Evolution of Newly Formed Dust in Population III Supernova Remnants and Its Impact on the Elemental Composition of Population II.5 Stars

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1. Introduction (1)

○ Role of dust in the early universe

- Dust absorb stellar light and re-emit it by thermal radiation,
  ➔ plays a crucial role in interpreting the SFR and the IMF of the early generation of stars from high-z observations

- Dust provides additional pathways for cooling of gas through their thermal emission and H_2 formation on their surfaces
  ➔ has great impacts on the formation processes of stars

The absorption and thermal radiation by dust grains strongly depend on their chemical composition, size, and amount

It is essential to clarify the properties of dust in the early epoch of the universe!

1. Introduction (2)

○ Sources of dust in the early universe

- At z > 5, the main formation sites of dust are considered to be in the ejecta of supernovae (SNe)
- The newly condensed dust is processed via sputtering in the hot gas swept up by the reverse and forward shocks

The efficiency of dust destruction is sensitive to the chemical composition and size

⬇

We investigated the formation of dust in Population III SNe

(Nozawa et al. 2003)

➔ the chemical composition, size distribution, and mass of dust grains formed in the SN ejecta

2. Aim of our study

We investigate the evolution of dust grains formed in Population III SNe

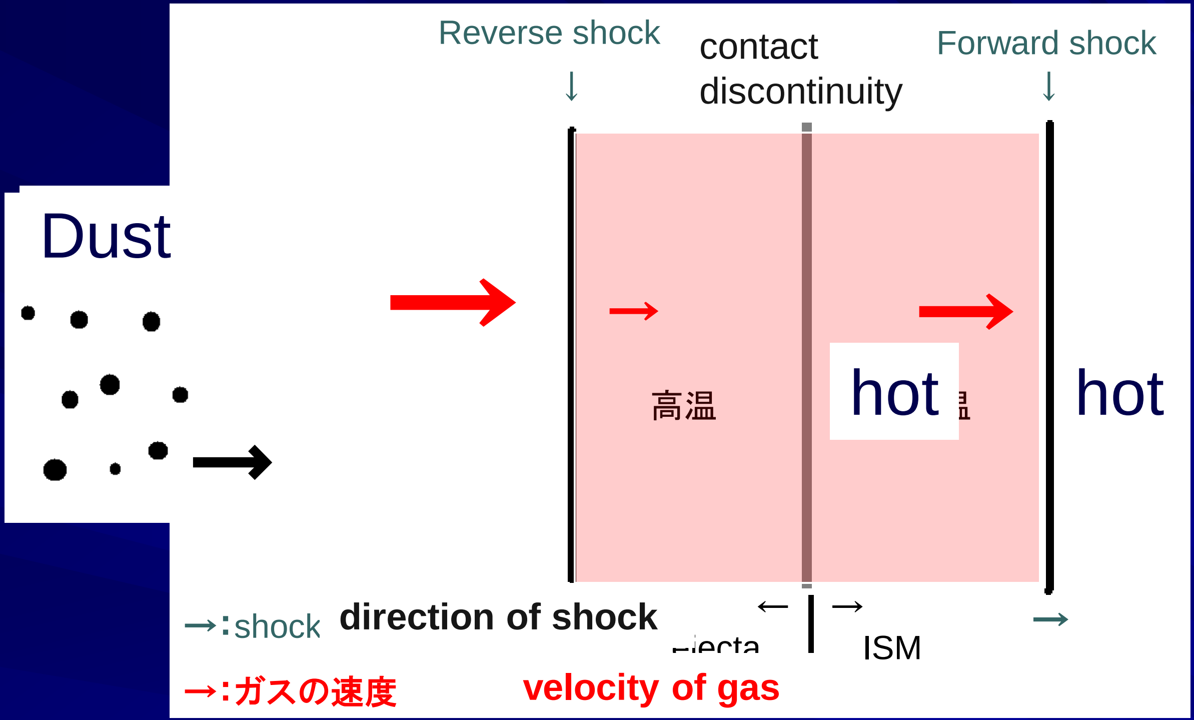
- the processing of dust through the collisions with the reverse shocks penetrating into the ejecta
- the transport of dust within SN remnants (SNRs)

chemical composition, size distribution, and amount of dust finally injected from SNe into the ISM

influences of dust on the elemental composition of Population II.5 stars

(the second-generation stars formed in the dense shell of Pop III SNRs; Mackey et al. 2003; Salvattera et al. 2004; Machida et al. 2005)

