超新星放出ガス中でのダスト形成と衝撃波中でのダスト破壊

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1. Introduction

- **supernovae (SNe)**: explosions of massive (early type) stars with \( M_{\text{ZAMS}} > 8 \, M_{\odot} \)

- SNe are important sources of interstellar dust?

  - huge amounts of dust grains (>\(10^8 \, M_{\odot}\)) are detected in host galaxies of quasars at redshift \( z > 5 \)
    
    \[ \rightarrow \] \( 0.1 \, M_{\odot} \) of dust per SN is needed to explain such massive dust at high-\( z \) (e.g. Dwek et al. 2007)

  - contribution of dust mass from AGB stars and SNe

    \[ \frac{n(\text{AGB stars})}{n(\text{SNe})} \sim 10-20 \]

    \( M_{\text{dust}} = 0.01-0.05 \, M_{\odot} \) per AGB (Zhukovska & Gail 2008)

    \( M_{\text{dust}} = 0.1-1.0 \, M_{\odot} \) per SN (Nozawa et al. 2003; 2007)
2. Dust Formation in Pop III SNe

- He-core
- H-envelope
- NS or BH
- He-layer (C>O)
- O–Ne–Mg layer
- Si–S layer
- Fe–Ni layer

Dust formation:
- at ~1 days
- at ~1-3 years after explosion
2-1. Dust formation in primordial SNe


Population III SNe model (Umeda & Nomoto’02)

- SNe II-P: $M_{\text{ZAMS}} = 13, 20, 25, 30\, M_\text{Sun}$ ($E_{51}=1$)
- PISNe: $M_{\text{ZAMS}} = 170\, M_\text{Sun}$ ($E_{51}=20$), $200\, M_\text{Sun}$ ($E_{51}=28$)

- nucleation and grain growth theory (Kozasa & Hasegawa’88)
- complete and no mixing of elements within the He-core
- complete formation of CO and SiO
2-2-1. Calculations of dust formation

- nucleation and grain growth theory taking account of chemical reaction at condensation (Kozasa & Hasegawa’87)

- key species: gas species with the least collision frequency among reactants

key species controls the kinetics of the nucleation and grain growth

<table>
<thead>
<tr>
<th>Dust species</th>
<th>Chemical reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe(_\text{s})</td>
<td>Fe(<em>\text{g}) → Fe(</em>\text{s})</td>
</tr>
<tr>
<td>FeS(_\text{s})</td>
<td>Fe(<em>\text{g}) + S(</em>\text{g}) → FeS(_\text{s})</td>
</tr>
<tr>
<td>Si(_\text{s})</td>
<td>Si(<em>\text{g}) → Si(</em>\text{s})</td>
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<tr>
<td>Ti(_\text{s})</td>
<td>Ti(<em>\text{g}) → Ti(</em>\text{s})</td>
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<tr>
<td>V(_\text{s})</td>
<td>V(<em>\text{g}) → V(</em>\text{s})</td>
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<tr>
<td>Cr(_\text{s})</td>
<td>Cr(<em>\text{g}) → Cr(</em>\text{s})</td>
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<tr>
<td>Co(_\text{s})</td>
<td>Co(<em>\text{g}) → Co(</em>\text{s})</td>
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<tr>
<td>Ni(_\text{s})</td>
<td>Ni(<em>\text{g}) → Ni(</em>\text{s})</td>
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<td>Cu(_\text{s})</td>
<td>Cu(<em>\text{g}) → Cu(</em>\text{s})</td>
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<td>C(_\text{s})</td>
<td>C(<em>\text{g}) → C(</em>\text{s})</td>
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<tr>
<td>SiC(_\text{s})</td>
<td>Si(<em>\text{g}) + C(</em>\text{g}) → SiC(_\text{s})</td>
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<tr>
<td>TiC(_\text{s})</td>
<td>Ti(<em>\text{g}) + C(</em>\text{g}) → TiC(_\text{s})</td>
</tr>
<tr>
<td>Al(_2)O(<em>3)(</em>\text{s})</td>
<td>2Al(<em>\text{g}) + 3O(</em>\text{g}) → Al(_2)O(<em>3)(</em>\text{s})</td>
</tr>
<tr>
<td>MgSiO(<em>3)(</em>\text{s})</td>
<td>Mg(<em>\text{g}) + 2SiO(</em>\text{g}) + 2O(_\text{g}) → MgSiO(<em>3)(</em>\text{s})</td>
</tr>
<tr>
<td>Mg(_2)SiO(<em>4)(</em>\text{s})</td>
<td>2Mg(<em>\text{g}) + 2SiO(</em>\text{g}) + 3O(_\text{g}) → Mg(_2)SiO(<em>4)(</em>\text{s})</td>
</tr>
<tr>
<td>SiO(<em>2)(</em>\text{s})</td>
<td>SiO(<em>\text{g}) + O(</em>\text{g}) → SiO(<em>2)(</em>\text{s})</td>
</tr>
<tr>
<td>MgO(_\text{s})</td>
<td>Mg(<em>\text{g}) + O(</em>\text{g}) → MgO(_\text{s})</td>
</tr>
<tr>
<td>Fe(_3)O(<em>4)(</em>\text{s})</td>
<td>3Fe(<em>\text{g}) + 4O(</em>\text{g}) → Fe(_3)O(<em>4)(</em>\text{s})</td>
</tr>
<tr>
<td>FeO(_\text{s})</td>
<td>Fe(<em>\text{g}) + O(</em>\text{g}) → FeO(_\text{s})</td>
</tr>
</tbody>
</table>
2-2-2. Nucleation rate of dust

