超新星ダストの形成と銀河ダストの物理化学進化 ーコンセンサスと課題ー
(Formation of SN-dust and Evolution of dust in galaxies ーconsensus and issuesー)

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The far-infrared and submm observations have confirmed the presence of dust in excess of \(10^8\) M\(_{\text{Sun}}\) in 30% of z > 5 quasars.

- In the MW, AGB stars are considered to be major dust sources → too old to supply dust in the early universe.

- 0.1 M\(_{\text{Sun}}\) of dust per SN is needed to explain massive dust at high-z (e.g. Morgan & Edmunds 2003; Maiolino+2006; Dwek+2007).

\(10^8\) - \(10^9\) M\(_{\text{Sun}}\) of dust in SDSS J1148+5251 at z = 6.4 (Leipski+2010)

\(~10^6\) M\(_{\text{Sun}}\) of dust in a galaxy at z = 8.4 (Laporte+2017)
1-2. Depletion of gas metals in the present ISM

Savage & Sembach (1996, ARAA, 34, 270)
1-3. Average extinction curve in the Milky Way

**astronomical silicate** (Draine & Lee 1984)
- hypothetical material to account for observed spectra from UV to infrared (i.e. its optical constant is artificial)
  
  assumed chemical composition: \( \text{Mg}_{1.1}\text{Fe}_{0.9}\text{SiO}_4 \)

**MRN dust model** (Mathis, Rumpl, & Nordsieck 1977)
- dust composition: silicate and graphite
- size distribution: power-law \( n(a) \propto a^{-q} \) with \( q=3.5 \),
  \( a_{\text{max}} = 0.25 \mu\text{m} \)
  \( a_{\text{min}} = 0.005 \mu\text{m} \)
- mass ratio: \( M_{\text{sil}} / M_{\text{gra}} \sim 2 \)
2-1. Key questions for dust formation in SNe

1. How much dust grains form?

2. What is the size distribution of dust?

3. When do the majority of grains form?
Dust mass formed in the ejecta is dominated by cold dust. Observed dust mass in CC-SNe/SNRs reverse shock destruction?

NIR/MIR FIR/submm extinction

Matsuura+2011 Balow+2010 Gomez+2012

2-2. Observed dust mass in CC-SNe/SNRs

Dust mass formed in the ejecta is dominated by cold dust.
2-3. Properties of dust ejected from SNe II-P

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

- Size distribution of dust after the shock-destruction is dominated by large grains (> 0.1 μm)

![Graph showing total mass of dust survived as a function of progenitor mass and density](image)


![Graph showing size distribution of dust](image)
Dust mass formed in the ejecta is dominated by cold dust. Observed dust mass in CC-SNe/SNRs: missing cold dust? Reverse shock destruction? Dust mass increasing with time? NIR/MIR, FIR/submm extinction.

Dust mass formed in the ejecta is dominated by cold dust.
2-4. Dust mass increases with time?

Dust mass estimated from IR SEDs
Gall et al. (2014, Nature)

Most of dust grains (> 0.1 M$_{\text{Sun}}$) form at ~20 yr post-explosion

Evolution of dust mass in SN 1987A derived from extinction of optical emission lines
Bevan & Barlow (2016)
We should not discuss the mass of newly formed grains by integrating the formation of dust in the ejecta and CDS. The mass of newly formed dust increases with time.

Dust formation in the ejecta

Dust formation in cool dense shell

Pre-existing circumstellar dust

Dust formed in the ejecta

Gall+2014, Nature

The mass of newly formed dust increases with time?
2-6. Timescale of grain growth

\[
\tau_{\text{grow}}^{-1} = \frac{1}{a} \left( \frac{da}{dt} \right) = \left( \frac{1}{a} \right) \eta_g \Omega_0 c_1 \left( \frac{kT}{2\pi m_1} \right)^{\frac{1}{2}}
\]

\[
\tau_{\text{grow}} \approx 50 \left( \frac{\eta_g}{1.0} \right)^{-1} \left( \frac{a}{0.01 \ \mu m} \right) \left( \frac{T}{50 \ \text{K}} \right)^{-\frac{1}{2}} \left( \frac{M_C}{0.01 \ \text{M}_\odot} \right)^{-1} \\
\times \left( \frac{V_{\text{core}}}{10^3 \ \text{km s}^{-1}} \right)^3 \left( \frac{t}{20 \ \text{yr}} \right)^3 \left( \frac{f_{\text{density}}}{10} \right)^{-1} \text{ yr}
\]

