Formation of Dust in the Ejecta of Type Ia Supernovae

Takaya Nozawa

IPMU (Institute for the Physics and Mathematics of the Universe, University of Tokyo)
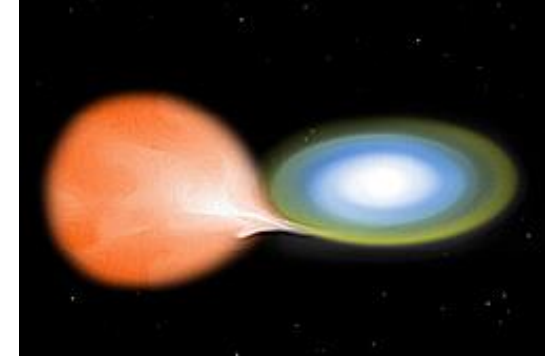
Collaborators:

K. Maeda (K-IPMU), T. Kozasa (Hokkaido University)

M. Tanaka, (NAOJ), K. Nomoto (K-IPMU),

H. Umeda (Univ. of Tokyo)

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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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 grains 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 M_{sun}**

- **E_{kin} = 1.3×10^{51} erg**

- **$M(^{56}Ni)$ = 0.6 M_{sun}**

  ## $M(^{56}Ni) \sim 0.06$ M_{sun} in typical CCSNe

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

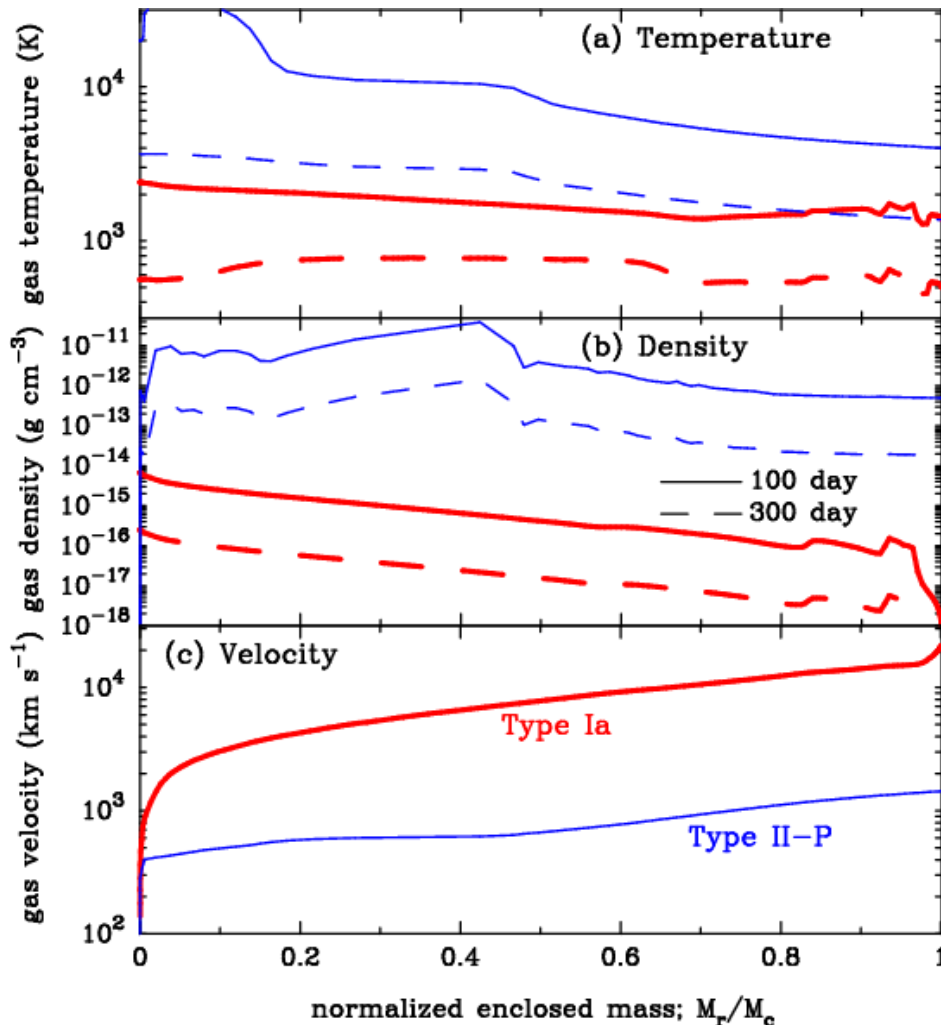 ## This assumption is supported observationally (e.g. Mazzali+08; Tanaka+11)

