Formation and evolution of dust in hydrogen-poor supernovae

Takaya Nozawa

(IPMU, Univ. of Tokyo)

Collaborators;

T. Kozasa (Hokkaido Univ.), N. Tominaga (Konan Univ.),
K. Maeda (IPMU), H. Umeda (Univ. of Tokyo),
K. Nomoto (IPMU/Univ. of Tokyo)

1-1. Introduction (1)

SNe are the major sources of interstellar dust?

- **mass estimate of dust condensing in the ejecta**

  → **M_{dust} < 10^{-3} M_{sun} from observations of SNe**
  (e.g., Miekle et al. 2007; Kotak et al. 2009)

  → **M_{dust} = 0.1-1 M_{sun} from theoretical studies**
  (Todini & Ferrara 2001; Nozawa et al. 2003)

It is essential to reveal the composition, size, and mass of dust by comparing theoretical model with observation

- a limited number of observations of dust forming-SNe
- a lack of sophisticated radiative transport model

1-2. Introduction (2)

- **Comparison of models with IR observations of SNRs**
  - **erosion by sputtering and stochastic heating**
  - **envelope-poor SNe are more favorable**

    (For type II-P SNe, the reverse shock collides with the He core after a few thousand years)

- **Dust formation and evolution in SN with no envelope**
  - **~30 % of CCSNe explode as SNe Ib/c and SN IIb**

    (Prieto et al. 2009; Smartt et al. 2008; Boissier & Prantzos 2009)

- **investigate the composition, size, and mass of dust formed in hydrogen-deficient SNe**
- **apply the results to the IR observations of young SNR such as Cas A**

2-1. Calculation of dust formation

○ nucleation and grain growth theory (Kozasa & Hasegawa 1987)

steady-state nucleation rate

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

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=1**
- **T_{dust} = T_{gas}** (dust temperature is the same as that of gas)

2-2. Model of Dust formation calculation

- ○ 1-D models of SNe

  ➔ ✕ clumpy structure and asymmetry explosion

- ○ formation of molecules (CO and SiO)

  — complete

  — taking account of formation and destruction

  (formation efficiency of molcules is 0.01-0.1)

- ○ time evolution of gas temperature

  — following a light curve calculation

  — adopting adiabatic approximation

- ○ mixing of elements within the He-core

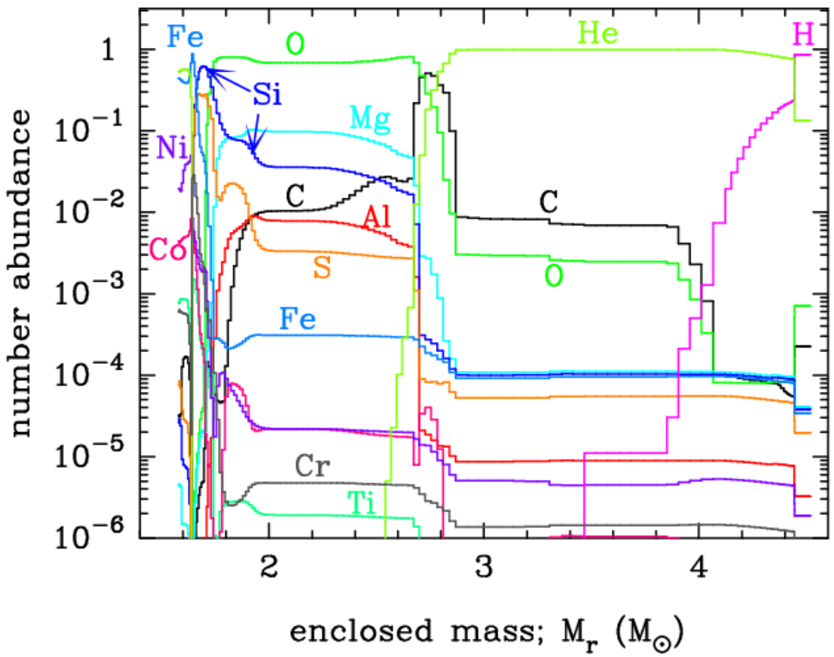
  — unmixed case (original onion-like composition)

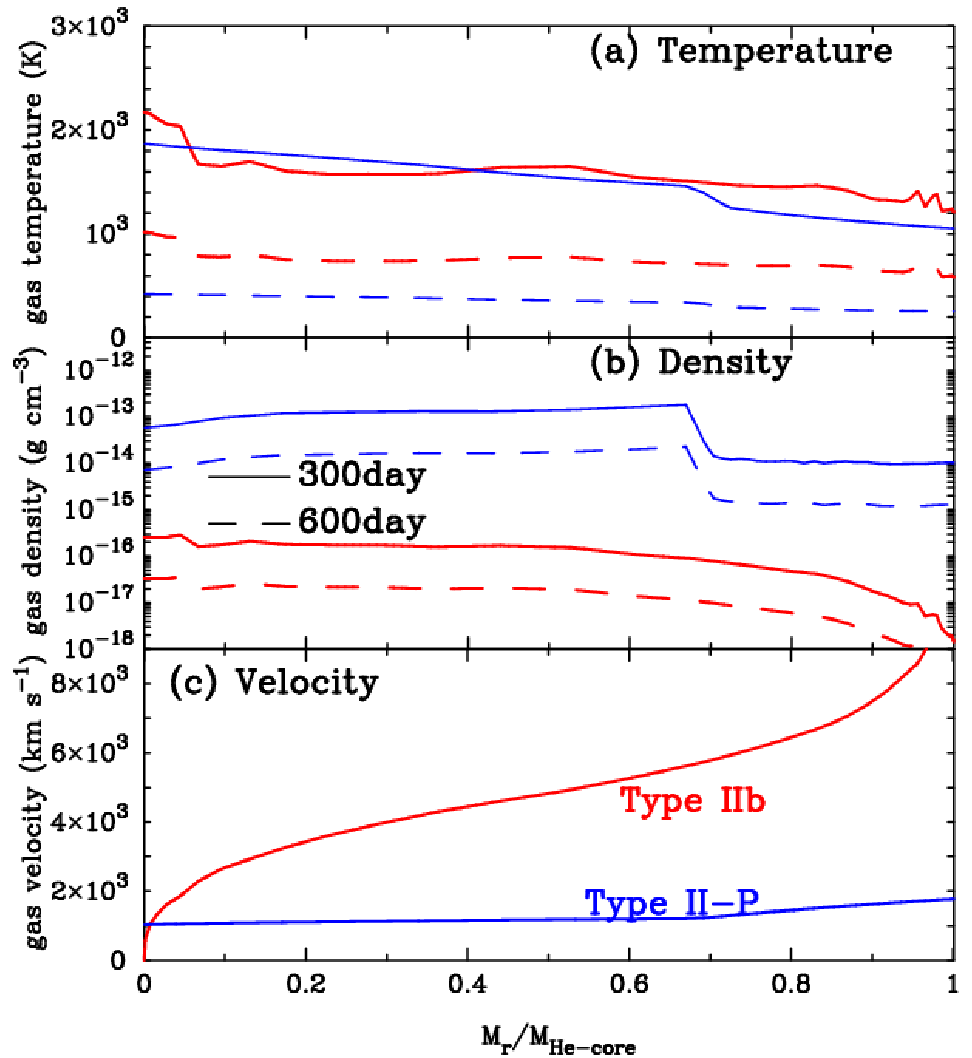
  — uniformly mixed case

2-3. Model of Type IIb SN

○ SN IIb model (SN1993J-like model)

