Formation and Destruction Processes of Dust in Supernovae

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SNe are important sources of interstellar dust?

- number (occurrence) ratio of SNe to AGB stars

\[
n(\text{SNe}) / n(\text{AGB stars}) \sim 0.05-0.1
\]

\[M_{\text{dust}} = 0.1-1.0 \, M_{\odot} \text{ per SN} \quad (\text{Nozawa et al. 2003; 2007})
\]

\[M_{\text{dust}} = 0.01-0.05 \, M_{\odot} \text{ per AGB} \quad (\text{Zhukovska & Gail 2008})
\]
0-2. Formation site of dust

〇 Formation sites of dust

- abundant metal (metal : Z > 5)
- low gas temperature (T < ~2000 K)
- high gas density (n > ~10^6 cm^{-3})

→ mass-loss winds of AGB stars
- expanding ejecta of supernovae
- molecular clouds (grain growth only)
- red giant, W-R stars, novae, protoplanetary disk …

→ relative contribution of these sources is unclear!
1. Observations of Dust Formation in SNe (and SNRs)
1-1. Summary of observed dust mass in CCSNe

Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe.
1-1. Summary of observed dust mass in CCSNe

Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe.

- SN1987A
- Cas A
- Crab
- Kepler
- Tycho
- Kes 75

By courtesy of M. Tanaka
Dust Evolution in SNRs

He core

FS
RS
CD

100 µm (cool dust)
ALMA reveals dust formed in SN 1987A

ALMA spatially resolves cool (~20K) dust of ~0.5 M\(_{\odot}\) formed in the ejecta of SN 1987A

⇒ SNe could be production factories of dust grains
1-3. Emission and absorption efficiency of dust

○ Thermal radiation from a dust grain

\[ F_\lambda \propto 4\pi a^2 \, Q_{\text{emis}}(a,\lambda) \, \pi B_\lambda(T_{\text{dust}}) \quad \# \, Q_{\text{emis}} = Q_{\text{abs}} \]

\[ F_\lambda \propto 4\pi a^3 \, (Q_{\text{emis}}[a,\lambda]/a) \, \pi B_\lambda(T_{\text{dust}}) \]

\[ \propto 4 \, M_{\text{dust}} \, \kappa_{\text{emis}}(\lambda) \, \pi B_\lambda(T_{\text{dust}}) \]

\( \Rightarrow \) IR emission is derived given \( M_{\text{dust}}, \kappa_{\text{abs}}, \) and \( T_{\text{dust}} \)

(Qemis/a) is independent of a
1-4. Origin of IR emission from SNe

Dust formation in the ejecta

IR echo by CS dust

Dust formation in dense shell

Shock heating of CS dust
1-5. Evidence for dust formation in SN 2006jc

- brightening of IR
- rapid decline of optical light
- blueshift of emission lines
- formation of CO and SiO molecules (more robust if SiO are depleted)

Di Calro+08  
Tominaga+08

Smith+08
1-6. Composition of dust formed in SNe

IS dust: **carbonaceous grain and silicate** \((\text{MgSiO}_3, \text{MgFeSiO}_4, \ldots)\)

**SN 2004et**
- **carbon** \(\rightarrow 1660\;\text{K}\)
- **silicate**

**SN 2006jc**
- **silicate** \(\rightarrow 1750\;\text{K}\)

**SN 2004et, Kotak+09**

**SN 2006jc, Smith+08**
1-7. Dust formation in Type II In SN 2010jl

Dust in SN 2010jl
- carbon grains
- grain radius: <0.1μm (possibly <0.01 μm)
- dust mass: ~10^{-3} M_{\odot}

Maeda, TN, et al. 2013
2. Dust Formation in Type IIb SNe
2-0. How do dust grains form?

- **Chemical approach**
  - gaseous atoms
  - molecules
  - formation of seed nuclei
  - large molecules
  - dust grains

