Formation of Dust in the Ejecta of Type Ia Supernovae

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1-1. Introduction

Type Ia supernovae (SNe Ia)

- thermonuclear explosions of C+O white dwarfs with the mass close to Chandrasekhar limit (~1.4 $M_{\odot}$)
  - deflagration (Nomoto+76, 84)
    -> subsonic wave, unburned C in the outer layer
  - (delayed) detonation (Khokhlov91a, 91b)
    -> supersonic wave, burning almost all C

- synthesize a significant amount of Fe-peak and intermediate-mass elements such as Si, Mg, and Ca
  -> play a critical role in the chemical evolution
  -> possible sources of interstellar dust?
1-2. Type Ia SNe are sources of dust?

**Suggestions on dust formation in SNe Ia**

- SNe Ia may be producers of Fe grains (Tielens98; Dwek98)
- the isotopic signature of presolar type X SiC grains can be explained if produced in SNe Ia (Clayton+97)

**Observations of normal SNe Ia**

- no increase of IR dust continuum (and no CO emission)
- no rapid decrease of the optical light curve
- no blueshift of atomic line emissions
  - these signatures have been reported for CCSNe
- no evidence for ejecta-dust in Tycho SNR (Douvion+01)
1-3. Aim of our study

Questions

- Are there any differences in formation process of dust between SNe Ia and (Type II) CCSNe?
- Is it possible for dust grains to form in SNe Ia?

Dust formation calculation in SNe Ia

- chemical composition, size, and mass of dust that can condense in the ejecta of SNe Ia
- dependence of dust formation process on SN types
- implication on the outermost layer in SNe Ia
- survival of the newly formed dust against destruction by the reverse shock
2-1. Model of SNe Ia (1)

〇 Type Ia SN model

C-deflagration W7 model
(Nomoto+84; Thielemann+86)

- $M_{\text{eje}} = 1.38 \, M_{\odot}$
- $E_{\text{kin}} = 1.3 \times 10^{51} \, \text{erg}$
- $M(^{56}\text{Ni}) = 0.6 \, M_{\odot}$

## $M(^{56}\text{Ni}) \sim 0.06 \, M_{\odot}$ in typical CCSNe

- stratified distribution
  (no mixing of elements)

## This assumption is supported observationally
(e.g. Mazzali+08; Tanaka+11)

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0.1 $M_{\odot}$ of C and O remained unburned in the outermost layer with $M_C/M_O \sim 1$
2-2. Model of SNe Ia (2)

- **Model of SNe Ia (2)**

**Hydrodynamic model**

- **Red lines: SNe Ia**
  - $M_{\text{ej}} = 1.38 \text{ Msun}$
  - $E_{\text{kin}} = 1.3 \times 10^{51} \text{ erg}$

- **Blue lines: Type II-P SNe**
  - $M_{\text{star}} = 20 \text{ Msun}$
  - $E_{\text{kin}} = 1.0 \times 10^{51} \text{ erg}$
  - $M_{\text{env}} = 13.2 \text{ Msun}$

- Gas density in the SN Ia is more than 3 orders of magnitude lower than that in the SN II-P
- Gas temperature in the SN Ia decreases more quickly
2-3. Calculation of dust formation

**nucleation and grain growth theory** (Nozawa+03, 08, 10)

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

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

- sticking probability : \( \alpha = 1 \) and 0.1

- LTE condition : \( T_d = T \)
  (dust has the same temperature as the gas)

The use of the same prescription enables the direct comparison with our earlier results
3-1. Results (1): Condensation time of dust

- different dust species form in different layers
  - Fe and Ni grains cannot condense significantly
  - SiC can never condense

- condensation time of dust
  : $t_c = 100\text{-}300$ days
  (tc $> \sim 300$ days in SNe II-P)
3-2. Results (2): Average radius of dust

- **SN Ia**: Because of low density of gas in the expanding ejecta, the radius of dust formed in H-stripped SNe is small.
  - SNe IIb/Ia with thin/no H-env \( \Rightarrow a_{\text{ave}} < 0.01 \mu m \)
  - SN II-P with massive H-env \( \Rightarrow a_{\text{ave}} > 0.01 \mu m \)
### 3-3. Results (3): Mass of each dust species

