Dust formation in dense CSM behind the shock: A study based on SN2010jl

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Overview

Dust is known to form in the quiescent outflows of AGB stars and in the explosively ejected matter of core collapse supernovae (CCSNe). Recent optical and near-infrared (IR) observations of the light curve of the ultra-luminous CCSN SN2010jl has shown evidence for the rapid rise of a thermal IR emission component attributed to the formation of new dust grains. Observations of the evolution of the broad H and He lines in the spectra show that the dust could not have formed in the SN ejecta, but must have formed in the CSM instead.The radiation emanating from the shocked CSM plays a pivotal role in determining the earliest epoch after which seed nucleation centers can form and survive in the post-shock region. Detection of the IR excess as early as 67 days post-explosion poses new challenges to our understanding of the dust scenario behind shocks. Our model provides a complete picture of the formation of dust in such extreme astrophysical environment and its manifestation on the SN light curve.

1 Type IIn Supernovae and SN2010jl

a) Pre-explosion star surrounded by dense and massive CSM
b) Presence of Hydrogen emission lines in the spectra
c) Light curve dominated by Shock-CSM interaction
d) massive progenitor

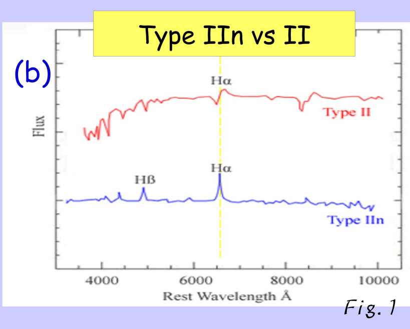


Fig. 1

SN2010jl
Ultra-luminous, Progenitor ~ 40 M_{sun}
Surrounded by ~ 10 M_{sun} of CSM during explosion (Ofek + 2013)

IR-optical: VLT/X-shooter spectrograph (Gall + 2014)
UV-optical: HST (Fransson + 2014)
X-ray: CHANDRA (Chandra + 2015)

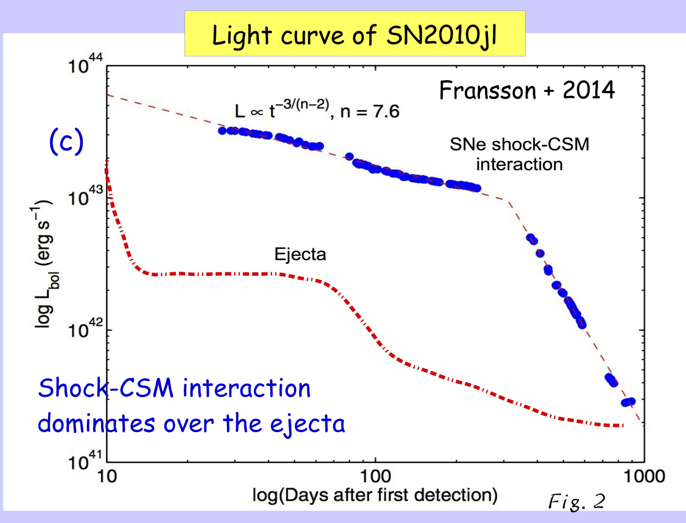
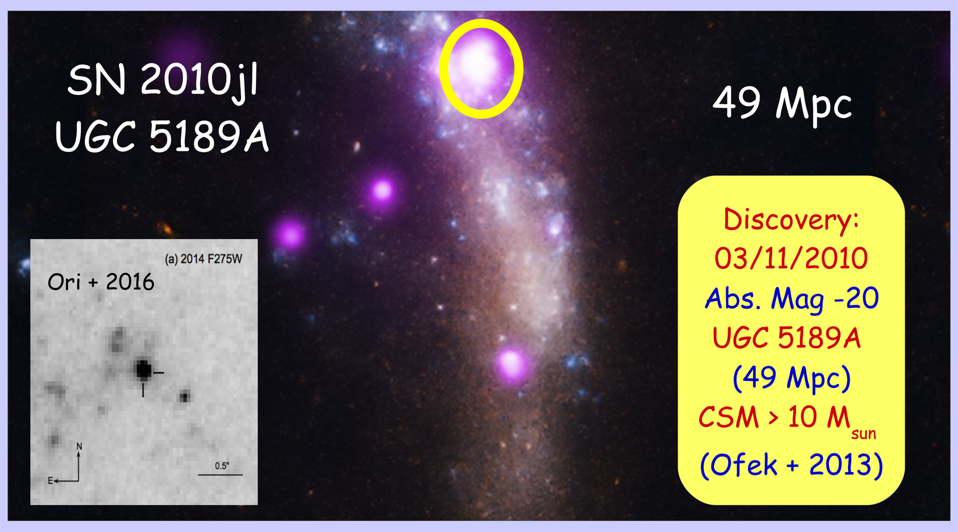


