Formation of Dust in Various Types of Supernovae

Takaya Nozawa

IPMU (Institute for the Physics and Mathematics of the Universe, Univ. of Tokyo)

Collaborators

T. Kozasa (Hokkaido University), N. Tominaga (NAOJ),
K. Maeda (IPMU), H. Umeda (UT), K. Nomoto (IPMU/UT)

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Contents

1. Introduction

1-1. Introduction

Supernovae are the important sources of dust?

- **theoretical studies of dust formation**
  - mass of dust formed in the ejecta of **SNe II**
    ➔ M_{form} = **0.1-2 M_{sun}**
    (Todini & Ferrara 2001; Nozawa et al. 2003)
    grain size : **> 0.01 μm** (Nozawa et al. 2003)
  - mass of dust surviving the reverse shock
    ➔ M_{sur} = **0.01-1 M_{sun}** for $n_{H,0}$=0.1-10 cm^{-3}
    (Nozawa et al. 2007; see also Bianchi & Schneider 2007)

- **a large amount of dust (10^8-10^9 M_{sun}) for QSOs at z > 5**
  (Bertoldi et al. 2003; Priddy et al. 2003; Robson et al. 2004)

  ➔ **0.1-1 M_{sun}** of dust per SN II are required to form to explain dust budget in high-z QSO systems
  (Morgan & Edmunds 2003; Dwek et al. 2007)

1-2. Introduction

○ IR observaitons of dust-forming SNe (~10 SNe)

M_{dust} = 10^{-5}-10^{-3} M_{sun}

SN 1987A ➔ 10^{-4}-10^{-3} M_{sun} (Elcolano et al. 2007)

SN 2003gd ➔ 0.02 M_{sun} (Sugerman et al. 2006)

➔ 4×10^{-5} M_{sun} (Miekle et al. 2007)

SN 2006jc ➔ ~7×10^{-5} M_{sun} (Sakon et al. 2008)

➔ 6×10^{-6} M_{sun} (Smith et al. 2008) , 3×10^{-4} M_{sun} (Mattila et al 2008)

○ IR observaitons of nearby young SNRs

M_{dust} = 10^{-4}-10^{-2} M_{sun}

(e.g., Hines et al. 2004, Temim et al. 2006; Morton et al. 2007)

Theoretical predictions overestimate dust mass?
Observations are seeing only hot dust (＞100K)?
Thermal emission from dust is optically thin?

1-3. Aim of our study

- **Cas A SNR** (SN type : IIb)
  - **dust formation in the ejecta of a SN**
  - **dust evolution in the shocked gas within SNRs**

How much and what kind of dust are supplied by SNe?

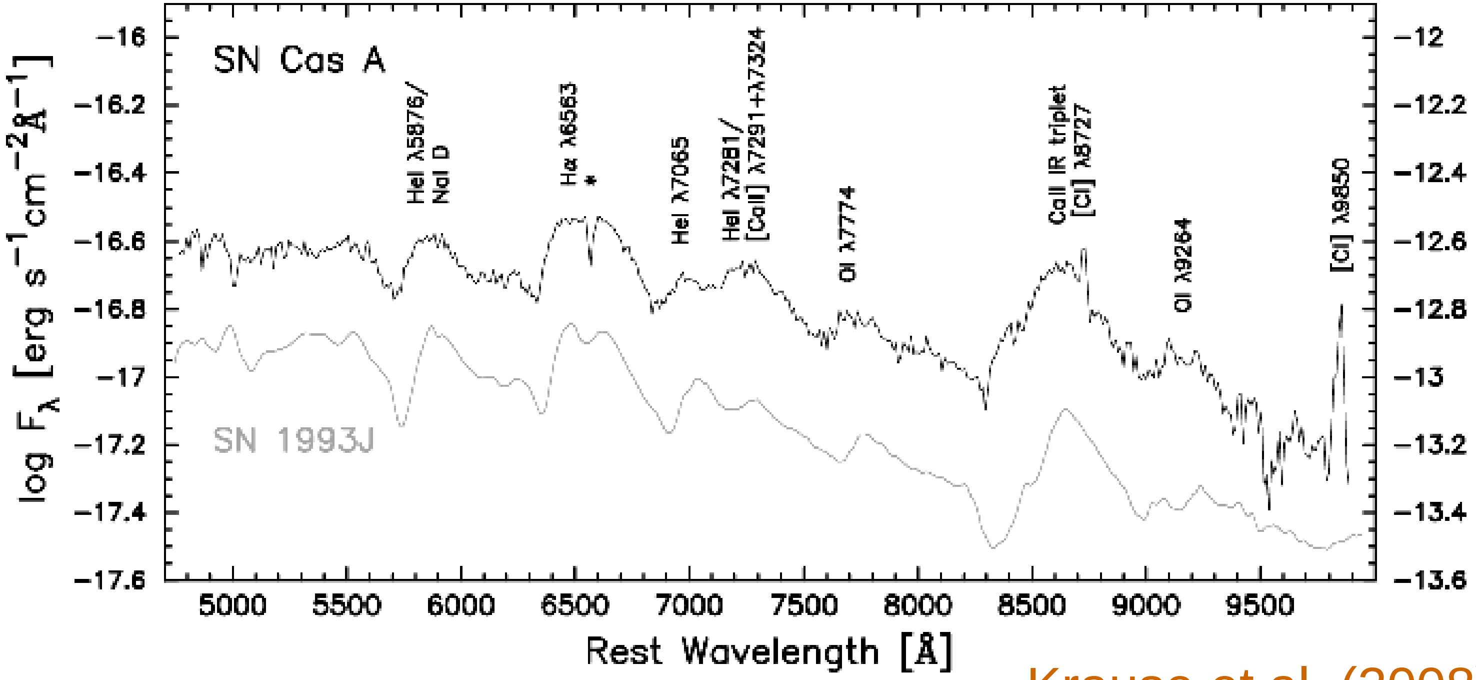
- Dust-forming SNe
  - Type IIp (SN1999em, SN 2003gd) ➔ 400-500 days
  - Type IIn (SN1998S) ➔ ~230 days
  - Type Ib (SN1990I, SN 2006jc) ➔ ~230 days
  - Type Ic ➔ not observed
  - **Type Ia ➔ not observed**

Formation process of dust in the ejecta depends on the type of SNe?

1-4. Cassiopeia A SNR

○ Cas A SNR (SN 1671)

