Formation of Dust in the Ejecta of Type Ia Supernovae

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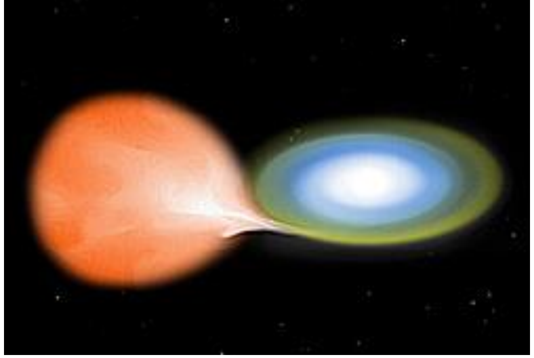
1-1. Introduction



○ Type Ia supernovae (SNe Ia)

— thermonuclear explosions of C+O white dwarfs with the mass close to Chandrasekhar limit (~1.4 M_{sun})

- deflagration (Nomoto+76, 84)
  ➔ subsonic wave, unburned C in the outer layer
- (delayed) detonation (Khokhlov91a, 91b)
  ➔ supersonic wave, burning almost all C

— synthesize a significant amount of Fe-peak and intermediate-mass elements such as Si, Mg, and Ca

➔ play a critical role in the chemical evolution

➔ possible sources of interstellar dust?

1-2. Type Ia SNe are sources of dust?

○ Suggestions on dust formation in SNe Ia

– SNe Ia may be producers of Fe grains
(Tielens98; Dwek98)

– the isotopic signature of presolar type X SiC grains can be explained if produced in SNe Ia (Clayton+97)

○ Observations of normal SNe Ia

– no increase of IR dust continuum (and no CO emission)

– no rapid decrease of the optical light curve

– no blueshift of atomic line emissions

➔ these signatures have been reported for CCSNe

– no evidence for ejecta-dust in Tycho SNR (Douvion+01)

1-3. Aim of our study

○ Questions

– Are there any differences in formation process of dust between SNe Ia and (Type II) CCSNe?

– Is it possible for dust grains to form in SNe Ia ?

○ Dust formation calculation in SNe Ia

➔ chemical composition, size, and mass of dust that can condense in the ejecta of SNe Ia

➔ dependence of dust formation process on SN types

➔ implication on the outermost layer in SNe Ia

➔ survival of the newly formed dust against destruction by the reverse shock

2-1. Model of SNe Ia (1)

○ Type Ia SN model

C-deflagration W7 model
(Nomoto+84; Thielemann+86)

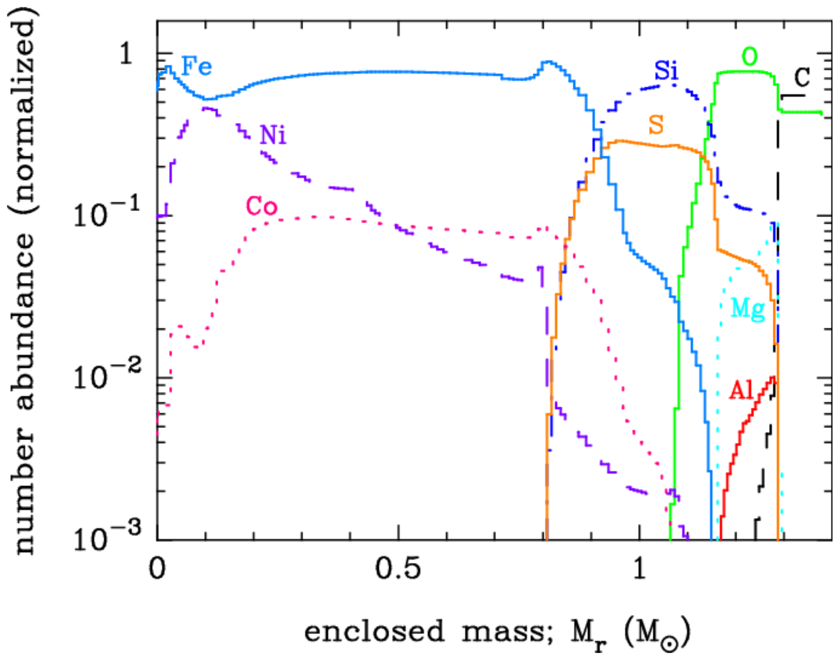
- **M_{eje} = 1.38 Msun**
- **E_{kin} = 1.3x10^{51} erg**
- **M(^{56}Ni) = 0.6 Msun**

  ## M(^{56}Ni) ~ 0.06 Msun in typical CCSNe

- **stratified distribution**
  (no mixing of elements)