- **Nucleation approach**
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(s)</td>
<td>Fe(g) → Fe(s)</td>
</tr>
<tr>
<td>FeS(s)</td>
<td>Fe(g) + S(g) → FeS(s)</td>
</tr>
<tr>
<td>Si(s)</td>
<td>Si(g) → Si(s)</td>
</tr>
<tr>
<td>Ti(s)</td>
<td>Ti(g) → Ti(s)</td>
</tr>
<tr>
<td>V(s)</td>
<td>V(g) → V(s)</td>
</tr>
<tr>
<td>Cr(s)</td>
<td>Cr(g) → Cr(s)</td>
</tr>
<tr>
<td>Co(s)</td>
<td>Co(g) → Co(s)</td>
</tr>
<tr>
<td>Ni(s)</td>
<td>Ni(g) → Ni(s)</td>
</tr>
<tr>
<td>Cu(s)</td>
<td>Cu(g) → Cu(s)</td>
</tr>
<tr>
<td>C(s)</td>
<td>C(g) → C(s)</td>
</tr>
<tr>
<td>SiC(s)</td>
<td>Si(g) + C(g) → SiC(s)</td>
</tr>
<tr>
<td>TiC(s)</td>
<td>Ti(g) + C(g) → TiC(s)</td>
</tr>
<tr>
<td>Al$_2$O$_3$(s)</td>
<td>2Al(g) + 3O(g) → Al$_2$O$_3$(s)</td>
</tr>
<tr>
<td>MgSiO$_3$(s)</td>
<td>Mg(g) + SiO(g) + 2O(g) → MgSiO$_3$(s)</td>
</tr>
<tr>
<td>Mg$_2$SiO$_4$(s)</td>
<td>2Mg(g) + SiO(g) + 3O(g) → Mg$_2$SiO$_4$(s)</td>
</tr>
<tr>
<td>SiO$_2$(s)</td>
<td>SiO(g) + O(g) → SiO$_2$(s)</td>
</tr>
<tr>
<td>MgO(s)</td>
<td>Mg(g) + O(g) → MgO(s)</td>
</tr>
<tr>
<td>Fe$_3$O$_4$(s)</td>
<td>3Fe(g) + 4O(g) → Fe$_3$O$_4$(s)</td>
</tr>
<tr>
<td>FeO(s)</td>
<td>Fe(g) + O(g) → FeO(s)</td>
</tr>
</tbody>
</table>
2-2. Formulation of dust formation

\begin{align*}
\frac{dc_n}{dt} &= J_n(t) - J_{n+1}(t) \quad \text{for} \quad 2 \leq n \leq n_*, \\
J_n(t) &= \alpha_{n-1}c_{n-1}c_1 - \beta_n c_n \quad \text{for} \quad 2 \leq n \leq n_*, \\
\alpha_n &= \frac{s_n}{1 + \delta_{1n}} \, 4\pi a_0^2 \, n^{\frac{2}{3}} \left( \frac{kT}{2\pi m_n} \right)^{\frac{1}{2}}, \\
\beta_n &= \alpha_{n-1} \frac{\dot{c}_{n-1}}{\dot{c}_n} \dot{c}_1,
\end{align*}
2-3. Steady-state nucleation rate

- steady-state nucleation rate: $J_s$
  - assuming $J_s = J_2 = J_3 = \cdots = J_\infty$

\[
(n_c - 1)^{\frac{1}{3}} = \frac{2}{3} \frac{\mu}{\ln S}.
\]

where
- $\mu = 4\pi a_0^2 \sigma / kT$
- $\sigma$: surface tension
- $S$: supersaturation ratio
  \[(S = p_1 / p_1 v)\]

\[
J_s = s_{\text{crit}} \Omega_0 \left(\frac{2\sigma}{\pi m_1}\right)^{\frac{1}{2}} c_1^2 \Pi \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2}\right],
\]
2-4. Basic equations for dust formation

- Equation of mass conservation

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

- Equation of grain growth

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

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

Growth rate is independent of grain radius
2-5. Dust formation calculation in the ejecta

Dust formation calculation
- non-steady nucleation and grain growth theory
  (Nozawa et al. 2003)

SN IIb model
(SN1993J-like model)
- $M_{\text{H-env}} = 0.08 \, M_{\odot}$
- $M_{\text{ZAMS}} = 18 \, M_{\odot}$
- $M_{\text{eje}} = 2.94 \, M_{\odot}$
- $E_{51} = 1$
- $M(^{56}\text{Ni}) = 0.07 \, M_{\odot}$

SN II-P model: $M_{\text{H-env}} = 13 \, M_{\odot}$, $M_{\text{ZAMS}} = 20 \, M_{\odot}$, $E_{51} = 1$
(Umeda & Nomoto 2002)
2-6. Birth of dust in the ejecta of Cas A

- Condensation time of dust: 300-700 days after explosion
- Total mass of dust formed:
  - 0.167 $M_{\odot}$ in SN IIb
  - $M_c = 0.07$ $M_{\odot}$
  - $M_{\text{silicate}} = 0.08$ $M_{\odot}$
  - 0.1-1 $M_{\odot}$ in SN II-P
2-7. Dependence of dust radii on SN type