Fig. 2



2 UVO & NIR observations: *Traces of early dust formation??*

1) IR excess dust to thermal emission from hot dust
2) Increased rate of fading of optical flux
3) Progressive blueshift of emission lines
(receding part of the object is blocked by dust)

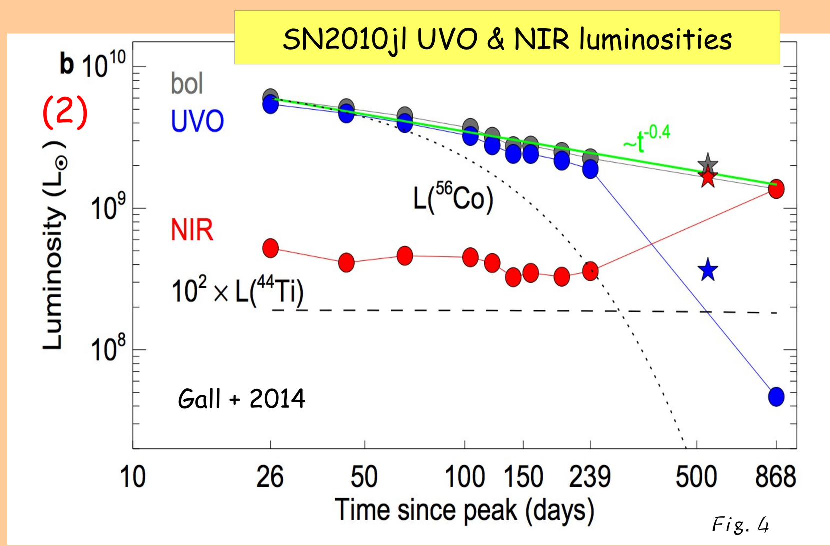


Fig. 4

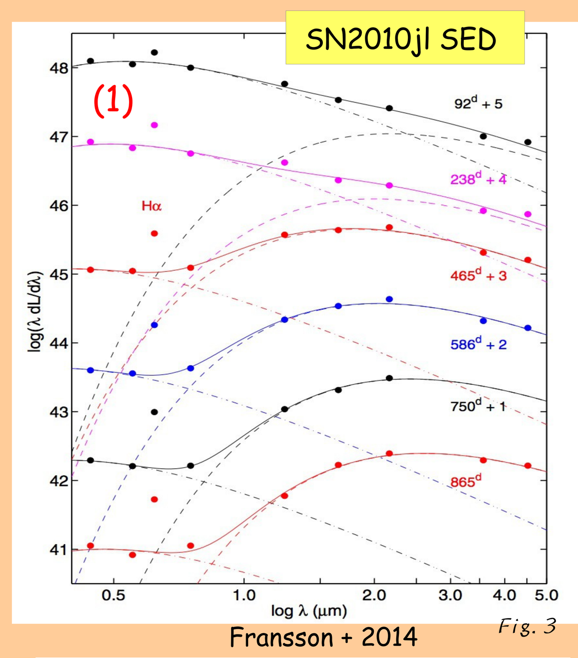


Fig. 3

Epoch (days)	T_{eff} (K)	R_{phot} (10^{15} cm)	T_{dust} (K)	R_{dust} (10^{16} cm)
92	6900	3.20	1685	1.60
238	7450	2.18	1830	1.44
465	9200	0.56	2040	2.21
586	9900	0.29	1790	2.61
750	9300	0.22	1520	3.24
880	7750	0.23	1410	3.43