  ## This assumption is supported observationally (e.g. Mazzali+08; Tanaka+11)

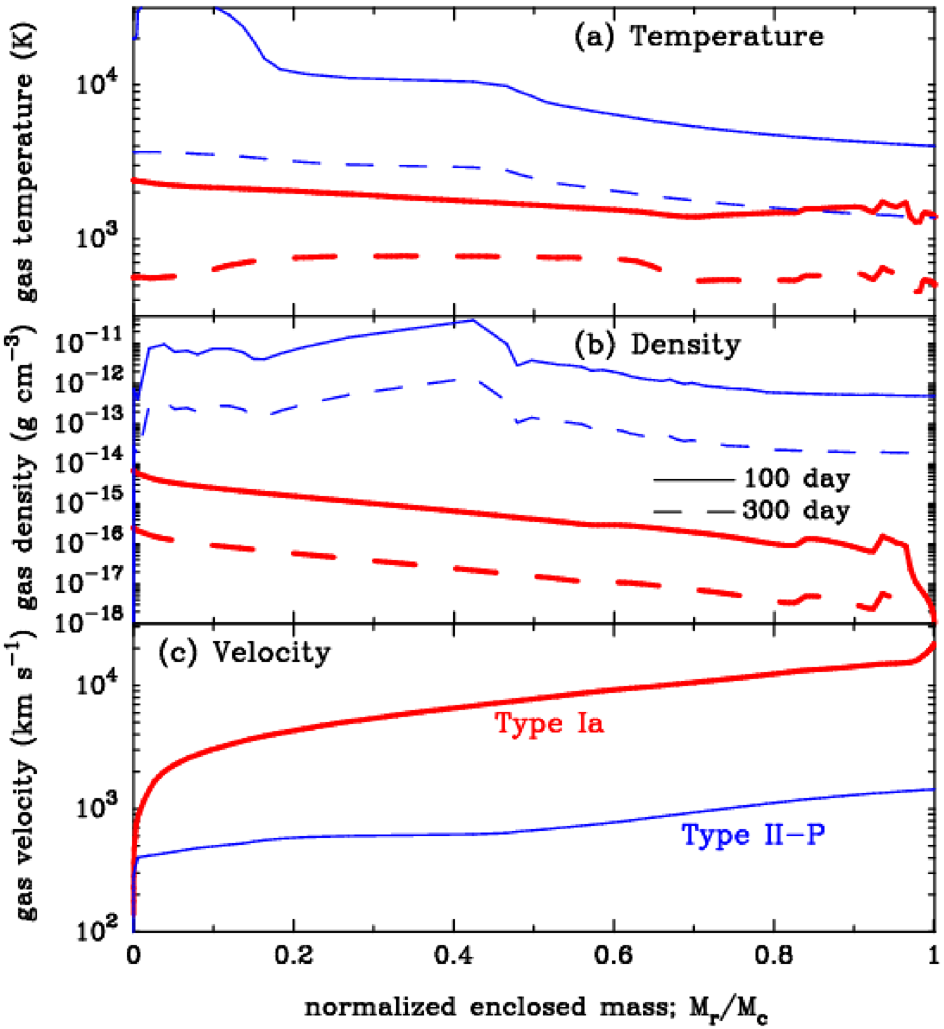
elemental composition



0.1 Msun of C and O remained unburned in the outermost layer with Mc/Mo ~ 1

2-2. Model of SNe Ia (2)

hydrodynamic model



red lines : SNe Ia

- M_{eje} = 1.38 Msun
- E_{kin} = 1.3x10^{51} erg

blue lines : Type II-P SNe

- M_{star} = 20 Msun
- E_{kin} = 1.0x10^{51} erg
- M_{env} = 13.2 Msun

— gas density in the SN Ia is more than 3 orders of magnitude lower than that in the SN II-P

— gas temperature in the SN Ia decreases more quickly

2-3. Calculation of dust formation

○ nucleation and grain growth theory

(Nozawa+03, 08, 10)

— steady-state nucleation rate

$$J_j^s(t) = \alpha_{sj}\Omega_j \left(\frac{2\sigma_j}{\pi m_{1j}}\right)^{1/2} \left(\frac{T}{T_d}\right)^{1/2} \Pi_j c_{1j}^2 \exp\left[-\frac{4}{27}\frac{\mu_j^3}{(\ln S_j)^2}\right],$$

— grain growth rate

$$\frac{\partial r}{\partial t} = \alpha_s \frac{4\pi a_0^3}{3}\left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1(t) = \frac{1}{3} a_0 \tau_{\rm coll}^{-1}$$

