爆燃Ia型超新星爆発時におけるダスト形成

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1-1. Introduction

○ Type Ia SNe

- thermonuclear explosion of a C+O WD with the mass close to Chandrasekhar limit
  - subsonic deflagration?
  - (delayed) detonation?

- eject a significant amount of Fe-peak and intermediate elements such as Si, S, and Ca

  ➔ play a role in the cosmic chemical evolution

- abundant metals in SNe Ia ➔ dust can form?

  Type II SN : 0.1-1 M_{sun} (from theories)

  $> 10^{-4}$ M_{sun} (from observations)

1-2. Dust in Type Ia SNe

○ Dust formation in SNe Ia

– SNe Ia may form a significant amount of **Fe grains**

(e.g. Dwek 1998)

– presolar **SiC grains** in meteorites may be produced in SNe Ia to account for their isotopic sinatures

(Clayton et al. 1997)

– no clear decrease of light curve by dust absorption

– no IR dust emission as well as CO molecules

SN 2003hv, SN 2005bv at 100-300 days

(Gerardy et al. 2007)

– no signature of ejecta-dust in Tycho SNR

(e.g., Douvion et al. 2001)

1-3. Aim of our study

- What is the difference in formation process of dust between SNe Ia and SNe II?

- Is it possible for dust grains to condense in the ejecta of Type Ia SN?

- chemical composition, size, and mass of newly formed dust

- dependence of dust formation process on types of SNe

- implication on nuclear burning in SNe Ia

2-1. Calculation of dust formation

○ nucleation and grain growth theory (Nozawa et al. 2003)

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

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

- key species:
  a gas species with the least collision frequency among reactants
- **sticking probability; α_{sj} = 1, 0.1, 0.01**
- **T_{dust} = T_{gas}** (dust temperature is the same as that of gas)

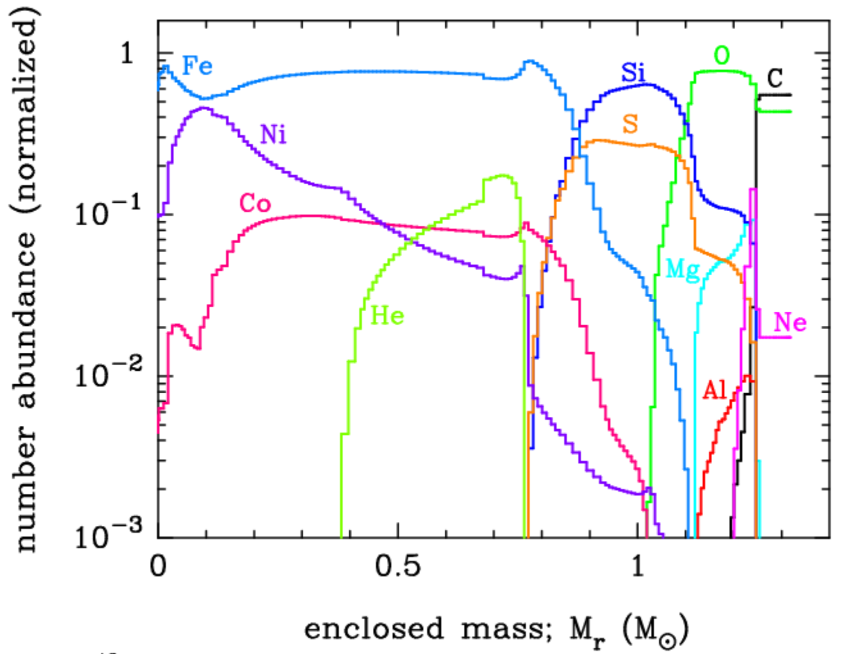
2-2. Dust formation calculation for SN Ia