3. Dust evolution in SNRs



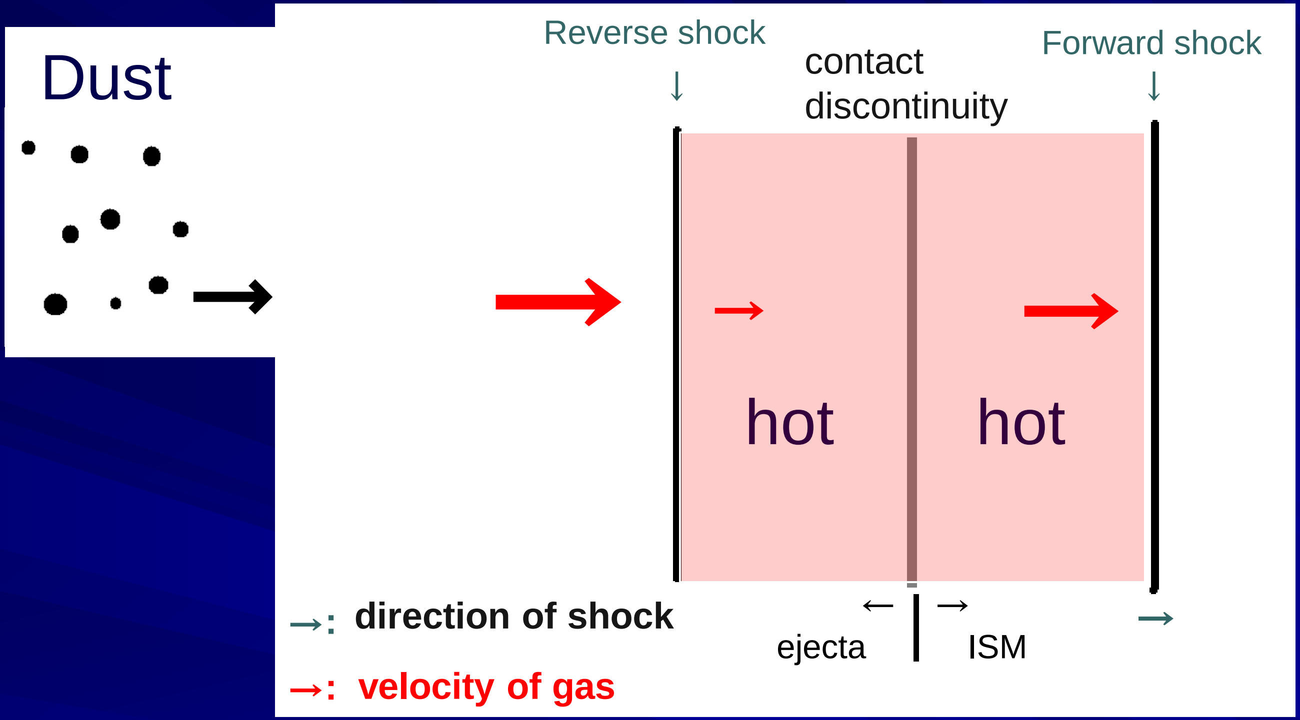
- <u>kinetic sputtering</u> : due to relative velocity of dust to gas
- <u>thermal sputtering</u> ： due to thermal velocity of gas

The deceleration rate and erosion rate of dust

⇐ the temperature and density of gas

⇐ the relative velocity of dust to gas

3. Dust evolution in SNRs



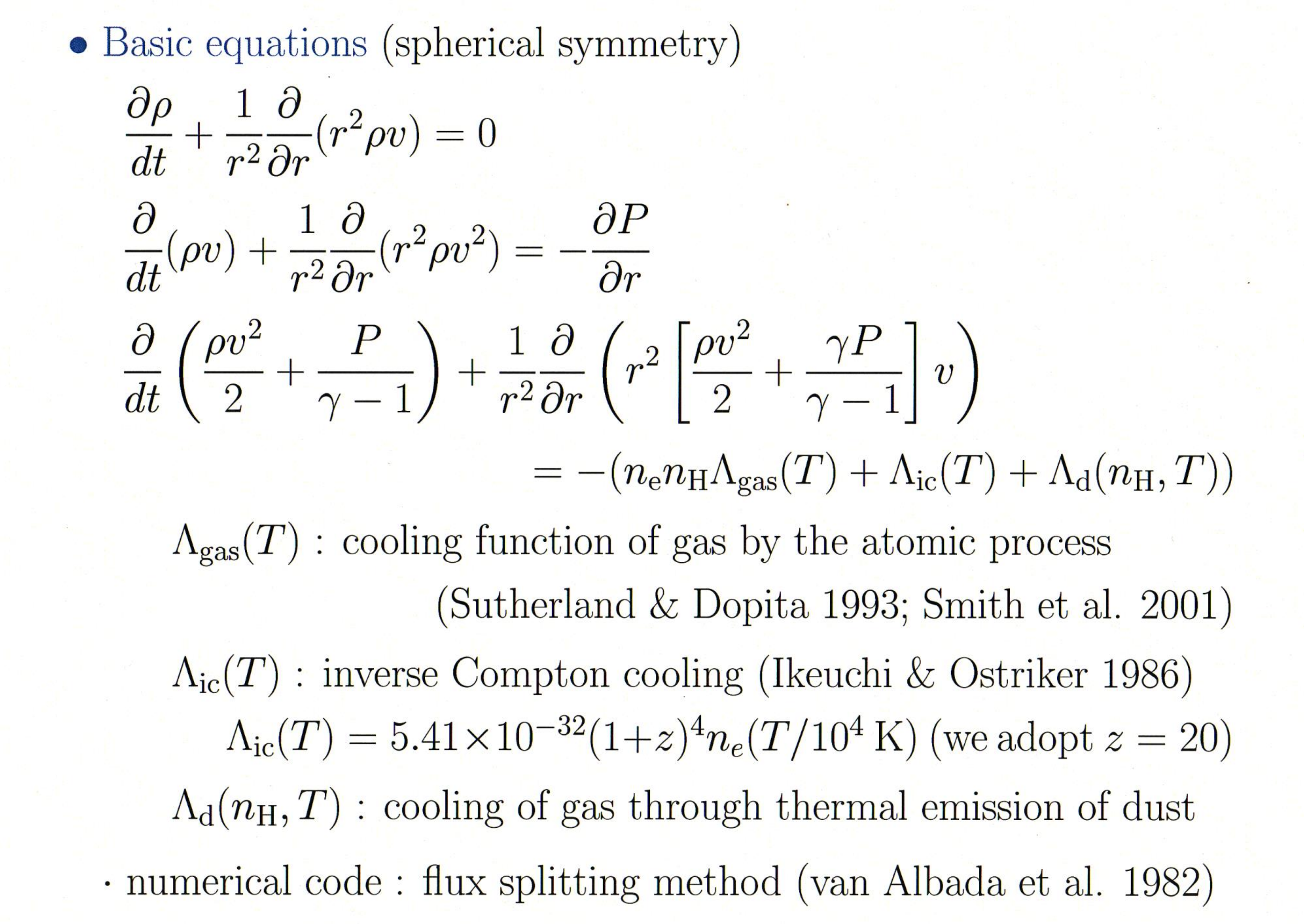
- kinetic sputtering : due to relative velocity of dust to gas
- thermal sputtering : due to thermal velocity of gas

The deceleration rate and erosion rate of dust

⇐ the temperature and density of gas

⇐ the relative velocity of dust to gas

3-1. Time evolution of SNRs



- Basic equations (spherical symmetry)

$$\frac{\partial \rho}{dt} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

$$\frac{\partial}{dt}(\rho v) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v^2) = -\frac{\partial P}{\partial r}$$