- M_{eje} = 2.94 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
  M_{star} = 18 Msun
- $E_{51} = 1$
- $M(^{56}Ni)$ = 0.07 Msun



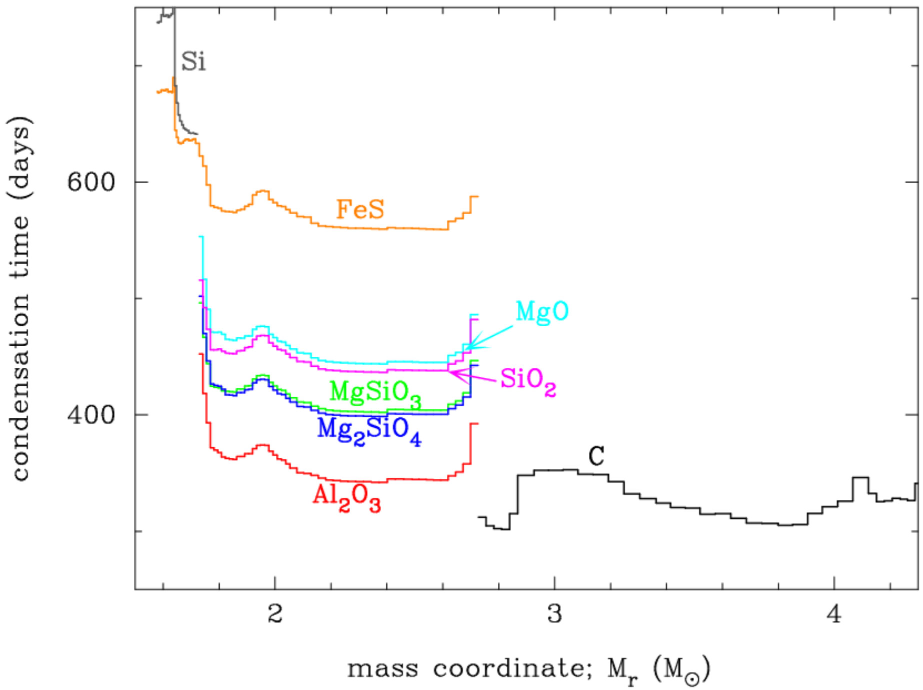


2-4. Composition and mass of dust formed

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

condensation time



Total mass of dust formed :

