Ia型超新星爆発時に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?
  - supersonic (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 $M_{\text{sun}}$ (from theories)
  $> 10^{-4} M_{\text{sun}}$ (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 signatures (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 detection of ejecta-dust in Tycho SNR (e.g., Douvion et al. 2001)
1-3. Aim of our study

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

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

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

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

- **sticking probability;** \( \alpha_s = 1, 0.1, 0.01 \)

- **\( T_{dust} = T_{gas} \)** (dust temperature is the same as that of gas)
2-2. Dust formation calculation for SN Ia

**O Type Ia SN model**

**W7 model (C-deflagration)**  
(Nomoto et al. 1984)

- \( M_{\text{eje}} = 1.32 \ M_{\odot} \)
- \( E_{51} = 1.3 \)
- \( M^{(56\text{Ni})} = 0.56 \ M_{\odot} \)

- **onion-like composition**  
  (no mixing of elements)
- **formation efficiency of CO and SiO ➔ 0 or 1**

\[
\begin{align*}
\frac{C}{O} > 1 & \rightarrow \text{all O atoms are locked into CO} \\
\frac{C}{O} < 1 & \rightarrow \text{all C atoms are locked into CO} \\
\frac{Si}{O} < 1 & \rightarrow \text{all Si atoms are locked into SiO}
\end{align*}
\]
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 : \( \sim 0.01 \) \( \mu \)m
- average radius of other dust species : \(< 0.01 \) \( \mu \)m

because of low density of gas in the expanding ejecta
3-4. Mass of dust formed in SN Ia

<table>
<thead>
<tr>
<th>dust species</th>
<th>A1</th>
<th>A0.1</th>
<th>A0.01</th>
<th>B1</th>
<th>B0.1</th>
<th>B0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.00 × 10⁻²</td>
<td>1.15 × 10⁻³</td>
<td>5.10 × 10⁻⁷</td>
<td>2.89 × 10⁻²</td>
<td>1.84 × 10⁻²</td>
<td>1.98 × 10⁻⁴</td>
</tr>
<tr>
<td>MgO</td>
<td>4.32 × 10⁻⁶</td>
<td>2.35 × 10⁻⁹</td>
<td>7.70 × 10⁻¹²</td>
<td>9.49 × 10⁻⁶</td>
<td>2.64 × 10⁻⁹</td>
<td>8.09 × 10⁻¹²</td>
</tr>
<tr>
<td>MgSiO₃</td>
<td>8.18 × 10⁻³</td>
<td>1.48 × 10⁻⁶</td>
<td>1.59 × 10⁻⁹</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mg₂SiO₄</td>
<td>7.32 × 10⁻³</td>
<td>1.66 × 10⁻⁶</td>
<td>2.46 × 10⁻⁹</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.46 × 10⁻²</td>
<td>1.01 × 10⁻⁵</td>
<td>5.16 × 10⁻⁹</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.07 × 10⁻⁶</td>
<td>9.25 × 10⁻¹⁰</td>
<td>6.07 × 10⁻¹²</td>
<td>1.16 × 10⁻⁶</td>
<td>9.63 × 10⁻¹⁰</td>
<td>6.25 × 10⁻¹²</td>
</tr>
<tr>
<td>Fe₃O₄</td>
<td>3.34 × 10⁻⁷</td>
<td>3.11 × 10⁻¹³</td>
<td>2.99 × 10⁻¹⁵</td>
<td>4.09 × 10⁻⁷</td>
<td>6.37 × 10⁻¹⁰</td>
<td>4.86 × 10⁻¹²</td>
</tr>
<tr>
<td>FeO</td>
<td>5.33 × 10⁻¹⁰</td>
<td>7.16 × 10⁻¹⁴</td>
<td>6.95 × 10⁻¹⁶</td>
<td>6.96 × 10⁻⁸</td>
<td>1.50 × 10⁻¹⁰</td>
<td>1.22 × 10⁻¹²</td>
</tr>
<tr>
<td>FeS</td>
<td>1.66 × 10⁻²</td>
<td>1.45 × 10⁻⁵</td>
<td>1.34 × 10⁻⁸</td>
<td>1.66 × 10⁻²</td>
<td>1.45 × 10⁻⁵</td>
<td>1.34 × 10⁻⁸</td>
</tr>
<tr>
<td>Si</td>
<td>6.13 × 10⁻²</td>
<td>3.15 × 10⁻⁵</td>
<td>2.23 × 10⁻⁸</td>
<td>6.48 × 10⁻²</td>
<td>3.23 × 10⁻⁵</td>
<td>2.38 × 10⁻⁸</td>
</tr>
<tr>
<td>Fe</td>
<td>1.43 × 10⁻⁴</td>
<td>1.63 × 10⁻⁸</td>
<td>4.39 × 10⁻¹²</td>
<td>1.43 × 10⁻⁴</td>
<td>1.63 × 10⁻⁸</td>
<td>4.39 × 10⁻¹²</td>
</tr>
<tr>
<td>Ni</td>
<td>7.28 × 10⁻⁶</td>
<td>9.73 × 10⁻¹⁰</td>
<td>5.60 × 10⁻¹³</td>
<td>7.28 × 10⁻⁶</td>
<td>9.73 × 10⁻¹⁰</td>
<td>5.60 × 10⁻¹³</td>
</tr>
<tr>
<td>Total</td>
<td>1.28 × 10⁻¹</td>
<td>1.21 × 10⁻³</td>
<td>5.55 × 10⁻⁷</td>
<td>1.10 × 10⁻¹</td>
<td>1.84 × 10⁻²</td>
<td>1.98 × 10⁻⁴</td>
</tr>
</tbody>
</table>