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$

$$= -(n_{\mathrm{e}} n_{\mathrm{H}} \Lambda_{\mathrm{gas}}(T) + \Lambda_{\mathrm{ic}}(T) + \Lambda_{\mathrm{d}}(n_{\mathrm{H}}, T))$$

$\Lambda_{\mathrm{gas}}(T)$: cooling function of gas by the atomic process

(Sutherland & Dopita 1993; Smith et al. 2001)

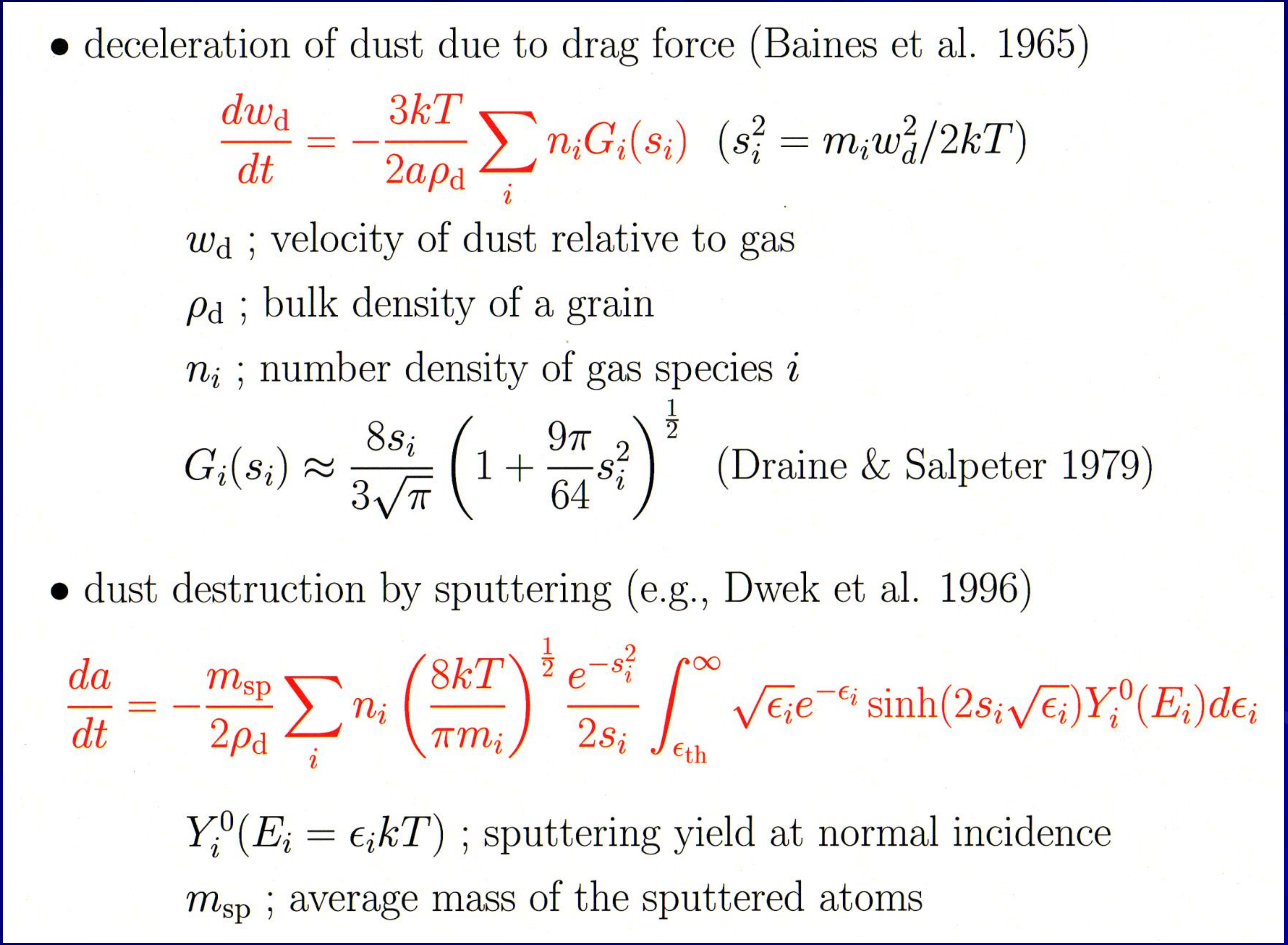
$\Lambda_{\mathrm{ic}}(T)$: inverse Compton cooling (Ikeuchi & Ostriker 1986)

$\Lambda_{\mathrm{ic}}(T) = 5.41 \times 10^{-32} (1+z)^4 n_e (T/10^4\ \mathrm{K})$ (we adopt $z = 20$)

$\Lambda_{\mathrm{d}}(n_{\mathrm{H}}, T)$: cooling of gas through thermal emission of dust

· numerical code : flux splitting method (van Albada et al. 1982)

3-2. Physics of dust in SNRs



- deceleration of dust due to drag force (Baines et al. 1965)

$$\frac{dw_{\mathrm{d}}}{dt} = -\frac{3kT}{2a\rho_{\mathrm{d}}} \sum_i n_i G_i(s_i) \quad (s_i^2 = m_i w_d^2 / 2kT)$$

w_{d} ; velocity of dust relative to gas

ρ_{d} ; bulk density of a grain

n_i ; number density of gas species i

$$G_i(s_i) \approx \frac{8s_i}{3\sqrt{\pi}} \left(1 + \frac{9\pi}{64} s_i^2\right)^{\frac{1}{2}} \quad \text{(Draine \& Salpeter 1979)}$$

- dust destruction by sputtering (e.g., Dwek et al. 1996)

$$\frac{da}{dt} = -\frac{m_{\mathrm{sp}}}{2\rho_{\mathrm{d}}} \sum_i n_i \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int_{\epsilon_{\mathrm{th}}}^{\infty} \sqrt{\epsilon_i} e^{-\epsilon_i} \sinh(2s_i\sqrt{\epsilon_i}) Y_i^0(E_i) d\epsilon_i$$

