Shattering and Coagulation of Dust Grains in Interstellar Turbulence

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Outline

1. Dynamical Grain-Gas Coupling
2. Interstellar Turbulence
3. Formulation of Shattering and Coagulation
4. In a Cosmological Context
1. Dynamical Grain-Gas Coupling

Dust is transported by gas ejection induced by stellar activity.

\[ V_{\text{escape}} = 280 \text{ km/s} \]

\[ 9 \text{ kpc} / 280 \text{ km/s} = 30 \text{ Myr} \]

Kaneda et al. (2009)

NGC 253

color: **AKARI** 90 µm

contour: **ROSAT** X-ray

The FIR extension coincides with the X-ray structure.

Dust is transported by gas ejection induced by stellar activity.
Grain-Gas Coupling

Gas drag timescale $t_d$:

$$m_{\text{gr}} = \frac{4}{3}\pi a^3 s$$

Grain motion is coupled with the gas motion on a scale $l$ large enough:

$$l \sim \nu t_d = \frac{(4/3)as}{m_H n_H} \sim \frac{10}{n_H}(a/0.1 \, \mu\text{m}) \, \text{pc}$$

Large grains tend to be coupled with larger motions.
2. Interstellar Turbulence

ISM is turbulent (often supersonic) (e.g., McKee & Ostriker 2007).

Implication for shattering (disruption):
\[ c_s \sim 10 \text{ km/s in warm (\sim 8000 K) medium} \rightarrow \text{above the shattering threshold (\sim a few km/s).} \]

Implication for coagulation (sticking):
\[ V_{\text{turb}} \gg \text{grain thermal speed.} \rightarrow \text{If grain motion is coupled with turbulence, grain-grain collision occurs frequently (e.g., Ossenkovpf 1993).} \]
Grain-Turbulence Coupling

Grain motion is coupled with the gas motion on a scale $l$ large enough:

$$l \sim v t_d = (4/3) a s / (m_H n_H) \sim (10/n_H)(a/0.1 \, \mu m) \, pc$$

Large grains tend to be coupled with larger motions.

Kolmogorov turbulence: $v_{turb} \propto l^{1/3}$

Large grains tend to acquire larger velocities.
Gyroresonance

Magnetic fields \((B^2/8\pi \sim nkT)\) + Grain charge
→ MHD wave + gyro-motion of grains
Resonance between wave and gyro-motion (gyroresonance): \(\omega - k_{//}v \cos \theta = n\omega_{\text{gyro}}\)

Large grains are further accelerated.
Grain Velocities

MHD turbulence model
hydro-drag, gyro-resonance

Yan, Lazarian, & Draine (2004)

Warm ionized medium
\[ T = 8000 \text{ K} \]
\[ n_H = 0.1 \text{ cm}^{-3} \]
\[ B = 3.4 \mu\text{G} \]

Warm neutral medium
\[ T = 6000 \text{ K} \]
\[ n_H = 0.3 \text{ cm}^{-3} \]
\[ B = 5.8 \mu\text{G} \]

Dense cloud
\[ T = 10 \text{ K} \]
\[ n_H = 10^4 \text{ cm}^{-3} \]
\[ B = 80 \mu\text{G} \]
Relative velocities can be excited by interstellar turbulence.

Shattering threshold:
2.7 km/s (silicate), 1.2 km/s (graphite)  
(Jones et al. 1996)

Coagulation rate = grain-grain collision rate  
Threshold: \(~ 10^3 \) cm/s
Grain Size Distribution and Extinction

Extinction (absorption+scattering)

\[ \tau_{\lambda,i} = \int_0^{\infty} \pi a^2 Q_\lambda(a) N_{\text{dust}}(a) da \]
\[ \tau_\lambda = \sum_i \tau_{\lambda,i} \]

\( i \): grain species (silicate, graphite)

Grain size distribution \( N_{\text{dust}}(a) \propto a^{-3.5} \)

with \( 0.005 \text{ \(\mu\)m} < a < 0.25 \text{ \(\mu\)m}: \) MRN

What determines the grain size distribution?

- Source (supernova, AGB stars, etc.)
- Shattering and coagulation?

Mathis, Rumpl, & Nordsieck (1977)
ISM Recycling and Dust

Nuclear reaction

star formation (astration)

molecular cloud (dust growth)

Interstellar gas

Gas

Metals

Dust

QuickTime Dz

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Turbulence is ubiquitous. → Grains are processed in turbulence?
Specific Questions

A) Evolution of grain size distribution by shattering and coagulation under the grain motion induced by *ubiquitous* turbulence.