— sticking probability : α = 1 and 0.1

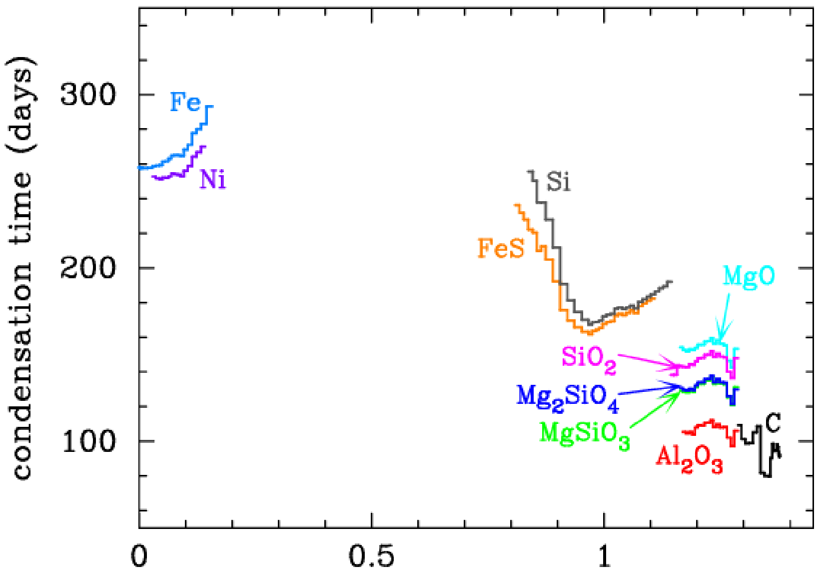
— LTE condition : $T_d = T$

(dust has the same temperature as the gas)

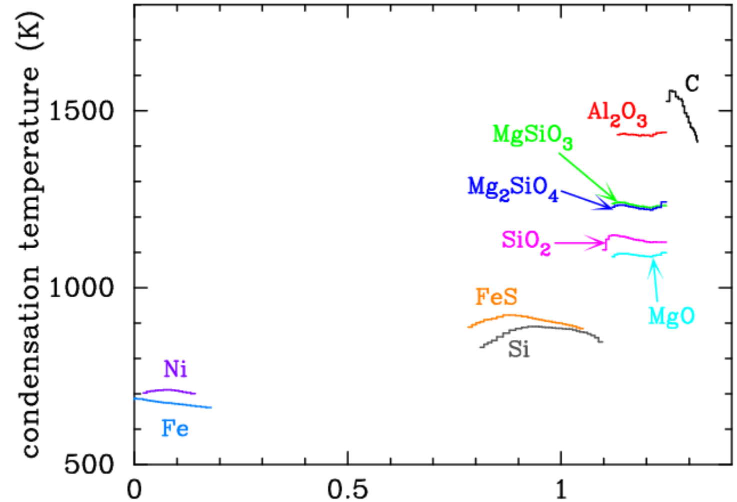
The use of the same prescription enables the direct comparison with our earlier results

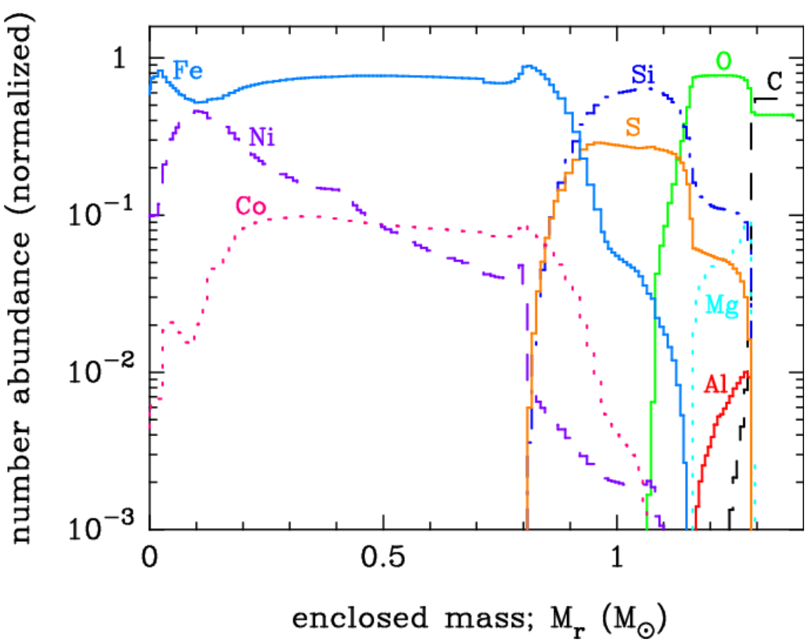
3-1. Results (1): Condensation time of dust