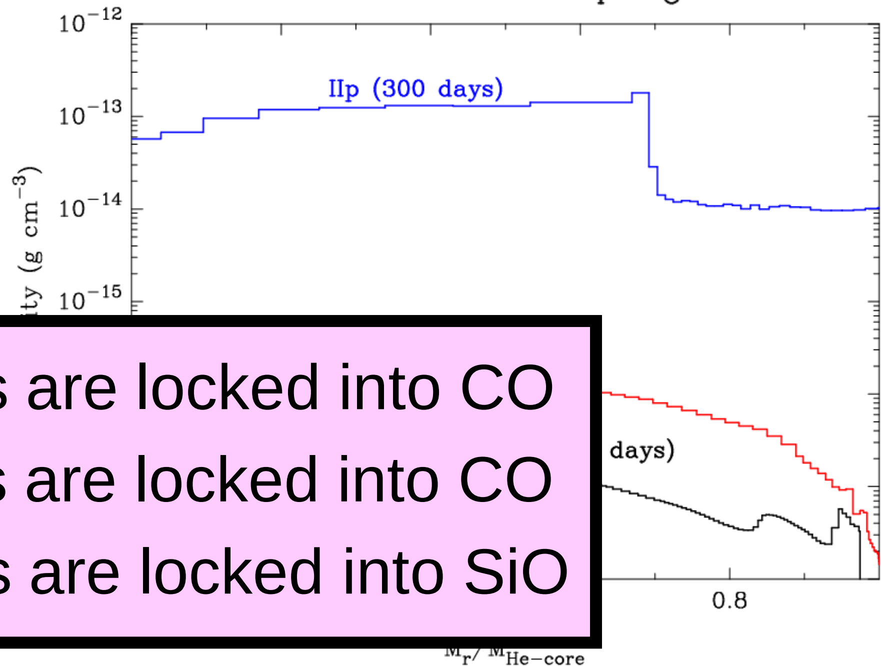
○ Type Ia SN model

W7 model (C-deflagration)

(Nomoto et al. 1984)

- **M_{eje} = 1.32 M_{sun}**
- E_{51} = 1.3
- **$M(^{56}Ni)$ = 0.56 M_{sun}**
- **onion-like composition**
  (no mixing of elements)
- **formation efficiency of CO and SiO ➔ 0 or 1**



