present our last data obtained with the *SPITZER* infrared satellite and the ESO VLT and Gemini telescopes: we show how together with Chandra observations, they contribute to the understanding of this fascinating object. We argue also that our imaging observations suggest that warm dust is still present in the ejecta, and we dispute the presence of huge amount of very cold dust in it, as it has been claimed on the basis of data obtained with the *HERSCHELl* satellite.

Keywords. supernovae: SN 1987A, ISM: supernova remnants, infrared: ISM

1. Introduction

There are several ways in which the presence of dust may be shown to be associated with supernovae. Each individually may not be unequivocal concerning its precise location and time of origin. This is mainly due to the fact that dust can form in the ejecta, but it may also form or be already present in the CSM. SN 1987A provided the means of examining these methods. Possible indicators for dust in the ejecta are: (i) the early presence of molecules, (ii) an apparent blueward line shifts, and (iii) light curves showing a decrease in the visual together with an increase in the infrared emission, while no effect is seen on the bolometric light curve. Some of these methods have been used to infer the presence of dust in or near other supernovae but never all of them simultaneously, but for SN 1987A.

2. Dust in the ejecta of SN 1987A

Our ground based observations showed an infrared emission excess starting at day ~ 76 after outburst (Suntzeff & Bouchet 1990, and Bouchet, Danziger, & Lucy 1991a), as well as an early (<150 days after outburst) SiO and CO molecules formation (Danziger & Bouchet 1989). However, these data were not judged conclusive at the time as far as the dust origin was concerned, and it was not until March 1989 (day 736) that Danziger *et al.* 1989 reported from observations carried out in August - September 1988, that the emission line profiles of OI (630.0 nm and 636.3 nm) and CI (982.4 nm and 985.0 nm) had become asymmetric with their peak emission blueshifted by 500-600 km/s, and that similar behavior had been seen later on in the Na I and H-alpha profiles. These authors attributed this effect to extinction by dust, and were then the first ones to report on the discovery of dust condensation within the metal-rich ejecta. It is worth noting that they even gave a simple modeling of this newly discovered dust in their IAU circular, which was further on elaborated in subsequent papers (Lucy *et al.* 1989, Lucy *et al.* 1991). The spectral energy distribution longward of 5 μm has evolved continuously in time. After day $\sim$ 300 a clear dustlike component appeared. SN 1987A was then regularly observed in the mid-infrared (where >90% of the total energy was radiated) until day $\sim$ 2000 (Danziger *et al.* 1991, and Bouchet & Danziger 1993), when it had faded so much that it was not observable any longer with the 4m-class ground based telescopes at ESO/La Silla and CTIO/NOAO, and their associated infrared instruments. SN 1987A was observed at day 4100 with ISOCAM, on board the ESA ISO satellite (Fischera & Tuffs 2000), and Bouchet 2004 reported a possible weak detection of the supernova at day 4300 with OSCIR at the CTIO 4-m Blanco telescope. Except for these two observations, there have been no other detections of the mid-IR emission from the ejecta/ring region of SN 1987A between 1998 and 2004.

We had to wait for the advent of T-ReCS and VISIR, the mid-IR instruments at the 8-m Gemini South telescope, and at the ESO/VLT respectively, to resume our observations. They have not been interrupted since. Bouchet *et al.* 2004 together with the first ever resolved image of a supernova environment in the mid-IR reported a detection of the central ejecta at 10 μm at day 6067, obtained during the commissioning time of T-ReCS at Gemini/South; subsequent observations showed that this faint emission was still present at days 7241, 7565, 8720 and most probably at day 9375, as it can be seen in Figure 1 (Bouchet, Danziger, & de Buizer 2013). Our measurements together with the current theoretical models set a temperature of $80K < T_{Dust,Ejecta} < 100K$ and a mass range $M_{Dust,Ejecta}$= 3 x 10^{-4} - 2 x 10^{-3} $M_\odot$ (Bouchet *et al.* 2006). The warm dust discovered at day 430 had not been destroyed and that it is what we are still observing now.