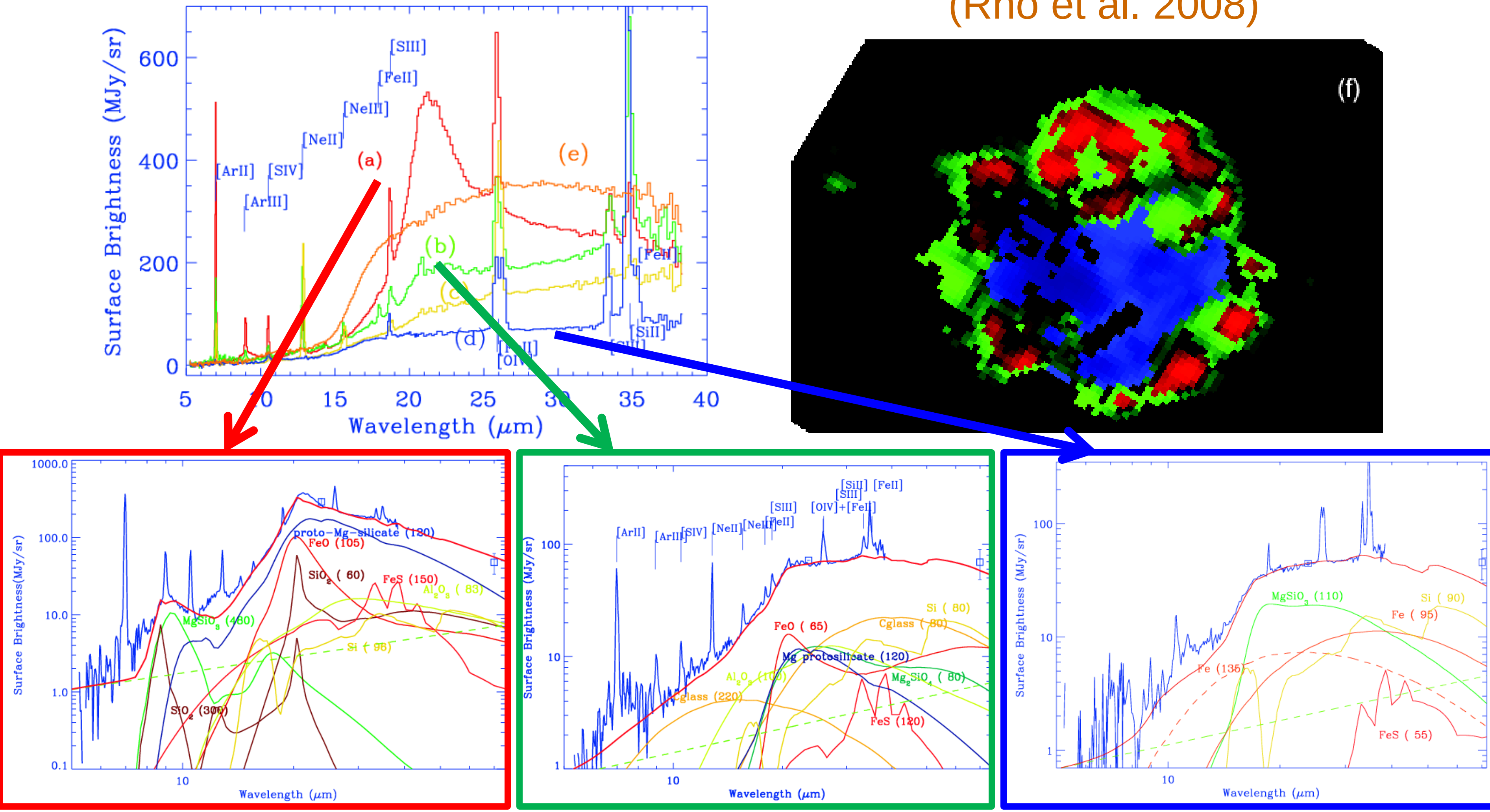
age: 337yr (Thorstensen et al. 2001)
distance: d=3.4 kpc (Reed et al. 1995)
radius: ~150" (~2.5 pc)
SN type : Type IIb (M_{MS}=15-25 M_{sun})



Krause et al. (2008)

1-5. Latest estimate of dust mass in Cas A

(Rho et al. 2008)



onion-like elemental composition remains

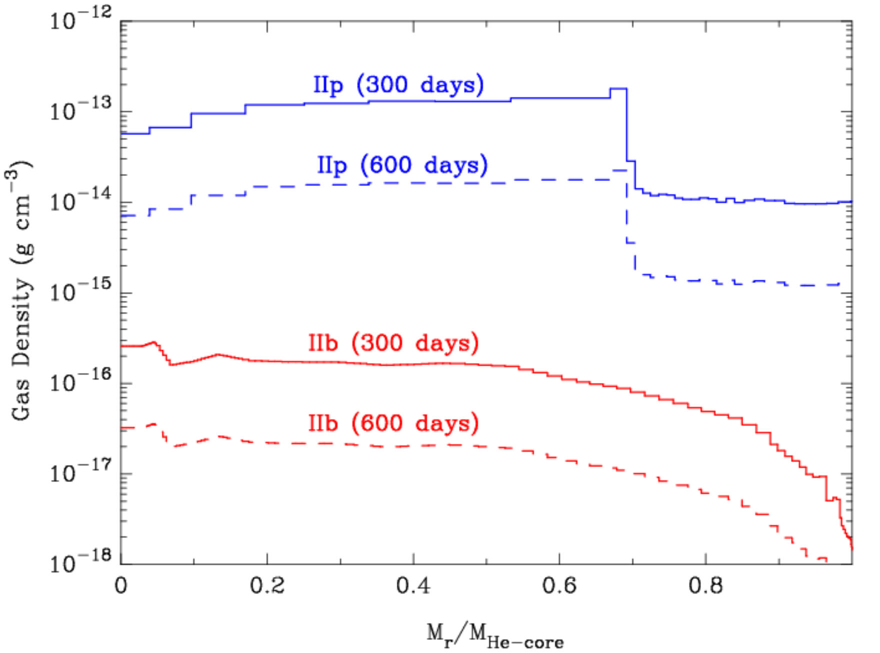
➔ Mdust = 0.02-0.054 Msun

2. Formation of dust in Type IIb SN

2-1. Dust formation calculation

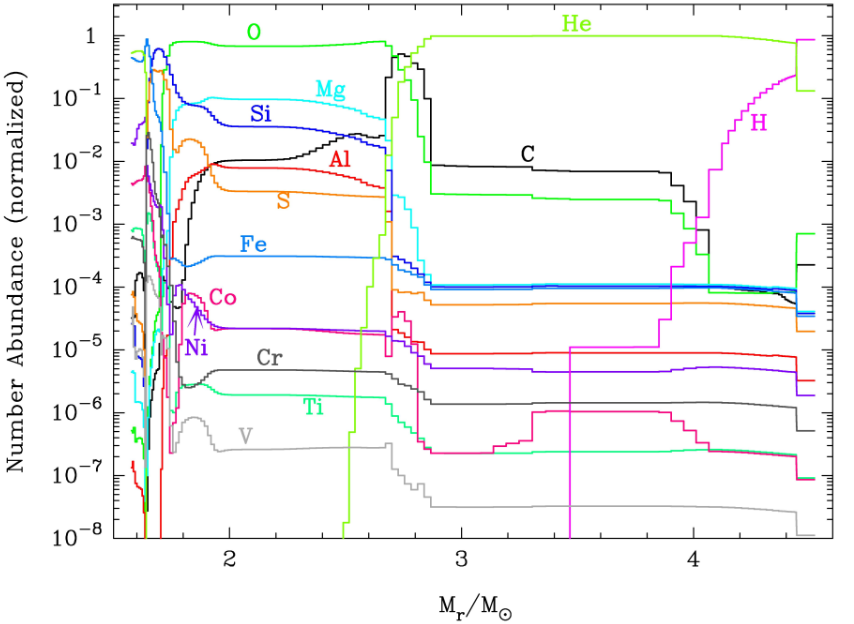
○ Type IIb SN model

- $M_{MS} = 18\ M_{sun}$
  $M_{ej} = 2.94\ M_{sun}$
  $M_{H\text{-}env} = 0.08\ M_{sun}$
- $E_{51} = 1$
- $M(^{56}Ni) = 0.07\ M_{sun}$



○ Dust formation theory

- non-steady nucleation and grain growth theory
  (Nozawa et al. 2003)
- onion-like composition
- sticking probability; $\alpha_s = 1$

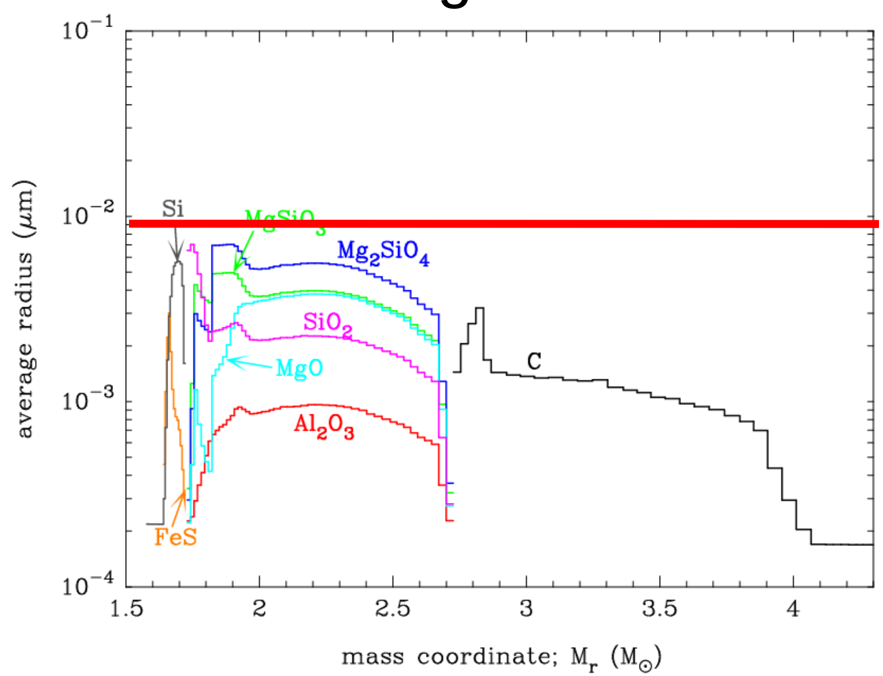


2-2. Mass and average radius of dust formed

Mass of dust formed

dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,total}$
C	7.08×10^{-2}	0.423
Al_2O_3	6.19×10^{-5}	3.7×10^{-4}
Mg_2SiO_4	1.74×10^{-2}	0.104
$MgSiO_3$	5.46×10^{-2}	0.326
SiO_2	1.57×10^{-2}	0.094
MgO	2.36×10^{-3}	0.014
FeS	1.47×10^{-3}	0.009
Si	5.07×10^{-3}	0.030
total	0.167	1