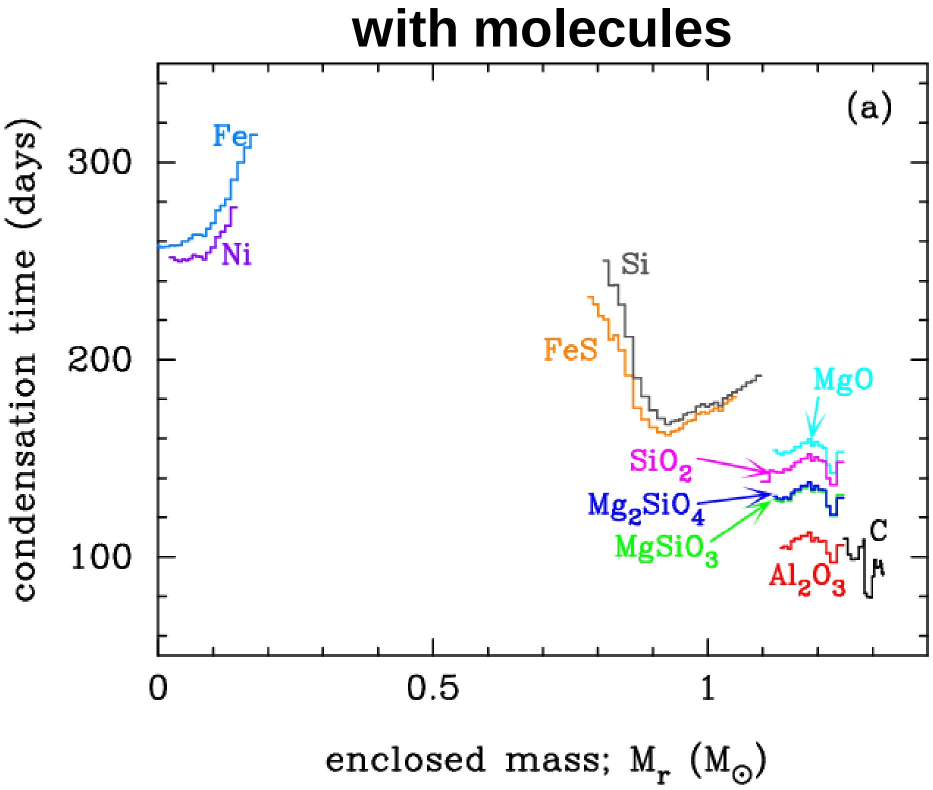


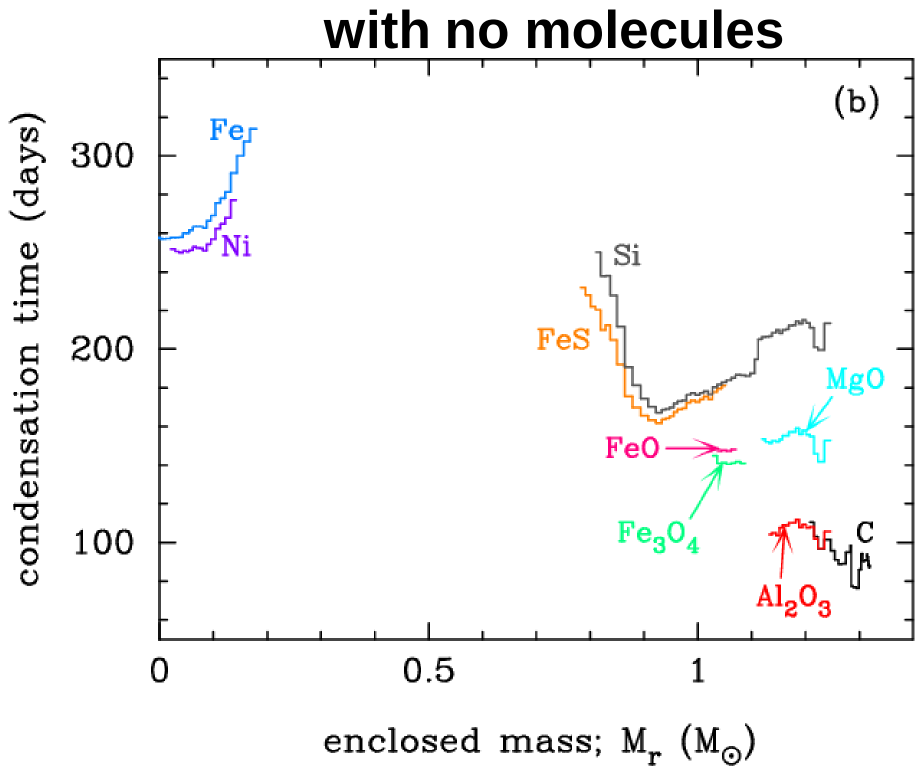
C / O > 1 ➔ all O atoms are locked into CO

