DUST in SN1987A

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Patrice Bouchet, Saclay
has been a collaborator
since 24 February, 1987.

Castiglione della Pescaia 16 Sep. 2013

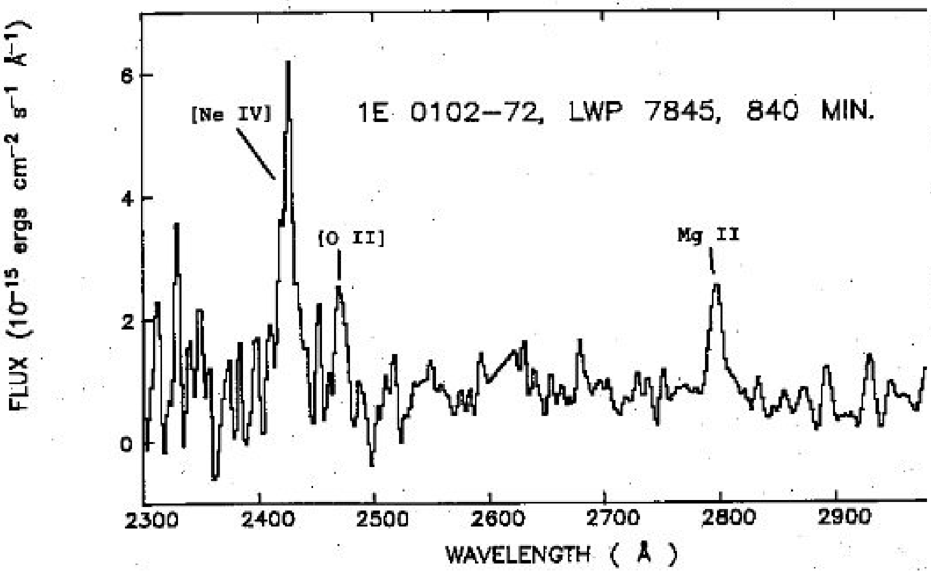
The first and only publication with Francesca.

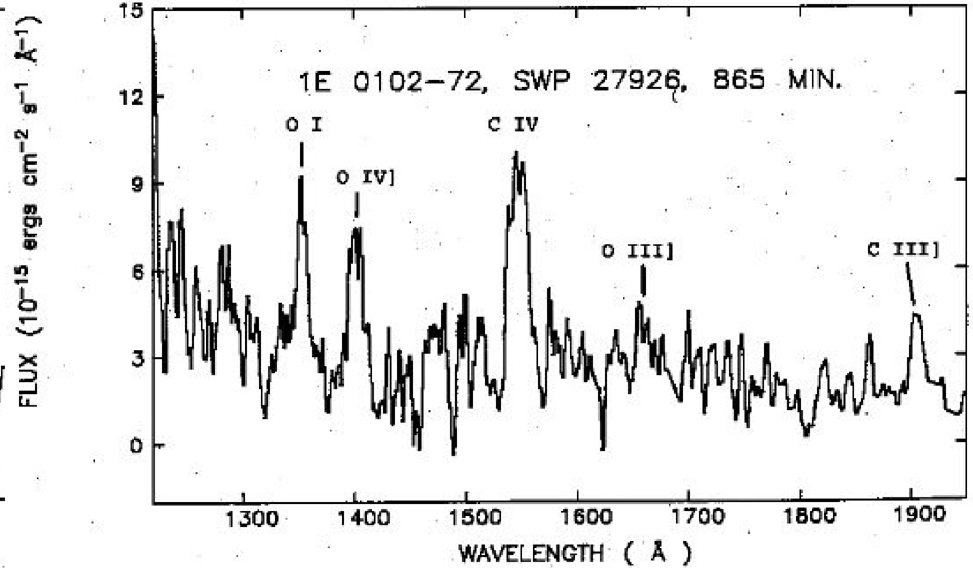
The UV Spectrum of an O-rich SNR in the SMC
(Blair, Raymond, Danziger, Matteucci 1989)

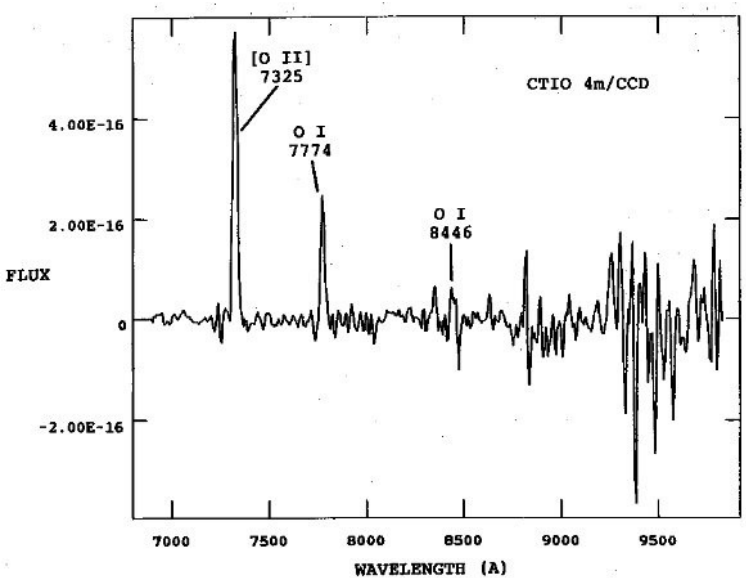
1E0102-7219 - bright non-thermal Xray (Einstein), high expansion velocity (6500km/s), Young SNR.

IUE spectra showed lines of OI, [OII], OIII], OIV], CIII]
CIV, [NeIV] and MgII
Recombination lines of OI in UV and V spectra allowed scaling to compare with shock models.
A combination of shock heating and photoionization (Xrays) provide best fit to line ratios.
Abundances relative to O were compared with WoosleyWeaver models for 15 and 25 Msun SNe. No details here.

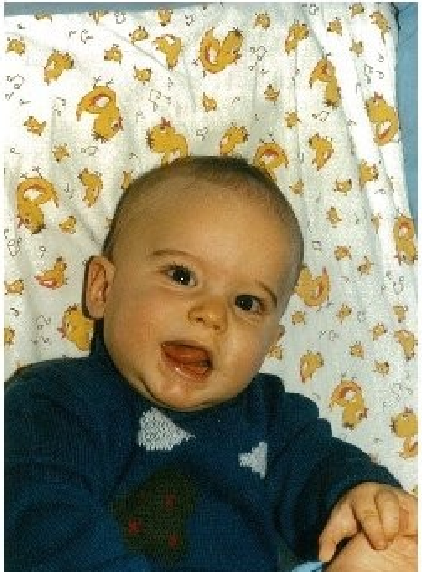
UV and optical spectra of 1E 0102-7219







Addendum!



This chap might have been included as a co-author of this paper since he participated in the observations with IUE at Vilspa even though he was – 3 months 9 days old at the time.

Perhaps it was that experience that caused him to leave astronomy to become a psychologist.
I never dared ask.

Dust forms in and around:

1. Red giant stars (AGB).
2. Circumstellar material around hot stars, LBV(ηCar) ,SNe.
3. Molecular clouds.
4. Novae ejecta.
5. Core-collapse supernovae (the basis of this talk).
   In this last case there have shown to be cases where dust apparently formed not only in the SN envelope but in the surrounding CSM as a result of the interaction.

NB. Dust is also destroyed in some environments.

SN1987A provides a good prototype because of the quality and temporal coverage.

How does the presence of dust manifest itself?

Possible dust indicators.

1. Presence of molecules prior to or after (>8 SNe).
2. Blueward line shifts. Arguably the most unequivocal.
3. Decrease in visual light curves (after 400 days).
4. Increase in IR emission.
5. Effects on Bolometric light curve.