Steady-state nucleation rate

\[ J_s(t) = \alpha_s \Omega \left( \frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \Pi c_1^2(t) \exp \left[ -\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right] \]

Supersaturation ratio

\[ \ln S = \ln \left( \frac{p_1}{\hat{p}_1} \right) = -\frac{1}{kT} (\hat{g}_s - \hat{g}_1) + \ln \left( \frac{p_1}{p_0} \right) \]

\( \alpha_s \): sticking probability of key species (\( \alpha_s = 1 \), in the calculations)
\( \Omega \): volume of the condensate per key species (\( \Omega = 4\pi a_0^3/3 \))
\( \sigma \): surface energy of the condensate
\( m_1 \): mass of key species
\( c_1(t) \): number density of key species
\( \mu \): \( \mu \equiv 4\pi a_0^2 \sigma / kT \); energy barrier for nucleation
2-2-3. Basic equations for dust formation

- Equation of mass conservation

\[ c_{10} - c_1 = \int_{t_0}^{t} J_{n_x}(t') \frac{a^3(t,t')}{{a_0}^3} dt', \]

- Equation of grain growth

\[ \frac{da}{dt} = s\Omega_0 \left( \frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left( 1 - \frac{1}{S} \right), \]

\[ \frac{dV}{dt} = s\Omega_0 \cdot 4\pi a^2 \left( \frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left( 1 - \frac{1}{S} \right), \]

Growth rate is independent of grain radius
2-3-1. Dust formed in primordial SNe

Various dust species (C, MgSiO$_3$, Mg$_2$SiO$_4$, SiO$_2$, Al$_2$O$_3$, MgO, Si, FeS, Fe) form in the unmixed ejecta, according to the elemental composition of gas in each layer.

- The condensation time: **300-600 days** for SNe II-P
  **400-800 days** for PISNe

2-3-2. Size distribution of newly formed dust

- C, SiO2, and Fe grains have lognormal size distribution, while the other grains have power-law size distribution.

- The composition and size distribution of dust formed are almost independent of type of supernova.
  (average dust radius is smaller for PISNe than SNe II-P)

Because oxygen is rich in the mixed ejecta, only silicates (MgSiO₃, Mg₂SiO₄, SiO₂) and oxides (Fe₃O₄, Al₂O₃) form.