Condensation time



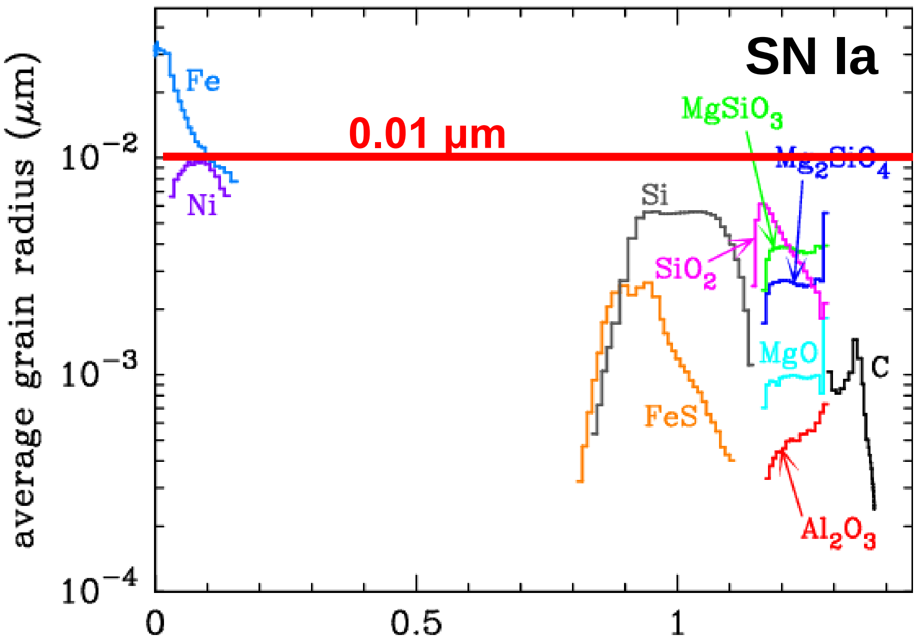
Condensation temperature

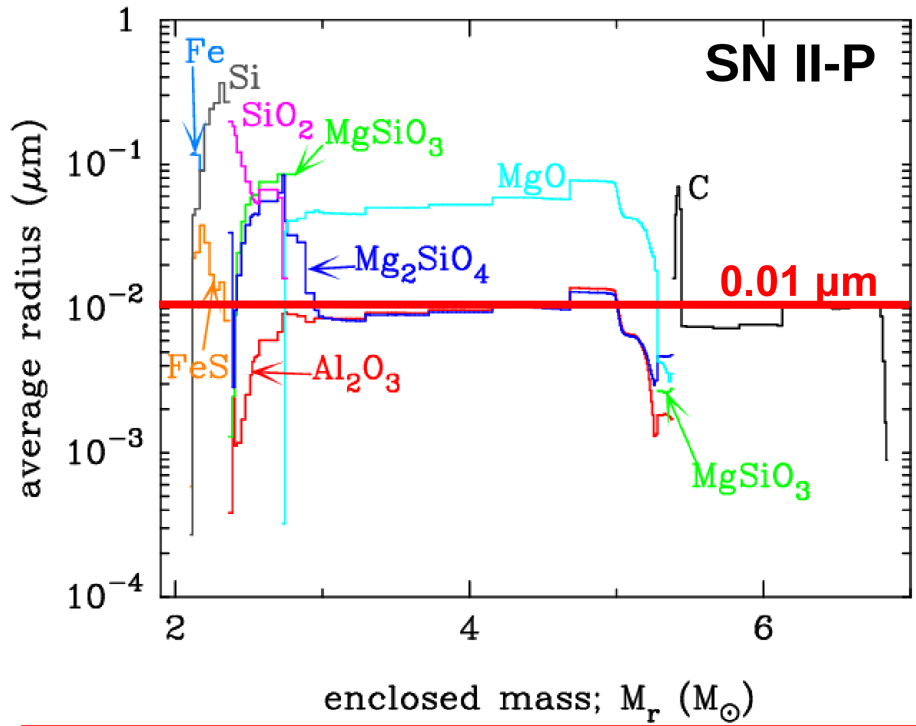


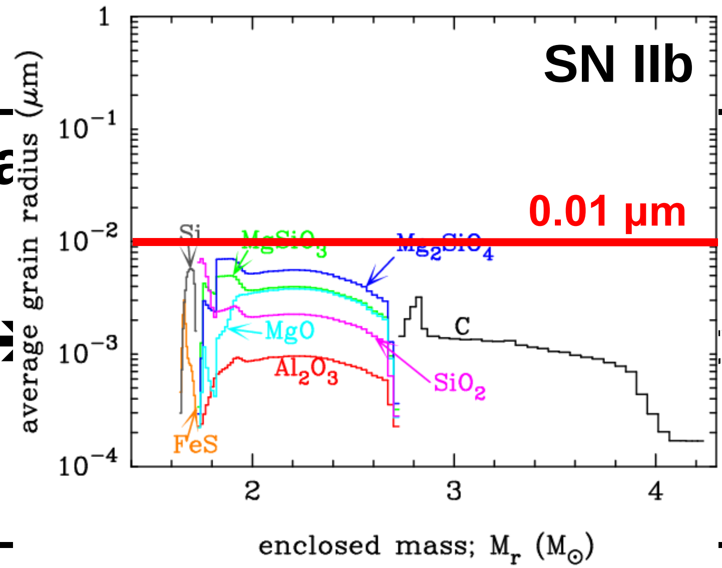


- **different dust species form in different layers**
  - Fe and Ni grains cannot condense significantly
  - SiC can never condense
- **condensation time of dust : tc = 100-300 days**
  (tc > ~300 days in SNe II-P)

3-2. Results (2): Average radius of dust







the radius of dust formed in H-stripped SNe is small

- **SNe IIb/Ia with thin/no H-env ➔ a_{ave} < 0.01 μm**
- **SN II-P with massive H-env ➔ a_{ave} > 0.01 μm**

3-3. Results (3): Mass of each dust species

dust species	A1 ($\alpha = 1$)	A0.1 ($\alpha = 0.1$)
C	5.66×10^{-3}	2.84×10^{-4}
MgO	3.17×10^{-6}	1.85×10^{-9}
$MgSiO_3$	7.59×10^{-3}	1.31×10^{-6}
Mg_2SiO_4	7.01×10^{-3}	1.50×10^{-6}
SiO_2	1.47×10^{-2}	9.94×10^{-6}
Al_2O_3	8.18×10^{-7}	7.48×10^{-10}
FeS	1.78×10^{-2}	1.53×10^{-5}
Si	6.30×10^{-2}	3.15×10^{-5}
Fe	9.52×10^{-5}	1.09×10^{-8}