elemental composition

number abundance (normalized) vs enclosed mass; M_r ($M_\odot$)
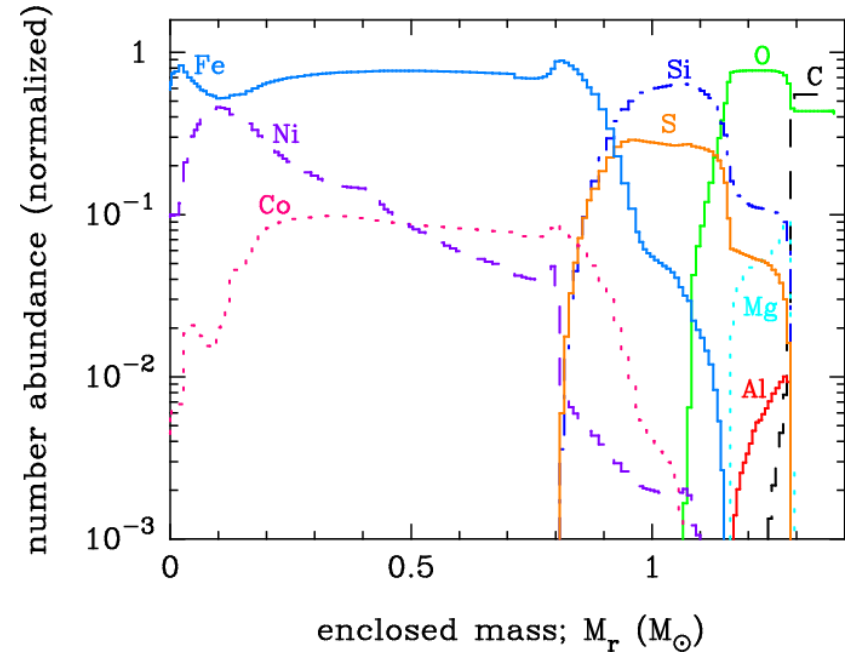
0.1 M_{sun} of C + O remained unburned in the outermost layer with $M_C/M_O \sim 1$

2-2. Model of SNe Ia (2)

hydrodynamic model

red lines : SNe Ia
- M_{eje} = 1.38 M_{sun}
- E_{kin} = 1.3x10^{51} erg

blue lines : Type II-P SNe
- M_{star} = 20 M_{sun}
- E_{kin} = 1.0x10^{51} erg
- M_{env} = 13.2 M_{sun}