<table>
<thead>
<tr>
<th>dust species</th>
<th>$\alpha = 1$</th>
<th>$\alpha = 0.1$</th>
<th>MC</th>
<th>Msilicate</th>
<th>MFeS</th>
<th>MSi</th>
<th>Mtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$5.66 \times 10^{-3}$</td>
<td>$2.84 \times 10^{-4}$</td>
<td>$0.006 , \text{M}_{\odot}$</td>
<td>$0.030 , \text{M}_{\odot}$</td>
<td>$0.018 , \text{M}_{\odot}$</td>
<td>$0.063 , \text{M}_{\odot}$</td>
<td>$0.116 , \text{M}_{\odot}$</td>
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<tr>
<td>MgO</td>
<td>$3.17 \times 10^{-6}$</td>
<td>$1.85 \times 10^{-9}$</td>
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<tr>
<td>MgSiO$_3$</td>
<td>$7.59 \times 10^{-3}$</td>
<td>$1.31 \times 10^{-6}$</td>
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<tr>
<td>Mg$_2$SiO$_4$</td>
<td>$7.01 \times 10^{-3}$</td>
<td>$1.50 \times 10^{-6}$</td>
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<td>SiO$_2$</td>
<td>$1.47 \times 10^{-2}$</td>
<td>$9.94 \times 10^{-6}$</td>
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<tr>
<td>Al$_2$O$_3$</td>
<td>$8.18 \times 10^{-7}$</td>
<td>$7.48 \times 10^{-10}$</td>
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<tr>
<td>FeS</td>
<td>$1.78 \times 10^{-2}$</td>
<td>$1.53 \times 10^{-5}$</td>
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<tr>
<td>Si</td>
<td>$6.30 \times 10^{-2}$</td>
<td>$3.15 \times 10^{-5}$</td>
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<tr>
<td>Fe</td>
<td>$9.52 \times 10^{-5}$</td>
<td>$1.09 \times 10^{-8}$</td>
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<tr>
<td>Ni</td>
<td>$1.48 \times 10^{-6}$</td>
<td>$2.22 \times 10^{-10}$</td>
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<tr>
<td>Total</td>
<td>$1.16 \times 10^{-1}$</td>
<td>$3.44 \times 10^{-4}$</td>
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</tbody>
</table>

Total mass of dust formed in SNe Ia: $M_{\text{dust}} < \sim 0.1 \, \text{M}_{\odot}$
Formation of dust grains (C, Si, and Fe) should be suppressed to be consistent with the observations.
4-2. Non-LTE effect on dust formation

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

- \( T_d(r) \): 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-averaged value of \( Q_\lambda(a) \)

Non-LTE dust formation

\[ M_{FeS} = 4 \times 10^{-4} \text{ M}_{Sun} \]
\[ M_{Si} = 1 \times 10^{-6} \text{ M}_{Sun} \]
\[ \Rightarrow T_{FeS} < 0.1 \text{ after 300 day} \]

\[ M_C = 0.0055 \text{ M}_{Sun} \]
\[ \Rightarrow T_C > 20 \text{ (too high to be consistent with the observations)} \]
4-3. Infrared thermal emission from dust

Observational data: SN 2005bf at day 200 and 400 (Gerardy+07)

- **black solid lines:**
  - SEDs including emission from C grains
  - much higher than the observational results

- **red solid lines:**
  - SEDs not including emission from C grains
  - not contradict with the observational results

0.03 Msun of silicate can be allowed as dust mass
4-4. Carbon dust and outermost layer of SNe Ia

- **Formation of massive carbon dust**
  - high sticking probability of $\alpha = 0.1-1$
    - if $\alpha < \sim 0.01$, any dust grain cannot condense
  - dust formation around 100 days, $M(56\text{Ni}) \sim 0.6 \, M_{\odot}$
    - dust formation can be destroyed by energetic photons and electrons prevailing in the ejecta
  - massive unburned carbon ($\sim 0.05 \, M_{\odot}$) in deflagration
    - change of WD composition by the He-shell flash
    - burning of carbon by a delayed detonation wave

Observationally estimated carbon mass in SNe Ia: $M_c < 0.01 \, M_{\odot}$ (Marion+06; Tanaka+08)
4-5. Dust formation in super-Chandra SNe?

--- super-Chandra SNe:

M(56Ni) > ~0.8 \( M_{\text{sun}} \)

detection of CII line

\( \rightarrow \) presence of massive unburned carbon

enhanced fading at ~200 day

\( \rightarrow \) formation of carbon dust?

SN 2009dc, Tarbenberger+10
5-1. Destruction of dust in Type Ia SNRs

newly formed grains are completely destroyed for ISM density of $n_H > 0.1 \text{ cm}^{-3}$

SNe Ia are unlikely to be major sources of dust

$10^{-3} \text{ M}_{\odot}$ of dust can survive for $n_H \sim 0.01 \text{ cm}^{-3}$ but too low ISM density

typical ISM gas density around SNe Ia

$\Rightarrow n_H = 1-5 \text{ cm}^{-3}$

(Borkowski+06)
Summary

— For $\alpha = 1$, C, silicate, Si, and FeS grains can condense in the ejecta of SNe Ia at 100-300 days, being earlier than $>300$ days in SNe II-P.

— Due to the low gas density in the ejecta, the average radii of dust grains are below 0.01 $\mu$m, being smaller than those in SNe II-P.

— The total mass of dust that can form in the ejecta of SNe Ia is up to 0.1 $M_{\odot}$. (0.03 $M_{\odot}$ of silicate is more conservative.)

— Formation of C grains is inconsistent with the observations
  - low sticking probabilities of $\alpha < \sim 0.01$
  - small C clusters can be destroyed by photons and electrons
  - preexisting C should be almost completely burned

— For the ISM density of $n_{H,0} > 0.1$ cm$^{-3}$, the newly formed grains are almost completely destroyed before being injected into the ISM.
  - SNe Ia are likely to be poor producers of interstellar dust