All of these manifestations were seen in SN1987A!
Some observed in other SNe of which there are now
More than 15 known examples none of which are Type Ia
SNe. There are however some Type Ib and Ic (?).

SN1987A

Dust preceded by molecule formation
CO, SiO <150 days

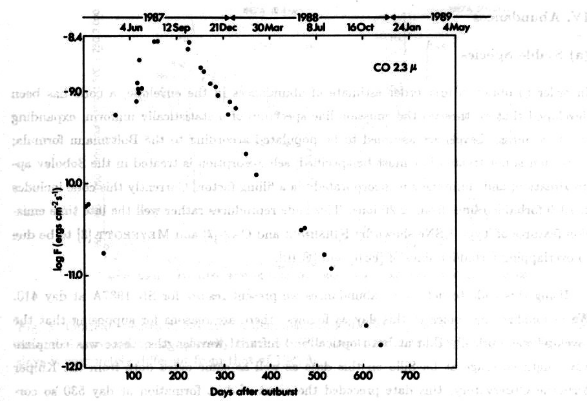


Fig. 6. The temporal behaviour of the flux in the CO 2.3 μ first overtone band of carbon monoxide.

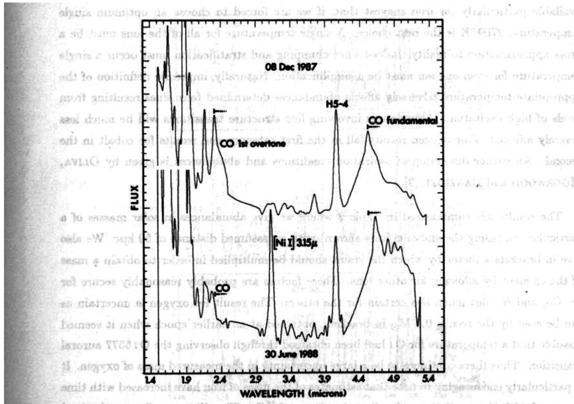
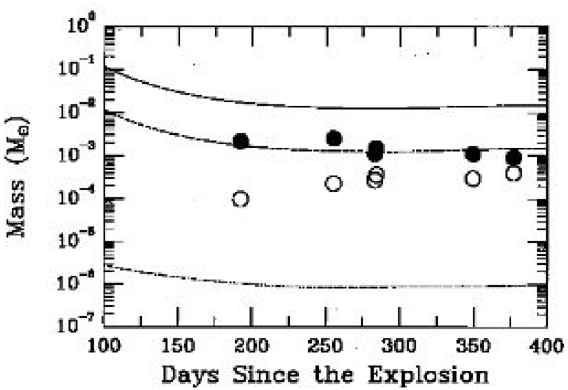


Fig. 7. CVF spectra from 1.4–5.4 μ of SN 1987A at 2 epochs. Note the temporal evolution of the strength of the fundamental and first overtone bands of CO, and the way in which the strength of the [Ni I] 3.12 μ has changed.

Temporal behaviour of 1st overtone band of CO

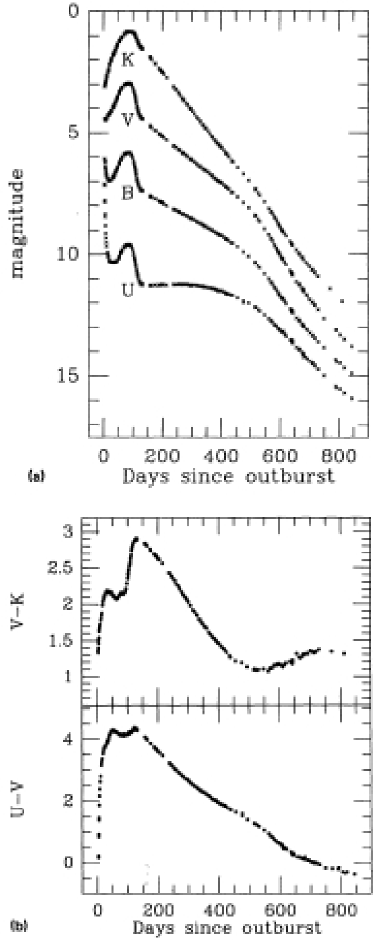


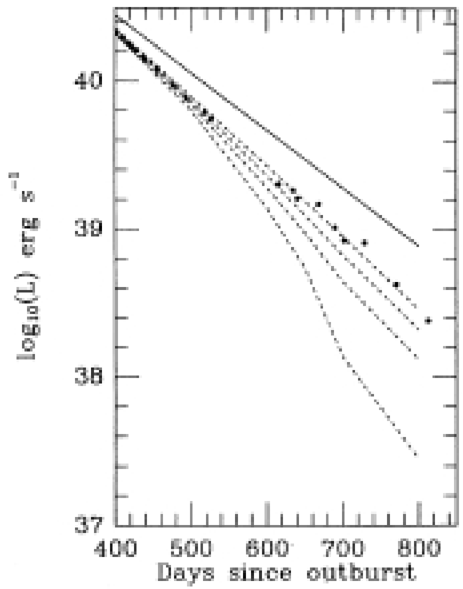
Liu et al.1992 derive CO mass as a function of time accounting for chemistry, optical depths, non-LTE (black dots).

Optical spectra when dust forms – an analytical approach.

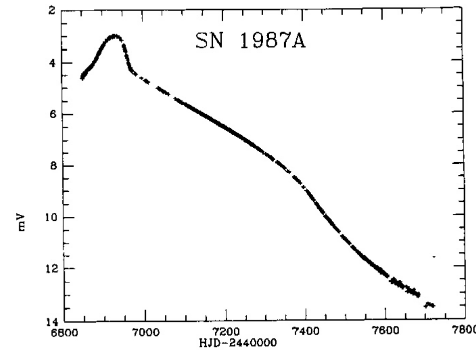
1. A parabolic shaped emission line indicated that dust was evenly distributed within a velocity of 1870k/s defined by the blue side of the profile.
2. The shift of the maximum of the profile and the profile shape at zero velocity gave independent determinations of the optical depth, and albedo.
3. The slowing of the increase of optical depths at day 775 suggested that the dust formation rate was slowing. A silicate dust mass at this epoch of $3x10^{-4}$ Msun was obtained.
4. The wavelength dependence of the shift of the line maximum (greater shift at shorter wavelengths) showed that the dust particles were small i.e. comparable to or smaller than the wavelength of the emission lines. Some evidence for dark clumps hiding dust.

Accurate Photometry





Bolometric



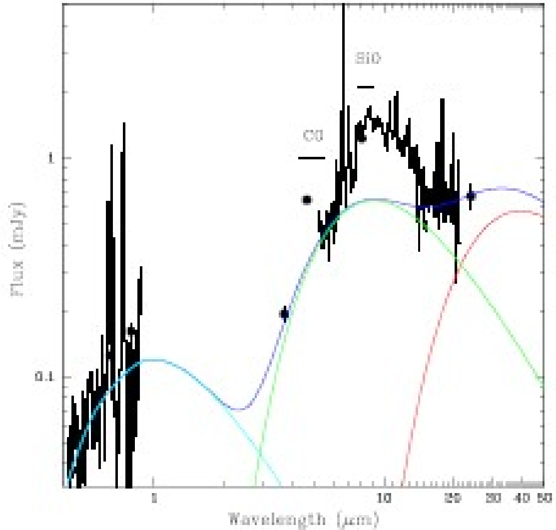
Geneva photometry

Suntzeff, Bouchet 1990

Faster decay of light curves B,V,Geneva
Suggests dust formation may have begun
As early as day 450!