─ 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

O nucleation and grain growth theory

– **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**

$$\frac{\partial r}{\partial t} = \alpha_s \frac{4\pi a_0^3}{3}\left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1(t) = \frac{1}{3}a_0 \tau_{\text{coll}}^{-1}$$
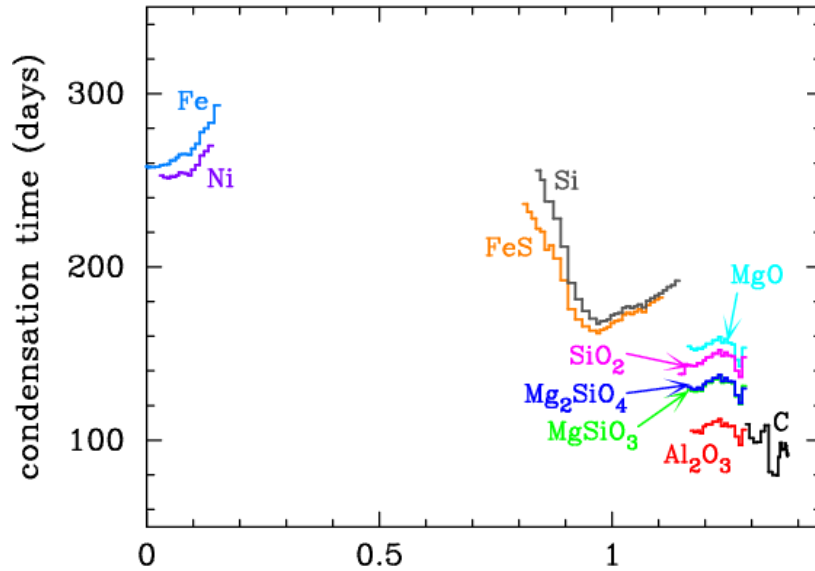
– **sticking probability : α = 1 and 0.1**

– **LTE condition** : $T_{dust} = T_{gas}$

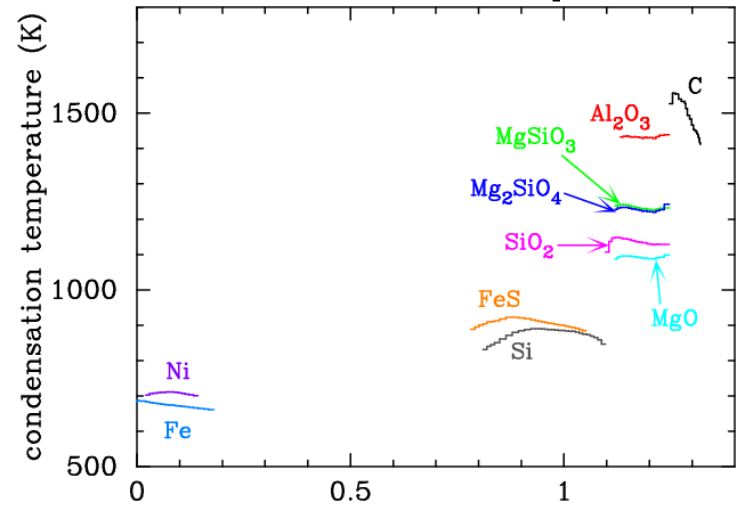**(dust has the same temperature as the gas)**