The radius of dust formed in H-stripped SNe is small

- SN IIb and SN Ib/Ic without massive H-env
  \[ \text{adust} < 0.01 \, \mu\text{m} \]

- SN II-P with massive H-env
  \[ \text{adust} > 0.01 \, \mu\text{m} \]
3. Dust Destruction in Cas A
3-1. Time evolution of SNRs

- Basic equations (spherical symmetry)

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

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

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

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

\(\Lambda_{\text{gas}}(T)\): cooling function of gas by the atomic process
(\cite{Sutherland1993, Smith2001})

\(\Lambda_{\text{ic}}(T)\): inverse Compton cooling (\cite{Ikeuchi1986})
\[\Lambda_{\text{ic}}(T) = 5.41 \times 10^{-32} (1 + z)^4 n_e (T/10^4 \text{ K})\] (we adopt \(z = 20\))

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

- numerical code: flux splitting method (\cite{vanAlbada1982})
3-2. Dynamics of dust

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

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

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

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

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

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

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

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

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

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

\[m_{\text{sp}}\]; 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)

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

where \[\epsilon = E/kT\]
3-4. 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

3-5. Calculation of dust evolution in SNRs

**Dust evolution calculations** (Nozawa et al. 2006, 2007)

- spherical symmetric hydrodynamic calculation based on the ejecta model of the SN IIb
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag
  - collisional stochastic heating

**density profile of CSM**

\[ n_H(r) = n_{H,1} \left( \frac{r}{r_1} \right)^{-2} / \text{cc} \]

\[ = 1 / \text{cc} \quad \text{for} \quad n_H < 1 / \text{cc} \]

\[ r_1 = r(\text{at 10 yr}) = 1.2 \times 10^{18} \text{cm} \]

\[ n_{H,1} = 30, 120, 200 / \text{cc} \]

(\( \Rightarrow \) \( dM/dt = 2.0, 8.0, 13 \times 10^{-5} \) \( M_{\odot} \)/yr for \( v_w = 10 \) \( \text{km/s} \))
3-6. Fate of dust in Cas A SNR

- All of the dust grains in Cas A would be destroyed in the shocked gas within the SNR before $\sim 2 \times 10^4$ yr
  - small grain size of newly formed dust
  - early arrival of the reverse shock at the He core
  - H-deficient SNe may not be major contributors of dust

- 0.01-0.8 $M_{\text{Sun}}$ of dust survive for SNe II-P (Nozawa+2007)
3-7. Comparison with observations of Cas A

- MIR, d = 0.008 Msun
  (Mshocked, d ~ 0.1 Msun)

- $\frac{dM}{dt} = 8 \times 10^{-5}$ Msun/yr
  $\rightarrow \frac{dM}{dt} \sim 2 \times 10^{-5}$ Msun/yr for Cas A (Chevalier & Oishi 2003)

- $\frac{dM}{dt} = (3-4) \times 10^{-5}$ Msun/yr
  for 93J (Suzuki & Nomoto 1995)
3-8. Contribution from unshocked dust

observed IR SED can be well reproduced!

\[ \uparrow \]
- \( M_{d,\text{warm}} \approx 0.008 \ M_{\odot} \)
- \( M_{d,\text{cool}} \approx 0.07 \ M_{\odot} \) with \( T_{\text{dust}} \approx 40 \ K \)

AKARI reduced 90\( \mu \)m image ➔ centrally peaked cool dust component

\[ \downarrow \]
- \( M_{d,\text{cool}} = 0.03-0.06 \ M_{\odot} \) with \( T_{\text{dust}} = 33-41 \ K \)

Sibthorpe et al. 2009
1) Birth of Dust in the ejecta of Cas A
Dust formed in Cas A was formed at 300-700 days after the explosion with $a_{\text{dust}} < 0.01 \mu\text{m}$ and $M_{\text{dust}} = 0.167 \text{ M}_{\odot}$

2) Brightening of dust in the shocked hot gas
Model of dust destruction and heating in Type IIb SNR can reasonably reproduce the observed SED of Cas A; $M_{\text{d, warm}} = 0.008 \text{ M}_{\odot}$, $M_{\text{d, cool}} = 0.07 \text{ M}_{\odot}$

$$\frac{dM}{dt} = \sim 8 \times 10^{-5} \text{ M}_{\odot}/\text{yr}$$

3) Fate of dust in Cas A SNR
Small dust grains in Cas A will be completely destroyed in the shocked gas without being injected into the ISM