Evolution of dust size distribution and extinction curves in galaxies

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References
- Asano, Nozawa, Hirashita, Takeuchi (2014 in prep.)
1-1. Dust alters the SEDs of galaxies

Dust absorbs UV/optical lights and re-emits thermal emission in the infrared.

70% of the star formation activity at 0.5 < z < 1.2 is obscured by dust.

\[ (h, \Omega_m, \Lambda_0) = (0.7, 0.3, 0.7) \]

Takeuchi+2005

Silva+1998
1-2. Aim of our study

to correct the obscuration by dust, many (observational) studies have assumed the MW, SMC, LMC extinction curves or the Calzetti extinction (attenuation) law

➔ however, the size distribution of interstellar dust must change as the galaxy evolves

we construct the evolution model of grain size distribution, with the aim at understanding how the extinction curve is modified in the course of galaxy evolution

- dust processes considered in our works
  - production of dust in SNe II and AGB stars
  - destruction of dust by interstellar shocks
  - grain growth due to metal accretion in molecular clouds
  - shattering and coagulation due to grain-grain collisions
2-1. Extinction curves in the Milky Way

- MRN dust model
  (Mathis, Rumpl, & Nordsieck 1977)
  - composition: silicate and graphite
  - size distribution: 
    \[ n(a) \propto a^{-q} \] with \( q=3.5 \), 
    \( 0.005 \, \mu m \leq a \leq 0.25 \, \mu m \)

- total-to-selective extinction ratio
  \[ R_V = \frac{A_v}{(A_B - A_v)} \]
  - small grains (small \( R_V \)) ➜ steep extinction curve
  - large grains (large \( R_V \)) ➜ flat extinction curve
2-2. Properties of dust ejected from SN II-P

mass of dust grains injected from a SN II into the ISM: 
0.07-0.8 \( M_{\odot} \) (\( n_{H,0} = 0.1-1 \text{ cm}^{-3} \))

size distribution of dust which is ejected from SNe II is dominated by large grains (> 0.01 \( \mu \text{m} \))

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at time of dust formation

- \( \text{Al}_2\text{O}_3 \)
- \( \text{MgO} \)
- \( \text{Mg}_2\text{SiO}_4 \)
- \( \text{MgSiO}_3 \)
- \( \text{C} \)
- \( \text{SiO}_2 \)
- \( \text{Fe} \)
- \( \text{Si} \)

after destruction of dust by reverse shock

- 20\( M_{\odot} \) unmixed case
- \( n_{H,0} = 1 \text{ cm}^{-3} \)
2-3. Properties of dust ejected from AGB stars

Zhukovska & Gail 2008; Valiante+2009

Mass of dust grains injected from a AGB star into the ISM:
0.001-0.01 $\text{M}_{\odot}$ ($\text{M}_{\text{star}} > 1 \text{ M}_{\odot}$)

Average radius of dust ejected from AGB stars is considered to be large ($a = 0.1-1.0 \mu\text{m}$)

Yasuda & Kozasa 2012
2-4. Destruction of dust in SN shocks

- Erosion rate by sputtering: \( \frac{da}{dt} \sim 10^{-6} \left( \frac{n_H}{1.0 \text{ cm}^{-3}} \right) \mu \text{m yr}^{-1} \)


- Timescale of dust destruction by SN shocks, \( T_{\text{dest}} \)

  \[
  T_{\text{dest}} = \left[ \frac{1}{M_{\text{dust}}} \frac{dM_{\text{dust}}}{dt} \right]^{-1} = \left[ \frac{\epsilon M_{\text{swept}} R_{\text{SN}}}{M_{\text{gas}}} \right]^{-1}
  \]

  \[
  \sim 5 \times 10^8 \text{ yr} \left( \frac{\epsilon}{0.3} \right)^{-1} \left( \frac{M_{\text{swept}}}{3000 \text{ M}_\odot} \right)^{-1} \left( \frac{R_{\text{SN}}}{0.02 \text{ yr}^{-1}} \right)^{-1} 
  \times \left( \frac{M_{\text{gas}}}{10^{10} \text{ M}_\odot} \right)
  \]
2-5. Growth of dust in molecular clouds

- timescale of grain growth, $T_{\text{grow}}$

$$T_{\text{grow}} = \left[ \frac{1}{md} \frac{dmd}{dt} \right]^{-1} = \left[ \frac{1}{3a} \alpha_s n_{\text{metal}} V_0 \langle v \rangle \right]^{-1}$$

$$\sim 2 \times 10^7 \text{ yr} \left( \alpha_s / 0.2 \right)^{-1} \left( a / 0.01 \mu\text{m} \right) \left( Z / 0.02 \right)^{-1} \left( n_{\text{gas}} / 30 \text{ cm}^{-3} \right)^{-1}$$

- grain growth is more efficient for a higher gas density, a higher metallicity (higher abundance of metals), and a smaller grain