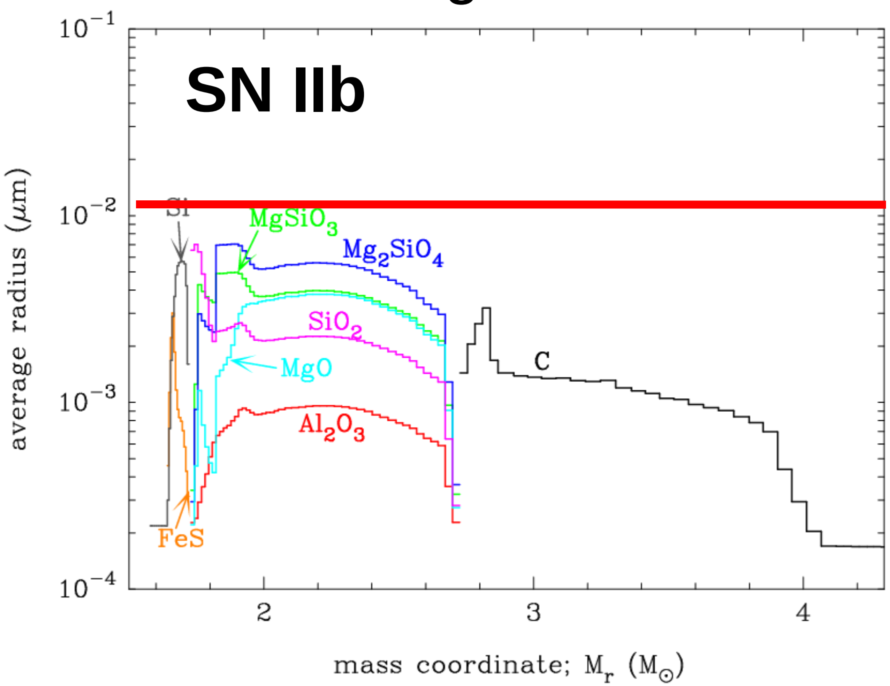
0.167 Msun in SN IIb

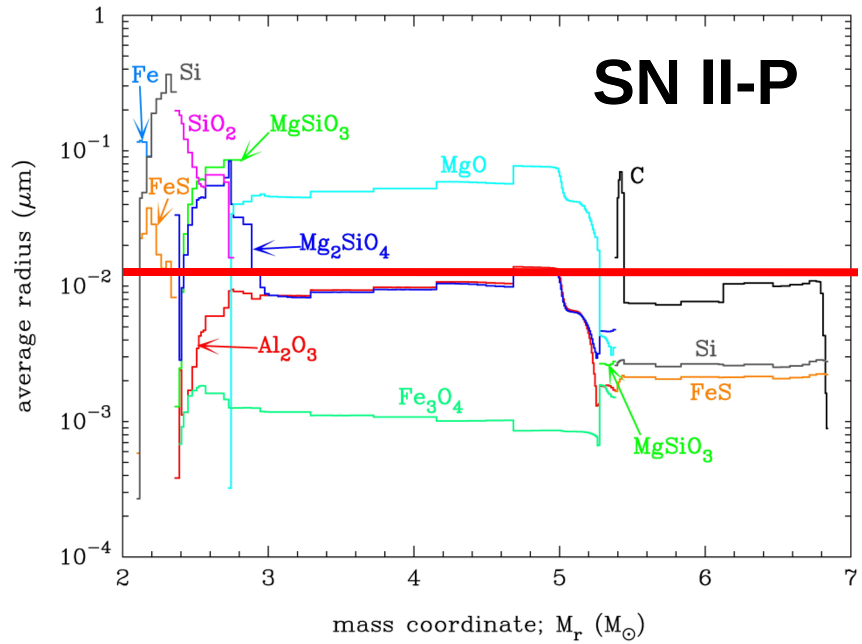
0.1-1 Msun in SN II-P

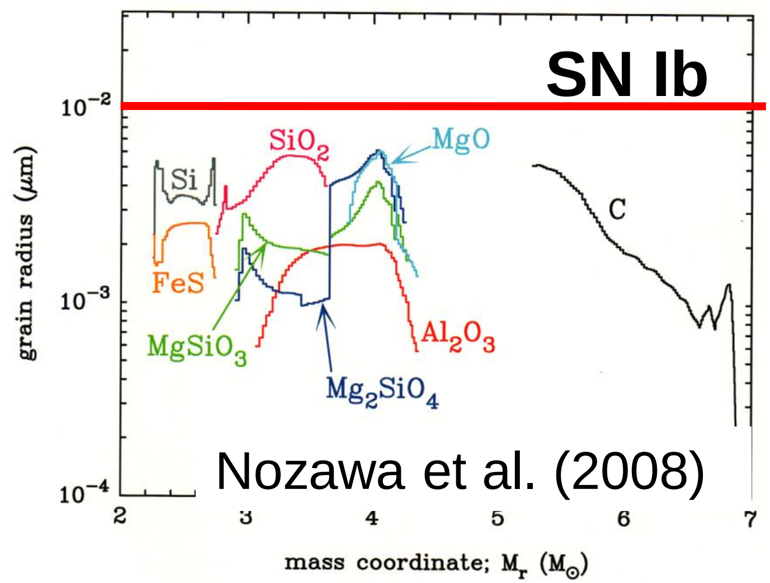
- different species of dust can condense in different layers
- condensation time: 300-700 days

2-5. Radius of dust formed in the ejecta

average radius







Nozawa et al. (2008)

Grain radius

➔ > 0.01 μm for SN IIP

➔ < 0.01 μm for SN IIb

Dust grains formed in H-deficient SNe are small

3-1. Dust destruction calculation

- **time evolution of shock wave**
  - **numerically (Nozawa et al. 2007)**
  - **semi-analytically (Bianchi & Schneider 2007)**
- **deceleration of dust due to the gas drag**
  - **inversely proportional to grain size and bulk density**
- • deceleration of dust due to drag force (Baines et al. 1965)

$$\frac{dw_\mathrm{d}}{dt} = \frac{F_\mathrm{drag}}{m_\mathrm{d}} = -\frac{3n_\mathrm{H}kT}{2a\rho_\mathrm{d}} \sum_i A_i G_i(s_i) \quad (w_\mathrm{d} : \text{relative velocity})$$

-

$$\frac{da}{dt} = -\frac{m_\mathrm{sp}}{2\rho_\mathrm{d}} n_\mathrm{H} \sum A_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \frac{e^{-s_i^2}}{2s_i} \times \int \epsilon^{\frac{1}{2}} e^{-\epsilon_i} \sinh(2s_i\epsilon_i^{\frac{1}{2}}) Y_i^0(\epsilon_i) d\epsilon_i$$

rmarized by n_H

ter 1979)

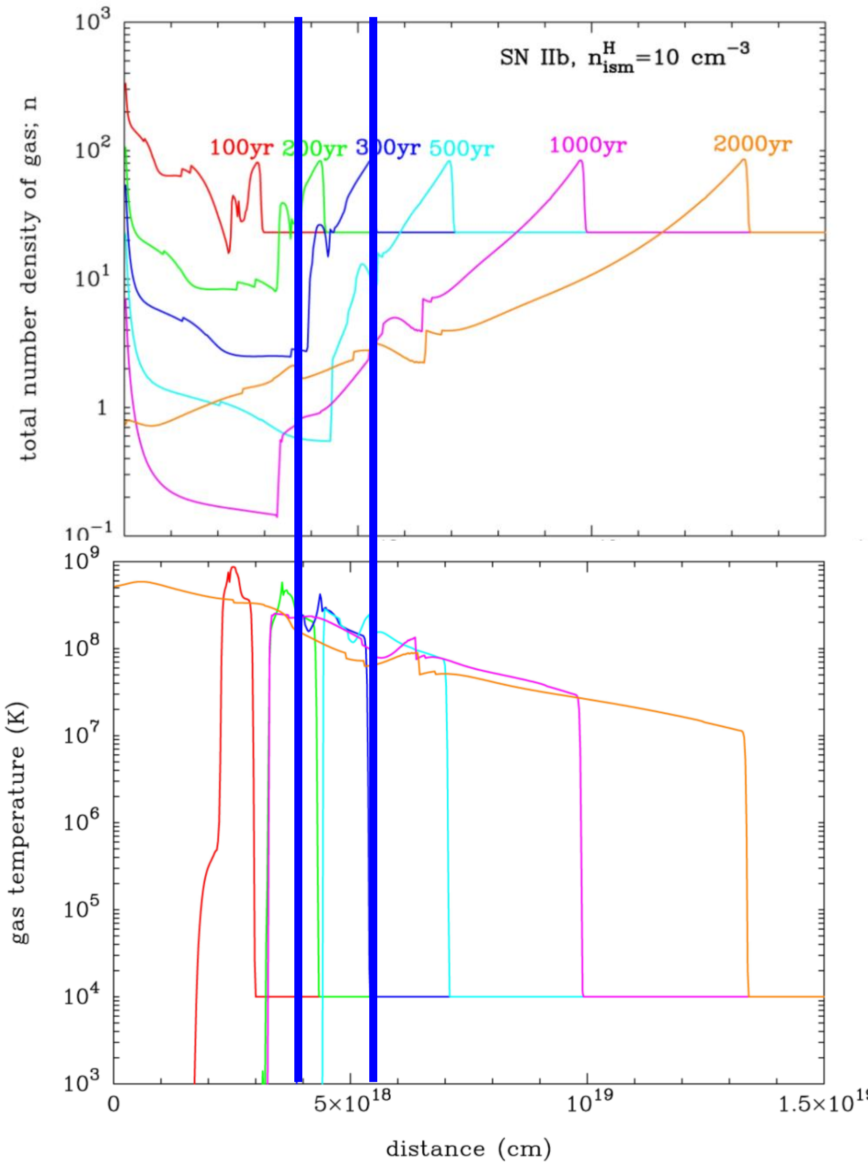
where $s_i^2 = m_i w_\mathrm{d}^2 / 2kT$