The size distribution of each dust species except for Al₂O₃ is lognormal-like.
2-3-4. Total mass of dust formed

- Total dust mass increases with increasing $M_{ZAMS}$
  - SNe II: $M_{dust} = 0.1-2\ M_{sun}$, $f_{dep} = M_{dust} / M_{metal} = 0.2-0.3$
  - PISNe: $M_{dust} = 10-60\ M_{sun}$, $f_{dep} = M_{dust} / M_{metal} = 0.3-0.5$

- Dust mass for the mixed case is generally larger than for the unmixed case
3. Dust Evolution in SNRs

\[ T = (1-2) \times 10^4 \text{ K} \]

\[ n_{H,0} = 0.1-1 \text{ cm}^{-3} \]
3-1-1. Time evolution of SNRs

- Basic equations (spherical symmetry)

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho v) = 0
\]

\[
\frac{\partial}{\partial t} (\rho v) + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho v^2) = -\frac{\partial P}{\partial r}
\]

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

\[
= -\left( n_e n_H \Lambda_{\text{gas}}(T) + \Lambda_{\text{ic}}(T) + \Lambda_d(n_H, T) \right)
\]

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

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

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

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

\( \Lambda_d(n_H, T) \) : cooling of gas through thermal emission of dust

- numerical code : flux splitting method (van Albada et al. 1982)
3-1-2. Initial condition for hydro calculations

- **Hydrodynamical model of SNe** (Umeda & Nomoto’02)
  - SNe II: $M_{pr}=13, 20, 25, 30$ M$_{\odot}$ ($E_{51}=1$)
  - PISNe: $M_{pr}=170$ ($E_{51}=20$), 200 M$_{\odot}$ ($E_{51}=28$)

- **The ambient medium** (homogeneous)
  - gas temperature: $T = 10^4$ K
  - gas density: $n_{H,0} = 0.1, 1, \text{ and } 10 \text{ cm}^{-3}$

- **Dust Model**
  - initial size distribution and spatial distribution of dust
    - results of dust formation calculations
  - treating as a test particle

The calculation is performed from 10 yr up to $\sim 10^6$ yr
3-2-1. Dynamics of dust

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

\[
\frac{dw_d}{dt} = \frac{F_{\text{drag}}}{m_d} = -\frac{3n_H k T}{2 a \rho_d} \sum_i A_i G_i(s_i) \quad (w_d : \text{relative velocity})
\]

\( \rho_d \) ; mass density of a grain

\( A_i \) ; the number abundance of gas species \( i \) normalized by \( n_H \)

\[
G_i(s_i) = \left( s_i^2 + 1 - \frac{1}{4 s_i^2} \right) e r f(s_i) + \left( s_i + \frac{1}{2 s_i} \right) \frac{e^{-s_i^2}}{\sqrt{\pi}}
\]

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

where \( s_i^2 = m_i w_d^2 / 2 k T \)
3-2-2. Erosion rate of dust by sputtering

- dust destruction by sputtering (e.g., Dwek, Foster & Vancura 1996)

\[
\frac{da}{dt} = -\frac{m_{sp}}{4\pi a^2 \rho_d} \sum_i R(Y_i(E))
\]

\[Y_i(E) = 2Y_i^0(E)\] ; the angle-averaged sputtering yield

\[m_{sp}\] ; average mass of the sputtered atoms

- rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

\[R(X_i(\epsilon)) = n_H A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} e^{-s_i^2} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon})X_i(\epsilon) d\epsilon\]

where \(\epsilon = E/kT\)
3-2-3. Erosion rate of dust by sputtering


- Erosion rate by sputtering quickly increases above $10^5$ K and peaks at $10^7$ - $10^8$ K

- Erosion rate: $\frac{da}{dt} \sim 10^{-6} n_H \mu m yr^{-1} cm^3$

for the primordial gas (H and He) at $T > 10^6$ K
3-3-1. Temperature and density of gas in SNRs


Model: \( M_{pr} = 20 \, M_{\odot} \) (\( E_{51} = 1 \))

\( n_{H_0} = 1 \, \text{cm}^{-3} \)

The temperature of the gas swept up by the shocks → \( 10^6-10^8 \, \text{K} \)

Dust grains residing in the shocked hot gas are eroded by sputtering
3-3-2. Evolution of dust in SNRs

The evolution of dust in SNRs heavily depends on initial radius and composition:

- $a_{ini} = 0.01 \mu m$ (dotted lines) → completely destroyed
- $a_{ini} = 0.1 \mu m$ (solid lines) → trapped in the shell
- $a_{ini} = 1 \mu m$ (dashed lines) → injected into the ISM


Model: $M_{pr} = 20 M_{\odot}$ ($E_{51} = 1$)

$n_{H,0} = 1 \text{ cm}^{-3}$

Dust grains in the He core collide with reverse shock at \((3-13) \times 10^3 \text{ yr}\).
3-3-3. Dust mass and size ejected from SN II-P

- Total dust mass surviving the destruction in Type II-P SNRs: 0.07-0.8 $M_{\text{sun}}$ ($n_{H,0} = 0.1-1 \text{ cm}^{-3}$)

- Size distribution of dust after RS destruction is dominated by large grains (> 0.01 μm)

Various species of dust form in the unmixed ejecta (almost all Fe, Mg, and Si atoms are locked in dust).