average radius

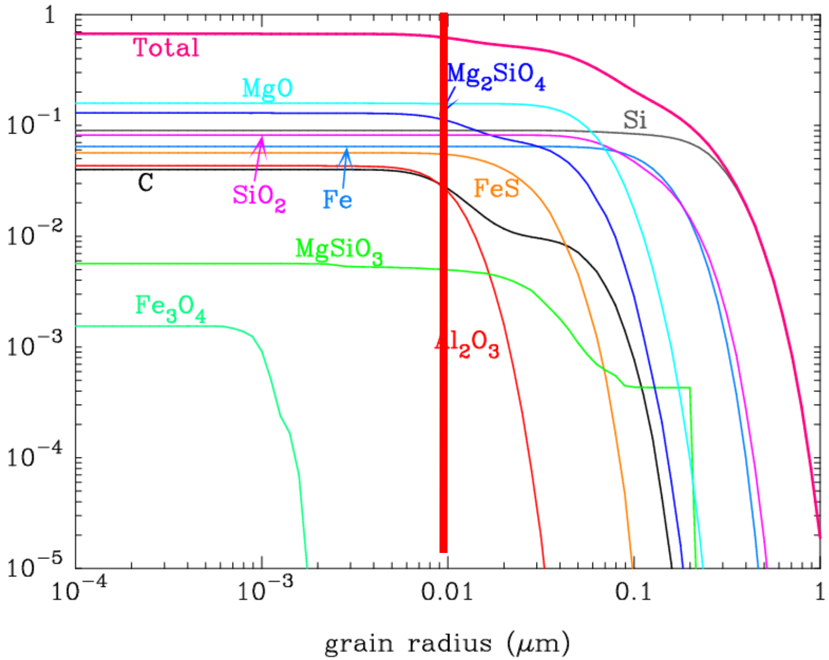


Total mass of dust formed in SN IIb is consistent with that in SN IIp

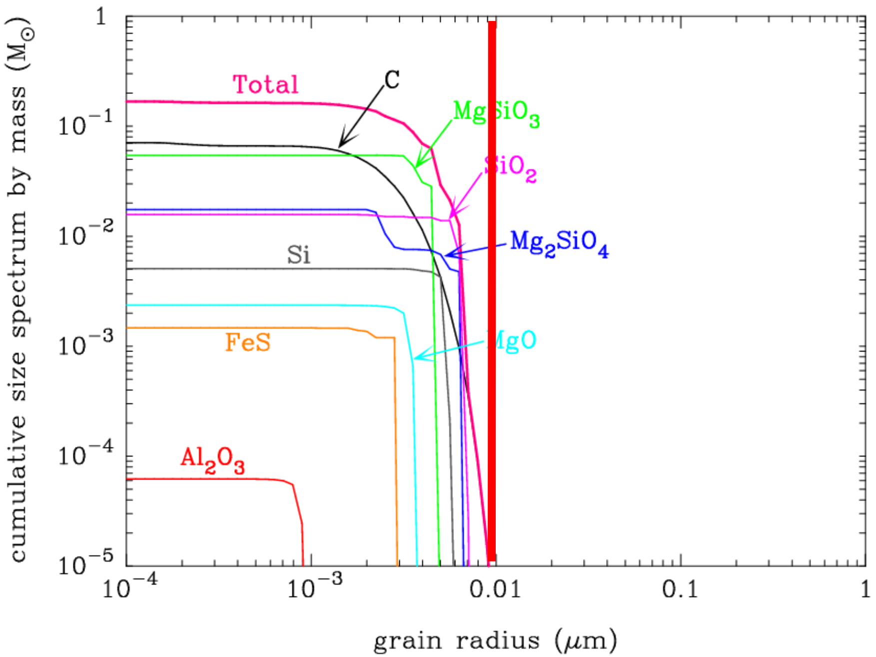
Low gas density in SN IIb prevents dust grains from growing up to large-sized (> 0.01μm) grain

2-3. Cumulative size spectrum of dust in mass

SN IIp (M_{MS}=20 M_{sun})



SN IIb (M_{MS}=18 M_{sun})