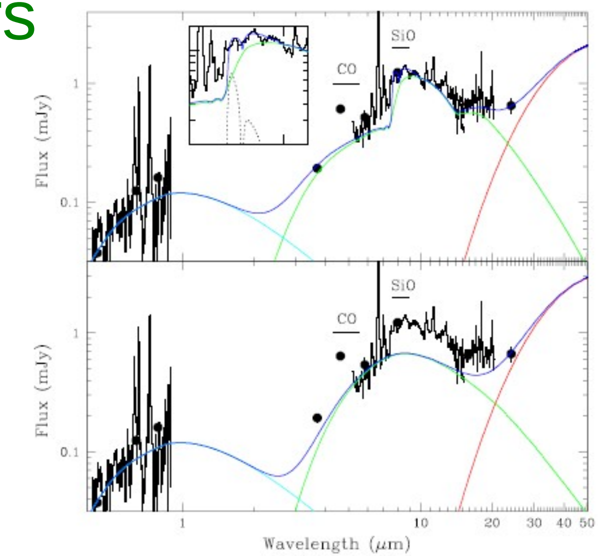
Other Dust Producers

Type IIP SN2004et
(compare with SN1987A)



Kotak et al. 2006

3 component BB fit at day 464.
T: 7000, 650,130

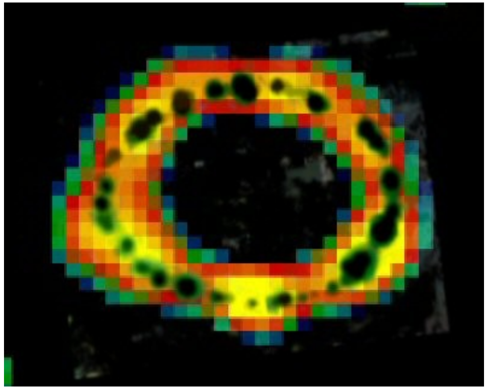


Green-silicates
Blue-optically thick gas
Red-IR echo IS dust

Green-amorphous C

Best fit with silicates.
Mass of dust ~10^{-4}Msun

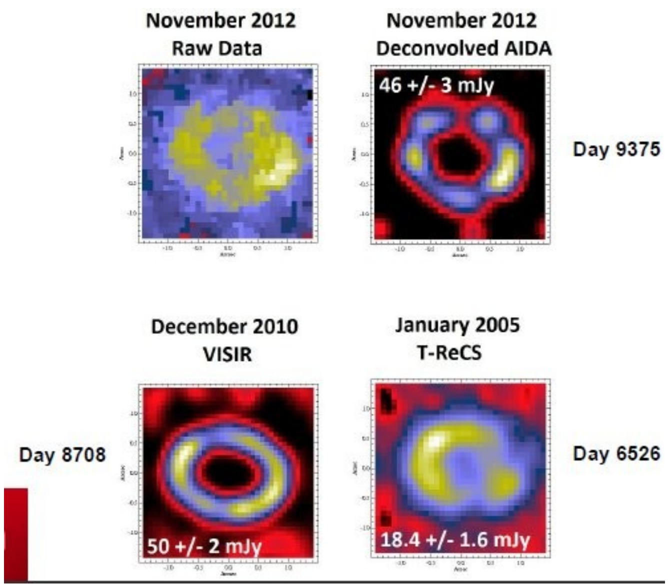
Dust formed inside ~1600km/s



Starting 2003 GeminiS, VLT showed ring dust and debris, with ring dust brightening, A result of ejecta-ring interaction.

Overlay of HST (Dec2006)(black) with VISIR (red-yellow)shows correlation far from 100%.

Other comparisons show dust anulus possibly thicker than visual HST anulus.

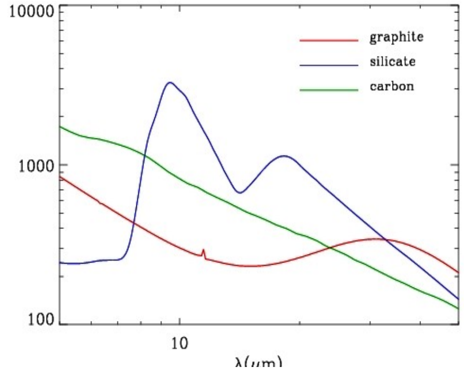


At 6067 days, T of ring dust ~180K
Ring dust mass ~ 10^{-6} Msun

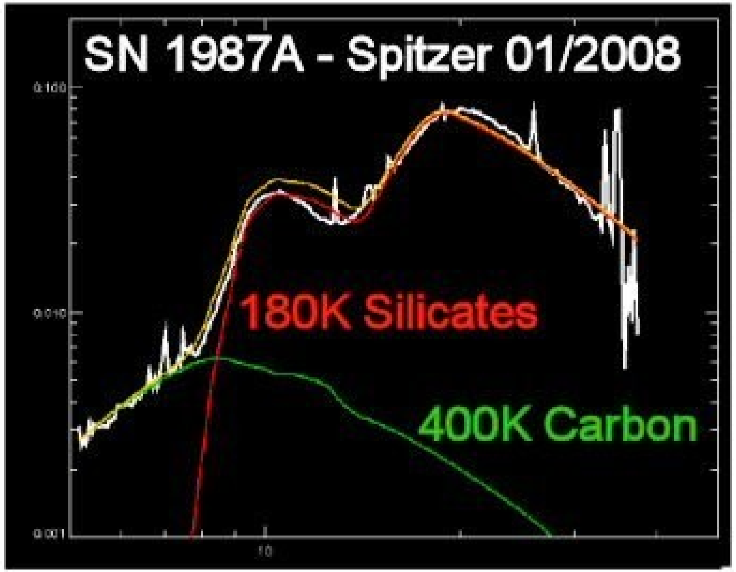
Most Recent Imaging at 10-11μ

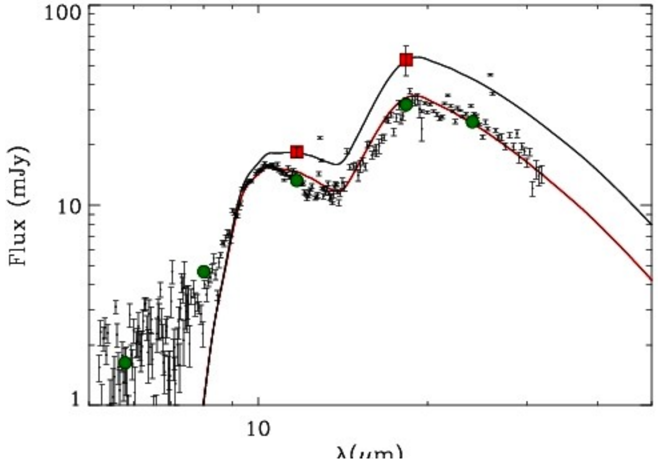
Detection of mid-IR emission in central debris made on days 6067 And 7241.

SPITZER - SN1987A

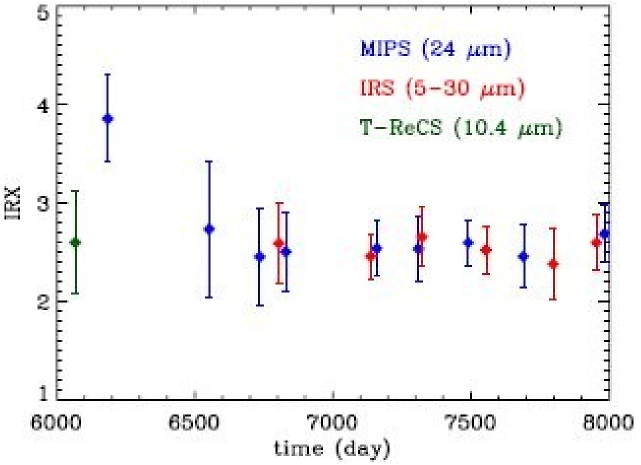


Dust mass abs. coeffs.