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

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

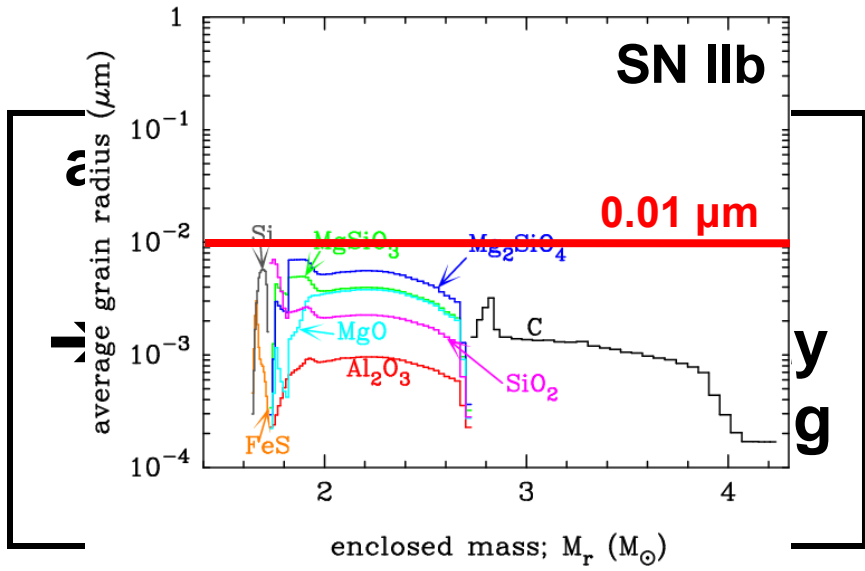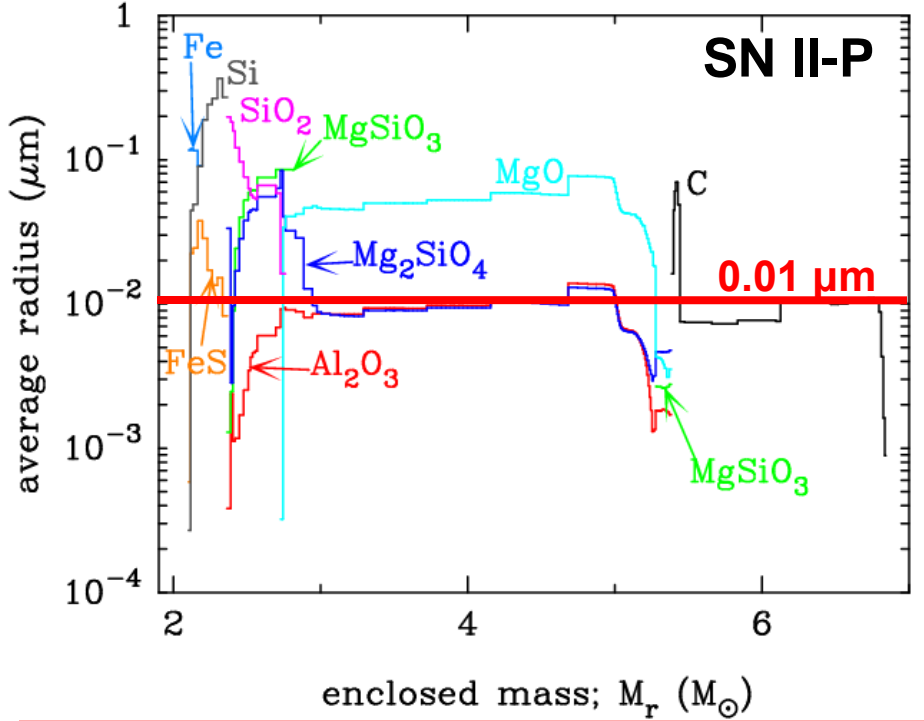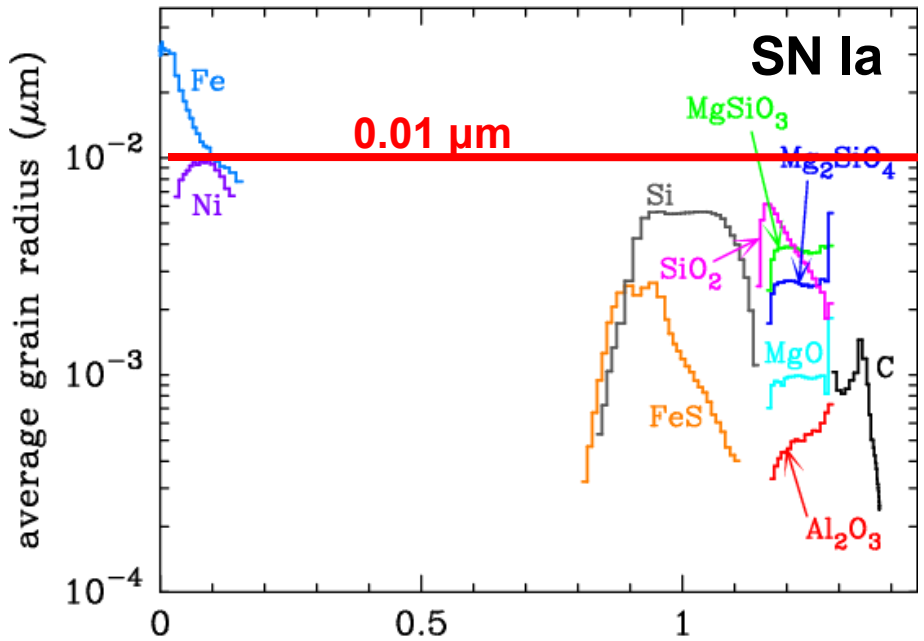**Condensation time**
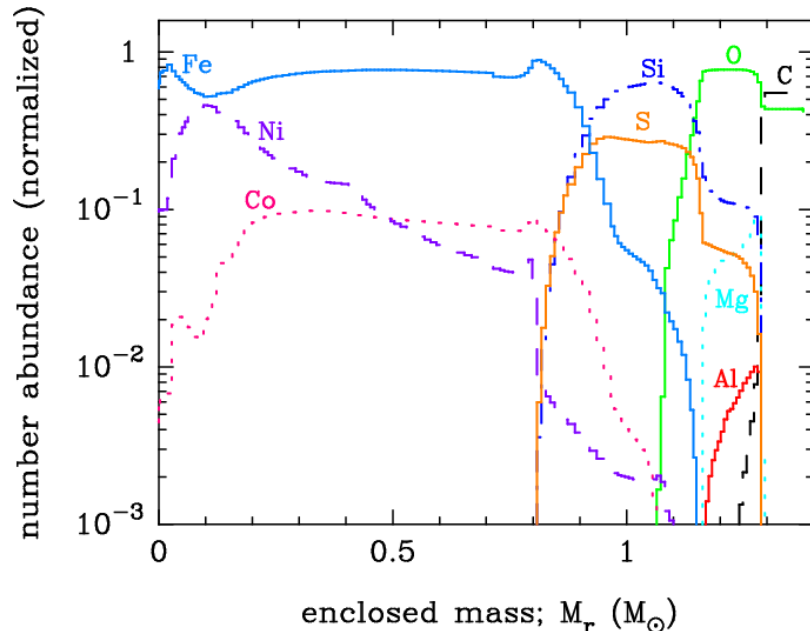
Condensation temperature