Ni	1.48×10^{-6}	2.22×10^{-10}
Total	1.16×10^{-1}	3.44×10^{-4}

M_C = 0.006 M_{sun}

$M_{silicate}$ = 0.030 M_{sun}

M_{FeS} = 0.018 M_{sun}

M_{Si} = 0.063 M_{sun}

M_{total} = 0.116 M_{sun}

Total mass of dust formed in SNe Ia : M_{dust} < ~0.1 M_{sun}

4-1. Optical depths by newly formed dust

V band (0.55 μm) opacity at 300 days for α = 1

M_{C} = 0.006 M_{sun}	→	T_{C} = 22
$M_{silicate}$ = 0.030 M_{sun}	→	$T_{silicate}$ = 0.01
M_{FeS} = 0.018 M_{sun}	→	T_{FeS} = 14
M_{Si} = 0.063 M_{sun}		T_{Si} = 78
M_{total} = 0.116 M_{sun}	→	T_{total} = 114

V band (0.55 μm) opacity at 300 days for α = 0.1

M_{total} ~ 3×10^{-4} M_{sun} → T_{total} = 1

Formation of dust grains (C, Si, and Fe) should be suppressed to be consistent with the observations

4-2. Non-LTE effect on dust formation

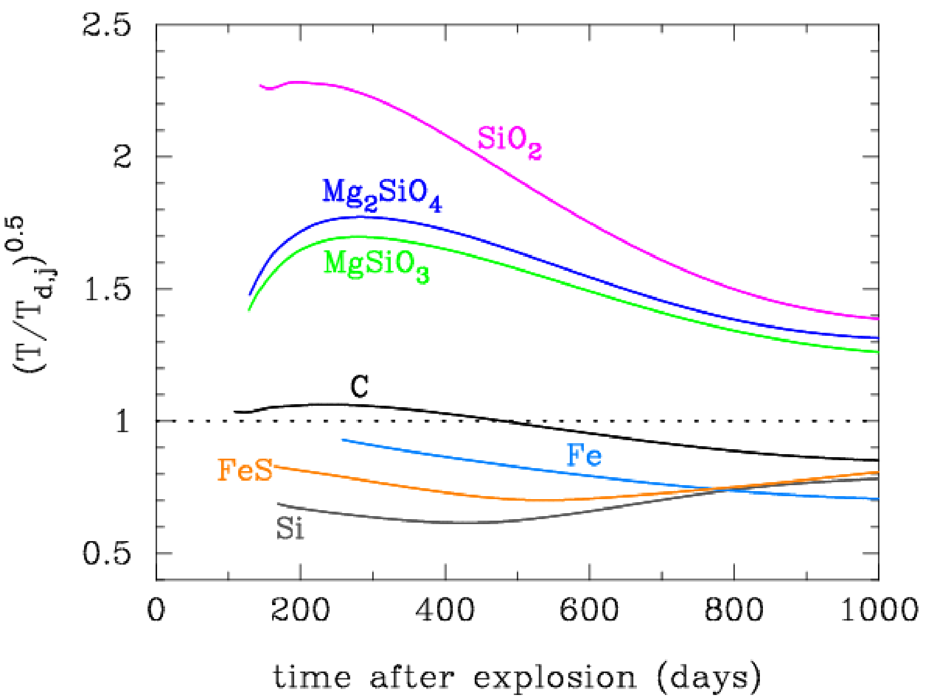
$$4\pi a^2 \sigma_B T_d(r)^4 \langle Q_\lambda(a, T_d)\rangle = \frac{F(r)}{\sigma_B T_{BB}^4} \int \pi a^2 Q_\lambda(a) B_\lambda(T_{BB}) d\lambda$$