3. Dust in the inner equatorial ring

3.1. *ESO/VLT and Gemini-South ground based observations*

The observed mid-IR flux in the region of SN 1987A is dominated by emission from dust in the inner equatorial ring (ER), which we have detected and resolved with T-ReCS and VISIR (Bouchet *et al.* 2004; Bouchet *et al.* 2006). So-called Hot spots similar to those found in the optical and near-IR are clearly present, and the morphology of the 10 μm

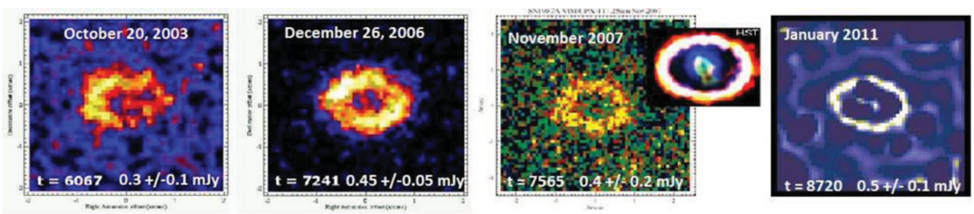

Figure 1. 10 μm imaging of SN 1987A at different epochs. Note the faint emission near but not exactly at the center of the ER.

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emission is globally similar to the morphology at other wavelengths from X-rays to radio (Figure 2). We do not have space here to discuss the changes in morphology, but see Bouchet, Danziger, & de Buyzer 2013. The mid-IR emission in the ER originates from 180 K dust collisionally-heated by X-ray emitting gas of T $\sim 5 \times 10^6$ K, with density $(2-4) \times 10^4$ cm^{-3}. The mass of this radiating dust is $\sim$1.2 $\times$ 10^{-6} M$_\odot$ (at day 7554) and it scales linearly with the IR flux. Note that there is no significant increase of the mid-IR flux between days 8708 and 9375.

3.2. *SPITZER Observations*

We have used the *SPITZER* satellite to monitor the mid-IR evolution of SN 1987A over a 5 year period spanning the epochs between days $\sim$ 6000 and 8000 since the explosion. Its radiative output during this epoch is dominated by the interaction of the SN blast wave with the pre-existing ER. The main results of our study can be briefly summarized as follows (Dwek *et al.* 2010):

(*a*) The dust grains are mainly silicates and their emission increased as t$^{0.87}$ up to day 8708, consistent with X-rays observations suggesting that the blast wave has transitioned from a free expansion to the Sedov phase (now expanding into the main body of the ER)(Figure 3a).

(*b*) A secondary emission component, the nature of which remains a mystery, dominates the spectrum in the 5 - 8 μm region: its intensity and spectral shape rule out any possible gas or synchrotron emission mechanism as the source of this emission. It must therefore be attributed to a secondary dust component radiating at temperatures above 350 K (Dwek *et al.* 2010) (Figure 3b). The question of whether this could be a clue to a binary coalescence origin of the progenitor should be addressed. However, it has to be stressed that the low angular resolution of the IRS (InfraRed Spectrograph) on board *SPITZER* (1.8 arcsec/pixel at most for the shortest wavelengths) is too low to argue that this second component lies inside the ER.

(*c*) The grain radii or IR emissivities of this secondary component must be significantly smaller than those of the silicates. Their sputtering lifetime could therefore be significantly shorter than, and their evolution quite different from, that of the silicates.

(*d*) The overall shape of the $\sim 5-8\mu$m dust spectrum has not changed during the observations, suggesting that the density and temperature of the soft X-ray emitting gas have not significantly changed during more than 5 years of observations. The spectral shape of this IR emission is remarkably constant, suggesting also that the mass ratio of the silicate to the secondary dust component remained roughly constant during that period.

(*e*) The infrared-to-X-ray ratio (IRX) is constant at 2.5 throughout this epoch. This value shows that the cooling of the shocked gas is dominated by IR emission from the

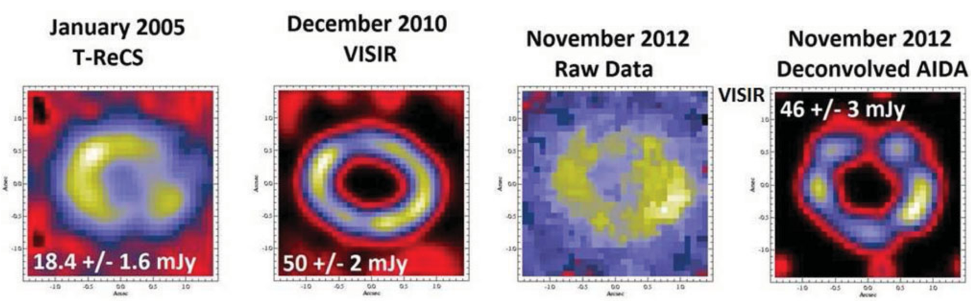

Figure 2. 10 μm imaging of the ER around SN 1987A at different epochs.