— **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	$\alpha = 1$ A1	$\alpha = 0.1$ A0.1
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 : $M_{dust} < \sim 0.1\ M_{sun}$

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}

M_{Si} = 0.063 M_{sun} ➡ T_{FeS} = 14

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
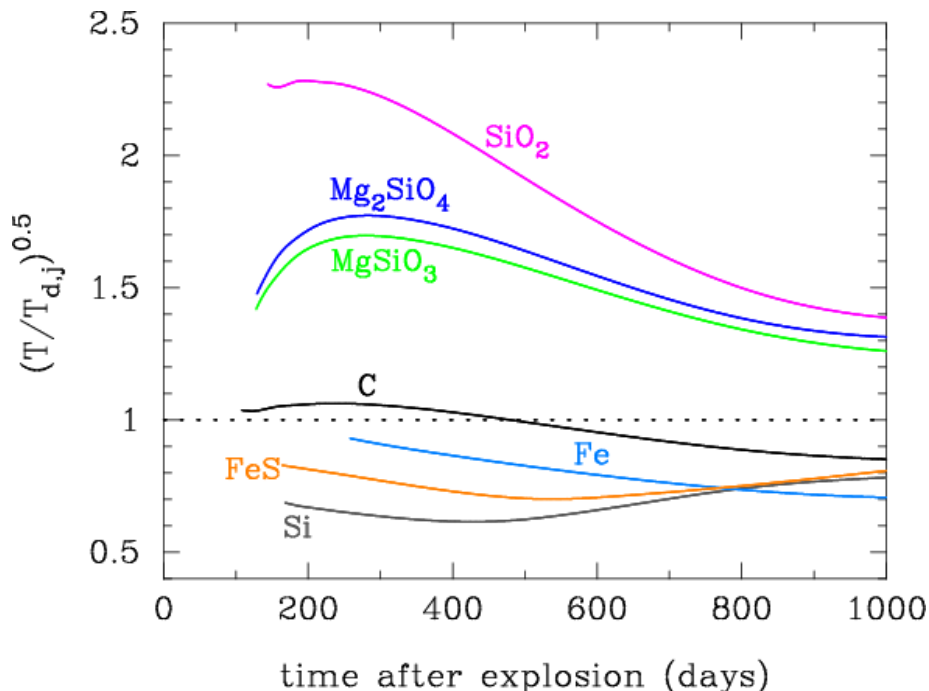
4-2. Non-LTE effect on dust formation