At 20 yr, the gas density is too low to form dust grains in the freely expanding ejecta.
2-7. Key questions for dust formation

1. How much dust grains form?
   - theoretical works ➜ 0.1-1 M\(_{\text{Sun}}\)
   - FIR/submm obs. ➜ 0.1-1 M\(_{\text{Sun}}\)

2. What is the size distribution of dust?
   - theory ➜ relatively large grains (>0.1 µm)
   - obs. ➜ very large (~1 µm) at the dust formation

3. When do the majority of grains form?
   - theory ➜ ~1-3 yr (within 5 yr; earlier is better)
   - obs. ➜ ~20 yr (dust mass gradually increases with time)
3-1. Cycling of interstellar dust in the universe

- Big Bang
- Molecular cloud in the universe
- Star evolution
- Molecular cloud
- Formation of the solar system
- Evolution of stars
- Late-type stars
- Molecular cloud
- Destruction and transformation of dust in interstellar space
- Construction of the solar system
- Molecular cloud
- Late-type stars
3-2. Dust evolution model in a galaxy (1)  

- one-zone closed-box model (no inflow and no outflow)

- star formation rate (SFR)
  Schmidt law with $n = 1$: $\text{SFR}(t) = \frac{M_{\text{gas}}(t)}{\tau_{\text{SF}}}$ with $\tau_{\text{SF}} = 5 \text{ Gyr}$

- initial mass function (IMF)
  Salpeter IMF: $\varphi(m) = m^{-q}$ with $q=2.35$ for $M_{\text{star}} = 0.1\text{-}100 \text{ M}_{\odot}$

- two-component dust model
  - graphite (carbonaceous grains)
  - astronomical silicate (silicate and the other grains species)

- two-phase ISM
  - WNM (warm neutral medium): $T = 6000 \text{ K}, n = 0.3 \text{ cm}^{-3}$
  - CNM (cold neutral medium): $T = 100 \text{ K}, n = 30 \text{ cm}^{-3}$
  $\eta_{\text{WNM}} = \eta_{\text{CNM}} = 0.5$
3-3. Dust evolution model in a galaxy (2)

- mass evolution of dust $\Delta M_d(a,t)$ with radii between $a$ and $a+da$

\[
\frac{d\Delta M_d(a,t)}{dt} = -\frac{\Delta M_d(a,t)}{M_{\text{ISM}}(t)} + \frac{\Delta Y_d(a,t)}{M_{\text{ISM}}(t)} - \frac{M_{\text{swept}}}{M_{\text{ISM}}(t)} \gamma_{\text{SN}}(t) \left[ \Delta M_d(a,t) - m(a) \int_0^\infty \xi(a,a') \Delta a f(a',t) da' \right] + \eta_{\text{CNM}} \left[ m(a) \Delta a \frac{\partial [f(a,t)]}{\partial t} \right] + \eta_{\text{WNM}} \left[ \frac{d\Delta M_d(a,t)}{dt} \right]_{\text{shat},\text{WNM}} + \eta_{\text{WNM}} \left[ \frac{d\Delta M_d(a,t)}{dt} \right]_{\text{coag},\text{WNM}} + \eta_{\text{CNM}} \left[ \frac{d\Delta M_d(a,t)}{dt} \right]_{\text{shat},\text{CNM}} + \eta_{\text{CNM}} \left[ \frac{d\Delta M_d(a,t)}{dt} \right]_{\text{coag},\text{CNM}}
\]

\[
\Delta Y_d(a,t) = \int_{m_{\text{cut}}(t)}^{100 \, M_{\odot}} \Delta m_d(m, Z(t - \tau_m), a) \phi(m) SFR(t - \tau_m) dm,
\]

Asano+2013, 2014
3-4. How dust mass increases in the ISM

**Shattering and grain growth necessary for achieving the observed high dust content**

Ejection of large grains from SNe/AGB stars

Growth of small grains via accretion of gas in the MCs

Production of small grains via shattering in the ISM

Asano+2013

![Graph showing dust mass increase with time](image)