$Y_i^0(E_i = \epsilon_i kT)$; sputtering yield at normal incidence

m_{sp} ; average mass of the sputtered atoms

3-3. Initial conditions

○ Models of Pop III SNe (Umeda & Nomoto 2002)

- Type II SNe (SNe II) : M_{pr}=13, 20, 25, 30 $M_\odot$ (E_{51}=1)

○ The ambient medium (homogeneous)

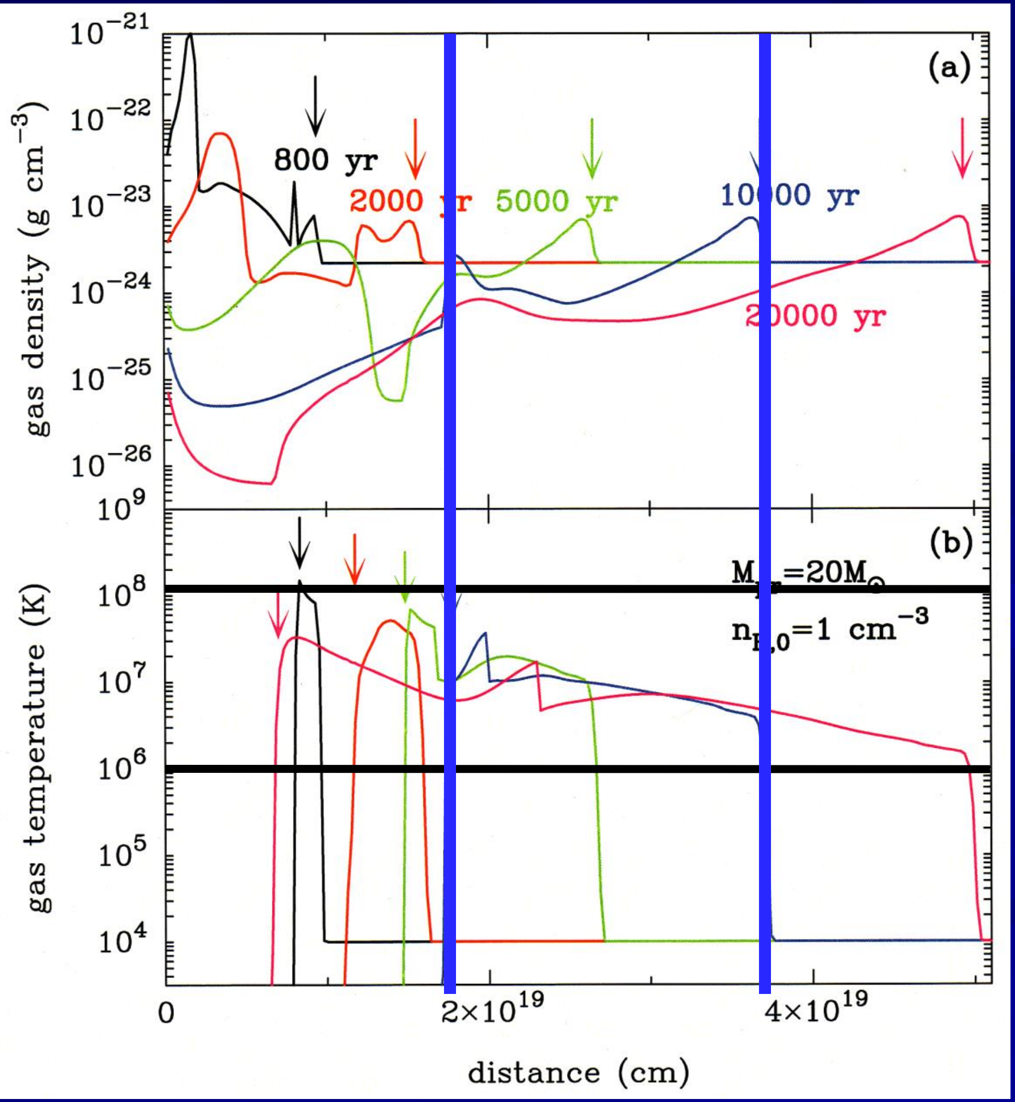
- gas temperature ; $T = 10^4$ K
- gas density ; **$n_{H,0}$ = 0.1, 1, 10 cm^{-3}**

○ Dust in the He core (Nozawa et al. 2003)

- size distribution and spatial distribution of each grain species formed in the unmixed ejecta
- dust grains → test particles

The calculation is performed from 10 yr up to ~10^6 yr.