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

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

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

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

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

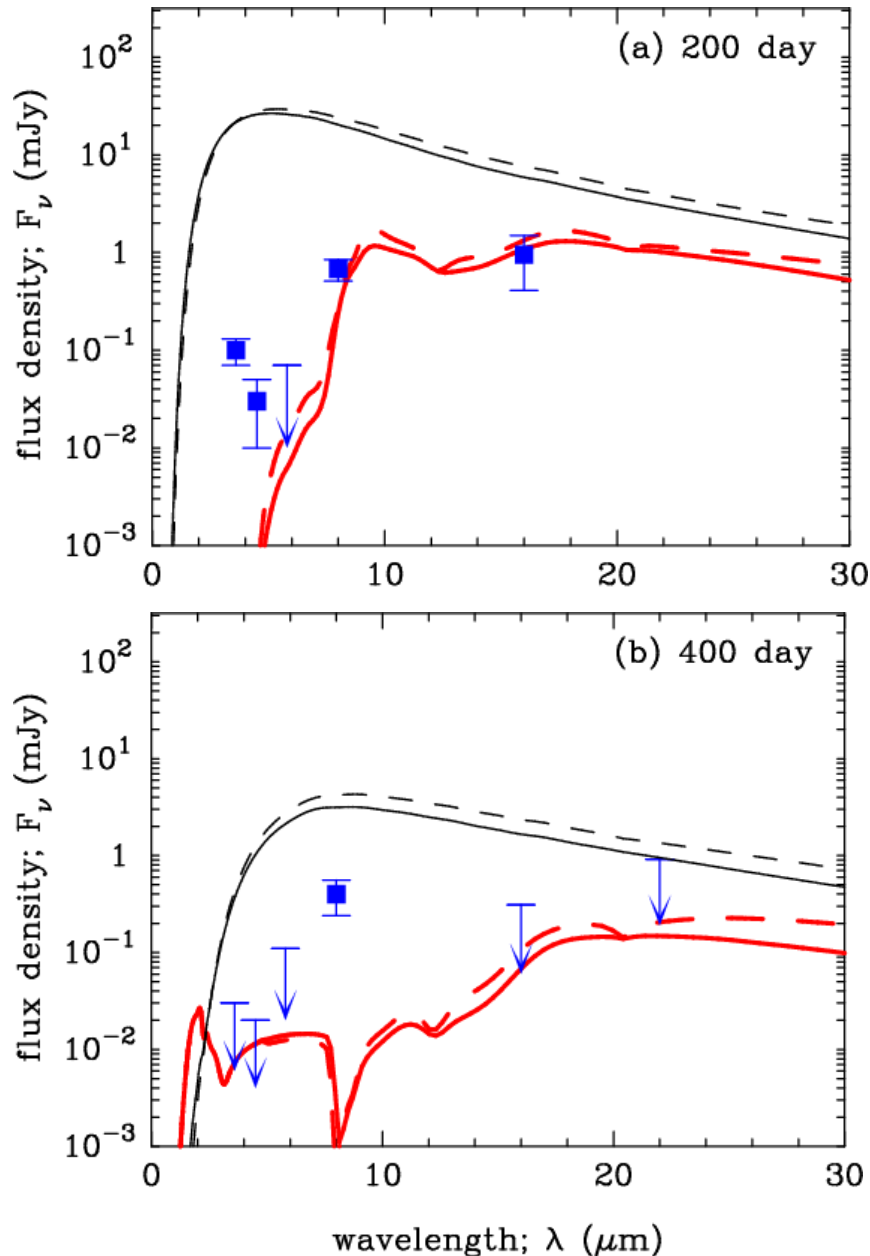**Non-LTE dust formation**

$M_{FeS} = 4 \times 10^{-4}\ M_{sun}$

$M_{Si}\ \ = 1 \times 10^{-6}\ M_{sun}$

→ $\tau_{FeS} < 0.1$ after 300 day

$M_C = 0.0055\ M_{sun}$

→ $\tau_C > 20$ (too high to be con-
sistent with the observations)