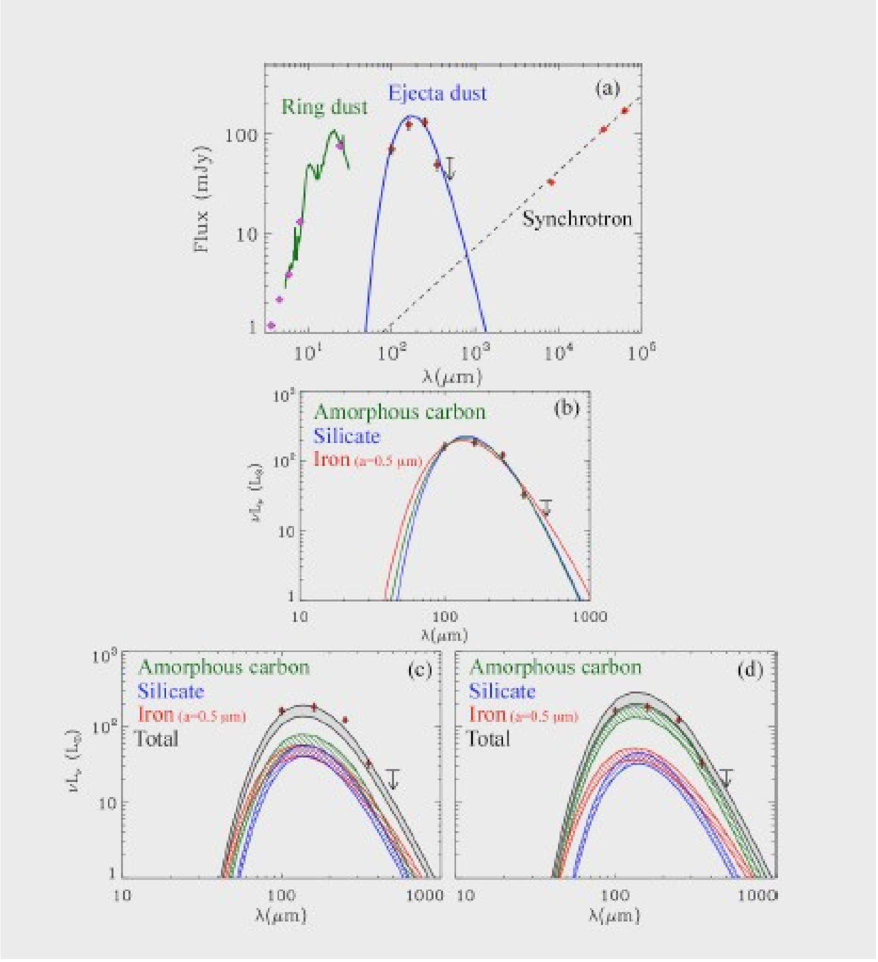
Spitzer 02/2004



No evidence for dust destruction so far.
Dwek et al. 2010.

Broad bands do not discriminate type of dust!

HERSCHEL – SN1987A (Matsuura et al.2011)



Cold dust 17-23K
Mass 0.4 – 0.7 Msun in ejecta.

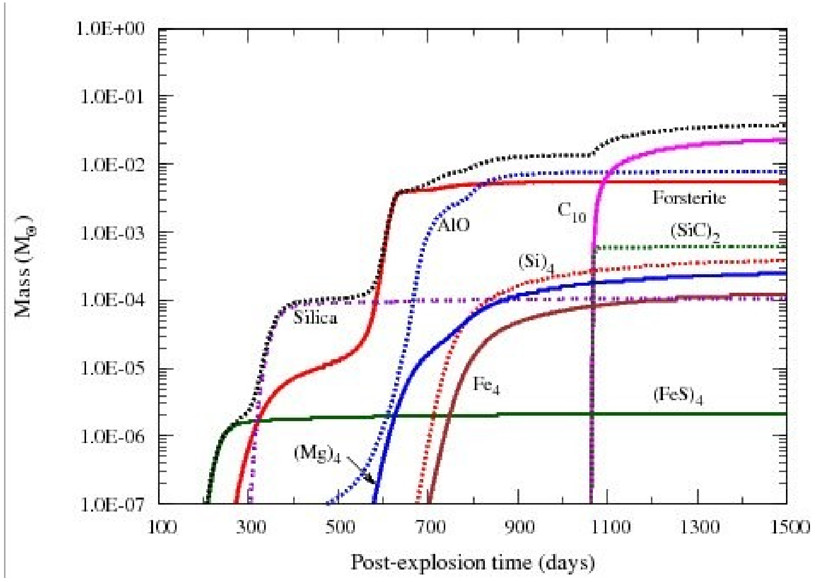
If correct this would help to explain dust at high z formed predominantly in CC SNe.

The fits of dust emission to the Herschel spectra require that all refractory elements expected from nucleosynthesis in models end up in dust.

Comments concerning understanding the HERSCHEL interpretation of high mass.

1. All available refractory element mass forms dust. i.e. 100% efficiency
2. The mass of dust in the debris should cause large absorption, not apparent. This should be modelled.
3. A drastic drop in emission lines from refractory elements would occur at least if this occurred early.
4. Temperature for HERSCHEL dust is 20K almost the same as ambient ISM. (T of debris dust at day 1316 was 155K. Dust condensation starts at ~1000K).
5. Dust around SNR detected with ISO is hotter.
6. IR emission from Herschel dust should be added to Bolometric energy budget.
7. Jerkstrand et al. 2011 have shown that at 8 years 0.58Msun of C/O are in clumps but all of this does not necessarily end up in dust.
8. It was noted (Danziger et al 1989) that when dust was forming at day 530 the [SiI]1.6 mic line was decreasing faster than would be expected if only dust extinction were responsible. One possible reason was that all the Si was going into SiO and grains. Other possible explanations exist.

Cherchneff (2012) models molecule formation in 15 Msun SNe progenitor with solar metal abundances. Yields from Heger and Woosley



Dominant molecular components: Silicates; oxides of Si, Mg, Fe; C solids; carbides (SiC); Fe ; also molecules of CO, SiO.

There are some general features in the model also seen in the observations. Onset of dust formation lasting for 1000days. Slow beginning, rapid rise and then slowing to zero molecule increase.

SN1987A

ALMA – Rotational lines of CO

Kamenetzky et al. 2013 – day ~9250

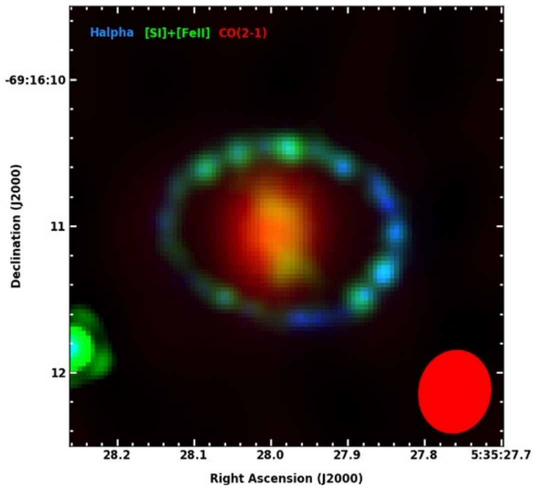


Figure 1. A color composite image of SN1987A. The unresolved ^{12}CO 2–1 line emission detected by ALMA is shown in red, and the red ellipse in the corner is the synthesized beam. Also shown are the Hα emission (blue) and [Si I]+[Fe II] 1.644 μm emission (green in the ring; yellow in the ejecta) observed with the *Hubble Space Telescope* (Larsson et al. 2013).