C / O < 1 ➔ all C atoms are locked into CO

Si / O < 1 ➔ all Si atoms are locked into SiO

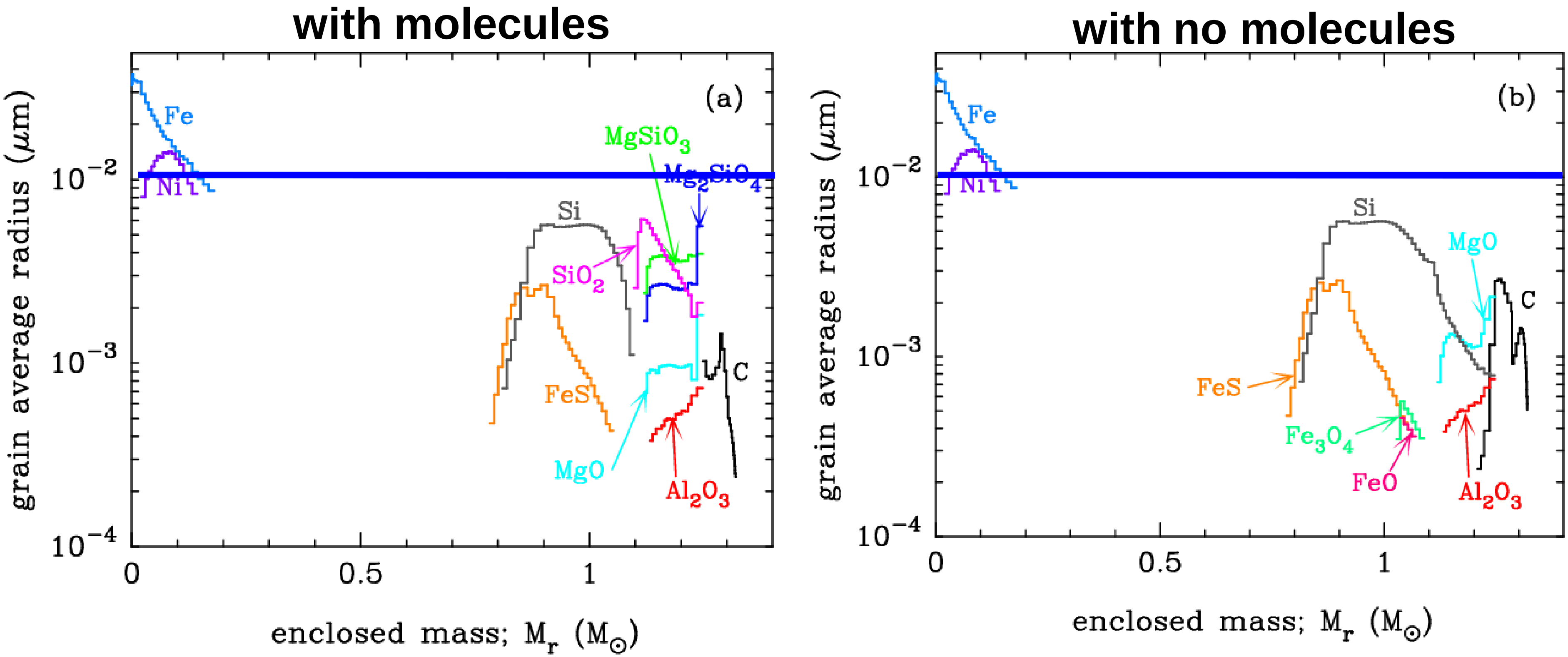
3-1. Condensation time of dust





- **Various species of dust condense in each layer**
- **species of dust depends on formation of molecules**
- **condensation time of dust : 100-300 days**

3-2. Average radii of dust



- average radius of Fe and Ni : ~ 0.01 μm
- average radius of other dust species : < 0.01 μm