4-3. Infrared thermal emission from dust

(a) 200 day

(b) 400 day

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 :
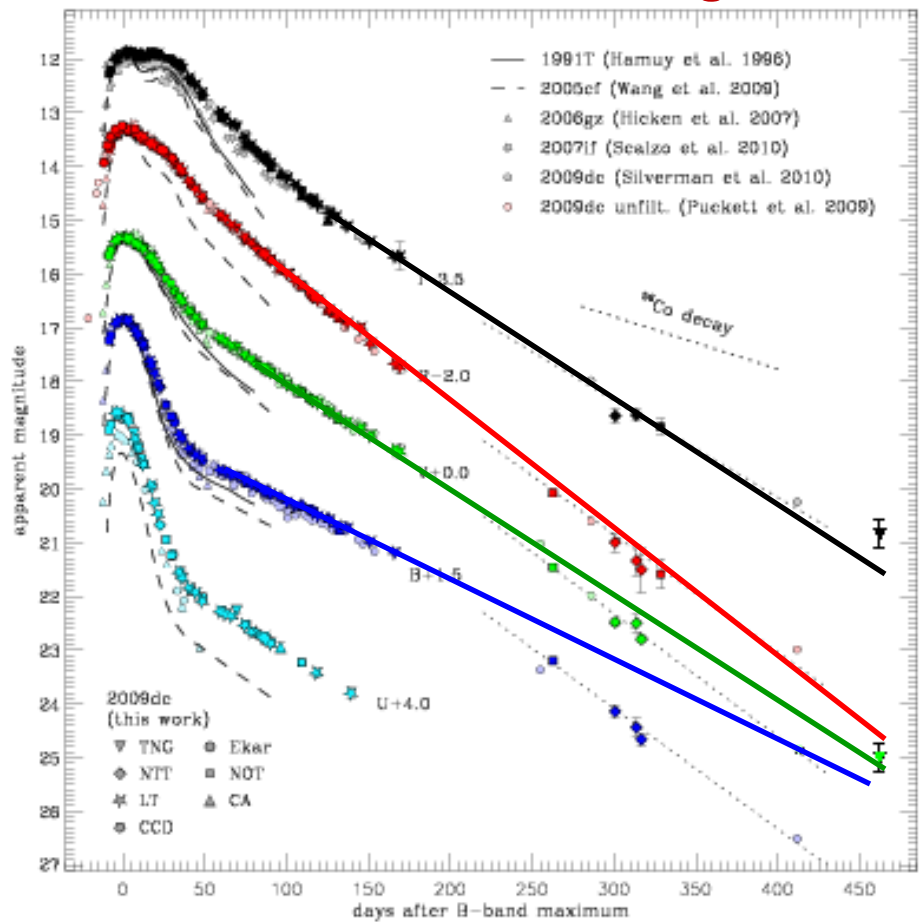M$_c$ < 0.01 M$_{sun}$ (Marion+06; Tanaka+08)