3 The mystery and the challenges

1) New dust in dense shell/SN-ejecta within 100 days ?
(*Ejecta powered by radioactivity*)

2) Early NIR due to echo from pre-existing dust ?
(*Dust temperatures > 1200 K at all times*)

3) How does the dust mass evolve ?
(*Relative time-scales of gas cooling vs seed nuclei formation*)

4) What is heating the dust at later times ?
(*Sharp decline in UVO luminosities post day 260*)

5) What is the contribution of shocked-CSM dust on SN-light curve ?
(*The NIR continue to increase until late times*)

4 What are the possible sites for the new and/or pre-existing dust

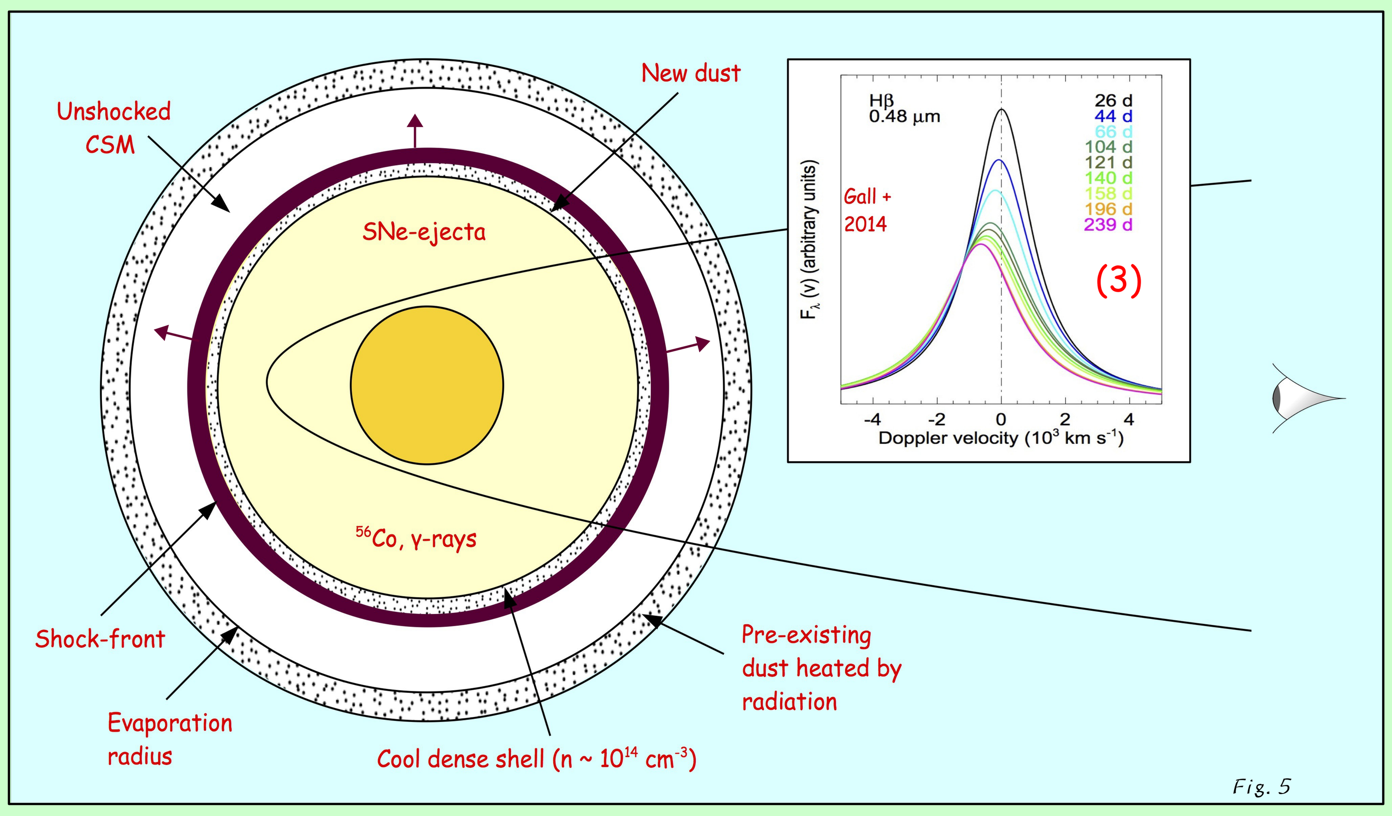
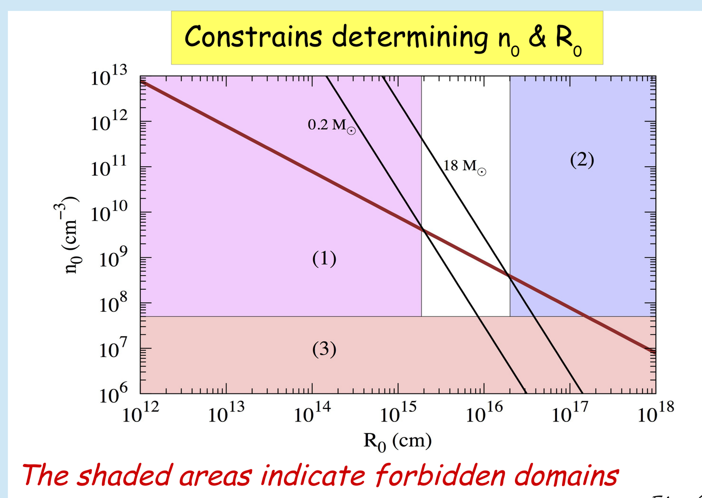


