Probing the formation and destruction processes of dust with large MIR telescopes

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1-1. Paradox in interstellar dust mass

**Injection rate of dust from CCSNe/AGB stars**

\[
\frac{dM_{\text{dust}}}{dt} \simeq 0.01 \left( \frac{\phi_{\text{sf}}}{4 \ M_\odot \ yr^{-1}} \right) \left( \frac{f_{\text{AGB-SN}}}{0.3} \right) \left( \frac{f_{\text{gas,ejected}}}{0.75} \right) \left( \frac{f_{\text{dust,form}}}{0.01} \right) \ M_\odot \ yr^{-1}
\]

- $\phi_{\text{sf}}$: Fraction of stars evolving to SNe/AGB
- $f_{\text{AGB-SN}}$: Mass fraction of gas ejected from SNe/AGB
- $f_{\text{dust,form}}$: Condensation efficiency of dust

**Destruction rate of interstellar dust by SN shocks**

\[
\frac{dM_{\text{dust}}}{dt} \simeq -0.06 \left( \frac{R_{\text{SN}}}{0.01 \ yr^{-1}} \right) \left( \frac{M_{\text{gas,swept}}}{2000 \ M_\odot} \right) \left( \frac{D_{\text{ISM}}}{0.01} \right) \left( \frac{f_{\text{dust,dest}}}{0.3} \right) \ M_\odot \ yr^{-1}
\]

- $R_{\text{SN}}$: SN rate
- $M_{\text{gas,swept}}$: Gas mass swept by a SN shock
- $D_{\text{ISM}}$: Dust-to-gas mass ratio
- $f_{\text{dust,dest}}$: Destruction efficiency of dust

Formation rate of dust in stellar sources is lower than destruction rate of dust

→ Interstellar dust must decrease with time
1-2. What is wrong?

- **Underestimate condensation efficiency of dust?**
  - CCSNe eject $\sim 10 \, M_\text{Sun}$ gas and $\sim 0.1 \, M_\text{Sun}$ dust
  - $\sim 90\%$ of dust destroyed by reverse shocks
  - $f_{\text{dust, form}} = 1 \%$ would be the optimistic estimate

- **Overestimate destruction efficiency of dust?**
  - There is uncertainties in destruction efficiency
  - Dust is destroyed by sputtering in shocked gas

- **Other sources of interstellar dust?**
  - RGs, RSGs, sAGB stars, LBVs, WR stars, Novae, …
  - Grain growth in molecular clouds
2-1. Observed dust mass in CCSNe/SNRs

Dust mass formed in the ejecta is dominated by cold dust.
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Observed dust mass in CCSNe/SNRs:
- Missing cold dust?
- Dust mass increasing with time?

NIR/MIR, FIR/submm extinction

Dust mass formed in the ejecta is dominated by cold dust.
2-2. Origin of IR emission from CCSNe

Dust formation in the ejecta

- SN 1987A with Kuiper Airborne Observatory
  - dust mass: $>10^{-4}$ Msun (optically thin assumed)

IR echo by CS dust

Wooden+93
2-3. Rapid decline of light curve in SN 1987A

Optical light curve starts to decline around 400 day → dust starts to form at ~400 day in the ejecta
2-4. CO and SiO molecules in SN 1987A

CO first overtone: 2.29-2.5 μm
CO fundamental: 4.65-6 μm
SiO fundamental: 7.6-9.5 μm

- Mco~4x10⁻³ Msun (Liu+1995)
- MSiO~7x10⁻⁴ Msun (Liu & Dalgarno 1996)

Abellan+2017, t~28 yr

CO (2-1)
SiO (5-4)
2-5. Observations of dust formation in SNe

- **Long-time monitoring of nearby CCSNe**
  - emission lines of CO and SiO molecules in N/MIR
  - thermal emission from newly formed dust in N/MIR
  - Extinction of light curve in optical
  - Blueshift of atomic emission lines in optical thru MIR

Monitor: from 100 to 1000 days
Nearby: <20 Mpc (~1 SN per yr)
→ should focus on a few targets

※ suspect that JWST can monitor a SN every 6 month
Dust mass formed in the ejecta is dominated by cold dust.

Observed dust mass in CCSNe/SNRs missing cold dust? Dust mass increasing with time?

NIR/MIR FIR/submm extinction

Dust mass formed in the ejecta is dominated by cold dust.
3-2. Destruction of dust in Cassiopeia A SNR

Nozawa+2010

Cas A at 330 yr

ALMA, 450 µm

0.07M\text{sun} of unshocked cool dust

Chandra, X-ray

0.008M\text{sun} of shocked warm dust

Nozawa+2010

SN 1987A at 28 yr

flux density (Jy)

wavelength (µm)

Nozawa 2014

AKARI, Sibthorpe+2010
3-3. CO detection in Cassiopeia A SNR

AKARI IRC spectra

Herschel PACS

CO (4.5 μm) dust (21 μm)

Rho+2012
Cas A at ~330 yr

Wallstrom+2013
3-4. Possible target: SNR 1E0102-72.3 in SMC

SNR 1E0102-72.3 in SMC
- O-rich (similar to Cas A)
- age: \(~1000\) yr
- \(M_{\text{warm}} \sim 10^{-3}\) \(M_{\odot}\)
- \(M_{\text{cool}} \sim ???\)

→ spatial distributions of CO and dust with TAO/MIMIZUKU

- what is the initial dust mass?
- how efficient is dust destruction?
- what fraction of dust can survive to be injected into the ISM?