Grain radius

➔ > 0.01 μm for SN IIp

➔ < 0.01 μm for SN IIb

Dust grains formed in H-deficient SNe can be small

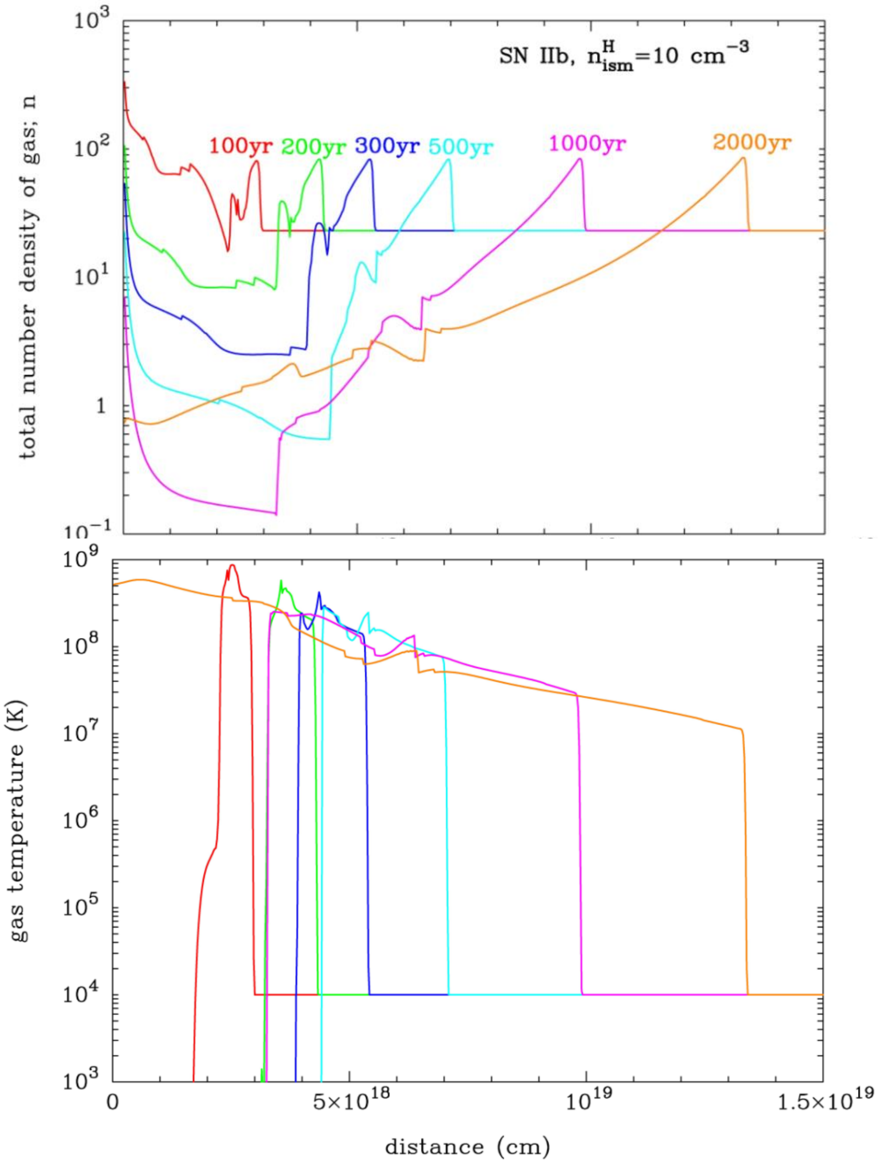
3. Evolution of dust in Cas A SNR

3-1. Calculation of dust evolution in SNRs

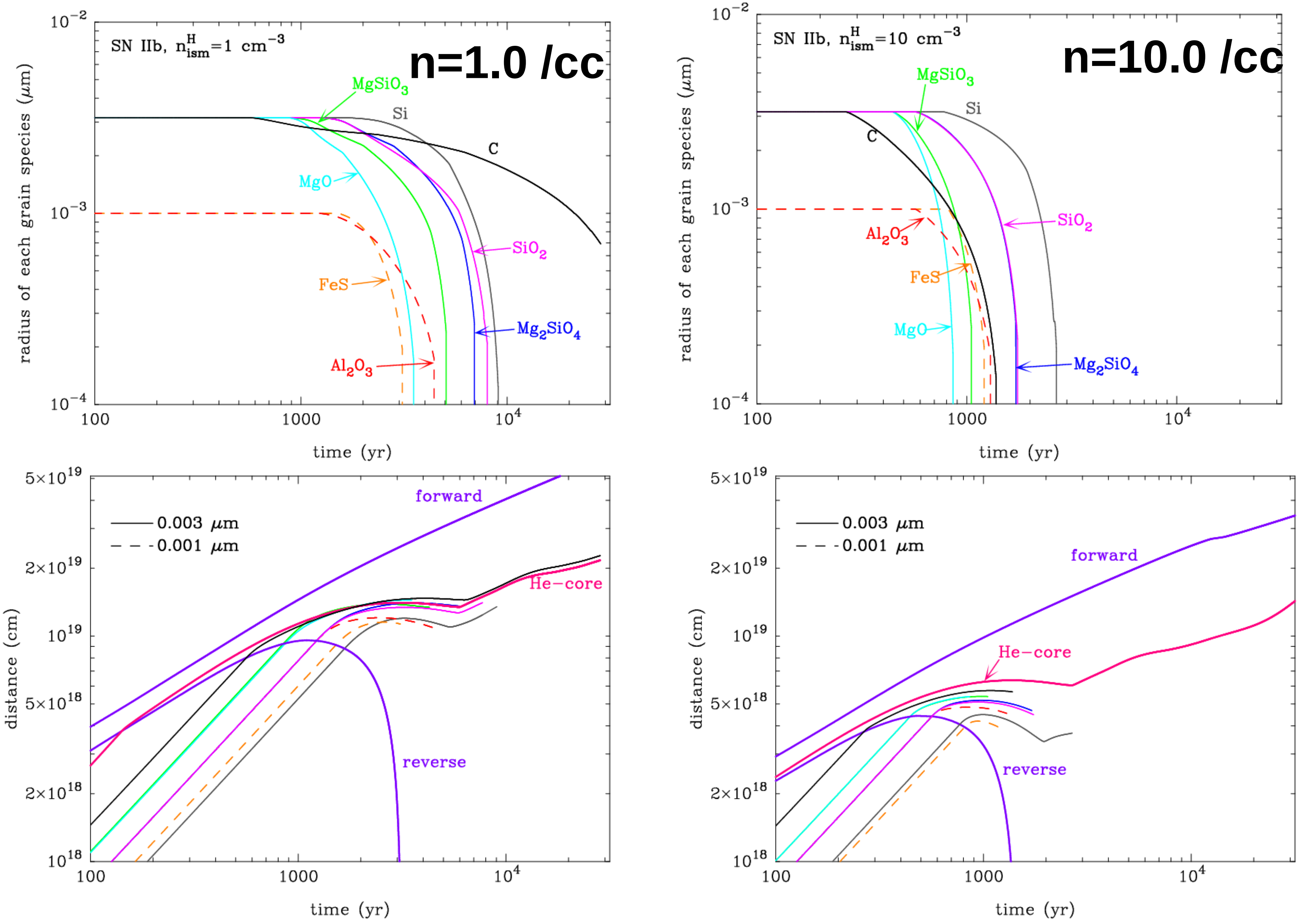
○ Model of calculations

(Nozawa et al. 2006, 2007)

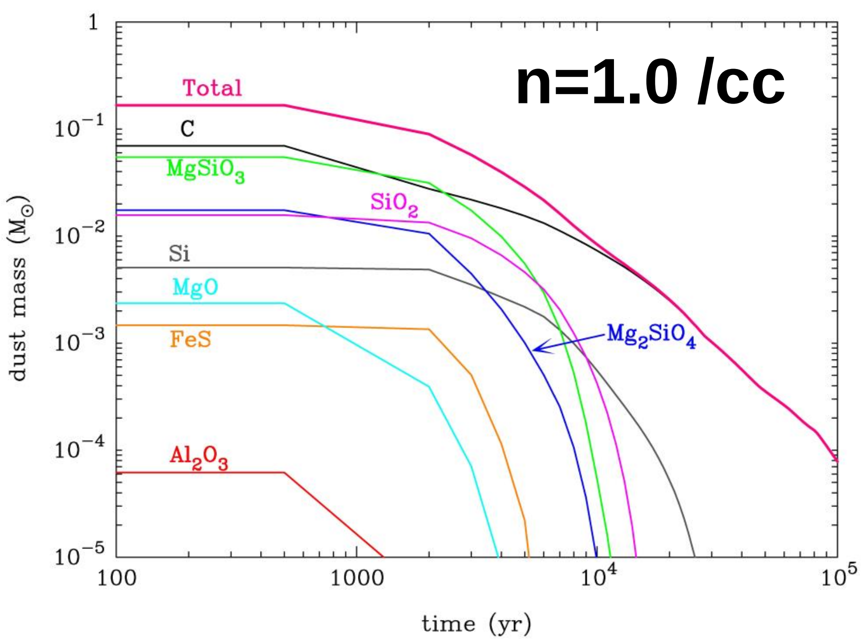
- ejecta model
  - hydrodynamic model for dust formation calculation
- ISM
  - homogeneous, $T_{gas}=10^4$ K
  - **n_H = 1.0 and 10.0 cm^{-3}**
  - solar composition of gas
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag
  - collsiional heating