Fig. 5

Dust can be present in: a) The pre-existing dust outside the evaporation radius, b) The cool dense shell immediately behind the shock, c) The supernova ejecta

5 The constraints on physical parameters



The shaded areas indicate forbidden domains
Fig. 6

The product of the n_0 and R_0 of the CSM is constrained by the H-column densities determined from X-ray observations (Chandra + 2015)

Forbidden because:
(1) $R_0 < R_{BB}$ (shock-photosphere)
(2) R_0 > v_shock x t_dust
(3) n_0 small ---> t_cool > t_dust

If the dust forms behind the shock R_{BB} (dust) should be smaller than R_shock

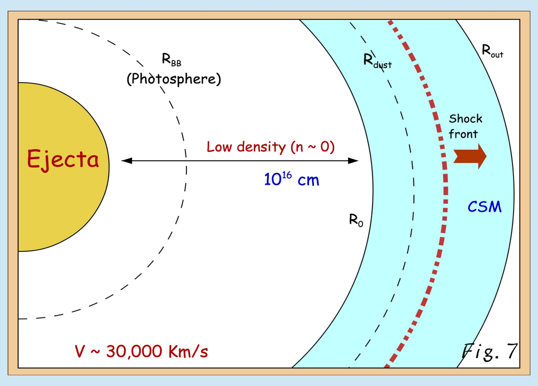
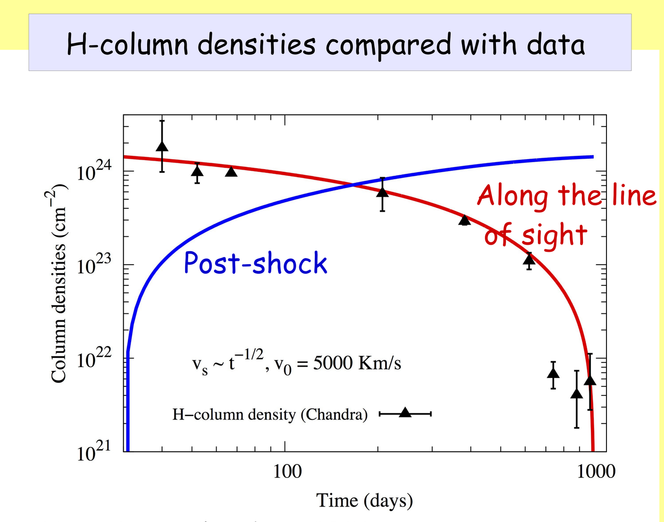