3-2. Calculation of dust evolution in SNRs

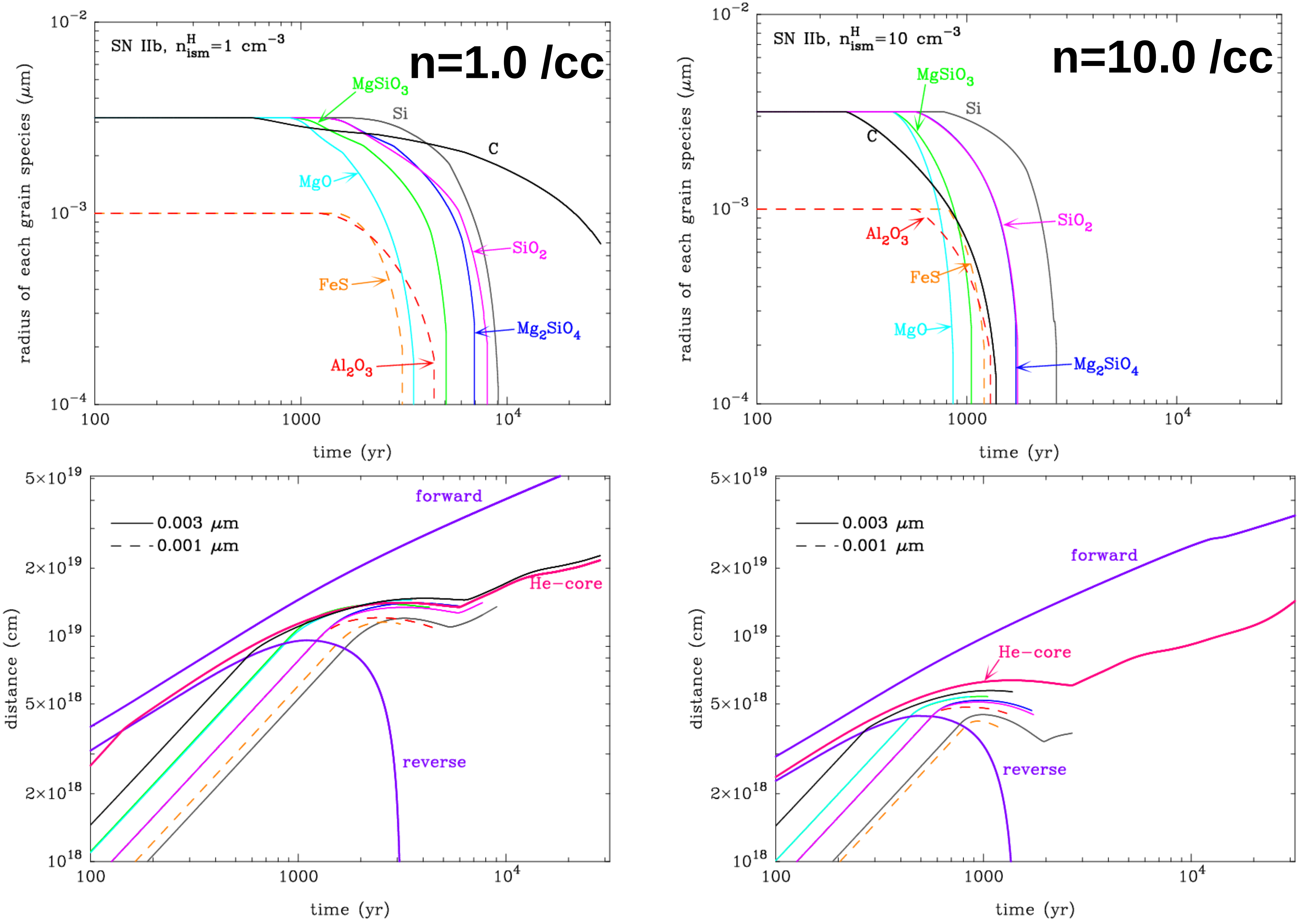
○ Model of calculations

(Nozawa et al. 2006, 2007)

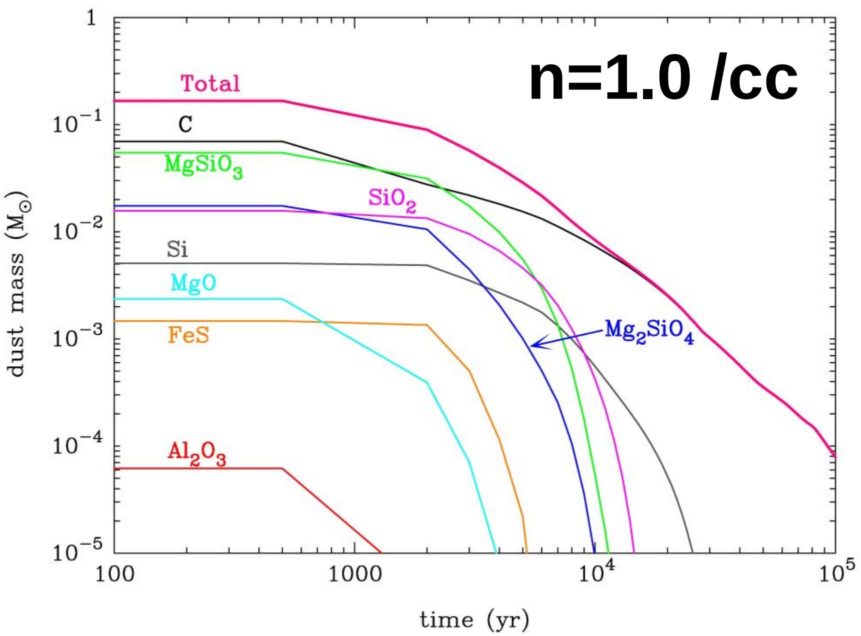
- ejecta model
  - hydrodynamic model for dust formation calculation
- CSM gas density
  - n_H = 1.0 and 10.0 cm^{-3}
  - $n_H(r) \propto M / (4\pi r^2 v_w)$ g/cm^{-3}
    (M = 2×10^{-5} Msun/yr)
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag
  - collsional heating