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

— **super-Chandra SNe :**
M(56Ni) ~ 1.0 M$_{sun}$

detection of CII line
➔ **presence of massive unburned carbon**
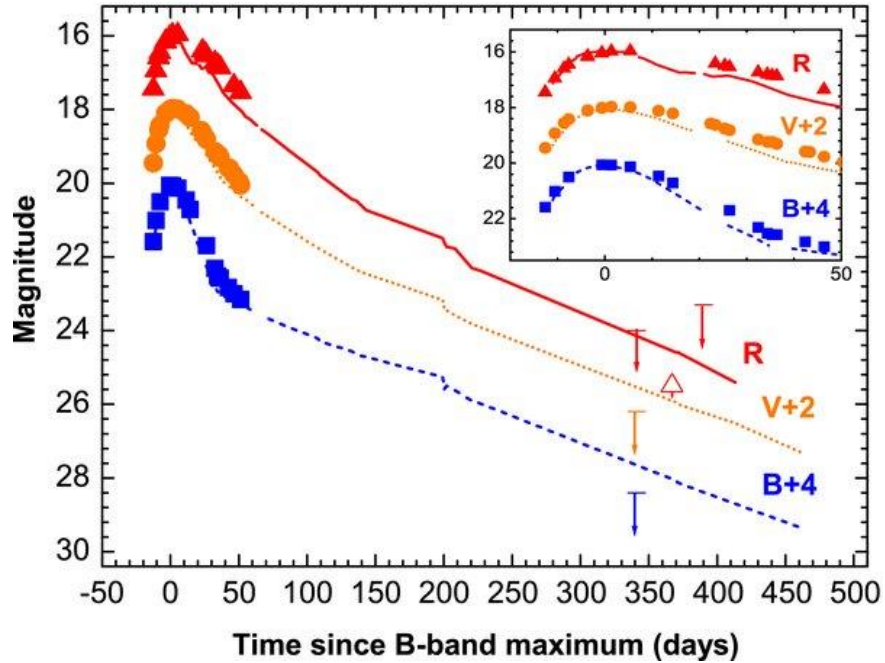
SN 2009dc, Tarbenberger+'10

SN 2006gz, Maeda+09

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

5-1. Destruction of dust in Type Ia SNRs
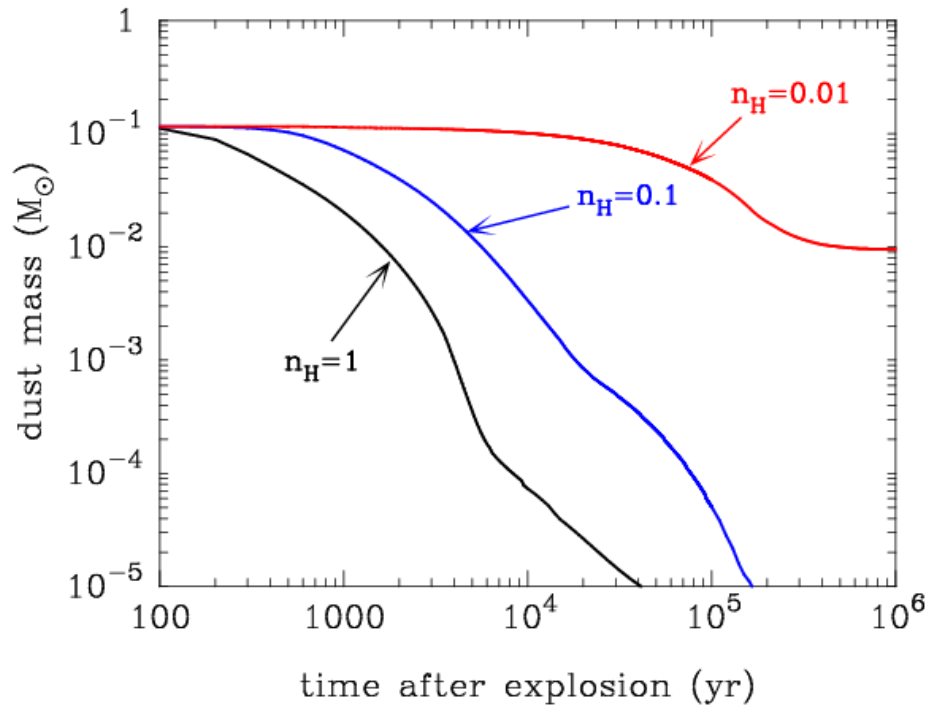
— 10^{-3} M$_{sun}$ of dust can survive for n_H ~ 0.01 cm^{-3} but too low ISM density

— 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