Fig. 7

6 The Hydrogen column densities are calculated & compared



X-ray Data: Chandra + 2015
Fig. 8

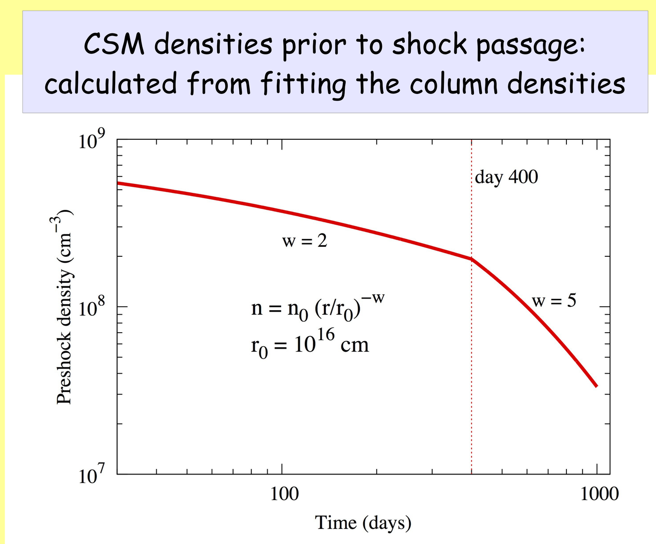


Fig. 9

Estimated pre-shock CSM density profile ~ r^{-2} (t < day 400) & r^{-5} (t > day 400), $R_0 \sim 10^{16}$ cm
$R_{out} \sim 3.0 \times 10^{16}$ cm, n_0 = 3.0×10^{8} cm^{-3}
Shock velocity: 3-5000 Km/s ~ $t^{-(w-3/m-w)}$, (m = 4,8 & w = 2, 5) (Ofek + 2014)

7 The post-shock gas cools rapidly forming a dense shell

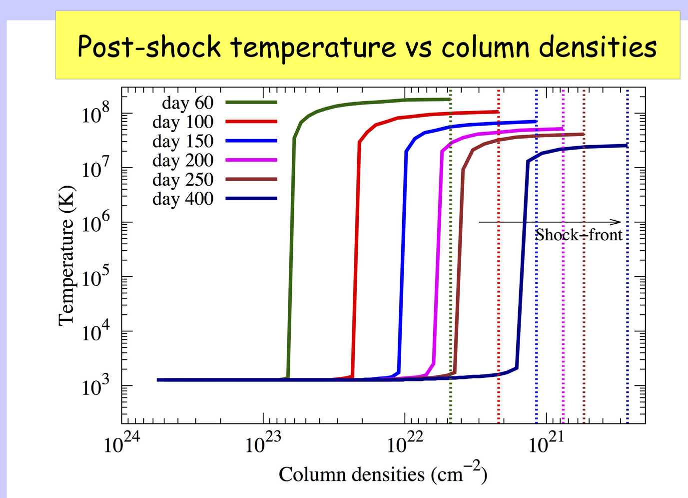


Fig. 10

Cooling time ~5-10 days

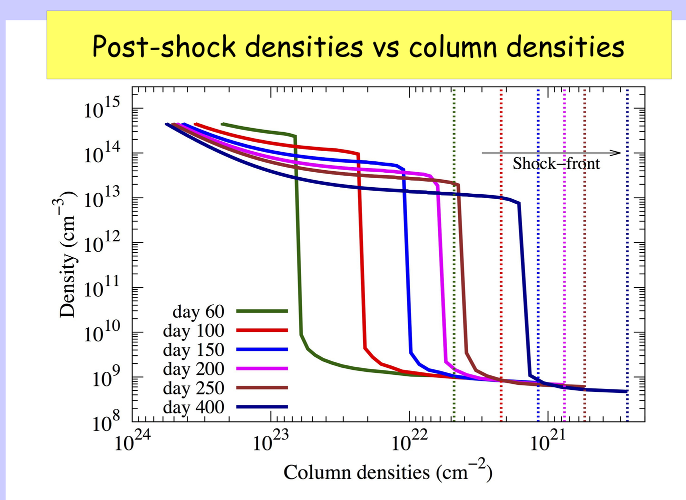


Fig. 12

Evolution of gas parameters:
The passage of the shock is shown with an arrow towards right, in Fig. 10 & 12, giving rise to a shell of ionized very hot gas (10^8-10^6 K) The shock sweeps the CSM with it, the continuity, momentum & energy equations determine the behavior of the post-shock gas