$T_d(r)$: equilibrium temperature of dust at a position r

$F(r)$: flux at a position r

(radiating as a blackbody with $T_{BB} = 5000\text{K}$)

$\langle Q_\lambda(a, T_d)\rangle$: Plank-averaged value of $Q_\lambda(a)$



Non-LTE dust formation

M_{FeS} = 4x10^{-4} Msun

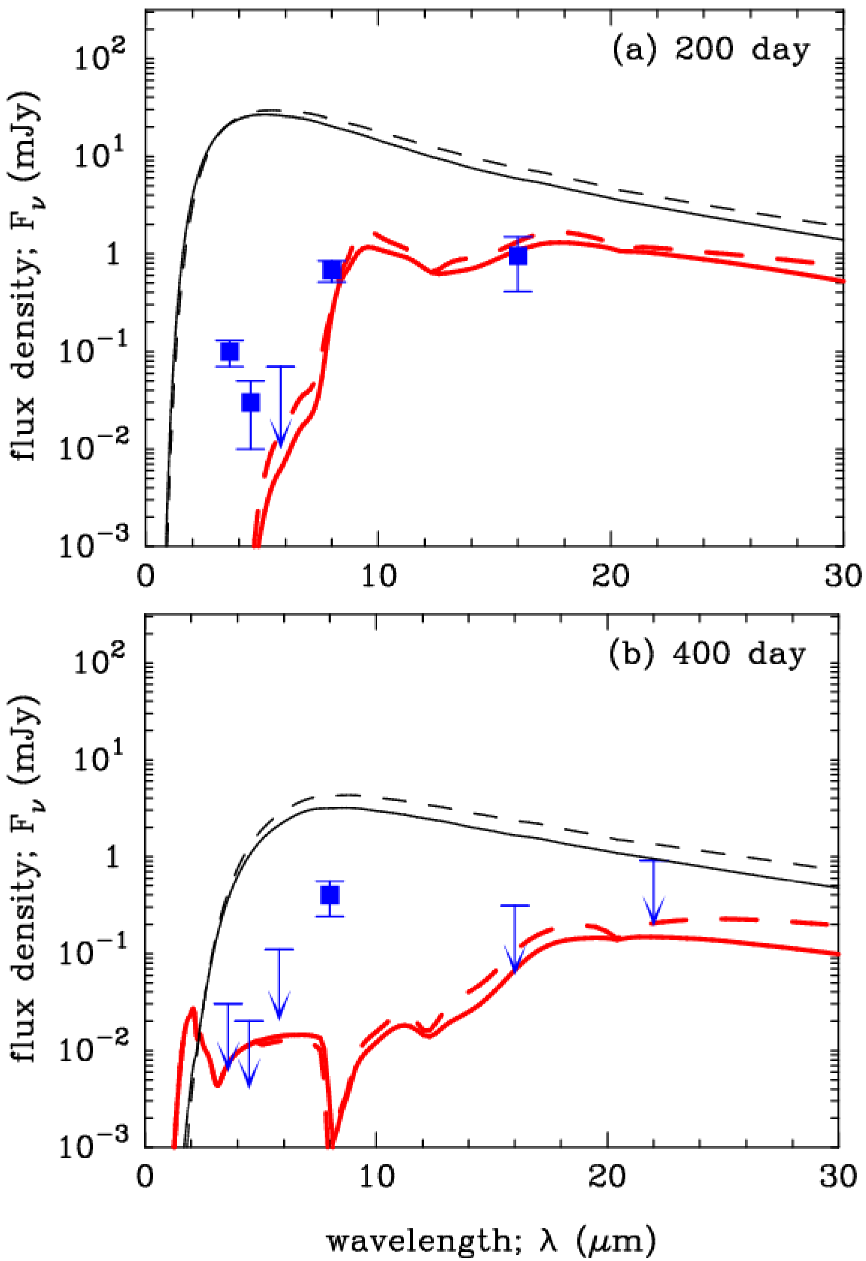
M_{Si} = 1x10^{-6} Msun

➔ τ_{FeS} < 0.1 after 300 day

M_C = 0.0055 Msun

➔ τ_C > 20 (too high to be consistent with the observations)