## grain growth is more efficient for a large surface-to-volume ratio of dust grains
2-6. Shattering and coagulation of dust

- Shattering at $V_{\text{rel}} > V_{\text{shat}}$
  where $V_{\text{shat}} = 1$-$3$ km/s

- Coagulation at $V_{\text{rel}} < V_{\text{coag}}$
  where $V_{\text{coag}} = 0.01$-$0.1$ km/s

in the interstellar turbulence, $V_{\text{rel}}$
is higher for a lower gas density
and a larger grain radius (Yan+2004)

These processes do not reduce dust
mass but change size distribution

- Timescale of shattering, $T_{\text{shat}}$

  $T_{\text{shat}} \sim 1 \left(\frac{\text{TSF}}{\text{Gyr}}\right)^{1/2}$ yr

  ## grain-grain collision processes
  ## becomes efficient once dust
  ## grains are enriched sufficiently
2-7. Dust evolution model (1)

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

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

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

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

- two-phase ISM
  WNM (warm neutral medium): $T = 6000 \ K$, $n = 0.3 \ \text{cm}^{-3}$
  CNM (cold neutral medium): $T = 100 \ K$, $n = 30 \ \text{cm}^{-3}$
  $\eta_{\text{WNM}} = \eta_{\text{CNM}} = 0.5$
2-8. Dust evolution model (2)

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

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

\[
\Delta Y_d(a,t) = \int_{m_{cut}(t)}^{100 \ M_\odot} \Delta m_d(m, Z(t - \tau_m), a) \phi(m) SFR(t - \tau_m) dm,
\]
3-1. Evolution of extinction curves in galaxies

- **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

3-2. Reproducing the MW extinction curve

Steep extinction curve is due to the presence of too much small grains

- Three-phase ISM
  - WNM
    \[ T = 6000 \text{ K}, \, n = 0.3 \text{ cm}^{-3} \]
  - CNM
    \[ T = 100 \text{ K}, \, n = 30 \text{ cm}^{-3} \]
  - MC (molecular clouds)
    \[ T = 25 \text{ K}, \, n = 300 \text{ cm}^{-3} \]
3-3. Extinction curves in high-z quasars

SDSS J1048+4637 at z=6.2: broad absorption line (BAL) quasars

→ interstellar dust in the early universe is SN origin?

Gallerani+10

Hirashita+2008

Huge amounts of dust grains are observed for the host galaxies of quasars at $z < 5$.

It is suggested that the grain growth is needed to account for such massive dust contents.

It seems only the contribution of dust from SNe II cannot explain the observed amount of dust grains in high-z quasars.

How can we explain the dust mass and unusual extinction curves observed for high-z quasars in a consistent way?
3-5. Explaining the high-z extinction curves

high-z quasar host: starburst galaxies ➔ indicating a high fraction of MC
cf. $M_{\text{H}2}/M_{\text{H}} \sim 5$ from observations
- two-phase ISM: WNM and MC
- $\tau_{\text{SF}} = 0.5$ Gyr
- amorphous carbon & silicate
4-1. ALMA reveals dust formed in SN 1987A

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

→ SNe could be production factories of dust grains
4-2. Dependence of dust radii on SN type

- condensation time of dust 300-700 d after explosion
- total mass of dust formed
  - 0.167 M$_{\odot}$ in SN IIb
  - 0.1-1 M$_{\odot}$ in SN II-P

- the radius of dust formed in H-stripped SNe is small
  - SN IIb without massive H-env $\rightarrow$ adust $< 0.01$ μm
  - SN II-P with massive H-env $\rightarrow$ adust $> 0.01$ μm

4-3. Destruction of dust in Type IIb SNR

Almost all of the newly formed grains are finally destroyed in shocked gas

- small radius of newly formed dust
- early arrival of reverse shock at the ejecta


Gas density in SN IIb is much smaller than in SNe II-P
4-4. Dust formation and evolution in SNe Ia

- condensation time: 100-300 days
- average radius of dust: \( a_{\text{ave}} \approx 0.01 \mu m \)
- total dust mass: \( M_{\text{dust}} \approx 0.1 M_{\odot} \)

→ SNe Ia are unlikely to be major sources of dust

Dust destruction in SNRs

5. Summary of this talk

We investigate the evolutions of grain size distribution and the extinction curve in galaxies.

- **early phase**: large grains (~0.1 μm) from SNe II and AGB stars → flat extinction curve
- **mid phase**: small grains (<0.03 μm) via shattering/grain growth → steep extinction curve
- **late phase**: shift of peak of size distribution due to coagulation → making extinction curve flatter

- our model can explain the unusual extinction curve and large amounts of dust grains observed for high-z quasars → a large fraction of molecular clouds, silicate and am.C

- envelope-stripped SNe (Type IIb, Ib Ia SNe) are not likely to be main sources of dust