 because of low density of gas in the expanding ejecta

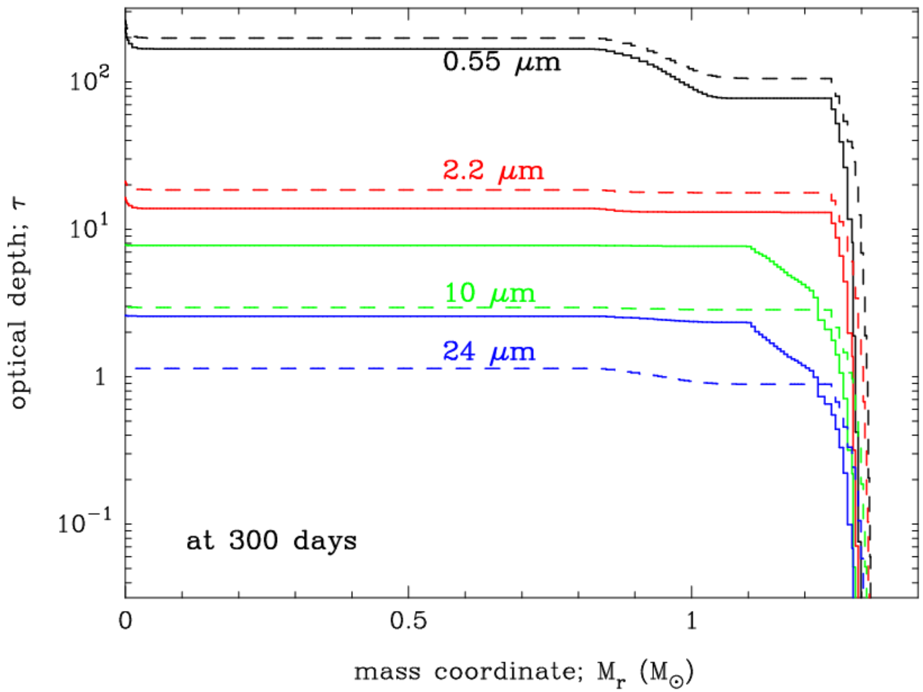
3-3. Mass of dust formed in SN Ia

dust species	A1	A0.1	A0.01	B1	B0.1	B0.01
C	2.00×10^{-2}	1.15×10^{-3}	5.10×10^{-7}	2.89×10^{-2}	1.84×10^{-2}	1.98×10^{-4}
MgO	4.32×10^{-6}	2.35×10^{-9}	7.70×10^{-12}	9.49×10^{-6}	2.64×10^{-9}	8.09×10^{-12}
$MgSiO_3$	8.18×10^{-3}	1.48×10^{-6}	1.59×10^{-9}	0	0	0
Mg_2SiO_4	7.32×10^{-3}	1.66×10^{-6}	2.46×10^{-9}	0	0	0
SiO_2	1.46×10^{-2}	1.01×10^{-5}	5.16×10^{-9}	0	0	0
Al_2O_3	1.07×10^{-6}	9.25×10^{-10}	6.07×10^{-12}	1.16×10^{-6}	9.63×10^{-10}	6.25×10^{-12}
Fe_3O_4	3.34×10^{-7}	3.11×10^{-13}	2.99×10^{-15}	4.09×10^{-7}	6.37×10^{-10}	4.86×10^{-12}
FeO	5.33×10^{-10}	7.16×10^{-14}	6.95×10^{-16}	6.96×10^{-8}	1.50×10^{-10}	1.22×10^{-12}
FeS	1.66×10^{-2}	1.45×10^{-5}	1.34×10^{-8}	1.66×10^{-2}	1.45×10^{-5}	1.34×10^{-8}
Si	6.13×10^{-2}	3.15×10^{-5}	2.23×10^{-8}	6.48×10^{-2}	3.23×10^{-5}	2.38×10^{-8}
Fe	1.43×10^{-4}	1.63×10^{-8}	4.39×10^{-12}	1.43×10^{-4}	1.63×10^{-8}	4.39×10^{-12}
Ni	7.28×10^{-6}	9.73×10^{-10}	5.60×10^{-13}	7.28×10^{-6}	9.73×10^{-10}	5.60×10^{-13}
Total	1.28×10^{-1}	1.21×10^{-3}	5.55×10^{-7}	1.10×10^{-1}	1.84×10^{-2}	1.98×10^{-4}

- **Total mass of dust formed in SNe Ia : $M_{dust} < 0.13\ M_{sun}$**
- **Fe and SiC grains cannot condense significantly**

4-1. Optical depth by dust

Optical depth at 300 days



τ(0.55) ~ 200 at 300 days

τ(0.55) ~ 100 by C grains

τ(0.55) ~ 100 by Si and FeS

➔ too high to be consistent with observations

early formation of dust ➔ 100-300 days

high M(56Ni) ➔ ~0.6 Msun

➔ dust evaporates soon after the formation by strong radiation field in the ejecta?