The fate of newly formed dust within primordial SNRs strongly depends on the initial radii and compositions.

The size distribution of dust surviving the destruction in SNRs is weighted to relatively large size (> 0.01 μm).

The total mass of dust injected into the ISM decreases with increasing the ambient gas density:

for \( n_{H,0} = 0.1\text{-}1 \text{ cm}^{-3} \)
- SNe II-P \( \rightarrow M_{\text{dust}} = 0.1\text{-}0.8 \text{ M}_{\odot} \)
- PISNe \( \rightarrow M_{\text{dust}} = 0.1\text{-}15 \text{ M}_{\odot} \)
3. Formation of dust grains in various types of SNe
5-1. Dust formation in Type IIb SN

SN IIb model (SN1993J-like model)

- $M_{\text{eje}} = 2.94 \, M_{\text{sun}}$
- $M_{\text{ZAMS}} = 18 \, M_{\text{sun}}$
- $M_{\text{H-env}} = 0.08 \, M_{\text{sun}}$
- $E_{51} = 1$
- $M^{(56}\text{Ni)} = 0.07 \, M_{\text{sun}}$
5-2. Dependence of dust radii on SN type

- condensation time of dust
  300-700 d after explosion

- total mass of dust formed
  - 0.167 M_{\odot} in SN IIb
  - 0.1-1 M_{\odot} in SN II-P

- the radius of dust formed in H-stripped SNe is small
  - SN IIb without massive H-env \rightarrow a_{dust} < 0.01 \mu m
  - SN II-P with massive H-env \rightarrow a_{dust} > 0.01 \mu m

5-3. Destruction of dust in Type IIb SNR

Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of \( n_H > 0.1 \) /cc

- small radius of newly formed dust
- early arrival of reverse shock at dust-forming region

\( n_{H,1} = 30, 120, 200 \) /cc \( \Rightarrow \) \( \frac{dM}{dt} = 2.0, 8.0, 13 \times 10^{-5} \) M\(_{\odot}\)/yr for \( v_w = 10 \) km/s

5-4. IR emission from dust in Cas A SNR

- total mass of dust formed
  \( M_{\text{dust}} = 0.167 \, M_{\odot} \)
- shocked dust : \( M_{\text{d, cool}} = 0.095 \, M_{\odot} \)
  \( M_{\text{d, warm}} = 0.008 \, M_{\odot} \)
- unshocked dust :
  \( M_{\text{d, cool}} = 0.072 \, M_{\odot} \)
  with \( T_{\text{dust}} \sim 40 \, \text{K} \)


AKARI observation
\( M_{\text{d, cool}} = 0.03 - 0.06 \, M_{\odot} \)
\( T_{\text{dust}} = 33 - 41 \, \text{K} \)
(Sibthorpe+'10)

Herschel observation
\( M_{\text{d, cool}} = 0.075 \, M_{\odot} \)
\( T_{\text{dust}} \sim 35 \, \text{K} \)
(Barlow+'10)
6. Summary of this talk

- **SNe are important sources of dust?**
  - maybe, Yes in the early universe
    (at least, to serve the seeds for grain growth in the ISM)

- **Size of newly formed dust depends on types of SNe**
  - H-retaining SNe (Type II-P) : $a_{\text{ave}} > 0.01 \, \mu m$
  - H-stripped SNe (Type IIb/Ib/Ic and Ia) : $a_{\text{ave}} < 0.01 \, \mu m$
    → dust is almost completely destroyed in the SNRs
    → H-stripped SNe may be poor producers of dust

- **Our model treating dust formation and evolution self-consistently can reproduce IR emission from Cas A**

- **Mass of dust in SNe must be dominated by cool dust**
  → FIR and submm observations of SNe are essential