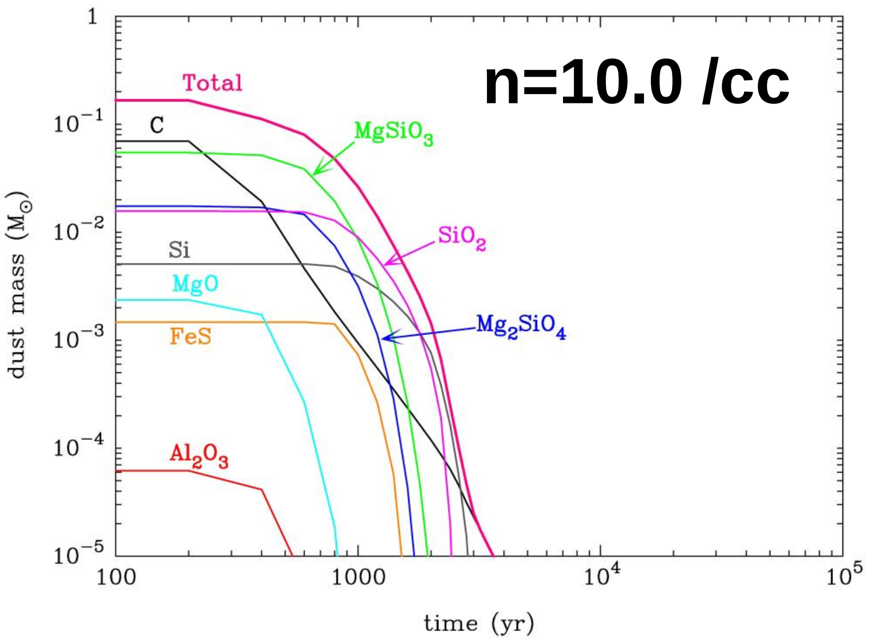


3-2. Evolution of dust in Cas A SNR



3-3. Time evolution of dust mass





M_{dust} ~ **10^{-4} M_{sun}** at 10^5 yr

M_{dust} = **0 M_{sun}** at 10^5 yr

Core-collapse SNe with thin H-envelope cannot be the main sources of dust

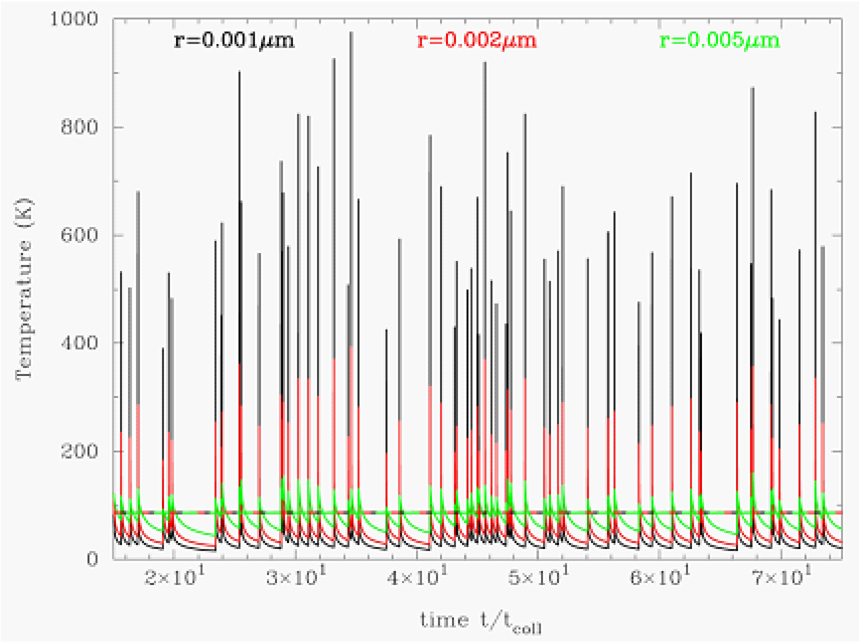
The radius of dust formed in the peculiar Type Ib SN 2006jc (M_{MS}=40 M_{sun}, E_{51}=10) is small (< 0.01 μm) (Nozawa et al. 2008)

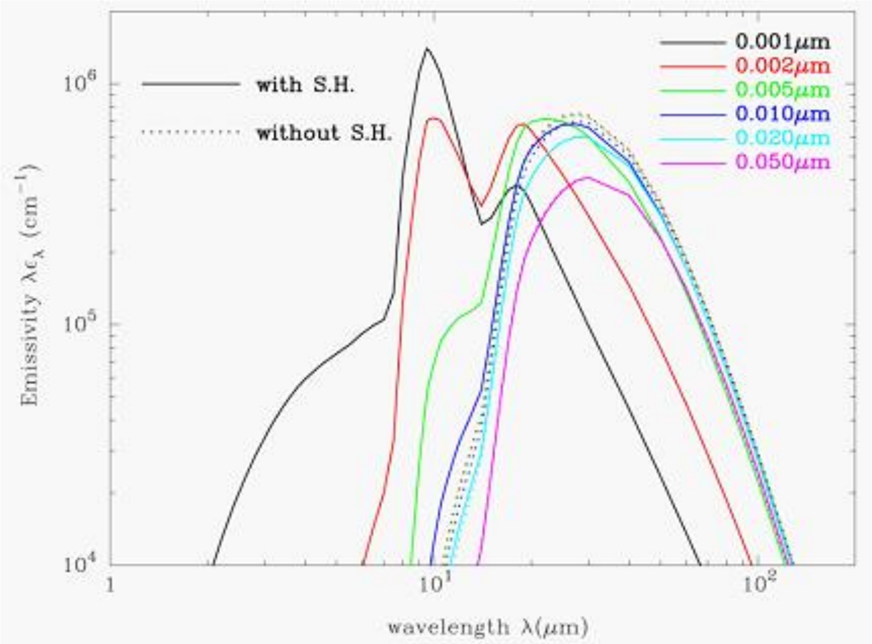
3-4. Thermal emission from dust in the SNR

- thermal radiation from dust ← temperature of dust
- equilibrium temperature of dust in SNR is determined by collisional heating with gas and radiative cooling

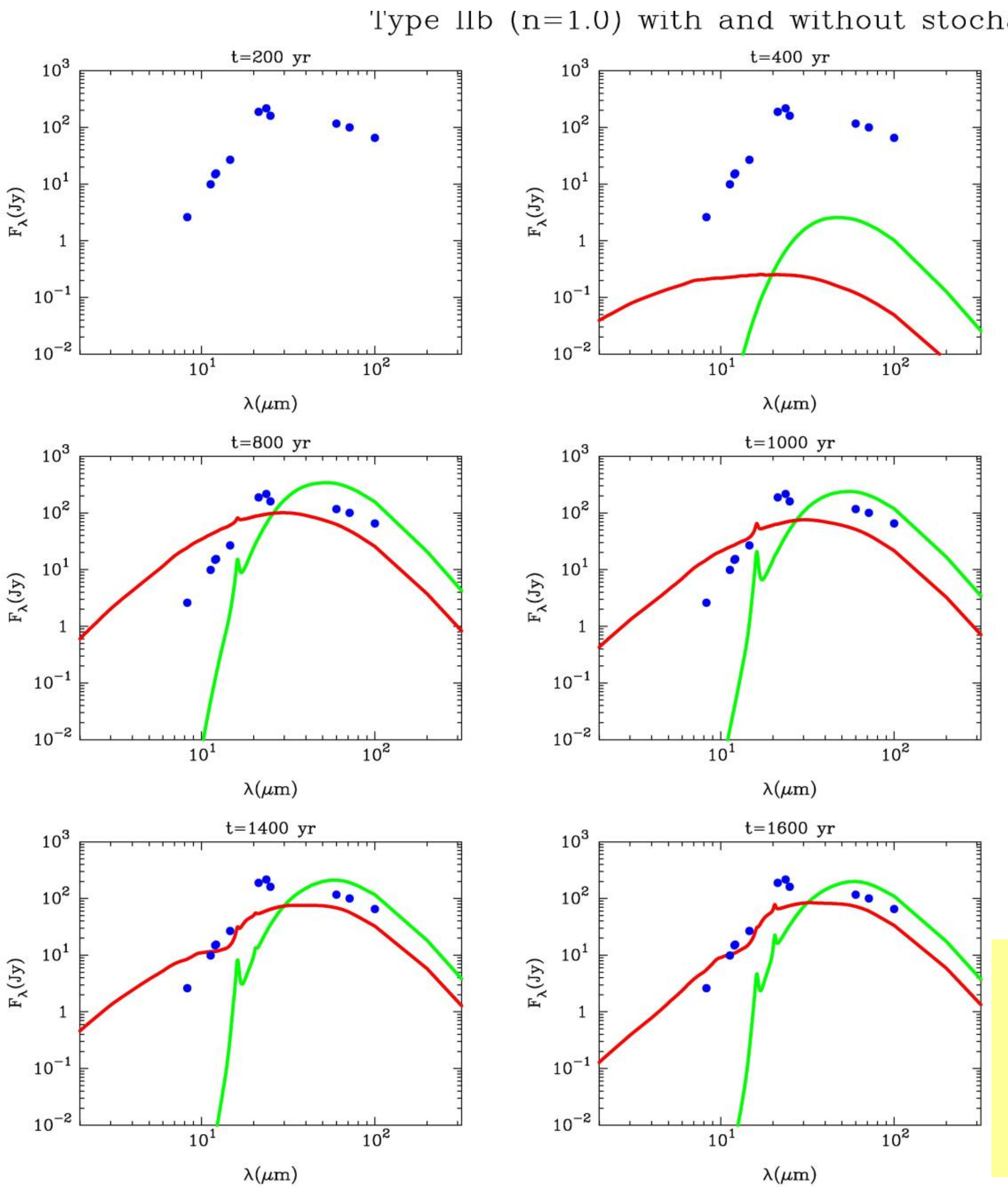
  $H(a, n, T_g) = \Lambda(a, Q_{abs}, T_d)$ ➔ thermal emission

- small-sized dust grains (＜0.01 μm) ➔ stochastic heating





3-5. Comparison with Cas A observation (1)