4-2. Dust temperature

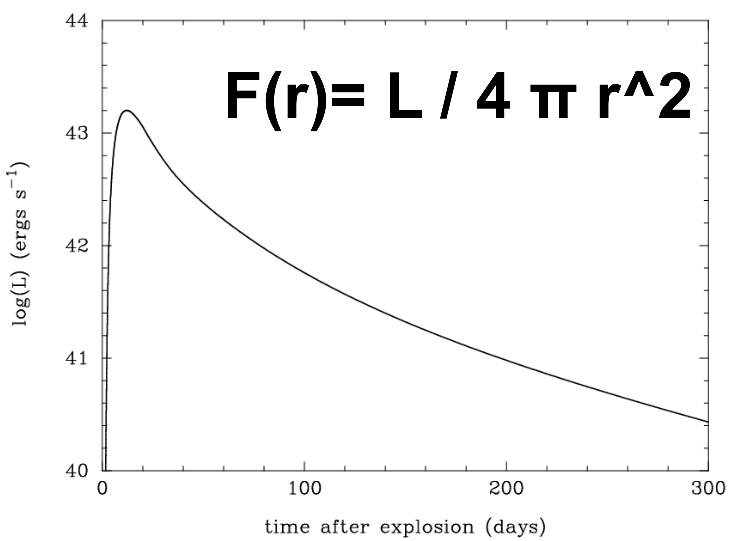
$$4\pi a^2 \sigma_B T_d(r)^4 \langle Q_\lambda(a, T_d) \rangle = \frac{F(r)}{\sigma_B T_{BB}^4} \int \pi a^2 Q_\lambda(a) B_\lambda(T_{BB}) d\lambda$$

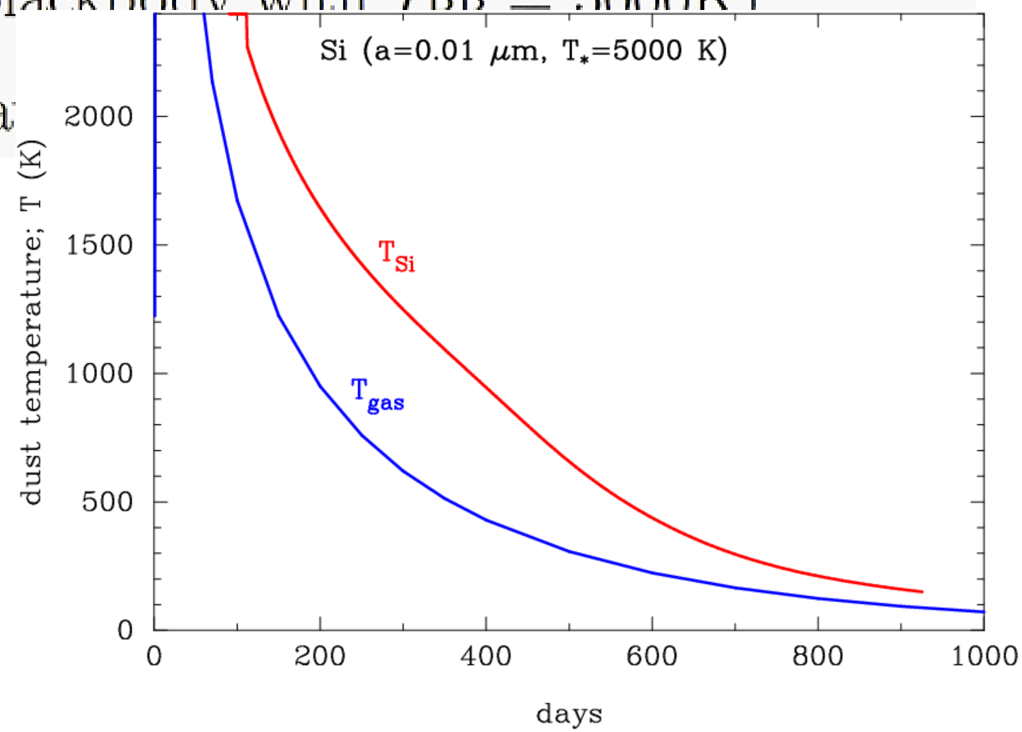
$T_d(r)$: equilibrium temperature of dust at a position r

