The Physics of Dust Evolution

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The Evolution of Dust: Physical Processes

**Formation:**
- Chemical kinetics
- Stellar winds and SN ejecta

**Destruction:**
- Sputtering, g-g collisions
- Diffuse ISM

**Buildup:**
- Asteroids, planetesimals
- Debris disks

**Evaporation:**
- Star formation
- Dense ISM

**Processing:**
- Accretion, coagulation
- Dense ISM
Dust Formation in CCSN Ejecta

Classical Nucleation Theory (CNT)

- Presence of radioactive $^{56}$Ni
- Hard radiation, fast electrons, ions He+, Ne+, Ar+ that break down stable molecules, SiO, CO
- Clumpy, stratified composition
- Mixing between layers
- Reverse shocks
- Uncertain composition and final yields

Molecular Kinetics

Addition of metals

<table>
<thead>
<tr>
<th>$\Delta G$</th>
<th>Oxidation</th>
<th>Addition of metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta G_{\text{surf}} = 4\pi R^2 \gamma$</td>
<td>$\Delta G_{\text{surf}} = -\frac{4\pi}{3} R^3 \rho_s \Delta \mu$</td>
<td>$\Delta G_{\text{surf}} = 187.4$</td>
</tr>
<tr>
<td>$\Delta G_{\text{surf}} = 187.4$</td>
<td>$\Delta G_{\text{surf}} = -76.3$</td>
<td>$\Delta G_{\text{surf}} = 238.2$</td>
</tr>
<tr>
<td>$\Delta G_{\text{surf}} = -76.3$</td>
<td>$\Delta G_{\text{surf}} = -143.4$</td>
<td>$\Delta G_{\text{surf}} = 96.8$</td>
</tr>
<tr>
<td>$\Delta G_{\text{surf}} = -143.4$</td>
<td>$\Delta G_{\text{surf}} = -298.7$</td>
<td>$\Delta G_{\text{surf}} = 11.2$</td>
</tr>
<tr>
<td>$\Delta G_{\text{surf}} = -298.7$</td>
<td>$\Delta G_{\text{surf}} = -357.8$</td>
<td>$\Delta G_{\text{surf}} = -49.7$</td>
</tr>
<tr>
<td>$\Delta G_{\text{surf}} = -357.8$</td>
<td>$\Delta G_{\text{surf}} = -553.6$</td>
<td>$\Delta G_{\text{surf}} = -687.5$</td>
</tr>
</tbody>
</table>
Sputtering

- Dependence on incident angle of projectiles
- Finite grain size
- Non-stochiometric sputtering
- Step-size in the Monte-Carlo simulations

TRIM/SRIM Monte-Carlo simulations of particle stopping power and sputtering yields in solids

Very preliminary comparisons
**Grain-grain collisions**

**Theoretical approach**
Shock wave in solids
(Tielens + 1994)

**Semi-empirical approach**
Theory+Lab data on cm-size solids
(Fujiwara+1989, Melosh+1992; Borkowski & Dwek 1994)

- impact velocity (shock strength)
- density, (porosity)
- size, composition
- eq. of state
- compressibility
- defects in solid
- tensile strength
Grain Destruction by SNR

Mass of dust destroyed by single SNR
(e.g. Slavin +2015; Hu + 2019)

$$m_d = Z_d \int_{v_0}^{v_f} f_d(v_s) \left[ \frac{dM_{ISM}}{dv_s} \right] dv_s$$

Dust lifetime (Dwek & Scalo 1980)

$$\tau_d(t) \equiv \frac{M_d}{m_d R_{SN}}$$

<table>
<thead>
<tr>
<th></th>
<th>$m_d[M_\odot]$</th>
<th>$\tau_d[\text{Gyr}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slavin+ 2015</td>
<td>~ 1.5</td>
<td>2-3</td>
</tr>
<tr>
<td>sput + g-g coll</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hu+ 2019</td>
<td>~ 1.4</td>
<td>0.4</td>
</tr>
<tr>
<td>sputtering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ISM morphology
- ISM density
- B-field
- Shock energy
- SN rate
- Correlated SNe
- Grain size distribution
- Total dust mass in ISM
Dust Lifetime in LMC-SMC

(Temim + 2015)

- ISM morphology
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\[
\begin{array}{|c|c|c|}
\hline
\text{ISM} & m_d [M_\odot] & \tau_d [M \text{yr}] \\
\hline
\text{LMC} & 2 - 6 & 10 - 50 \\
\text{SMC} & 1 - 3 & 20 - 110 \\
\hline
\end{array}
\]

Dust destruction rate
\[ \sim 2 \times 10^{-2} \ M_\odot \text{yr}^{-1} \]

Dust formation rate
\[ \sim 1 \times 10^{-3} \ M_\odot \text{yr}^{-1} \]
Accretion in Dense ISM

THE EVOLUTION OF REFRACTORY INTERSTELLAR GRAINS
IN THE SOLAR NEIGHBORHOOD
Dwek & Scalo 1980

 Problems that need to be resolved in accretion models

✦ Nature of impinging molecules and accretion sites
✦ Compositions (MgO, SiO\textsubscript{2}, refractory organics), sticking probabilities
✦ The origin if the interstellar depletion pattern
✦ The properties of the regrown dust are not the same as regular interstellar dust
✦ In particular, cold accretion will not form the SiO\textsubscript{4} tetrahedral structure needed to give rise to the 9.7 and 18 µm silicate emission features
✦ Amount of needed accretion still uncertain
✦ Uncertain rates of dust production and destruction
✦ Iron is SOFAR the only element that needs to be grown in the ISM independent on grain destruction rates
In galaxy cluster simulations (Gjergo + 2018)

In galaxy mergers

Fundamental issues

✦ Fate of dust in galaxy merger/assembly process
✦ Grain destruction efficiency (too high)
✦ Grain growth in the dense ISM (dust properties do not match the general ISM)
✦ How does the grain size evolve (two size approx)
The very presence of dust in the universe highlights the many physical processes that lead to the formation, survival, destruction, and reformation of dust in the various sources and the general ISM.

Understanding these processes is a major challenge in astrophysics.
END