4-1. Temperature and density of gas

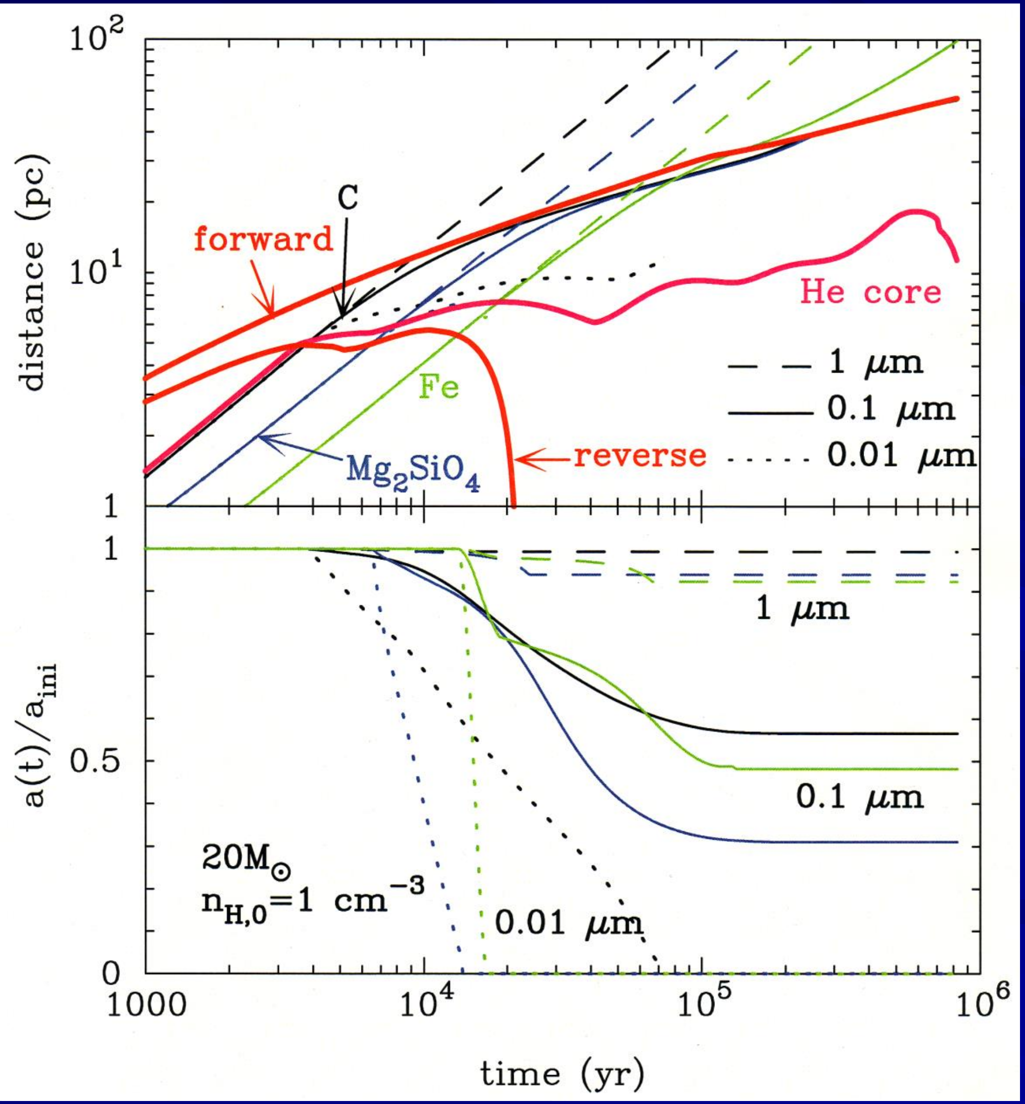


Model : $M_{pr}=20\ M_\odot\ (E_{51}=1)$
$n_{H,0} =\ 1\ cm^{-3}$

Downward-pointing arrows:
forward shock in upper panel
reverse shock in lower panel

The temperature of the gas swept up by the shocks
➔ 10^6-10^8 K
↓
Dust grains residing in this hot gas are eroded by sputtering

4-2. Evolution of dust in SNRs



Dust grains in the He core collide with reverse shock at (3-13)×10^3 yr

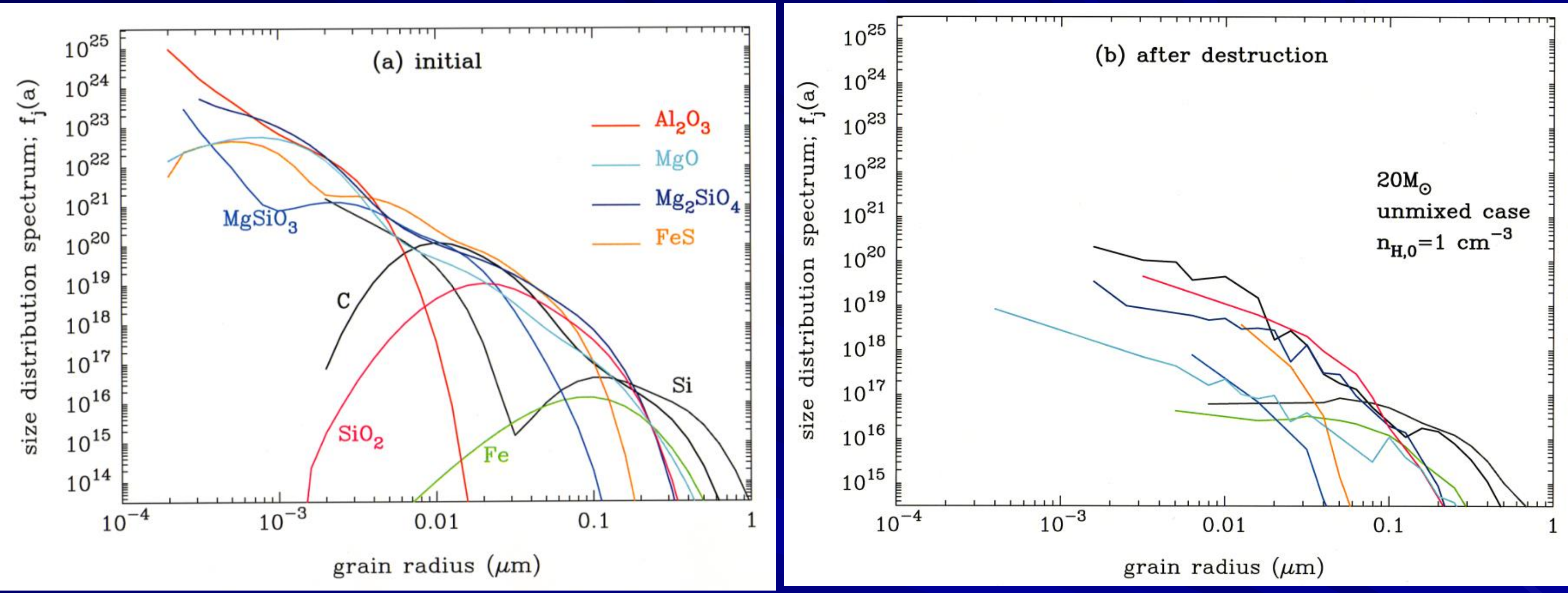
The evolution of dust heavily depends on the initial radius and composition