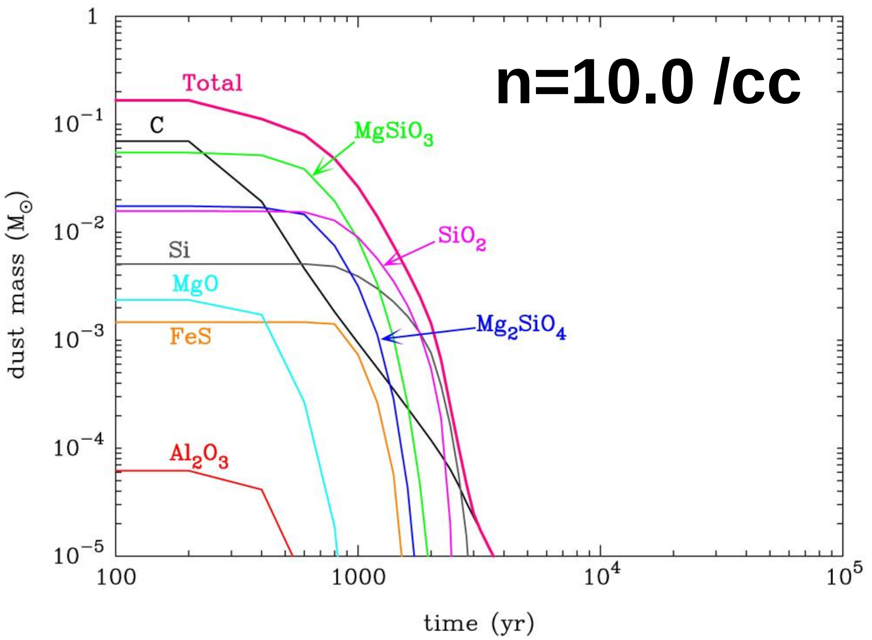


3-3. Evolution of dust in Type IIb SNR



3-4. Time evolution of dust mass





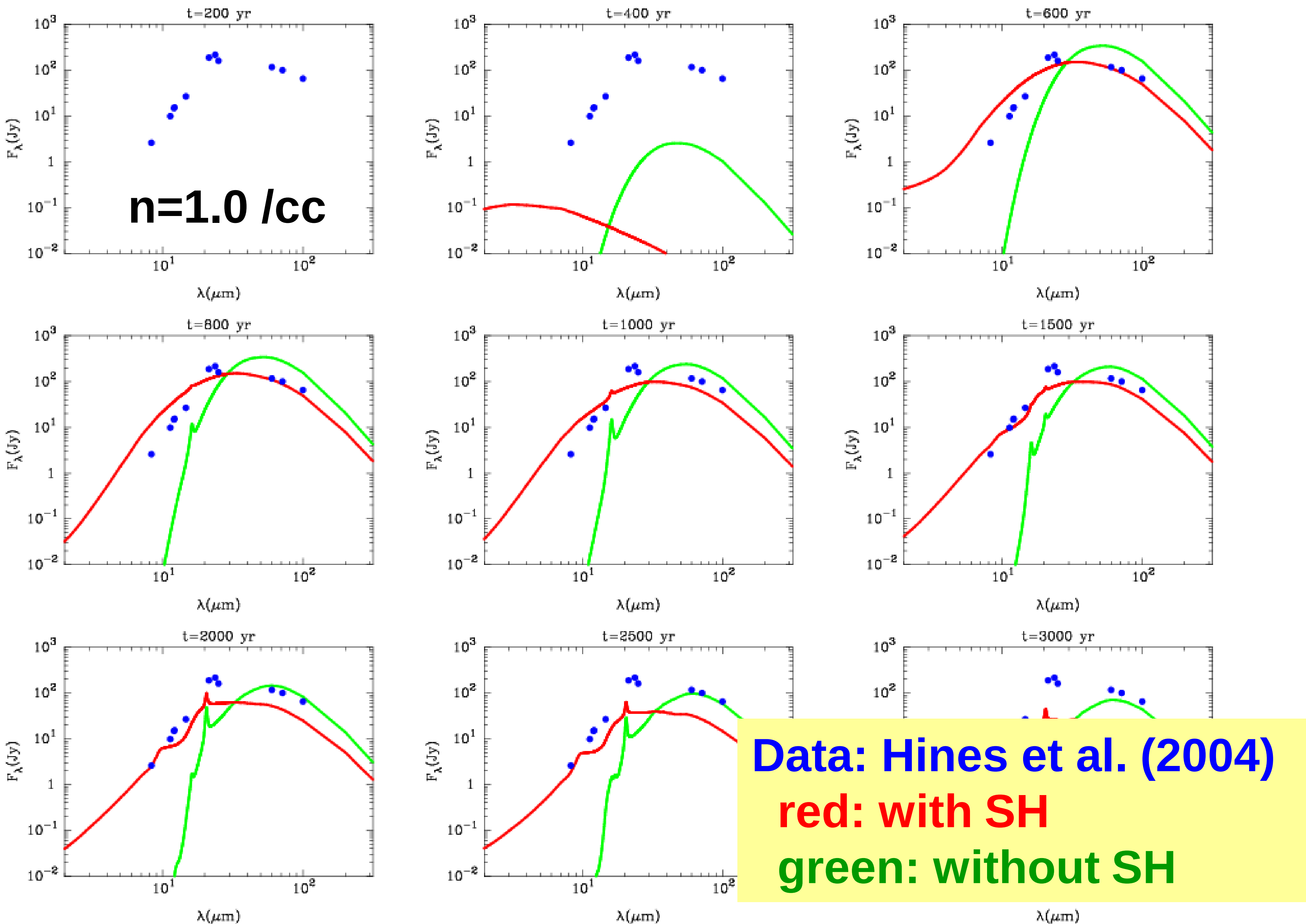
M_{dust} ~ **10^{-4} M_{sun}** at 10^5 yr