(A color version of this figure is available in the online journal.)

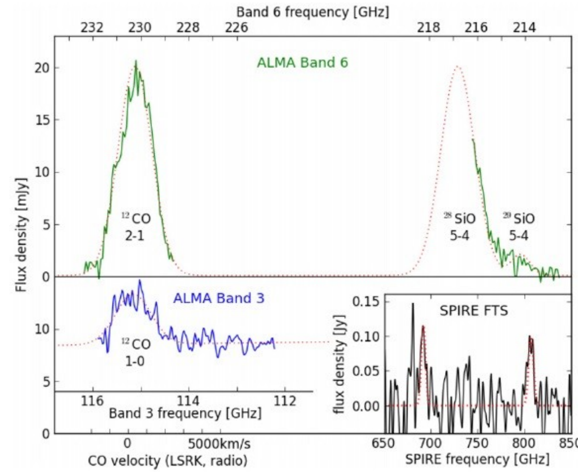


Figure 2. ALMA spectra at the center of SN1987A. The 2.6 mm Band 3 (bottom left) and the 1.3 mm Band 6 (top) are plotted with a common velocity axis calculated for the ^{12}CO 1–0 and 2–1 lines, respectively. The dotted lines are the best-fit Gaussians to the ^{12}CO lines, ^{28}SiO and ^{29}SiO and a continuum with synchrotron spectral index of −0.8. A zoomed-in portion of the continuum-subtracted SPIRE spectrum is shown in the bottom right, with the best-fit Gaussians of the $J = 6$–5 and $J = 7$–6 lines as dotted lines.

(A color version of this figure is available in the online journal.)

Mass of CO at least 0.01 Msun
T > 14K. Possible backwarming by soft Xrays from the ring needs to be understood.
Red – unresolved CO emission
Velocity of CO 2200k/s (cf.1870k/s day 600).

An Interpretation of Dust Evolution in SN1987A (no dust destruction included)

Molecules formed early; amorphous warm dust started forming near 450 days with some clumping; ring dust present from red supergiant phase heated by ejecta-ring interaction; cold dust began to form from Increasing mass of molecules in the central region (20 years of accumulation), small percentage (?) of molecular gas still present in central regions together with dust.

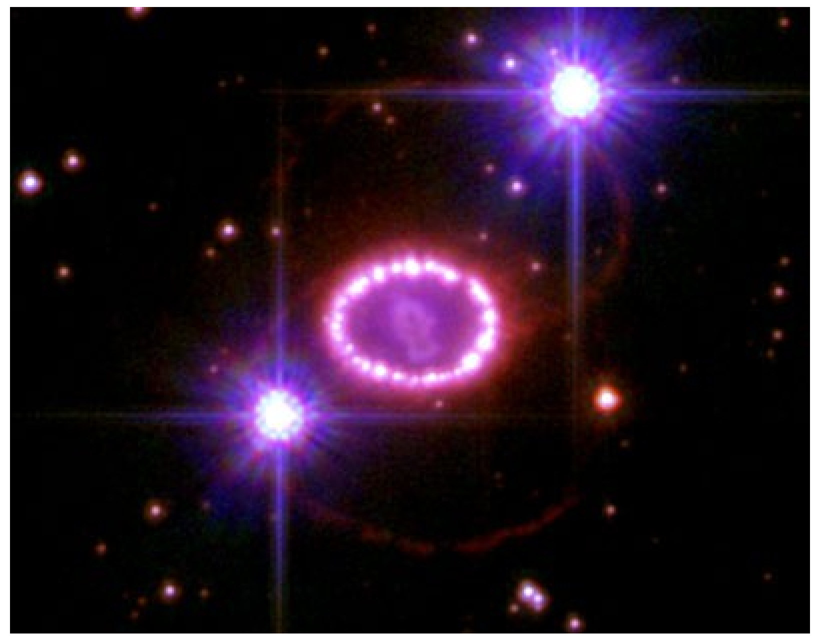
Observations leave uncertain: type of dust (ring excepted), efficiency, pulsar excluded by cold central region? At days 6067,7241 a central mid-IR (N band) object exists which cannot be cold dust

New instruments have been successful in elaborating the nature of the dust associated with SN1987A.
They include: Mid-IR imaging at ESO, CTIO; SPITZER (spectra); HERSCHEL (spectra); ALMA (spectra, imaging)

Some Continuing Uncertainties Concerning Dust

1. The nature of dust in the envelope of SN87A and other SNe. This includes not only grain compositions (silicates, carbon, Fe) but sizes and shapes.
2. Do different SNe produce different types of dust and if so what are the defining parameters.e.g. progenitor mass and metallicity
3. Clump sizes and optical depths.
4. The formation of dust at large redshifts. Clearly dust in the Milky Way has been significantly contributed to by more than SNe. Strong contenders e.g. AGB stars, ISM (molecular clouds) but at $z>6$ are CC SNe the only realistic candidates?

END



Dust particle sizes?

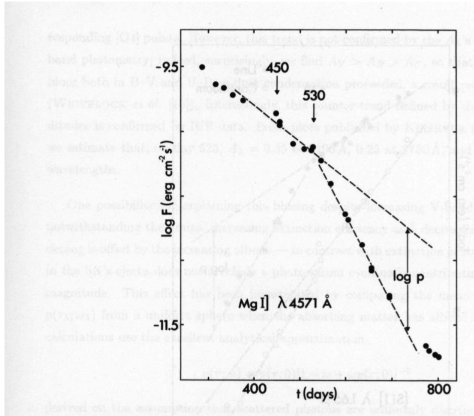


Fig. 2. Measured fluxes for the Mg I λ4571 Å emission line. Least-squares line and their use to estimate the escape probability and hence A_λ illustrated. segments intersect at t = 530d.

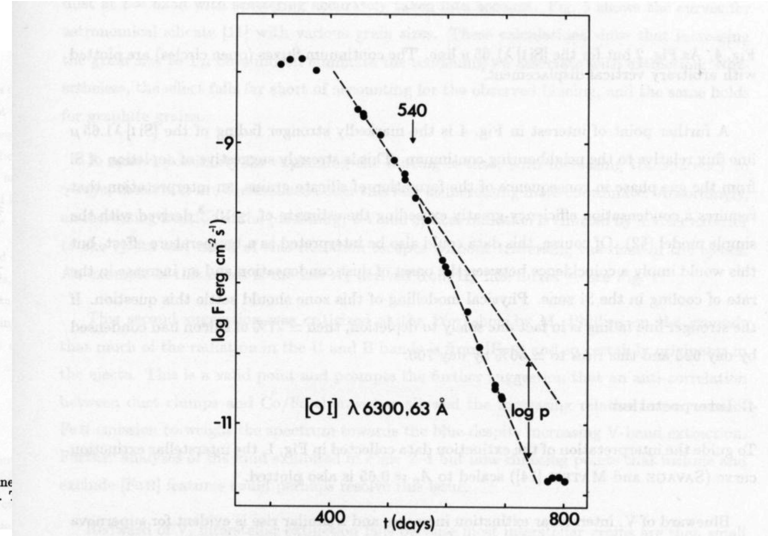


Fig. 3. As Fig. 2 but for the [O I] doublet.