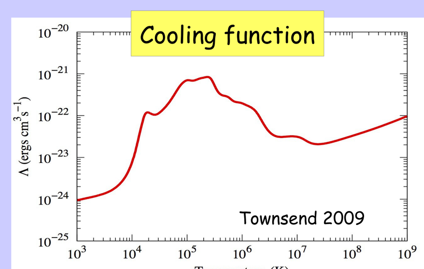


Fig. 11

Formation of dense shell:
The ionized gas cools following the cooling function (Fig. 11). The drop in temperature leads to a sharp increase in gas densities resulting to the formation of a dense shell
The dense shell remains warm due to radiation from the preceding shock (CLOUDY)

8 Radiative heating: *Dust cannot form in the dense shell until day 250 !*

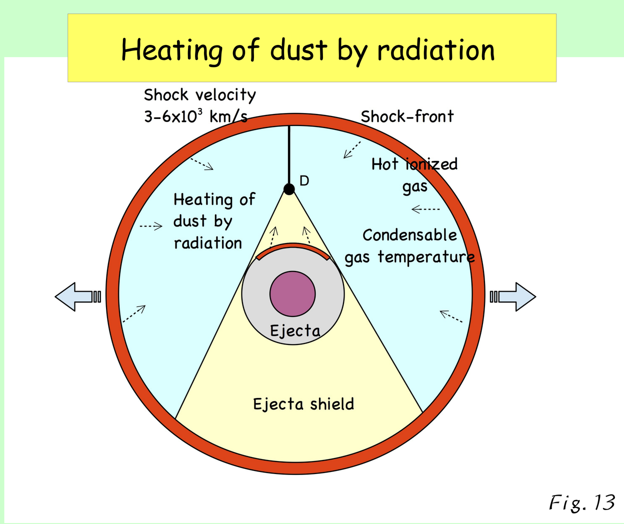
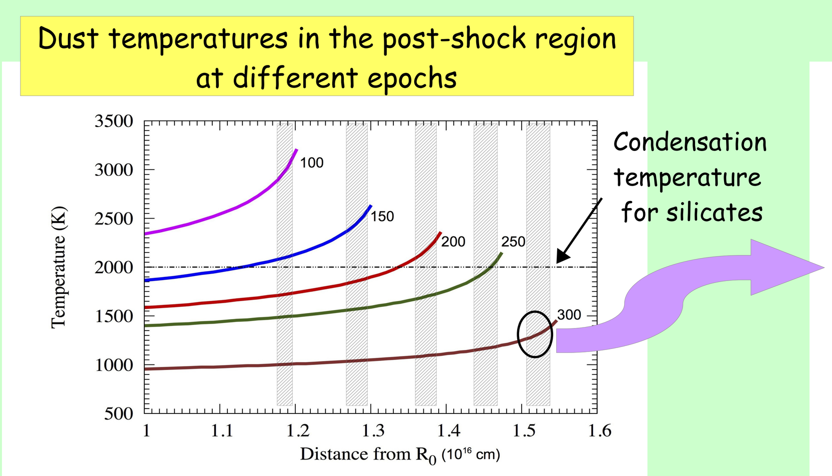