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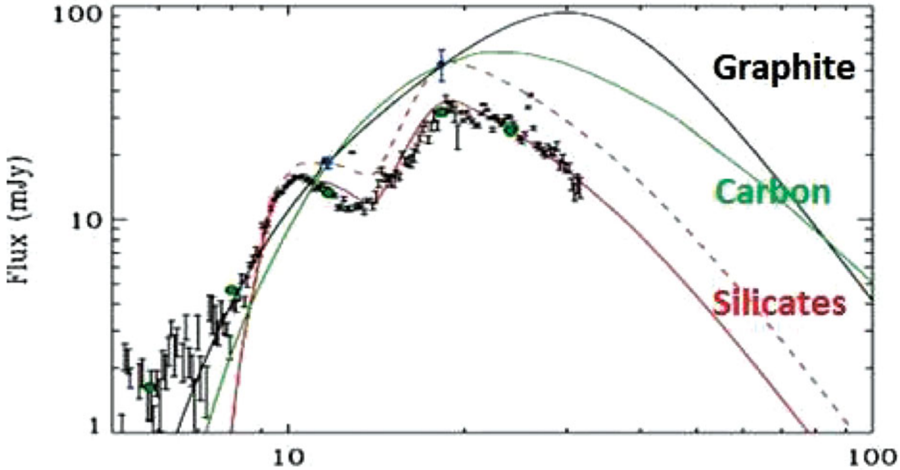

Figure 3. The low resolution spectrum of SN 1987A obtained with the InfraRed Spectrograph (IRS) on board the infrared satellite *SPITZER* with theoretical fitting for three grains species. It is clear that silicates are the main dust component.

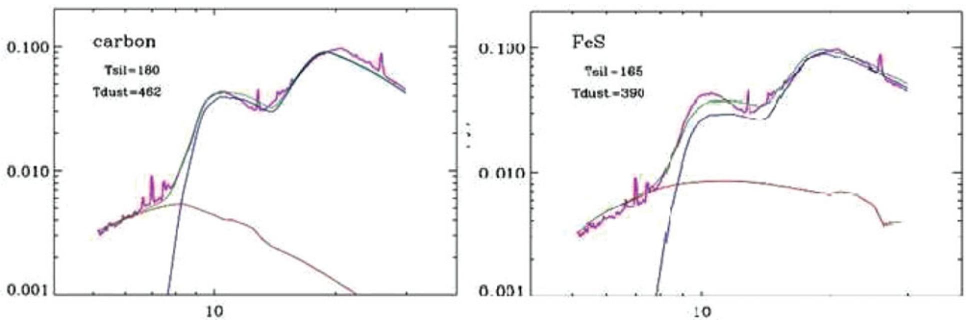

Figure 4. The low resolution IRS spectrum of the SN 1987A environment with two fits of the blue region excess emission corresponding to the second dust component. Carbon species at T = 462 K give the best fit for a corresponding temperature of the silicates T = 180 K. The temperature would be slightly lower (T $\sim$ 39 K) were FeS grains dominate.

collisionally-heated dust with radii >0.30 μm, and that a significant fraction of the refractory elements in the ER is depleted onto dust.

(*f*) The constancy of the IRX means that neither grain destruction by sputtering nor cooling of the shocked gas has played a significant role during the epoch of the observations. It was expected that grain destruction becomes important only at day 9200, whilst the X-ray emission may not be affected until t $\sim$ 30 years (Dwek *et al.* 2010). Indeed, there are hints in our last observations at day 9375 that this is actually occurring (Bouchet, Danziger & de Buyzer 2013).

4. The Interpretation of data collected by *HERSCHEL*

Matsuura *et al.* 2011 argue that their observations of SN 1987A with *HERSCHEL* point to the presence of a huge amount (M = 0.4 - 0.7 $M_\odot$) of cold dust (17 K < T < 23 K), and they claim that this dust lies in the ejecta. Clearly the Herschel angular resolution cannot resolve this region (for PACS, 3.2 arcsec/pixel and 6.4 arcsec/pixel, for the short and long wavelengths respectively, while - I would like to remind the audience