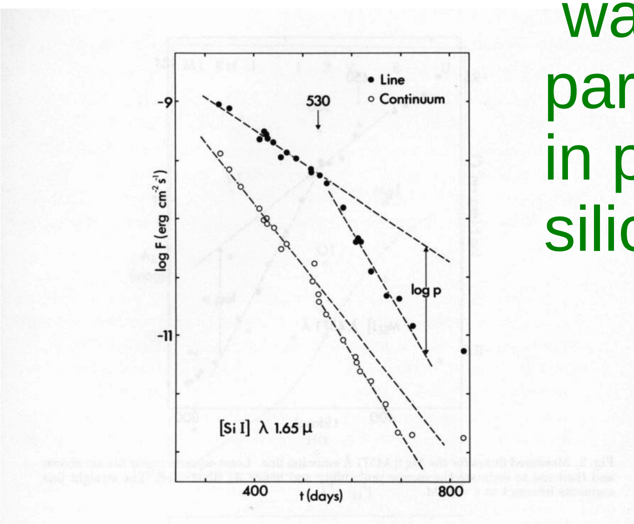
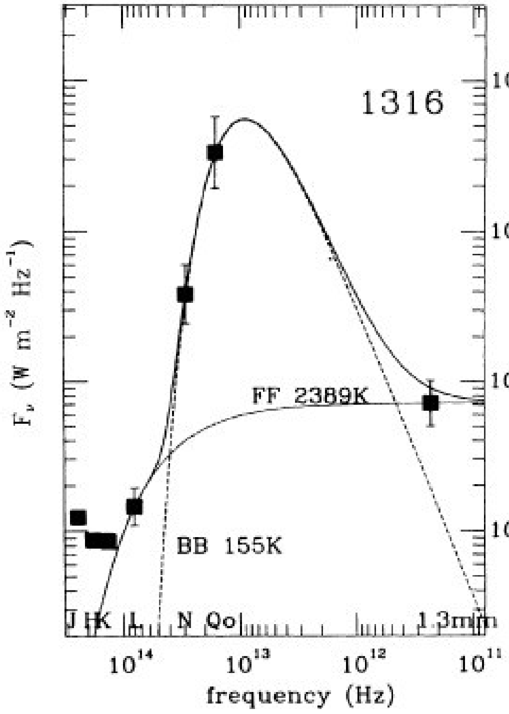


Fig. 4. As Fig. 2 but for the [Si I] λ1.65 μ line. The continuum fluxes (open circles) are plotted with arbitrary vertical displacement.

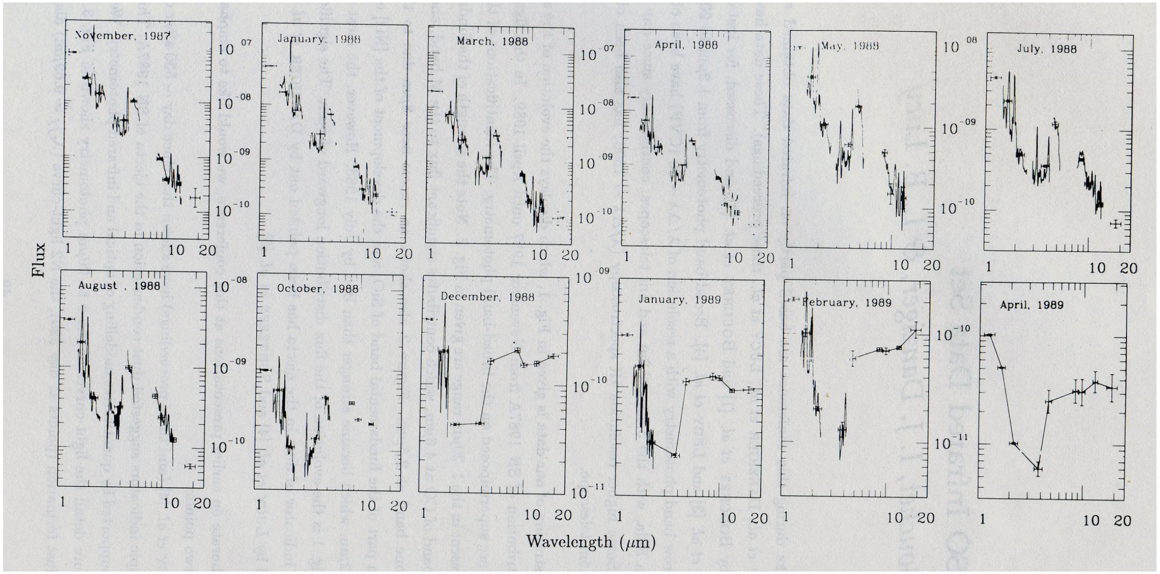
Plots of emission line strengths vs. time show wavelength dependence, thus very small particles < wavelength of light. Effect also seen in photometry. Originally identified as diffuse silicate dust.

But note extra effect for [SiI]1.65m. Si into silicates, IR catastrophe, or fading of [FeII] line blended with [SiI] due to recombination.

Early IR Spectra of SN1987A



Temporal series



Day 1316

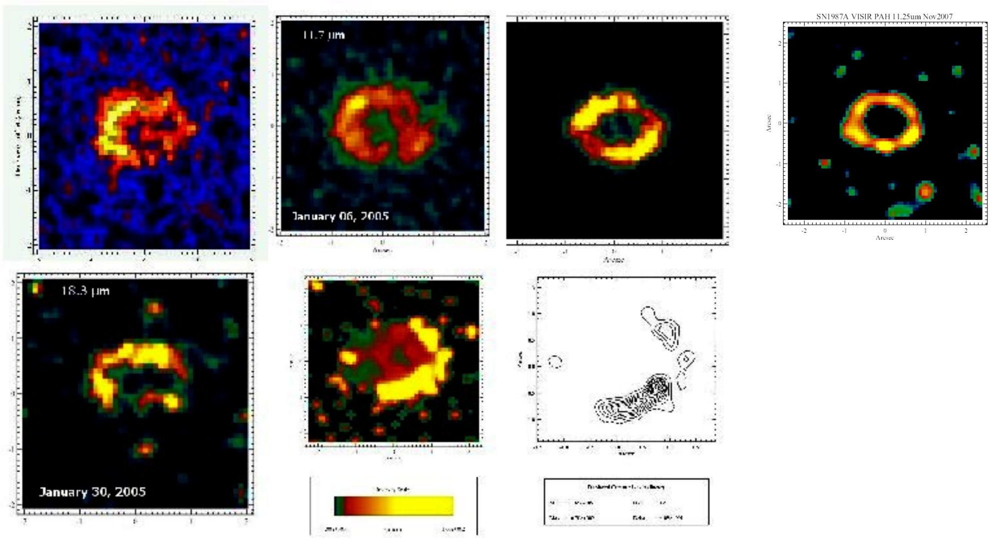
Already at BB 155k
Peak longwards of N,M

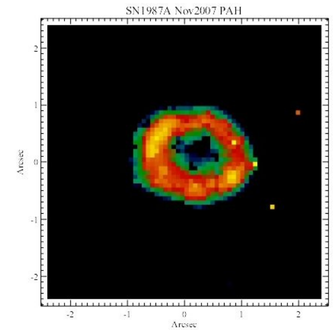
First one sees broad emission features due to molecular bands, then thermal emission by dust.

CIRCUMSTELLAR DUST

Starting 2003 (GeminiS and VLT) midIR imaging showed ring dust and debris? increasing brightness together with Xray, radio, HST V.

A result of ejecta-ring interaction which began much earlier.