a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

4-3. Size distribution of surviving dust

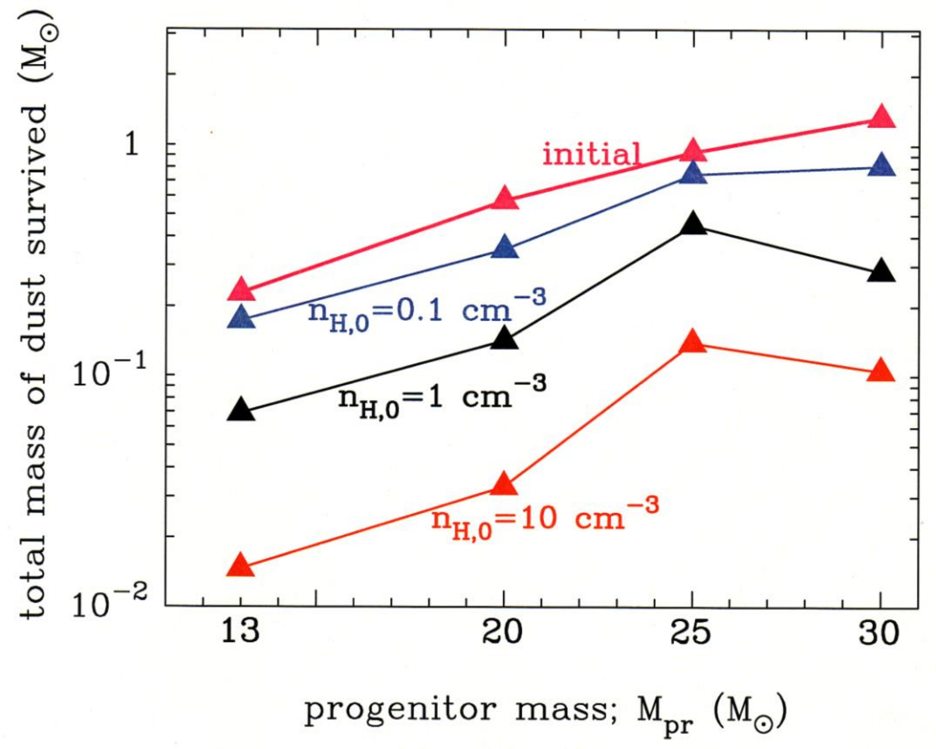


The size distribution of surviving dust is greatly deficient in small-sized grains, compared with that at its formation

The grains in the early ISM are relatively large (> 0.01 μm)

This result is almost independent on the progenitor mass

4-4. Total mass of surviving dust



The initial radius below which dust is completely destroyed

a_{ini} <~0.01 μm
for $n_{H,0}$ = 0.1 cm^{-3}

a_{ini} <~0.05 μm
for $n_{H,0}$ = 1 cm^{-3}

a_{ini} <~0.2 μm
for $n_{H,0}$ = 10 cm^{-3}

The total mass of surviving dust decreases with increasing the density in the ambient medium

total mass of surviving dust; 0.01-0.8 $M_\odot$ for $n_{H,0}$ = 10-0.1cm^{-3}

(total mass of dust at the formation; 0.2-1 $M_\odot$)

5-1. Elemental abundance in the shell (1)

dust grains surviving the destruction but not injected into the ambient medium are piled up in the dense shell in 10^5 to 10^6 yr