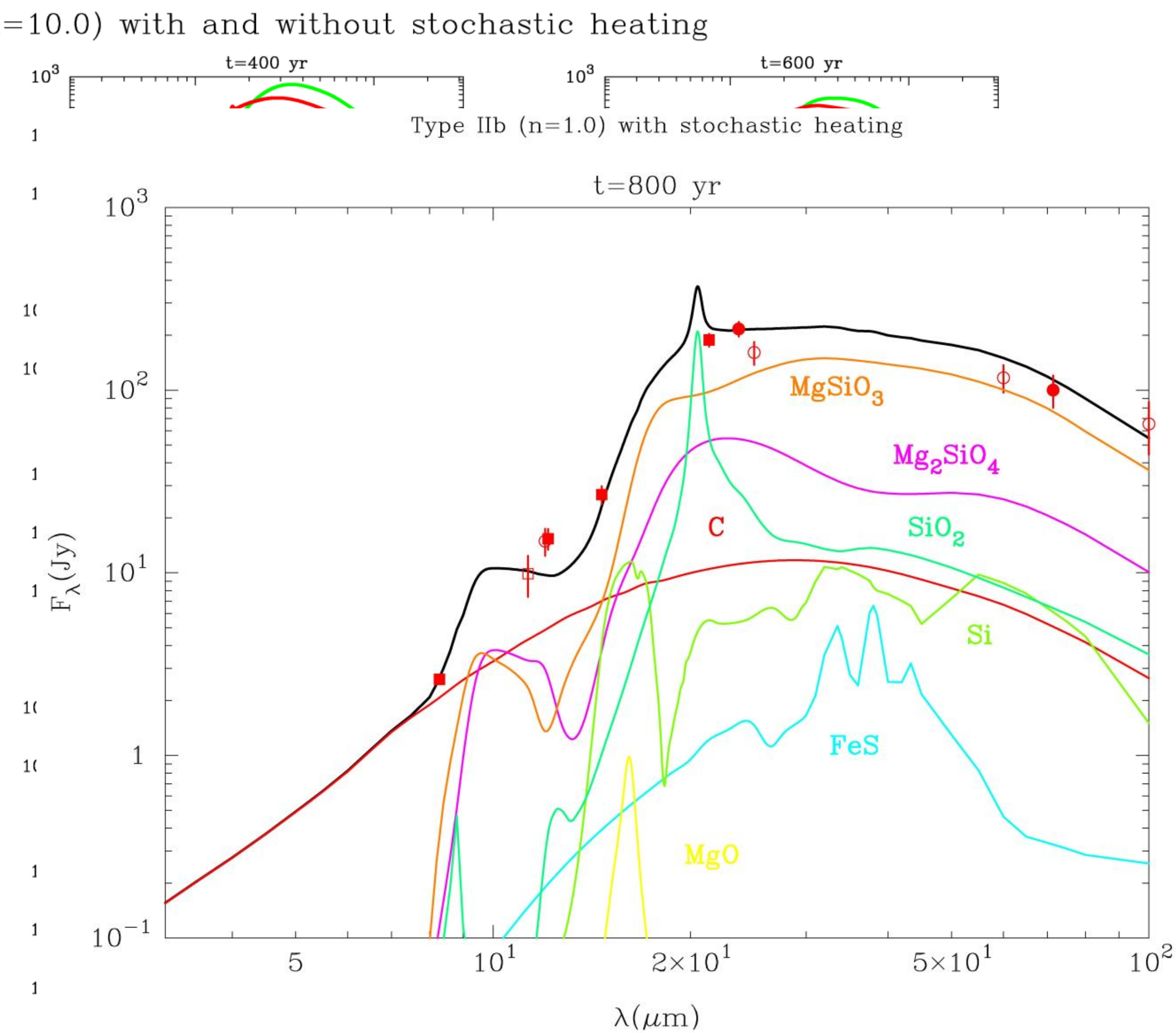


Data: Hines et al. (2004)
red: with SH
green: without SH

3-6. Comparison with Cas A observation (2)

dust mass

dust species	$M_{d,j}(M_\odot)$
C	1.60×10^{-3}
Al_2O_3	3.99×10^{-7}
Mg_2SiO_4	6.46×10^{-3}
MgO	1.59×10^{-5}
$MgSiO_3$	1.72×10^{-2}
SiO_2	1.08×10^{-2}
FeS	1.04×10^{-3}
Si	3.62×10^{-3}
total	0.0407



Dust mass of 0.04 Msun is consistent with mass of dust (~0.02-0.054 Msun) in Cas A derived by Rho et al. (2008)

4. Formation of dust in Type Ia SN

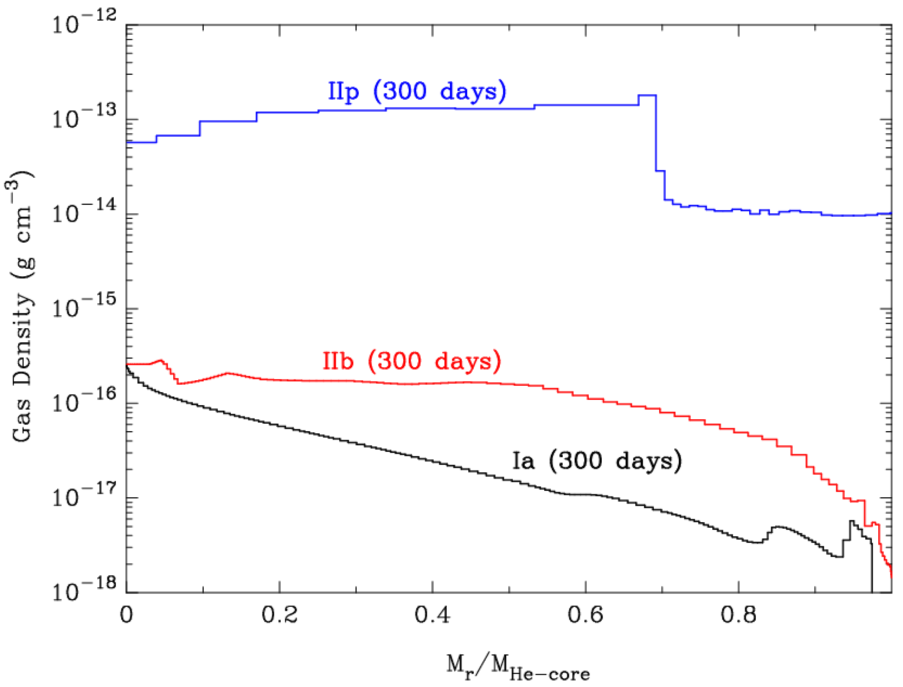
4-1. Dust formation calculation for SN Ia

○ Type Ia SN model

W7 model (C-deflagration)

(Thielemann et al. 1986)