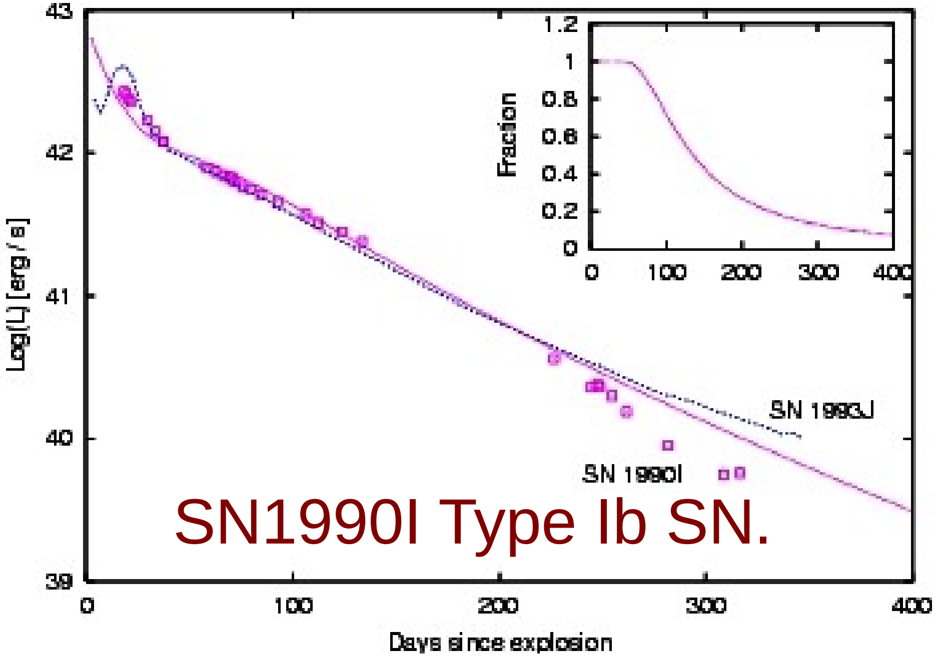


Different cut for faint stuff inside ring.

Mid-IR images at different epochs.
Top left to right. N-band at day 6067,
11.7μ day 6526, N-band day 7241, 11.7μ day 7569.
Bottom left to right. Q-band at day 6526,
ratio of N-bands day 7241/6067, this ratio
Contoured. Ring dust temperatures ~180K.

Ring dust mass
~ 10^{-6} Msun.

Dust also in Type Ib



SN1990I Type Ib SN.

Both light curve and blue line shifts support dust formation near 230 days.

How much dust? Not determined!

SN1957D in M83

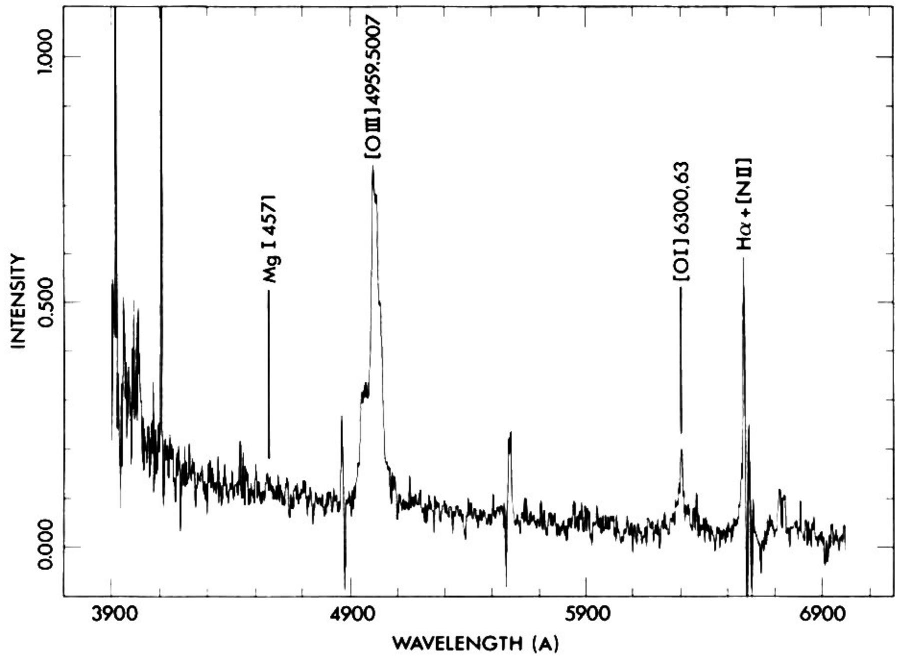
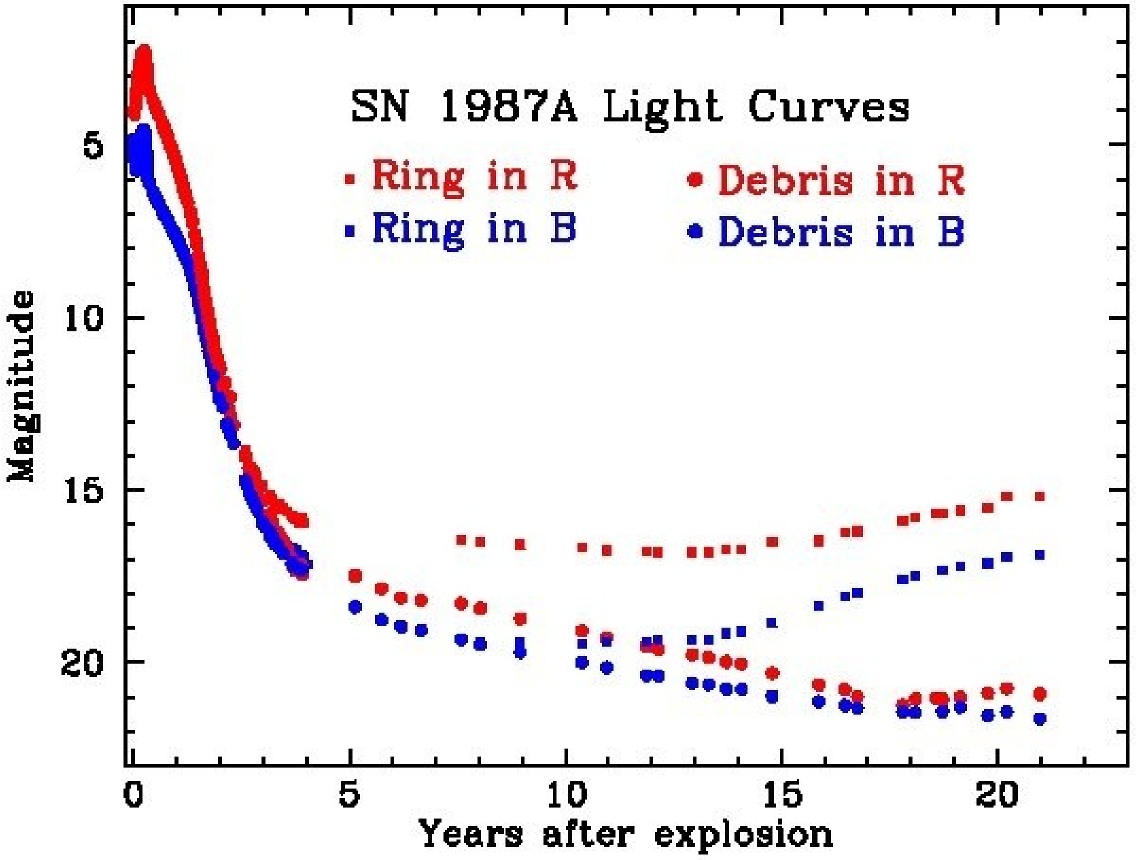


Figure 2: *Spectrum of SN 1957d. Wavelength identifies features discussed in the text, since the redshift of M83 is only 500 km s^{-1}.*

Spectrum observed 30 years later shows lines blue shifted by about 650km/sec. Dust?

HST Photometry



No indication in LC of central debris to indicate formation of massive amounts of dust in debris. Nor have there been additional significant blueward line shifts.

Observational

SNe suggesting possible evidence of dust.

Spectra +	IR
SN1987A	1979C
SN1999em	1985L
SN1990I	
SN1998S	1994Y
SN1980K NB	1997ab
SN2003gd NB	1999el
SN2002hh	2006jc
SN2005bf	
SN2004et (see below)	

Theory

Attempts to show how very large masses of dust are produced in SNe to explain the high z IR luminosities. (e.g. Kozasa, Todini, Ferrara-results said to be robust). More later.