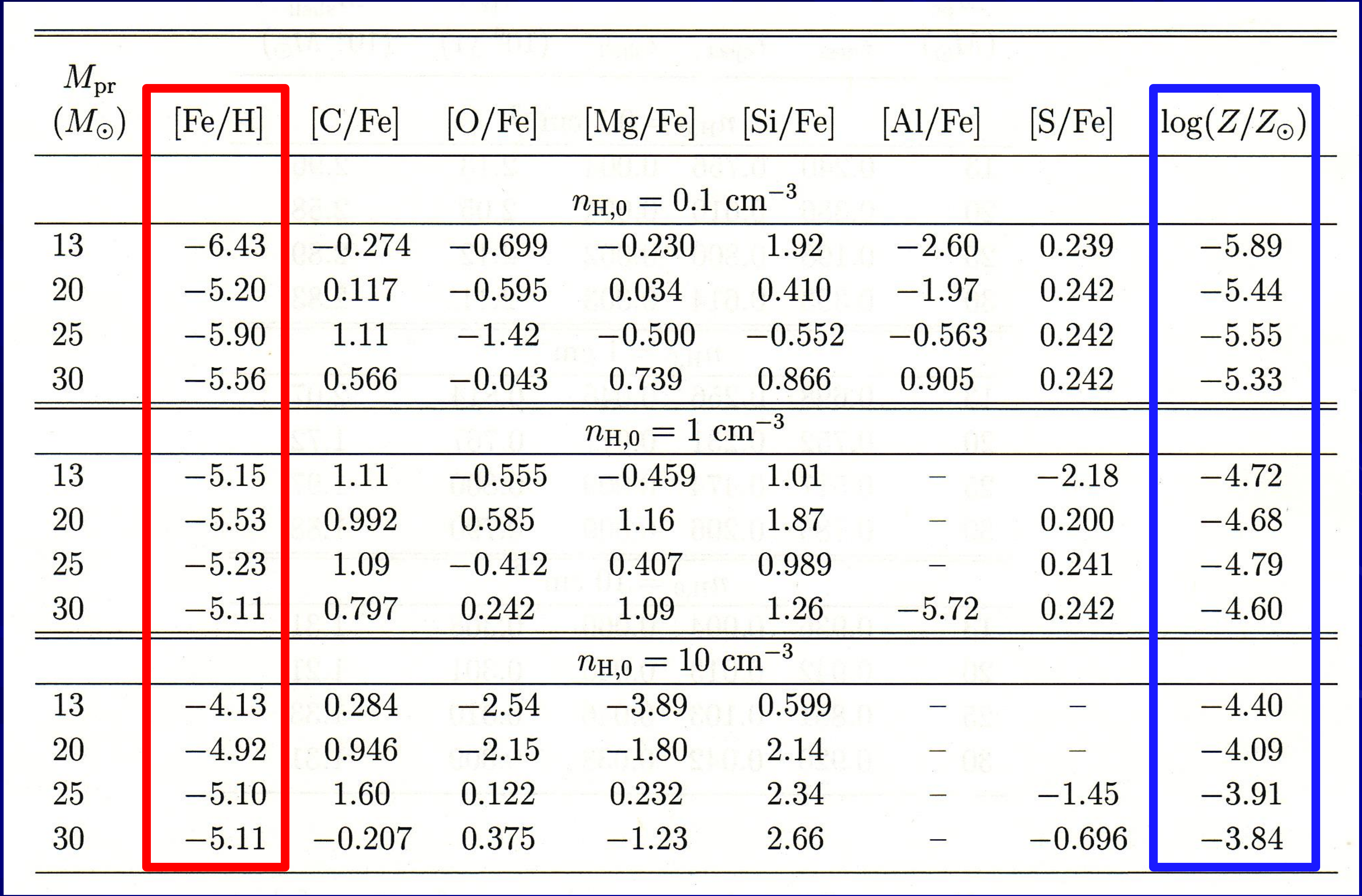
↓

- dust in the shell may enable to the formation of stars with solar mass scales through its thermal emission for matellicities of $-6 < \log(Z/Z_{\odot}) < -4$ (Omukai et al. 2005; Schneider et al. 2006)
- It is expected that the elemental composition of piled-up grains reflects the elemental abundance of Population II.5 stars formed in the shell of SNRs

↓

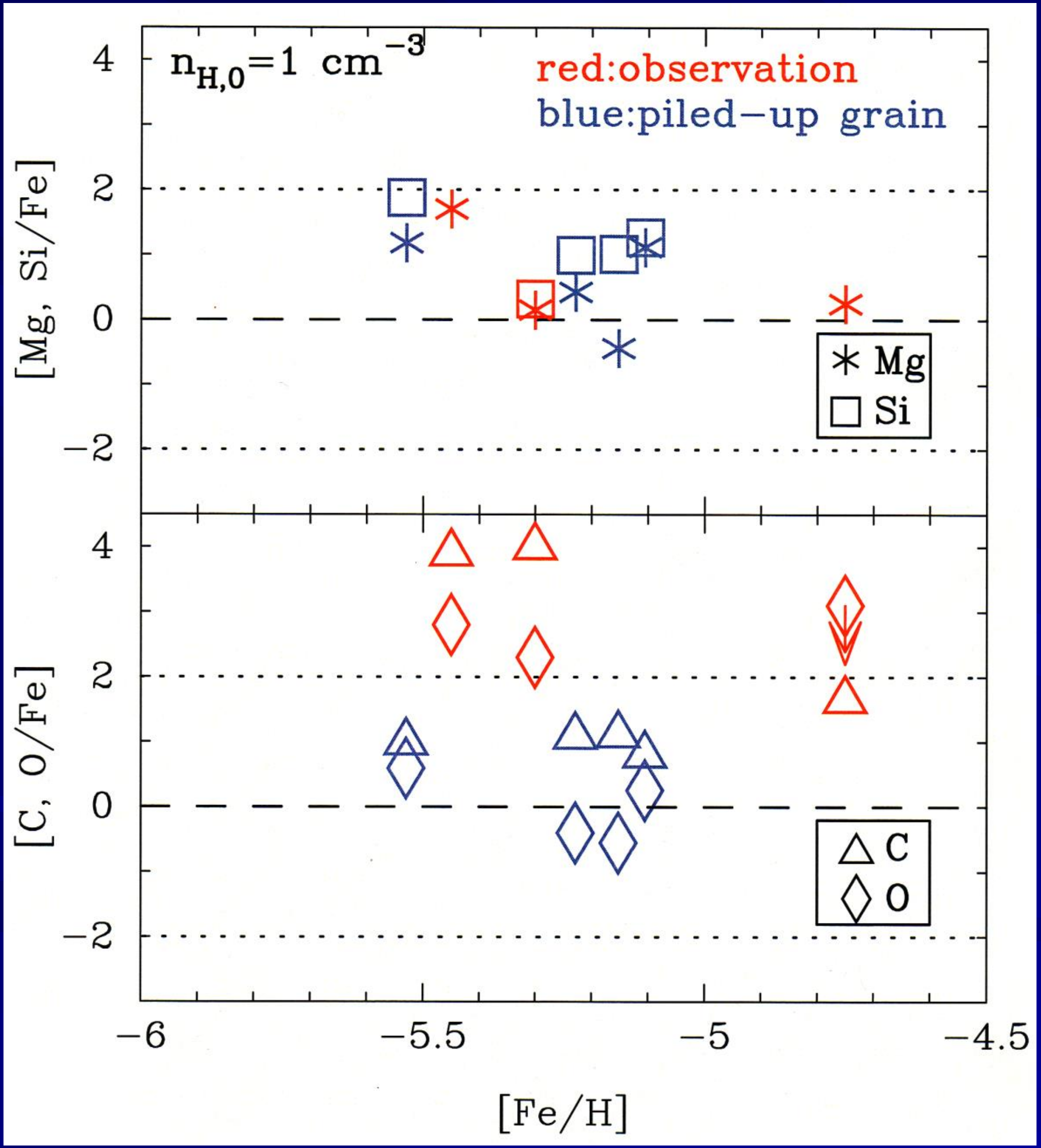
We calculate the metal abundance patterns in the shell, and compare with observations of HMP and UMP stars

5-2. Elemental abundance in the shell (1)