Fig. 13



The shaded region represents the relative position of the dense shell
Fig. 14

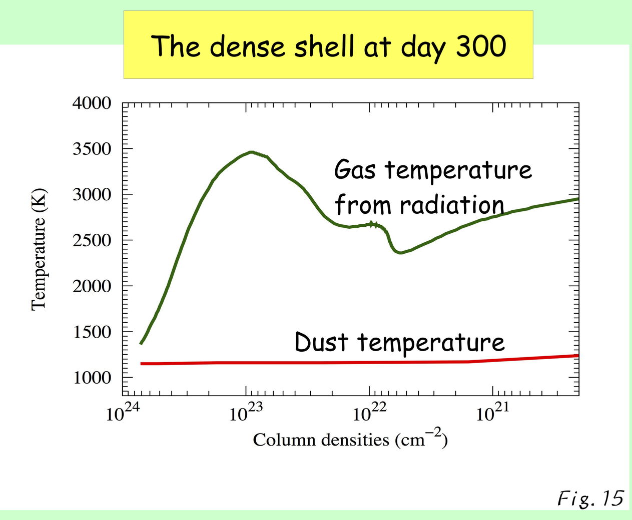
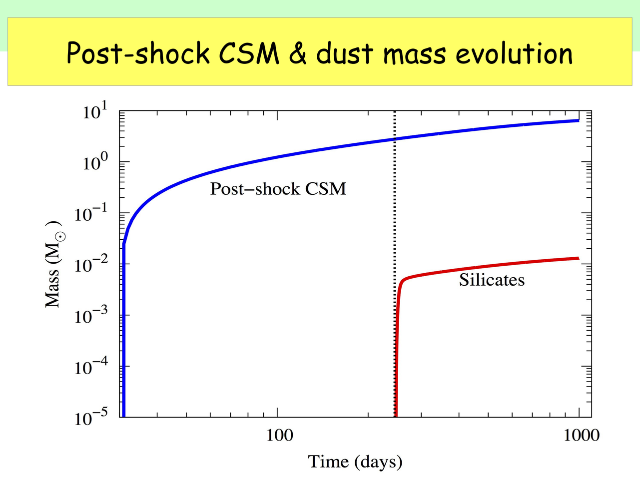


Fig. 15

The Scenario
Post-shock heating:
a) radiation from the shock & ejecta
b) Collision with the ambient gas
Fast cooling & high density (n_{DS}/n_0 ~ 10^6)
Ideal environment to form dust

BUT heating by post-shock radiation Field of L ~ 10^9 L_{sun}, T_{phot} ~ 8000 K, delays the first epoch of dust formation in the dense shell
Dilution factor: $f_D = (R_{BB}/R_s)^2$



N-enhanced gas, C/O < 1, no C-dust
Fig. 17

Epoch of dust synthesis
Dust formation in the dense shell is delayed until day ~ 250 (Fig 14)
Dust mass varies from 4.0×10^{-3} to 10^{-2} M_{sun}
Sharp decline in bolometric luminosity post day ~ 260 (Fig. 4),
the dust temperature from radiation is ~ 1000 K. However, the ambient gas still remains hot ~ 2000 K can heat the dust (Fig. 15)
That would lead to a dust temperature ~ 1600 K at day 300
(Comparable to observations)

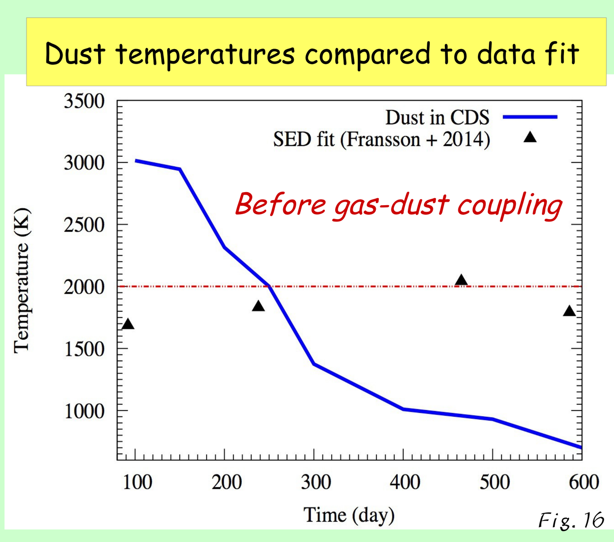


Fig. 16

9 The highlights & probable scenarios

- Dust formation in the dense shell is delayed until day ~ 250 due to radiation from the hot gas behind the shock
(*Plausible cause for the rise in NIR after day 250 ?*)
- The post-shock gas cools rapidly within 5-10 days, forming the dense shell (n ~ 10^{13}-10^{14} cm^{-3})
- The dense shell remains warm due to the radiative heating by the shock which can thereby collisionally heat the dust
(*Probable heating source for dust*)
- Final dust mass varies from 4.0×10^{-3} at day 250 to 10^{-2} M_{sun} , comprised of essentially silicates

Probable scenario that can explain NIR & progressive blue-shift of emission lines before day 250

(a) Echo from pre-existing dust
(constraint: evaporation radius, progressive blue-shift)

(b) Ejecta dust (constraint: ejecta powered by radioactivity)

(c) Clumpy CSM (constraint: surface filling factor, opacities)