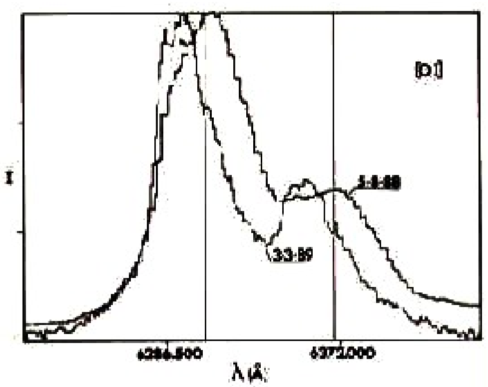
Sample of youngSN Remnants showing IR emission from associated dust (SPITZER)

Tycho
Kepler
Crab
Cas A
Also older SNRs.

SN1987A

Analytic approach

Fig. 1: Emission profile of [OI]λ6300,6363 Å on 5 Aug '88 and 3 Mar '89. Expected wavelengths at velocity of LMC are indicated. The profiles are scaled to same peak intensity for violet component.



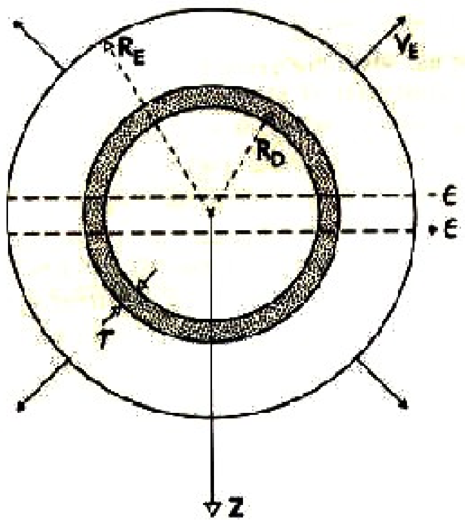


Fig. 2: Model for expanding ejecta with dust condensation in thin shell (Model I). The observer is at z = + ∞.

Blue shift of [OI]6300,6363 lines near day 530. See accurate photometry later.

Dust in thin shell not supported by observations of line profiles.

Analytic modelling

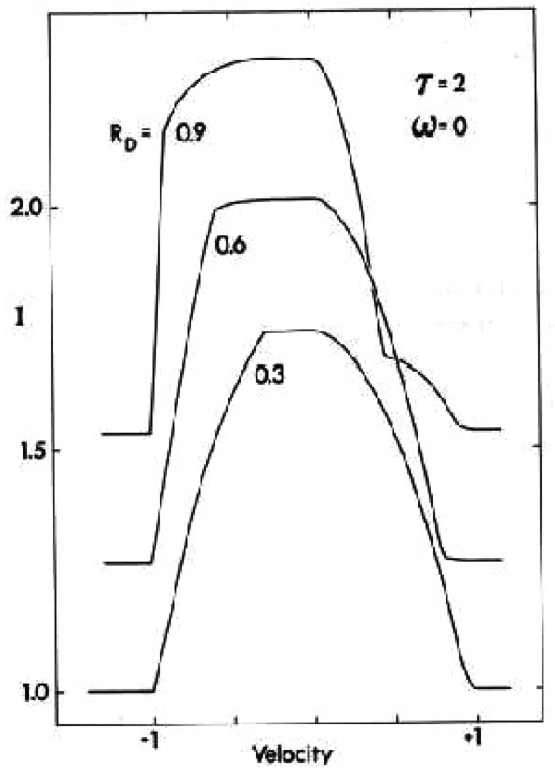


Fig. 3: Theoretical line profiles for Model I. Thin shells of zero-albedo dust with $\tau = 2$ at various radii R_D. Line emissivity is constant.

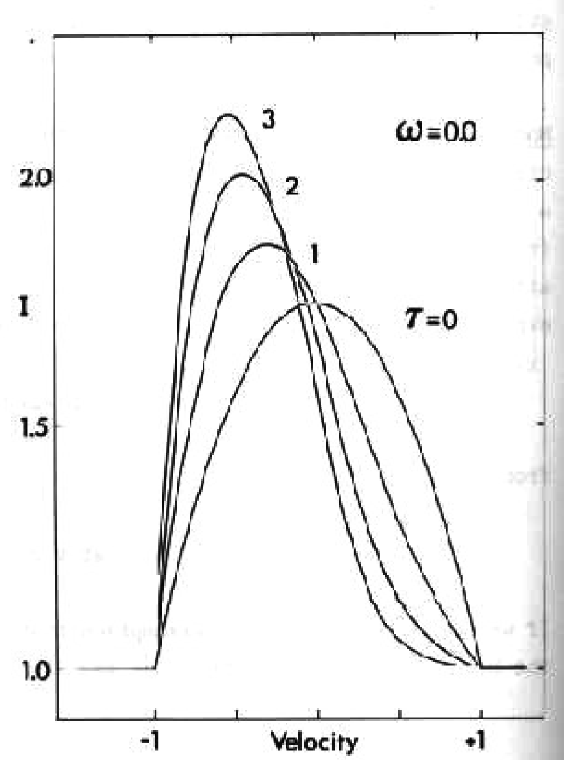


Fig. 4: Theoretical line profiles for Model II. Zero-albedo dust uniformly distributed in the ejecta with various values of $\tau = \kappa\rho R_E$. Line emissivity is constant.

τ = optical depth
ω = albedo

Thin shell produces flat top profiles – not observed.

Uniformly distributed dust produces parabolic shaped profiles varying with τ and ω.

Analytic models vs. observations.

Good agreement between 2 independent measures of τ supports model.

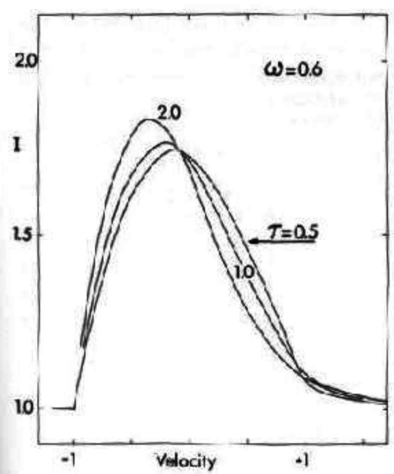


Fig. 5: Theoretical line profiles for Model III. Dust with albedo = 0.6 is uniformly distributed through the ejecta with indicated values of $\tau = k\rho R_E$.

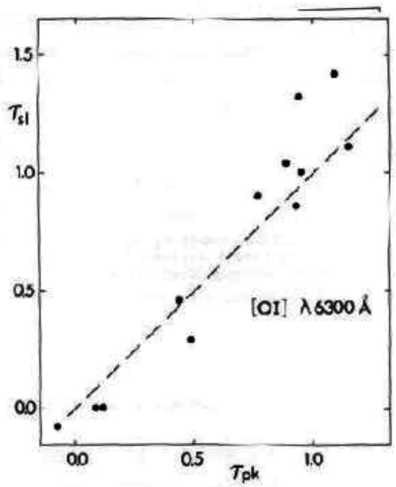


Fig. 6: Comparison of independent estimates of $\tau = k\rho R_E$ for Model II from observed [OI]λ6300 Å profile.

Shows effect of τ on line shift and shape at 0 velocity. (2 independent measures).

Profile shape shows dust contained within 1870km/s. More concentrated in SN99em.

At day 775 when dust formation indicated by optical depths has slowed down masses of dust using τ were obtained:
Amorphous silicates 3×10^{-4} Msun.
Fe, graphite, amorphous C 1-2 orders of mag. less.