- **Total mass of dust formed in SNe Ia**: $M_{dust} < 0.13 \, M_{\odot}$
- Fe and SiC grains cannot condense significantly
4-1. Optical depth by dust

For $\alpha_s=1$,

$\tau(0.55) \sim 200$ at 300 days
$\tau(0.55) \sim 100$ by C grains
$\tau(0.55) \sim 100$ by Si and FeS
$\Rightarrow$ too high to be consistent with observations

early formation of dust $\Rightarrow$ 100-300 days
high $M(^{56}\text{Ni})$ $\Rightarrow$ $\sim 0.6\ M_\odot$

$\Rightarrow$ Can newly formed dust survive against 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 \( T_{BB} = 5000K \))
- \( \langle Q_\lambda(a, T_d) \rangle \): Plank-\( a \)

\[ F(r) = \frac{L}{4 \pi r^2} \]
### 4-3. Mass of dust survived

**Mass of dust formed**

<table>
<thead>
<tr>
<th>dust species</th>
<th>$M_{1,d,j} \ (M_\odot)$</th>
<th>$M_{2,d,j} \ (M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$2.00 \times 10^{-2}$</td>
<td>$2.00 \times 10^{-2}$</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>$1.07 \times 10^{-6}$</td>
<td>$1.07 \times 10^{-6}$</td>
</tr>
<tr>
<td>Mg$_2$SiO$_4$</td>
<td>$7.32 \times 10^{-3}$</td>
<td>$7.32 \times 10^{-3}$</td>
</tr>
<tr>
<td>MgSiO$_3$</td>
<td>$8.18 \times 10^{-3}$</td>
<td>$8.18 \times 10^{-3}$</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>$1.46 \times 10^{-2}$</td>
<td>$1.46 \times 10^{-2}$</td>
</tr>
<tr>
<td>MgO</td>
<td>$4.32 \times 10^{-6}$</td>
<td>$4.32 \times 10^{-6}$</td>
</tr>
<tr>
<td>FeS</td>
<td>$1.66 \times 10^{-2}$</td>
<td>$3.63 \times 10^{-4}$</td>
</tr>
<tr>
<td>Si</td>
<td>$6.13 \times 10^{-2}$</td>
<td>$1.38 \times 10^{-7}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$1.43 \times 10^{-4}$</td>
<td>$7.72 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ni</td>
<td>$7.28 \times 10^{-6}$</td>
<td>—</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>$1.28 \times 10^{-1}$</td>
<td>$5.01 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

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

If we ignore C grains in SN Ia

$$M_{\text{dust}} \sim 0.03 \ M_{\odot} \ (\text{silicate})$$

$$\tau(0.55) \sim 1 \text{ at 300 day}$$
Summary

1) Dust formed in the ejecta of SNe Ia
   - various grain species with average radius: $< 0.01 \mu m$
   - upper limit of total dust mass: $\sim 0.13 \, M_{\odot}$

2) Strong radiation field in the ejecta of SNe Ia
   - destroy most of FeS and Si but not C and silicate
     - dust mass: $< 0.05 \, M_{\odot}$

3) Formation of C grains is inconsistent with observations
   - preexisting C should be burned by nuclear burning
     - absence of C layer
   - dust mass: $< 0.03 \, M_{\odot}$

4) Newly formed dust grains of $< 0.01 \mu m$ may not be able to survive the reverse shock due to their small radii
   (Nozawa et al. submitted, arXiv/0909.4145)