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

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

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

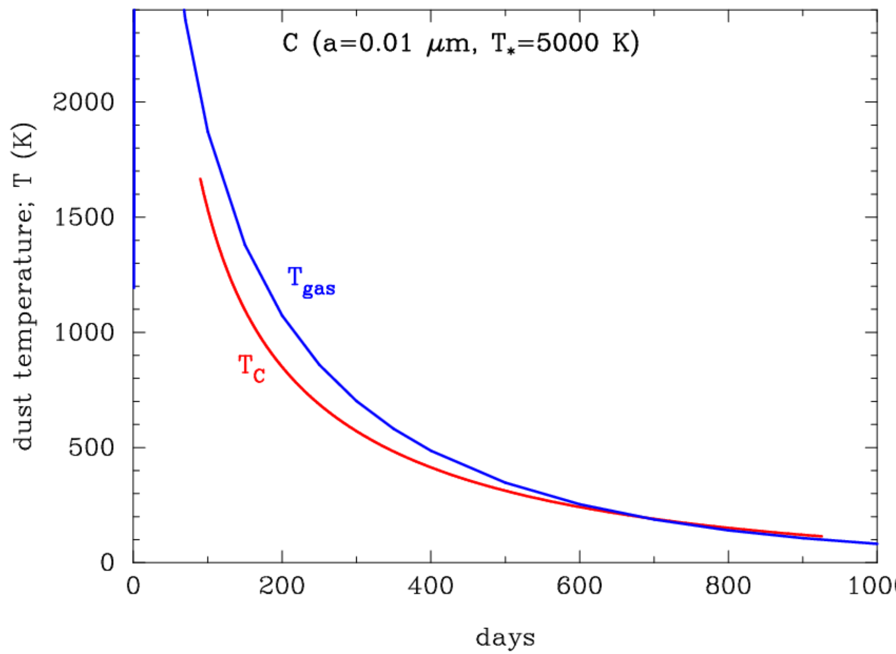




4-3. Mass of dust survived

Mass of dust formed

dust species	$M_{1,d,j}$ ($M_\odot$)	$M_{2,d,j}$ ($M_\odot$)
C	2.00×10^{-2}	2.00×10^{-2}
Al_2O_3	1.07×10^{-6}	1.07×10^{-6}
Mg_2SiO_4	7.32×10^{-3}	7.32×10^{-3}
$MgSiO_3$	8.18×10^{-3}	8.18×10^{-3}
SiO_2	1.46×10^{-2}	1.46×10^{-2}
MgO	4.32×10^{-6}	4.32×10^{-6}
FeS	1.66×10^{-2}	3.63×10^{-4}
Si	6.13×10^{-2}	1.38×10^{-7}
Fe	1.43×10^{-4}	7.72×10^{-6}
Ni	7.28×10^{-6}	—
total	1.28×10^{-1}	5.01×10^{-2}



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

If we ignore C grains in SN Ia

M_{dust} ~ 0.03 M_{sun}

τ(0.55) ~ 1 at 300 day

Summary

1) Dust formed in the ejecta of SNe Ia

- **various grain species with average radius : < 0.01 μm**
- **upper limit of total mass : ~0.1 M_{sun}**

2) Strong radiation field in the ejecta of SNe Ia

➔ destroy most of FeS and Si but not C and silicate

3) Formation of C grains is inconsistent with observations

➔ preexisting C should be burned by nuclear burning

absence of C layer ➔ dust mass : 0.03 M_{sun}

4) Newly formed dust grains of < 0.01μm may not be able to survive the reverse shock due to their small radii

(Nozawa et al. to be submitted soon!)