- **M_{pr} = 1.38 M_{sun}**
- E_{51} = 1
- **$M(^{56}Ni)$ = 0.6 M_{sun}**

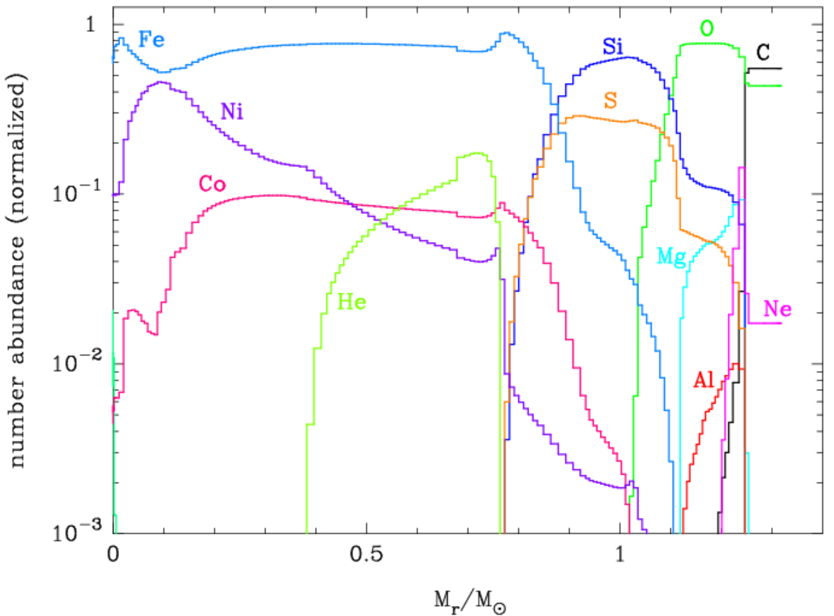


○ Dust formation theory

- non-steady nucleation and grain growth theory

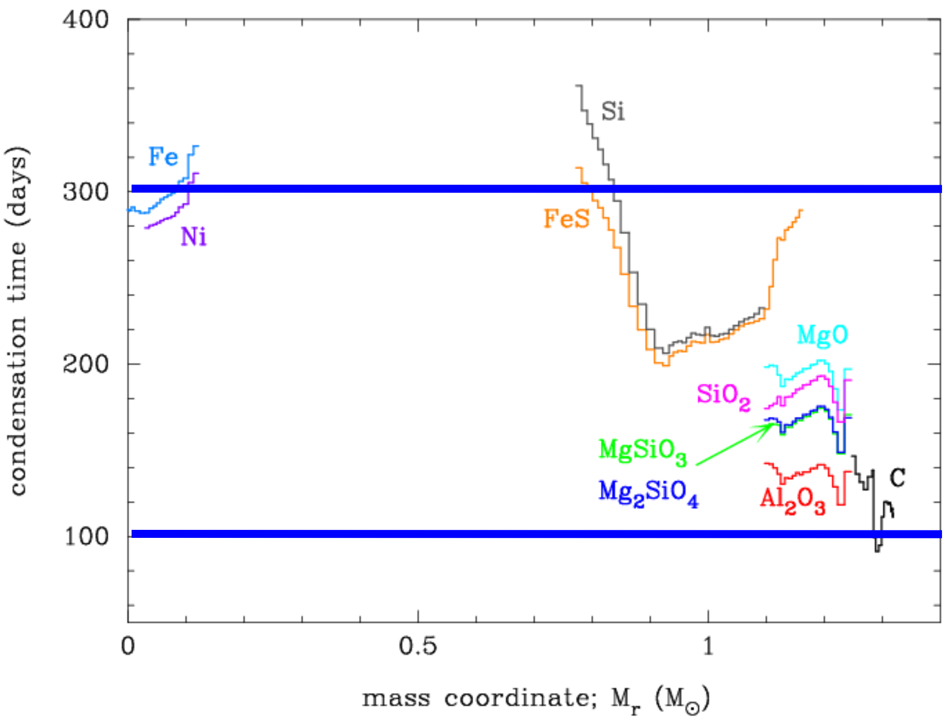
(Nozawa et al. 2003)

- onion-like composition
- sticking probability; α_s = 1

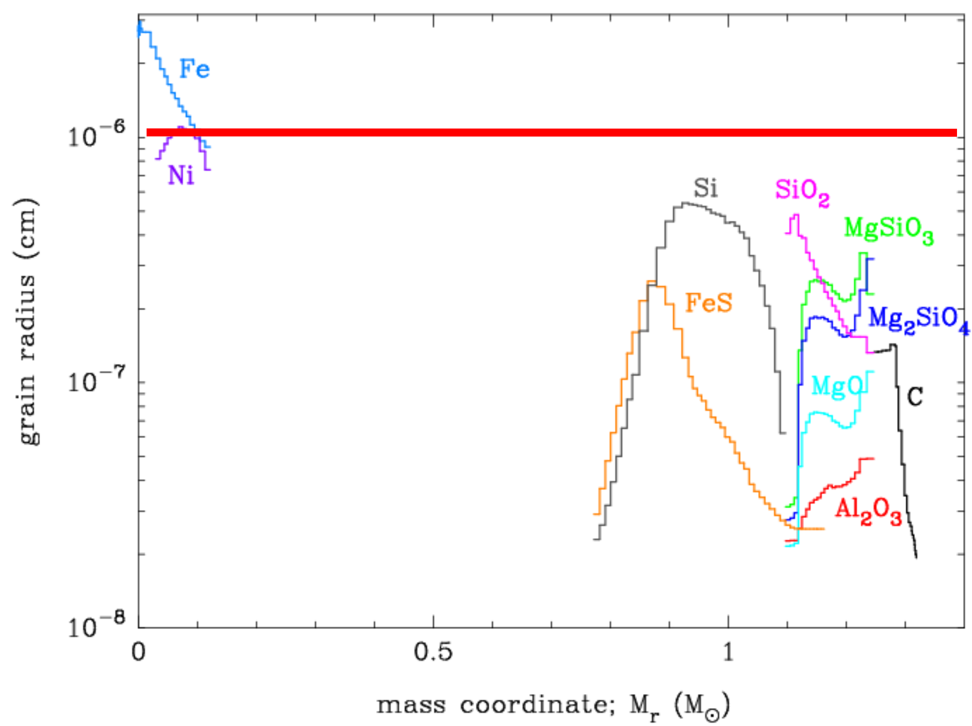


4-2. Results of dust formation calculation

Condensation time



Average radius of grain



Condensation time of dust : **100-300 days**

Average radius of dust : **< 0.01 μm**

4-3. Mass of dust formed in SN Ia

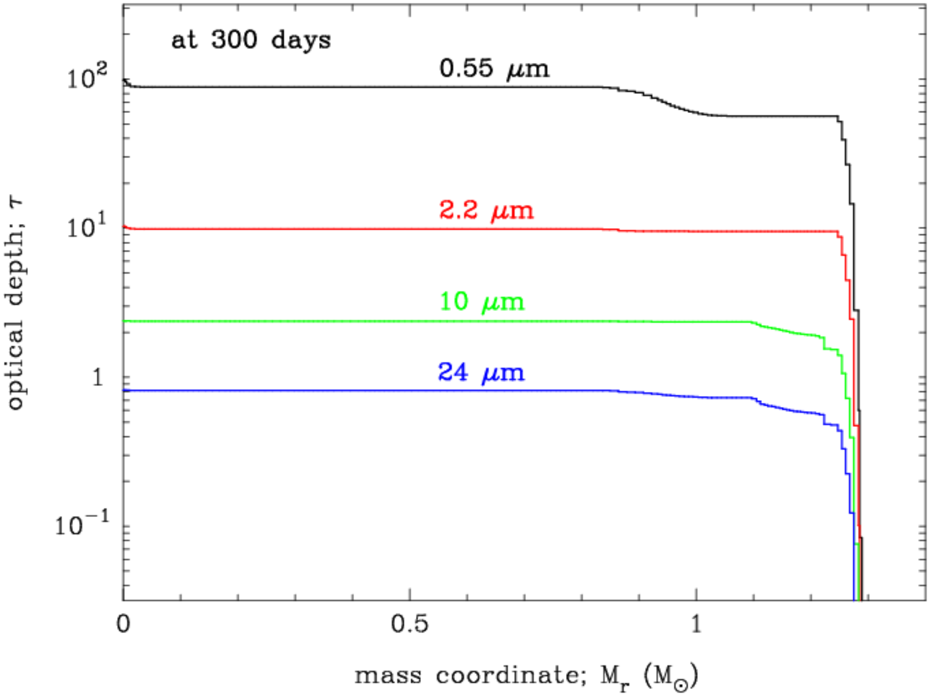
Mass of dust formed

dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,total}$
C	1.46×10^{-2}	0.311
Al_2O_3	1.29×10^{-6}	2.7×10^{-7}
Mg_2SiO_4	1.10×10^{-3}	0.023
$MgSiO_3$	1.12×10^{-3}	0.024
SiO_2	2.40×10^{-3}	0.051
MgO	4.65×10^{-7}	1.0×10^{-5}
FeS	6.63×10^{-3}	0.141
Si	2.11×10^{-2}	0.450
Fe	4.78×10^{-5}	1.0×10^{-3}
Ni	2.16×10^{-6}	4.6×10^{-5}
total	4.69×10^{-2}	1