4-3. Infrared thermal emission from dust



Observational data : SN 2005bf at day 200 and 400 **(Gerardy+07)**

black solid lines :
SEDs including emission from C grains
➔ much higher than the observational results

red solid lines :
SEDs not including emission from C grains
➔ not contradict with the observational results

0.03 Msun of silicate can be allowed as dust mass

4-4. Carbon dust and outermost layer of SNe Ia

○ Formation of massive carbon dust

− high sticking probability of α = 0.1-1

➔ if α < ~0.01, any dust grain cannot condense

− dust formation around 100 days, M(56Ni) ~ 0.6 M_{sun}

➔ dust formation can be destroyed by energetic photons and electrons prevailing in the ejecta

− massive unburned carbon (~0.05 M_{sun}) in deflagration

➔ change of WD composition by the He-shell flash

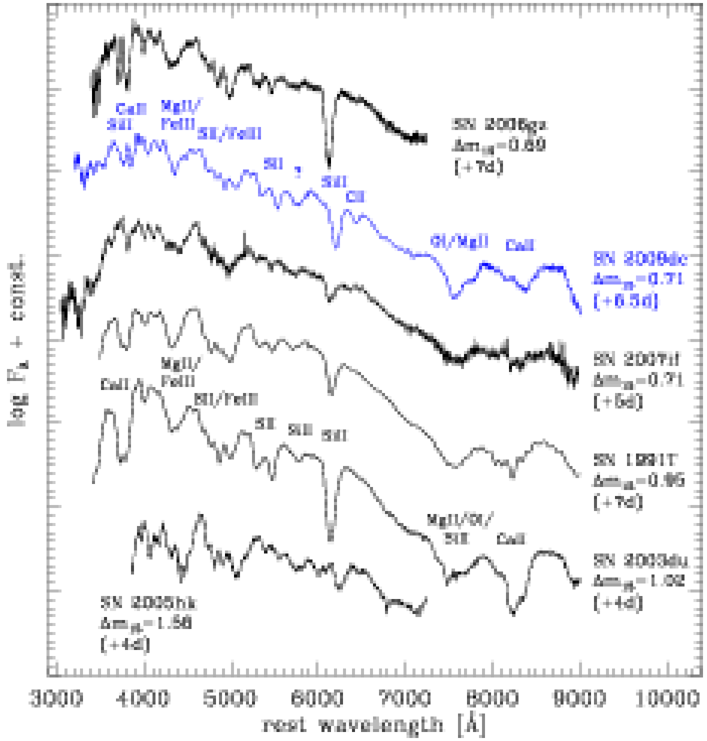
➔ burning of carbon by a delayed detonation wave

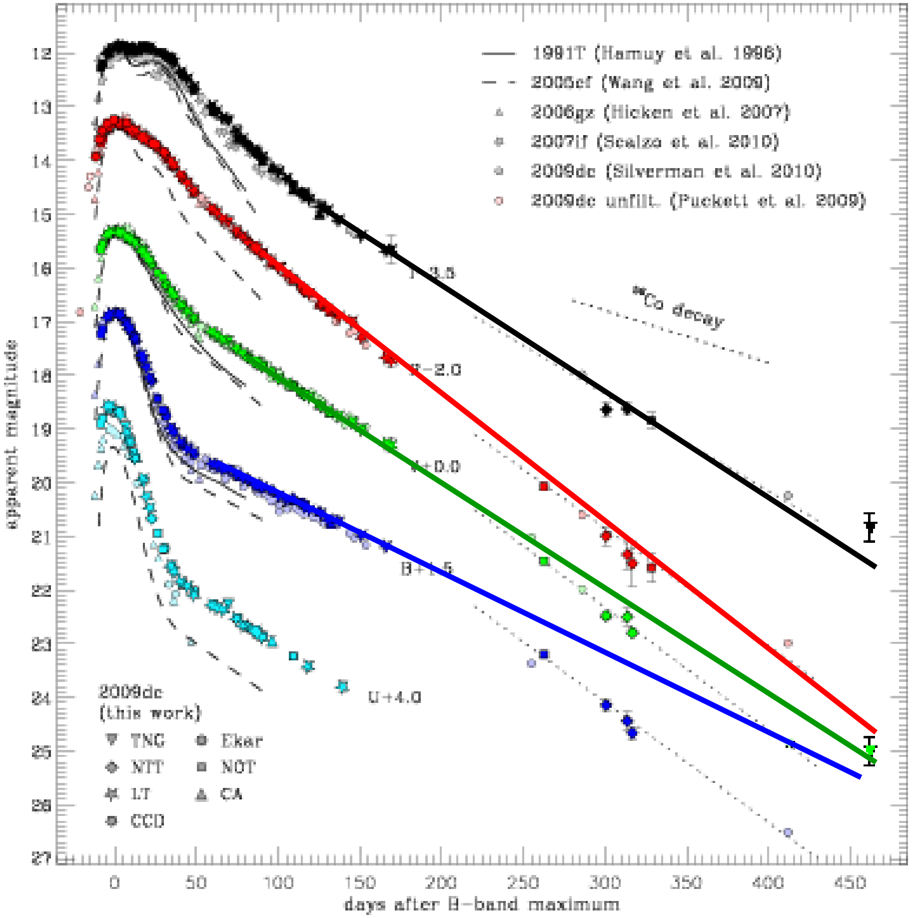
observationally estimated carbon mass in SNe Ia :
M_c < 0.01 M_{sun} (Marion+06; Tanaka+08)