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

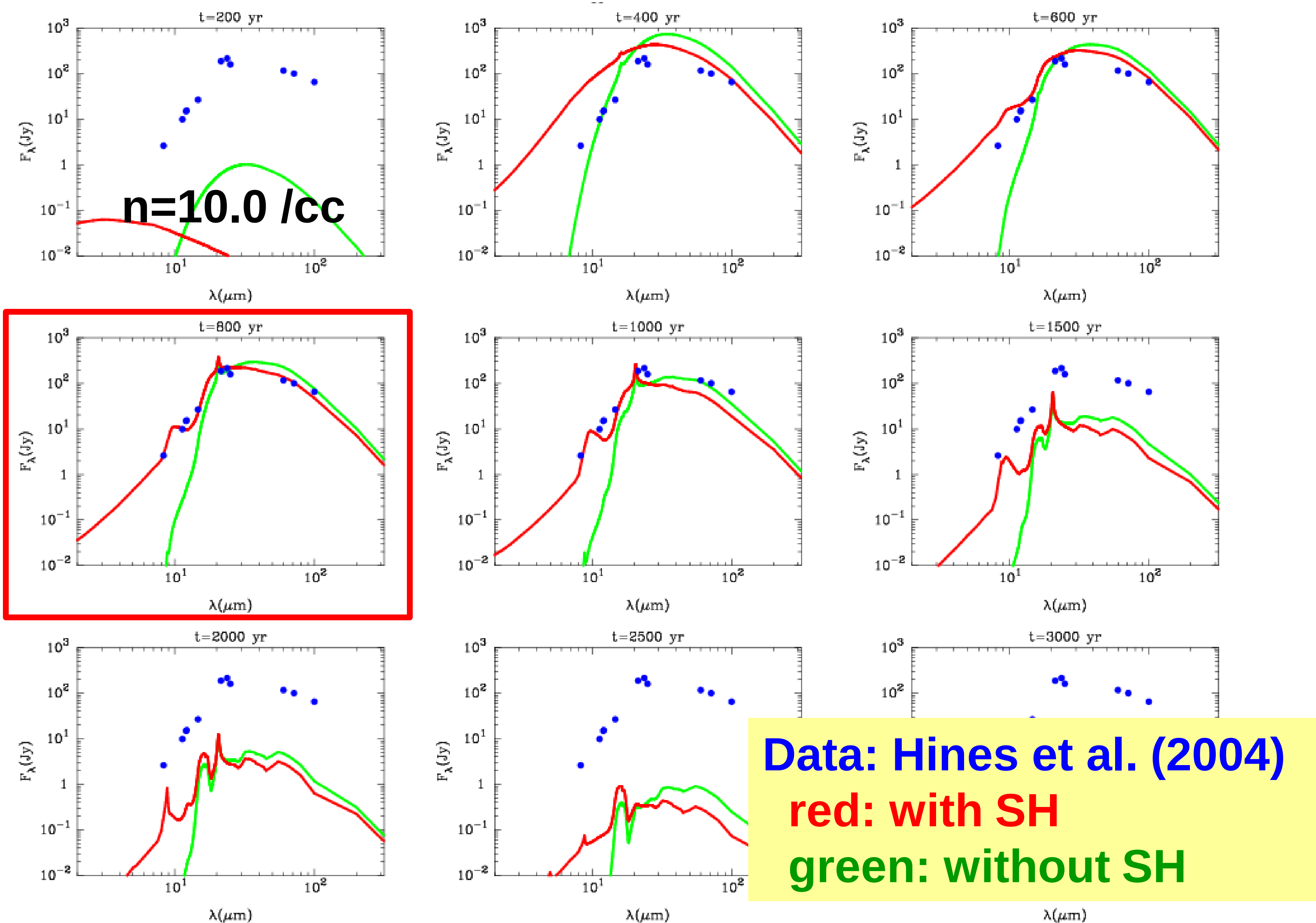
Newly formed dust grains in the ejecta are completely destroyed in the shocked gas within the SNR

Core-collapse SNe with low-mass outer envelope cannot be main sources of dust

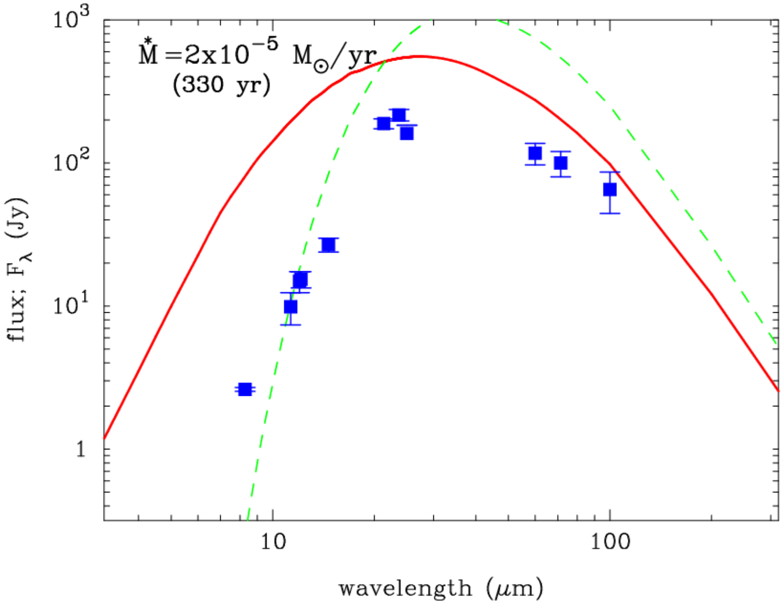
3-5. Time evolution of IR thermal emission (1)



3-6. Time evolution of IR thermal emission (2)