$M_{\rm pr}$ $(M_\odot)$	[Fe/H]	[C/Fe]	[O/Fe]	[Mg/Fe]	[Si/Fe]	[Al/Fe]	[S/Fe]	$\log(Z/Z_\odot)$
				$n_{\rm H,0} = 0.1\ {\rm cm}^{-3}$				
13	−6.43	−0.274	−0.699	−0.230	1.92	−2.60	0.239	−5.89
20	−5.20	0.117	−0.595	0.034	0.410	−1.97	0.242	−5.44
25	−5.90	1.11	−1.42	−0.500	−0.552	−0.563	0.242	−5.55
30	−5.56	0.566	−0.043	0.739	0.866	0.905	0.242	−5.33
				$n_{\rm H,0} = 1\ {\rm cm}^{-3}$				
13	−5.15	1.11	−0.555	−0.459	1.01	–	−2.18	−4.72
20	−5.53	0.992	0.585	1.16	1.87	–	0.200	−4.68
25	−5.23	1.09	−0.412	0.407	0.989	–	0.241	−4.79
30	−5.11	0.797	0.242	1.09	1.26	−5.72	0.242	−4.60
				$n_{\rm H,0} = 10\ {\rm cm}^{-3}$				
13	−4.13	0.284	−2.54	−3.89	0.599	–	–	−4.40
20	−4.92	0.946	−2.15	−1.80	2.14	–	–	−4.09
25	−5.10	1.60	0.122	0.232	2.34	–	−1.45	−3.91
30	−5.11	−0.207	0.375	−1.23	2.66	–	−0.696	−3.84

5-3. Elemental abundance in the shell (3)



$-6 < [Fe/H] < -5$

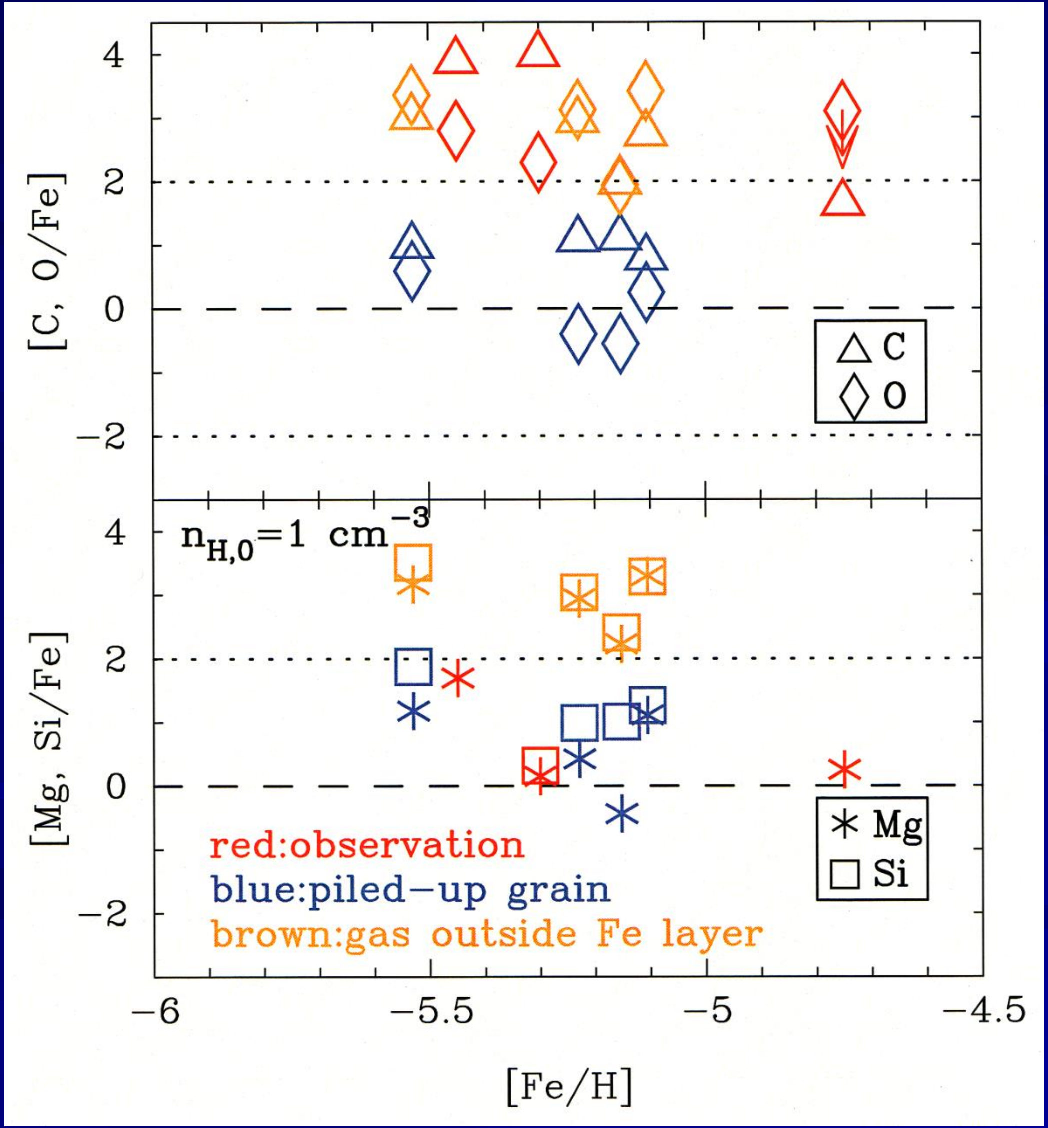
$0 < [Mg, Si/Fe] < 2$

↓

Elemental composition of dust piled up in the shell can reproduce abundance patterns in HMP stars

The transport of dust segregated from metal-rich gas can be responsible for the abundance patterns in HMP and UMP stars

5-4. Elemental abundance in the shell (4)



We assume that the gas outside the innermost Fe layer in the ejecta is incorporated into the shell

↓

reproducing the extreme overabundance of C and O

leading to more than 100 time excesses of Mg and Si

It might be possible to reproduce the elemental abundances of HMP stars if the SI-Mg-rich layer is not mixed the gas in the shell

6. Summary

1. Once dust grains inside the He core collide with the reverse shock, they undergo the different transport and destruction in SNRs, depending on their initial radii and compositions.

2. Size distribution of surviving dust is largely deficient in small-sized grains, compared with that at the time of dust formation.

3. Total mass of surviving dust is 0.01-0.8 $M_\odot$ and decreases with increasing the ambient gas density.

4. Segregation of dust from metal-rich gas can be responsible for abundances of Mg, Si, and Fe in HMP stars if they were the second-generation stars formed in the shell of Pop III SNRs.

5. It might be possible to reproduce the elemental abundance of HMP stars if SI-Mg-rich layer is not mixed the gas in the shell.