4-5. Dust formation in super-Chandra SNe?

– super-Chandra SNe :
M(56Ni) > ~0.8 Msun

detection of CII line
➔ presence of massive unburned carbon

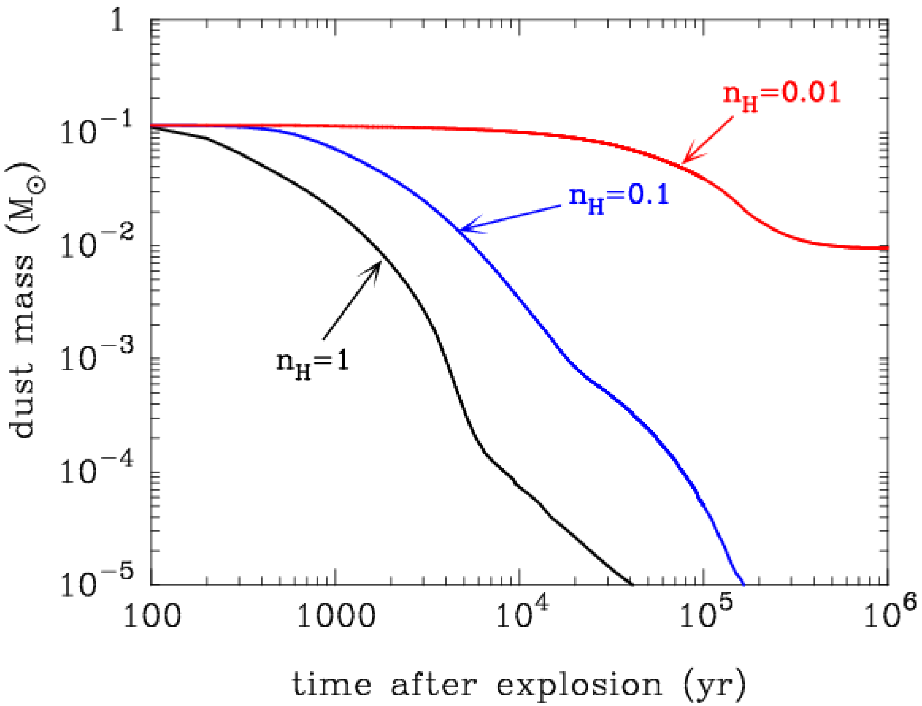




enhanced fading at ~200 day
➔ formation of carbon dust?

SN 2009dc, Tarbenberger+10

5-1. Destruction of dust in Type Ia SNRs



- 10^{-3} M_{sun} of dust can survive for $n_H \sim 0.01$ cm^{-3} but too low ISM density
- typical ISM gas density around SNe Ia
  → n_H = 1-5 cm^{-3}
  (Borkowski+06)

newly formed grains are completely destroyed for ISM density of $n_H > 0.1$ cm^{-3}

SNe Ia are unlikely to be major sources of dust

Summary

– For α = 1, C, silicate, Si, and FeS grains can condense in the ejecta of SNe Ia at 100-300 days, being earlier than >300 days in SNe II-P.

– Due to the low gas density in the ejecta, the average radii of dust grains are below 0.01 μm, being smaller than those in SNe II-P.

– The total mass of dust that can form in the ejecta of SNe Ia is up to 0.1 M_{sun}. (0.03 Msun of silicate is more conservative.)

– Formation of C grains is inconsistent with the observations

➔ low sticking probabilities of α < ~0.01

➔ small C clusters can be destroyed by photons and electrons

➔ preexisting C should be almost completely burned

– For the ISM density of $n_{H,0}$ > 0.1 cm^{-3}, the newly formed grains are almost completely destroyed before being injected into the ISM.

➔ SNe Ia are likely to be poor producers of interstellar dust