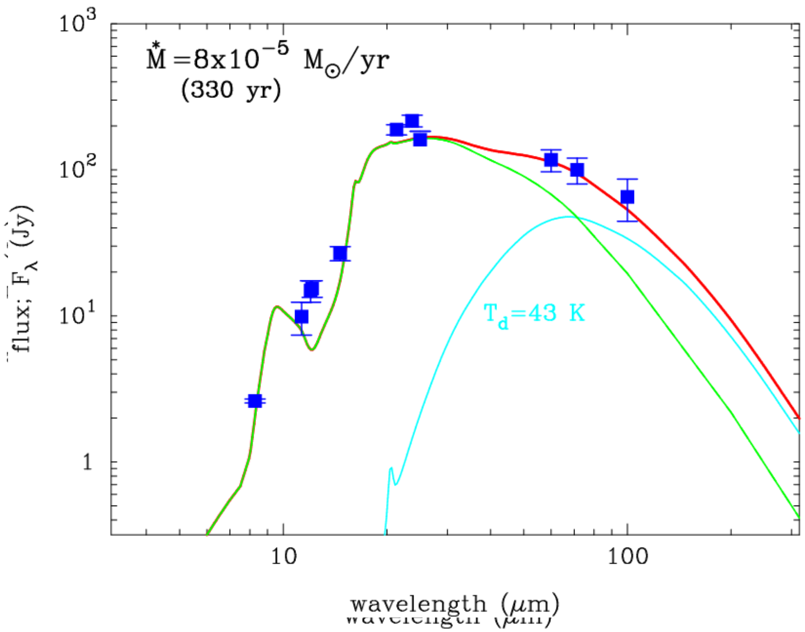


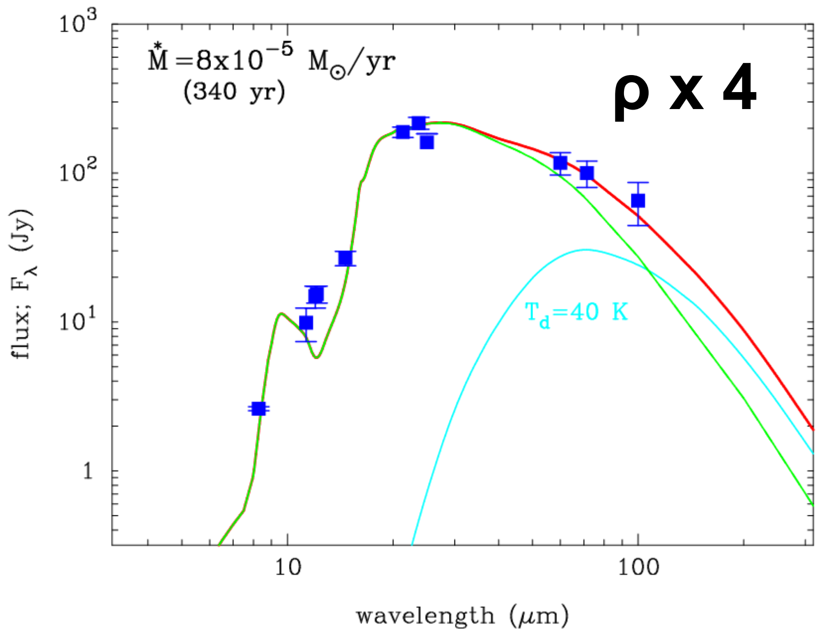
3-7. Contribution from unshocked dust



dM/dt = 2x10^{-5} Msun/yr

Md,warm ~ 0.006 Msun,
Md,cool ~ 0.08 Msun
dM/dt = 8x10^{-5} Msun/yr





4-1. Dust formation calculation for SN Ia

○ Type Ia SN model

W7 model (C-deflagration)

(Thielemann et al. 1986)

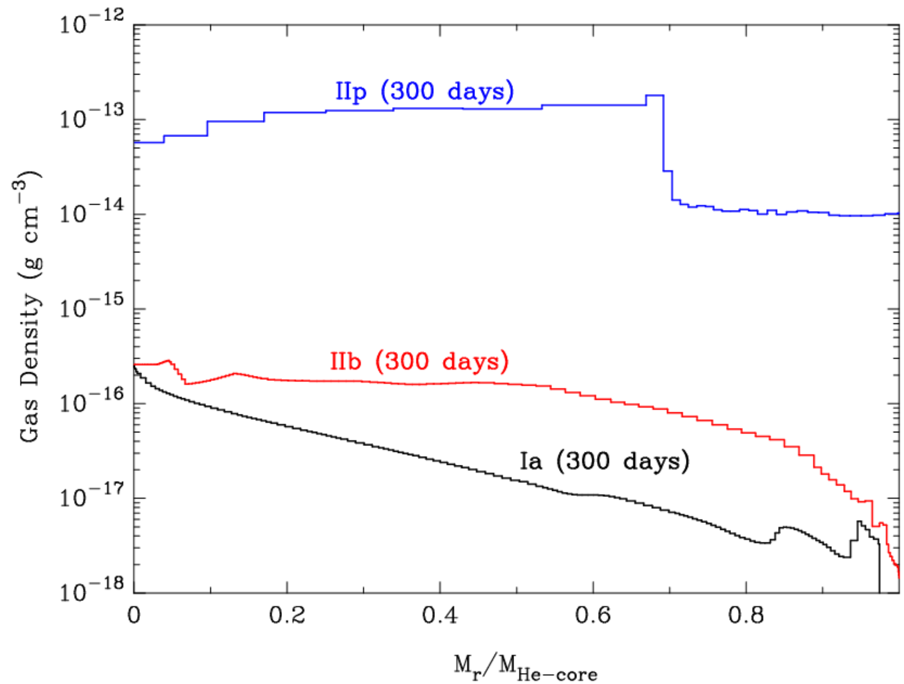
- **M_{pr} = 1.38 M_{sun}**
- E_{51} = 1
- **$M(^{56}Ni)$ = 0.6 M_{sun}**

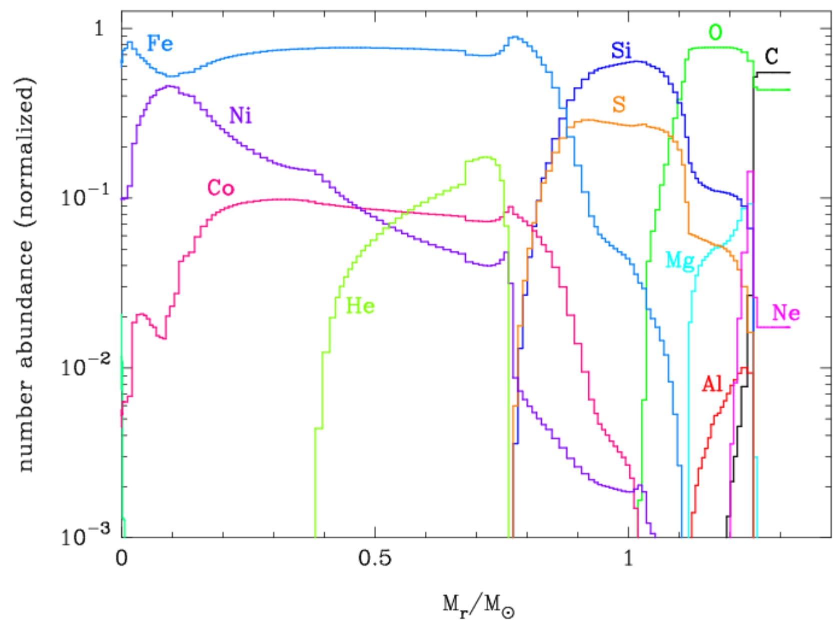
○ Dust formation theory

- non-steady nucleation and grain growth theory

  (Nozawa et al. 2003)

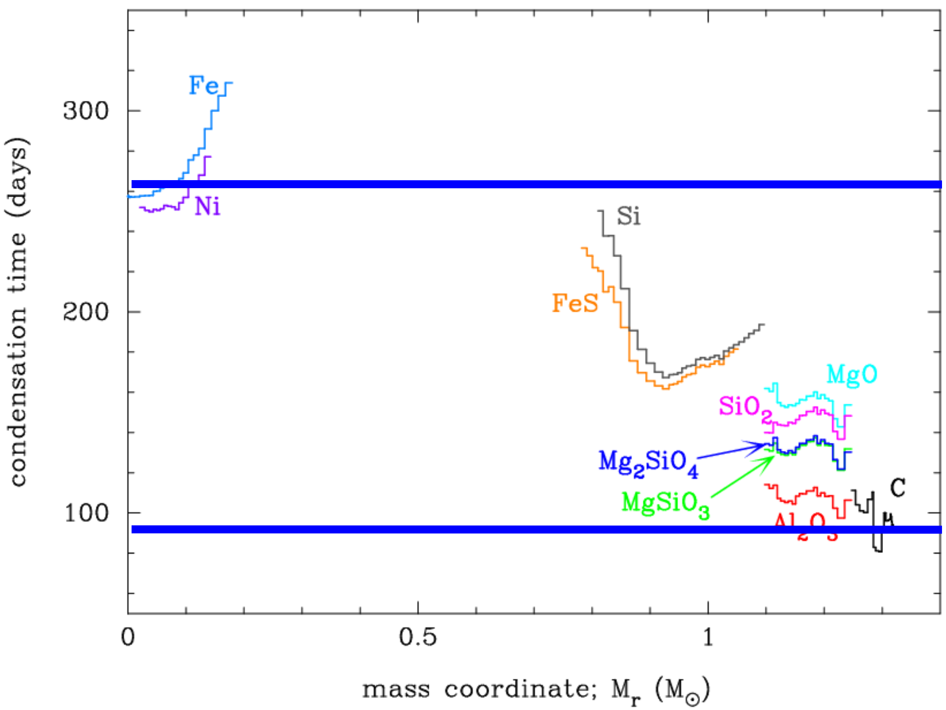
- onion-like composition
- sticking probability; α_s = 1