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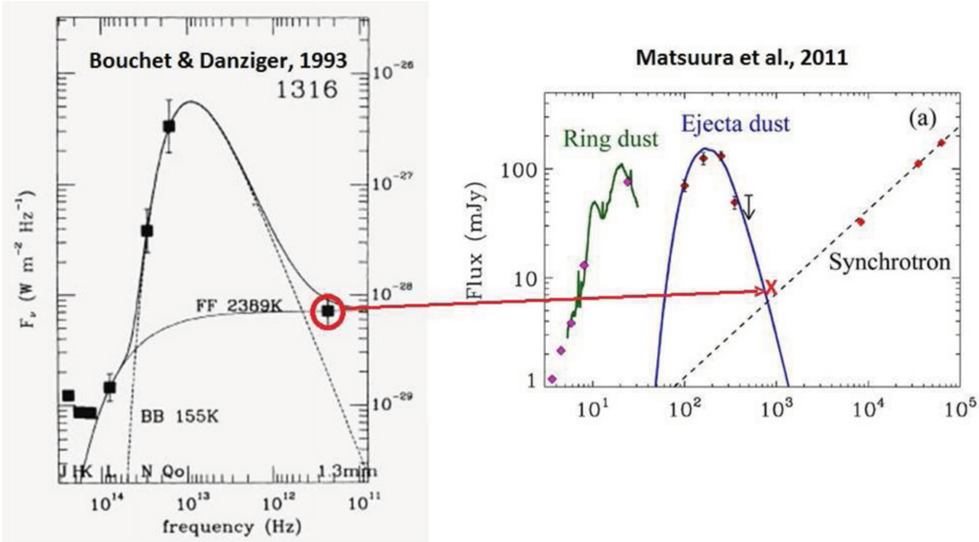

Figure 5. The SED of SN 1987A at day 1316, and the one derived from *Herschel* observations. Note the data point at 1.3 mm obtained with the SEST telescope at La Silla.

- the ER is about 1 arcsecond diameter wide), and there are strong arguments against this interpretation. Among them, let me quote the following ones:

• When would have this dust appeared in the ejecta? The observed energy budget up to day 2100, more than 90% of which is radiated in the mid-IR by the warm dust discovered at day 430, was perfectly consistent with a powering by the radioactive decays of ^{56}Co, ^{57}Co, ^{44}Ti and ^{22}Na, and some theoretical considerations as time-dependent effects due to long recombination and cooling time leading to a frozen-in structure of the ejecta (Fransson & Kozma 1993). The observed bolometric light curve agrees remarkably well with these theoretical models and there was then no room from the '*HERSCHEL*' dust at that time.

• We strongly believe that our mid-IR observations show that the warm dust is still present in the ejecta at the time of the *HERSCHEL* observations: although the issue of whether both warm and cold dust could cohabit should be addressed, it seems highly improbable.

• We could envisage that a fraction of the 'warm' dust has cooled down. However, how a few 'warm' 10^{-4} $M_\odot$ could lead to 0.4 - 0.7 $M_\odot$ of cold dust?

• According to Matsuura *et al.*'s (2011) model, all refractive elements must go into dust. Nonetheless, there is no evidence of the enormous absorption in the visible which would be expected; moreover, there is emission from the refractive elements in the debris so not all by far has gone into grains.

• The temperature of the '*HERSCHEL*' dust is the same as the general ISM 20 K and inside the debris heated by strong shocks, X-rays and radioactivity, which seems highly suspicious to us.

• We have been monitoring regularly the supernova at 1.3mm with the ESO/Swedish SEST radio telescope at La Silla between 1989 and 1997. Bouchet, Danziger & Lucy 1991) report a data point of $\sim$ 9 mJy at this wavelength for day 1316. Figure 4 shows that this value is surprisingly quite consistent with the spectral energy density shown in Matsuura *et al.*'s (2011) figure 2: this suggests that the flux density at this wavelength has remained constant for more than $\sim$ 8000 days, and should the dust detected by

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HERSCHELL be in the ejecta, it would thus have been there also at day 1316. This is in total contradiction with the energy balance at this epoch.

We therefore strongly object that the dust seen by the *HERSCHELL* satellite originates from the ejecta. Within the angular resolution of the instruments used, the SN 1987A environment is so rich and diverse that this cold dust may lie anywhere in a nearby ISM, for instance in the outer rings of which we still do not know anything. ALMA with its superb angular resolution will most probably give a definite answer.

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Discussion

Cesarsky: So, you do not believe that *Herschel* detected that amount of cold dust in the ejecta?

Bouchet: Absolutely and definitely not! These data are indeed very valuable, and I agree that most probably this far-infrared emission originates from dust, but I object that this dust be in the ejecta. As I said, there are many places where it could lie, and my guess goes toward the outer rings. But this is just a guess