Total mass of dust

Mdust =0.047 Msun

Optical depth at 300 days



τ(0.55) ~ 100

τ(0.55) ~ 60 by C grains

τ(0.55) ~ 35 by Si and FeS grains

→ too high

4-4. NLTE dust formation

Early formation of dust ➔ 100-300 days

Large M(56Ni) ➔ 0.6 Msun

$$J = \alpha_s \Omega_0 \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \left(\frac{T}{T_v} \right)^{\frac{1}{2}} c_1^2 \exp \left[- \frac{4\mu^3}{27 (\ln S')^2} \right] ,$$

$$\ln S_j = -\frac{\Delta G_j^0}{kT} + \sum_i \nu_{ij} \ln P_{ij},$$

lnS' (Tv) = lnS(T) +0.5 ln(T/Tv)

4-5. Dust temperature

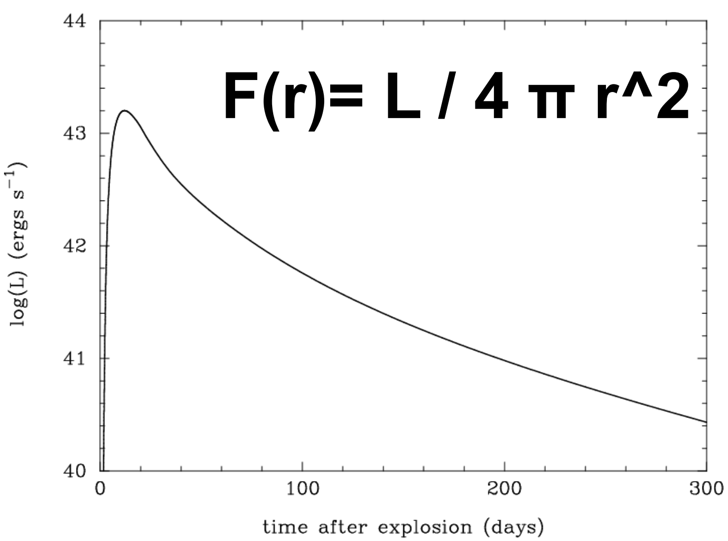
$$4\pi a^2 \sigma_{\rm B} T_{\rm d}(r)^4 \langle Q_\lambda(a, T_{\rm d})\rangle = \frac{F(r)}{\sigma_{\rm B} T_{\rm BB}^4} \int \pi a^2 Q_\lambda(a) B_\lambda(T_{\rm BB}) d\lambda$$

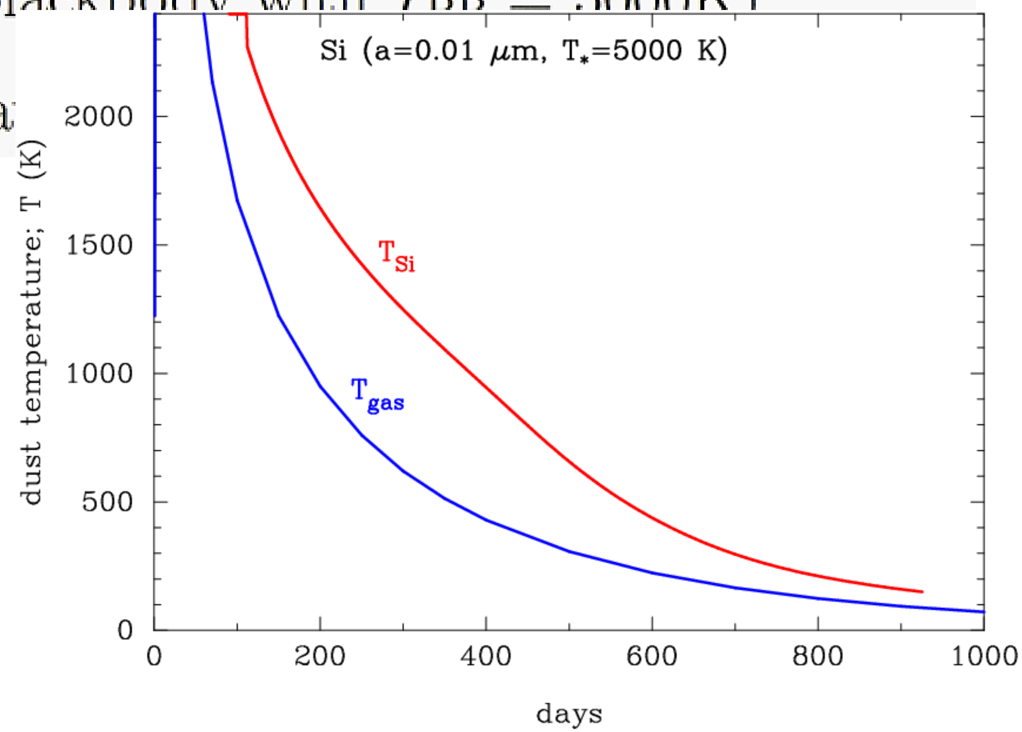
$T_{\rm d}(r)$: equilibrium temperature of dust at a position r

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

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

$\langle Q_\lambda(a, T_{\rm d})\rangle$: Plank-a

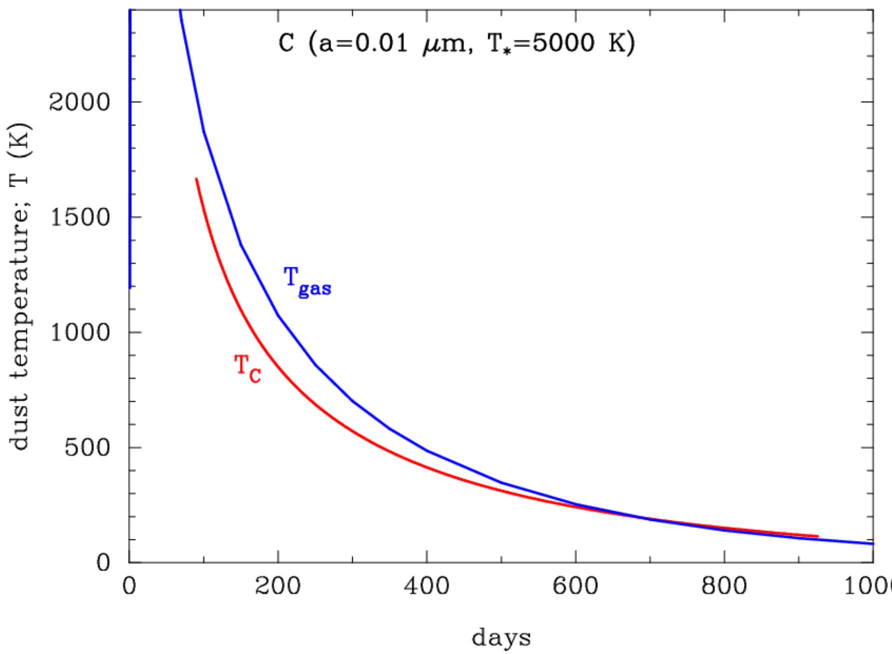




4-6. mass of dust formed

Mass of dust formed

dust species	$M_{1,d,j}$ ($M_\odot$)	$M_{2,d,j}$ ($M_\odot$)
C	1.46×10^{-2}	1.46×10^{-2}
Al_2O_3	1.29×10^{-6}	1.29×10^{-6}
Mg_2SiO_4	1.10×10^{-3}	1.10×10^{-3}
$MgSiO_3$	1.12×10^{-3}	1.12×10^{-3}
SiO_2	2.40×10^{-3}	2.40×10^{-3}
MgO	4.65×10^{-7}	4.65×10^{-7}
FeS	6.63×10^{-3}	5.09×10^{-4}
Si	2.11×10^{-2}	6.23×10^{-7}
Fe	4.78×10^{-5}	—
Ni	2.16×10^{-6}	—
total	4.69×10^{-2}	1.97×10^{-2}



There is no evidence that C has been detected in SN Ia

If we ignore C grains in SN Ia

Mdust = 5x10^-3

τ(0.55) ~ 0.8 at 300 day

Summary

1) The size of dust formed in the ejecta of Type IIb SN is relatively small because of low gas density of the ejecta

2) Newly formed dust grains in Type IIb SN cannot survive the reverse shock since their radii are small (< 0.01 μm)

3) Model of dust destruction and heating in Type IIb SNR for n_H=10.0 cm^{-3} reproduces the observed SED of Cas A

   ➔ circumstellar / interstellar dust
   ➔ density structure of circumstellar medium
   ➔ thermal emission from dust at various positions

4) For Type Ia SN, the effect of radiation on dust formation can be important