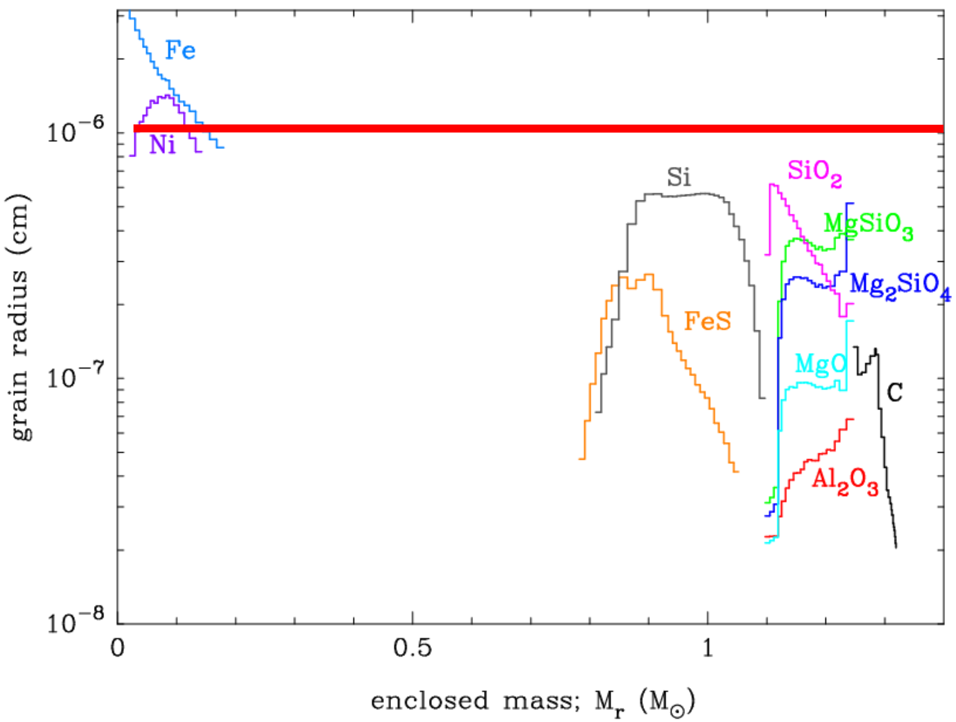


4-2. Results of dust formation calculation

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

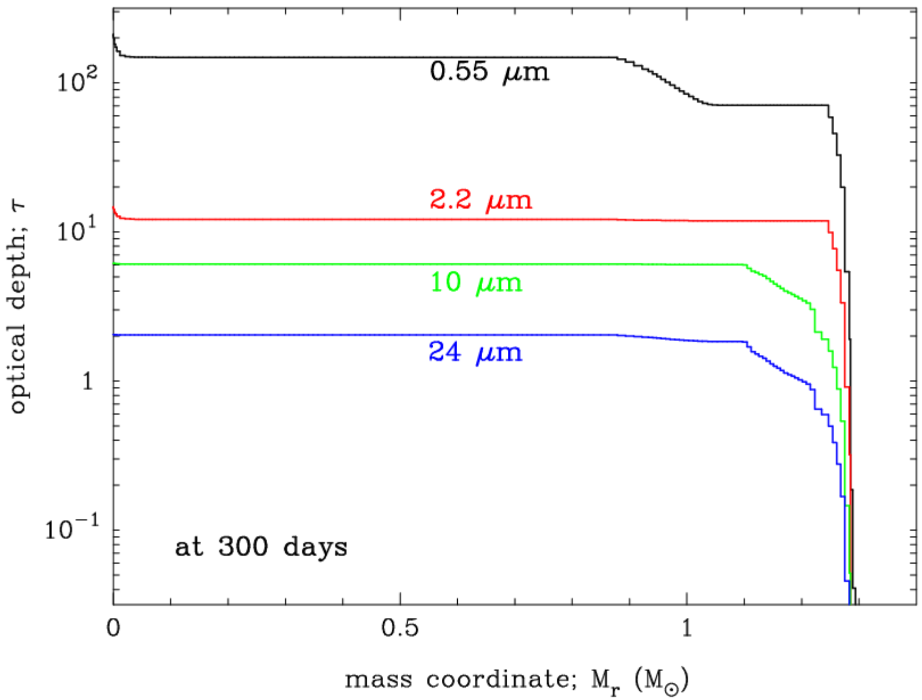
Mass of dust formed

dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,total}$
C	1.81×10^{-2}	0.153
Al_2O_3	6.95×10^{-7}	5.89×10^{-6}
Mg_2SiO_4	5.45×10^{-3}	0.046
$MgSiO_3$	6.01×10^{-3}	0.051
SiO_2	1.09×10^{-2}	0.092
MgO	3.22×10^{-6}	2.7×10^{-5}
FeS	1.66×10^{-2}	0.140
Si	6.10×10^{-2}	0.517
Fe	1.43×10^{-4}	1.2×10^{-3}
Ni	7.28×10^{-6}	6.2×10^{-5}
total	1.18×10^{-1}	1

Total mass of dust

M_{dust} =0.12 M_{sun}

Optical depth at 300 days



τ(0.55) ~ 100

τ(0.55) ~ 60 by C grains

τ(0.55) ~ 35 by Si and FeS

➔ too high

Summary

1) The radius of dust formed in the ejecta of Type IIb SN is quite small (< 0.01 μm) because of low ejecta density

2) Small dust grains formed in Type IIb SN cannot survive destruction in the shocked gas within the SNR

3) Model of dust destruction and heating in Type IIb SNR to reproduce the observed SED of Cas A is

$M_{d,warm}$ = 0.005-0.007 M_{sun}, $M_{d,cool}$ = 0.07-0.09 M_{sun}

dM/dt = 6-8x10^{-5} Msun/yr

4) IR SED reflects the destruction and stochastic heating

➔ properties (size and composition) of dust

➔ density structure of circumstellar medium