B) Do shattering and coagulation have a significant imprint in the extinction curve?
3. Formulation

Discrete size bins $a_0, ..., a_N$
The $i$-th bin contains grains of

\[ \tilde{\rho}_i \text{ [g cm}^{-3}\text{]} \]

**Shattering**

\[
\frac{d\tilde{\rho}_i}{dt}_{\text{shat}} = -m_i \tilde{\rho}_i \sum_{k=1}^{N} \alpha_{ki} \tilde{\rho}_k + \sum_{j=1}^{N} \sum_{k=1}^{N} \alpha_{kj} \tilde{\rho}_k \tilde{\rho}_j m^{kj}_{\text{shat}}(i),
\]

\[ \alpha_{ki} = \begin{cases} \frac{\sigma_{ki} v_{ki}}{m_i m_k} & \text{if } v_{ki} > v_{\text{shat}}, \\ 0 & \text{otherwise}, \end{cases} \]

**Coagulation**

\[
\frac{d\tilde{\rho}_i}{dt}_{\text{coag}} = -m_i \tilde{\rho}_i \sum_{k=1}^{N} \alpha_{ki} \tilde{\rho}_k + \sum_{j=1}^{N} \sum_{k=1}^{N} \alpha_{kj} \tilde{\rho}_k \tilde{\rho}_j m^{kj}_{\text{coag}}(i),
\]

\[ \alpha_{ki} = \begin{cases} \frac{\sigma_{ki} v_{ki}}{m_i m_k} & \text{if } v_{ki} < v_{\text{coag}}, \\ 0 & \text{otherwise}. \end{cases} \]

The grain velocities are adopted from Yan et al. (2004) (MHD turbulence).

Hirashita & Yan (2009)
Grain Velocities

MHD turbulence model
hydro-drag, gyro-resonance

Yan, Lazarian, & Draine (2004)

Warm ionized medium
$T = 8000 \text{ K}$
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Warm neutral medium
$T = 6000 \text{ K}$
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Dense cloud
$T = 10 \text{ K}$
$n_H = 10^4 \text{ cm}^{-3}$
$B = 80 \mu \text{G}$
Results

Shattering of large grains on a short timescale

Upper limit?

Small grains are strongly depleted.

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\( T = 8000 \text{ K} \)
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\( B = 80 \mu \text{G} \)
Effects on the Extinction Curves

1. The UV slope correlates with the bump strength in the right sense.
2. The central position of the carbon bump is unchanged.
3. Small variation in IR extinction curve.

Shattering and Coagulation in ISM can regulate the grain size distribution (and the extinction curve).
4. In a Cosmological Context

Dust already existed at $z \sim 6$ (Bertoldi et al. 2003).

Extinction curve at $z \sim 6$

Maiolino et al. (2004)

Suggesting a rapid dust enrichment by supernovae
Shattering of SN Dust

Small grain production by shattering contributes to the steepness of the UV extinction curve (in solar metallicity).

Hirashita et al. (2010)
Hirashita (2010)

extinction curve at $z = 6.2$
(Maiolino et al. 2004)
Scenario as a Summary

(1) The grain size distribution in the formation by supernovae (or AGB stars) is not processed by turbulence if the metallicity is \(< 1/10 Z_\odot\).

(2) After the metallicity enrichment, grain processing in ISM should be considered.

(3) In considering the origin of the grain size distribution at the present cosmic age, interstellar processing by turbulence should be important (occurs everywhere \(\rightarrow\) easy to explain the universality).
Thank you.
3. Effects of Coagulation on SF

Hirashita & Omukai (2009)

(1) How about the denser regime?
(2) Importance of dust grains in star formation:
   A) H$_2$ formation (H$_2$ is an efficient coolant for $Z < 0.01 Z_\odot$) $\Rightarrow$ The grain surface $S$ is important.
   B) Dust cooling $\Rightarrow$ The grain opacity $\kappa_P$ is important.

We calculate the variation of $S$ and $\kappa_P$ in star-forming (collapsing) clouds.

Grain motion is assumed to be thermal.
Gas Evolution in Collapsing Clouds

H$_2$ formation on grain surface: important coolant for log ($Z/Z_\odot$) < −2

Omukai et al. (2005)

Numbers = log ($Z/Z_\odot$)

Schneider et al. (2004)

dust cooling (induce fragmentation)

Omukai et al. (2005)

Schneider et al. (2004)
Change of Grain Surface and Opacity by Coagulation
Change of Grain Surface and Opacity by Coagulation
Physical Considerations

☆ Grain surface is dominated by small grains. → Once the smallest grains are affected by coagulation, $S$ begins to decrease (however, $H_2$ formation occurs faster).

• $t_{ff} > t_{coag} \iff n_H > 10^7 (Z/Z_\odot)^{-2} (T/30 \text{ K})^{-1} \text{ cm}^{-3}$

☆ Opacity ($\kappa_p \propto \pi a^2 Q_\lambda \propto a^3$) is only a function of mass as long as $a \ll \lambda$. ⇒ $\kappa_p$ does not change even if coagulation proceeds.

Coagulation has no effect on the thermal evolution in protostellar collapse.
1. Dust Grains in Galaxies

- Gas, plasma (heating by supernovae, stellar radiation, etc.; radiative cooling)
- Turbulence
- Magnetic fields
- Condensation of dust grains

- Formation/ejection of heavy elements ($\geq \text{C}$)