※ SNR age: \(~>10^5\) yr
3-5. Destruction rate of dust by sputtering

- Erosion rate of dust by sputtering

\[ \left| \frac{da}{dt} \right| = 10^{-6} \left( \frac{n_H}{1\ cm^{-3}} \right) \ \mu m \ yr^{-1} \]

Sputtering yield

\[
4\pi a^2 \left( \frac{da}{dt} \right) = -\Omega_0 \pi a^2 n_i \langle v_i Y_i \rangle \\
\frac{da}{dt} = -\frac{\Omega_0}{4} n_i \langle v_i Y_i \rangle
\]

Targets of experimental data

- bulk materials
- crystal
- no void
- smooth surface

...
3-7. Destruction of dust by sputtering

- **Erosion rate of dust by sputtering**

\[
\left| \frac{da}{dt} \right| = 10^{-6} \left( \frac{n_H}{1 \text{ cm}^{-3}} \right) \mu\text{m yr}^{-1}
\]

- **Erosion rate of inner wall of nuclear fusion**

\[
\left| \frac{da}{dt} \right| = 10^8 \left( \frac{n_H}{10^{14} \text{ cm}^{-3}} \right) \mu\text{m yr}^{-1} \text{ cm}^{-3}
\]
\[
= 10^4 \left( \frac{n_H}{10^{14} \text{ cm}^{-3}} \right) \text{ cm yr}^{-1} \text{ cm}^{-3}
\]
\[
\approx 30 \left( \frac{n_H}{10^{14} \text{ cm}^{-3}} \right) \text{ cm day}^{-1} \text{ cm}^{-3}
\]

Is this erosion rate correct?
4-1. Expected IR images of SN 1987A

On 4 Oct 2003
Gemini T-ReCS
(λ = 10.36 μm)
2 pixels : 0.18”
(Bouchet+2004)

AKARI
24 μm
(Seok+2008)

SN 87A with MIMIZUKU
- spatially resolving equatorial ring
- multi-epoch (monitoring)
  ➜ evolution of CS dust
- MIR flux: 10-100 mJy

On 6 Jan and 1 Feb 2005 (Bouchet+2006)

Chandra image
(Park+2007)
4-2. Properties of CS dust around SN 1987A

- IR fluxes increase in all bands by a factor of ~3 between 17 yr and 22 yr

- properties of CS dust in ER
  - silicate
  - $T_{\text{dust}} = 180$ K
  - $M_{\text{dust}} = \sim 10^{-5}$ $M_{\odot}$
  - $L_{\text{IR}} = 10^{36}-10^{37}$ erg/s
    (Seok+2008, Dwek+2008)

- grain radius:
  - $a = 0.02$-0.2 μm
  - relatively large
4-3. Re-formation of dust in equatorial ring?

**SOFIA observations of SN 1987A**

- 30-70 µm excess appeared at 10000 day
  - cool dust = \( \sim 4 \times 10^{-4} \) M\(_\odot\)
  - hot dust = \( \sim 10^{-5} \) M\(_\odot\)
5-1. What is LBVs?

- **LBVs (luminous blue variables)**
  - $\log_{10}(L / L_{\text{sun}}) = 5.5-6.5$
  - $\log_{10}(T_{\text{eff}} / K) = 3.8-4.6$
  - $M_{\text{star}} = 40-150 \ M_{\text{sun}}$

17 LBVs in our Galaxy (at Mar 2016)

**Is Type II In SN 2005gl explosion of a LBV?**

$\rightarrow$ Challenge to the stellar evolution theory
5-2. Dusty envelopes around LBVs

70% of LBVs have thick circum-dust envelopes

→ dust formation in mass-loss winds
5-3. Dust formation in mass-loss winds of LBVs

- **Two difficulties of dust formation in LBVs**
  - fast wind velocity (~100-300 km/s) ⇒ low gas density
    \[ \rho_{\text{gas}} = \frac{M_{\text{dot}}}{(4 \pi r^2 v_{\text{wind}})} \]
    cf. \( v_{\text{wind}} = 10\text{-}30 \text{ km/s} \) for AGB stars
  - high BB temperature ⇒ dissociation of dust by UV radiation

  Studies of dust formation in LBVs are challenging!!

- **Dust formation in dense clumps?**
  - high gas density, shielding of UV photons

  Spatial distribution of CS dust
  ⇒ N/MIR high spatial-resolution mapping of LBVs

Wray15-751
Vamvatira-Nakou+2013
5-4. Most LBVs only from southern hemisphere

16 of 17 LBVs in southern sky

→ ideal targets to be observed by TAO/MIMIZUKU

[Diagram showing distribution of LBVs with P Cygni and Eta Carina as examples]

AKARI FIR images, Credit: JAXA/ISAS
5-5. Significance of studying LBVs

**Important topics related to LBVs**

- Dust formation processes in extreme environments
  → laboratories that probe dust condensation in space

- Mechanisms of (explosive) mass loss
  → mass-loss rate, asymmetry of ejected gas

- Relationship with Type II In SNe
  → Are LBVs progenitor stars of Type II In SNe?

- Understanding of massive star binaries
  → many of LBVs are binaries

Observations of LBVs ➔ Dust formation theory
Stellar evolution theory
Obs targets w.r.t. dust formation/destruction

(1) long-term monitoring of nearby CCSNe with TMT
   ➔ line emissions of CO/SiO and Fe group elements
   ➔ IR emission and optical extinction of dust grains

(2) young SNRs in LMC/SMC
   ➔ spatial distribution of CO and dust grains
   ➔ dust destruction of dust by reverse shocks

(3) MIR monitoring of SN 1987A with TAO/MIMIZUKU
   ➔ evolution of dust in the equatorial ring
   ➔ derivation of dust destruction efficiency

(4) IR mapping observations of Galactic LBVs
   ➔ most of LBVs are seen only from southern sky