- **w/ shattering**
- **w/o shattering**
- **w/o grain growth & shattering**
- **early phase**: formation of dust in SNe II and AGB stars
  - large grains (>0.1 μm) are dominant → flat extinction curve

- **middle phase**: shattering, grain growth due to accretion of gas metal
  - small grains (< 0.03 μm) are produced → steep extinction curve

- **late phase**: coagulation of small grains
  - shift of peak of size distribution → making extinction curve flatter
3-6. Reproducing the MW extinction curve

- two-phase ISM
  - WNM (T = 6000 K, n = 0.3 cm⁻³)
  - CNM (T = 100 K, n = 30 cm⁻³)

- three-phase ISM
  - WNM (T = 6000 K, n = 0.3 cm⁻³)
  - CNM (T = 100 K, n = 30 cm⁻³)
  - MC (molecular clouds)  \( \Rightarrow T = 25 \text{ K}, n = 300 \text{ cm}^{-3} \)

- three-phase ISM model including the MC phase can reproduce the average extinction curve in the MW

- ISM phase is one of the important quantities in constructing the evolution model of interstellar dust

Nozawa+2015
3-7. Explaining massive dust in high-z quasars

- two-phase ISM:
  \[ \text{WNM} = 0.3 \text{ and } \text{MC} = 0.7 \]
  \[ \tau_{SF} = 0.5 \text{ Gyr} \]

high-z quasar host: starburst galaxies

\[ \rightarrow \] indicating a high fraction of MM

\[ \frac{M_{\text{H}_2}}{M_{\text{H, total}}} \approx 0.7-0.97 \] (Calura+2014)

Nozawa+2015
4-1. Issues of dust evolution model (1)

〇 What is property of C grains?

- Asano dust evolution model
  high-z : amorphous carbon
  present : graphite

  silicate and graphite (am.car)
  ➞ three-component dust model
  consisting of silicate, am.car, PAH

## cannot explain the SMC dust
4-2. Issues of dust evolution model (2)

- Too much (small) C grains
  - stronger (sharper) 2175A bump than observed in the MW
    \[ \text{larger amount of (small) C grains} \]
  - dust evolution model
    \[ \text{efficient grain growth in MCs} \]
    \[ \text{almost all C atoms (>90%) accrete onto dust grains} \]
  - depletion of C atoms in the ISM
    \[ 50-70\% \text{ of C locked in dust grains} \]

Nozawa+2015

Aoyama+2017; Hou+2017
4-3. Issues of dust evolution model (3)

○ Gas accretion onto dust grains in MCs really works?

- selective accretion (coagulation)
  Si, Mg, Fe, O $\rightarrow$ silicate grains
  C $\rightarrow$ carbon grains

## heterogeneous dust grain model
(Jones+2013, 2016, 2017)

- formation of ice mantle in MCs
  $\Rightarrow$ ice mantle would form before efficient accretion of metal gas
  (Ferrara+2016)

## high CMB temperature would suppress grain growth at high z

(Jones+2013)
4-4. Issues of dust evolution model (4)

- Fe-missing problem
  - two-component dust model
    Si, Mg, Fe, O ➔ silicate grains
  - no evidence for Fe-rich silicate grains
  - no evidence for formation of pure Fe grains in Type Ia SNe
  - 99% of Fe locked up in the ISM
  - Fe atoms must be incorporated into dust grains in dense MCs (Dwek 2016)
4-5. Consensus and issues for dust evolution

**Consensus**

Grain growth is needed to account for a large amount of interstellar dust in both high-z and nearby galaxies (Draine 2009; Michalowski+ 2010; Gall+ 2011a, 2011b; Pipino+ 2011; Mattsson+ 2011; Inoue 2011; Valiante+ 2011, 2014; Kuo & Hirashita 2012; Asano+ 2013a, 2013b, 2014; Calura+ 2014; Dwek+ 2014; Nozawa+ 2015; Michalowski+ 2015; Aoyama+ 2017; Hou+ 2017; Hirashita & TN 2017)

**Issues**

- Grain growth efficiently takes place in the MCs?
- Grain growth is an important process to regulate the composition, size, and mass of interstellar dust?
- Grain growth naturally explain the properties of interstellar dust extracted from observations?