Dust sputtering by supernova shocks in hydrodynamical simulations

arXiv:1902.01368

Chia-Yu Hu (CCA)

with Svitlana Zhukovska, Rachel Somerville, Thorsten Naab

Dusting the Universe, UA, Tucson

04.03.2019
Dust is an important component of the ISM

Dust provides **photoelectric heating**

Molecular hydrogen ($H_2$) forms on the surfaces of dust

Dust modifies the **spectra of galaxies**
Dust is an important component of the ISM

However, dust is either totally neglected in galaxy formation simulations, or is assumed to linearly scales with metals, which is an oversimplification.

Need to account for dust evolution in galaxy formation simulations!
Dust evolution in cosmological simulations

Hydrodynamical simulations (McKinnon et al. 2015)

Semi-analytic models (Popping et al. 2017)
Dust evolution in cosmological simulations

Large-scale cosmological simulations can only reach ~kpc resolution, which is too poor to follow the small-scale physics, e.g. dust destruction in SN shocks, dust growth in the ISM, etc.

Therefore, very crude sub-grid models have to be adopted to follow dust evolution

$$\left( \frac{dM_{i,\text{dust}}}{dt} \right)_d = - \frac{M_{i,\text{dust}}}{\tau_d}$$
Modeling the small-scale physics directly

**Sputtering:** collision between gas and dust return dust material into gas phase

\[
\frac{dm_{\text{dust}}}{dt} = \frac{3n_H m_{\text{dust}}}{a} Y_{\text{tot}}
\]

One-fluid approach: dust is spatially coupled with gas

But with nonzero dust-gas relative velocity \( v_{\text{rel}} \)

\( \rightarrow \) integrate the equation of motion for dust

\[
\frac{dv_{\text{rel}}}{dt} = a_{\text{drag}} + a_{\beta \text{eta}} - a_{\text{hydro}}
\]

- direct collision
- plasma drag
- betatron acceleration

\[
Y [\mu m \text{ yr}^{-1} \text{ cm}^3] \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5}
\]

thermal sputtering

\[
T [K] \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \quad 10^{10}
\]

- C
- Si

\[
Y [\mu m \text{ yr}^{-1} \text{ cm}^3] \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5}
\]

nonthermal sputtering

\[
v_{\text{rel}} [\text{km/s}] \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5
\]
Dust destruction by single SN in a uniform medium

Nonthermal sputtering dominates in typical SN environments

![Graph showing dust destruction by single SN in a uniform medium](image-url)
Dust destruction in a **multiphase ISM**

**Gas properties:**

- $\log_{10}(\Sigma_{\text{gas}} [M_\odot \text{ pc}^{-2}])$
- $\log_{10} n_{\text{H}} [\text{cm}^{-3}]$
- $\log_{10} T [\text{K}]$

**Dust properties:**

- $\log_{10}(\text{GDR}_{\text{C}+\text{Si}})$
- $\log_{10}(\text{DGR}_C)$
- $\log_{10}(\text{DGR}_S)$

*Movie here*
Dust destruction timescales

\[ \tau = \frac{M_{\text{gas}}}{\delta_{\text{SN}} R_{\text{SN}} M_{\text{cl}}} \]

(N.B. depending on the assumed SN rate and energy!)

<table>
<thead>
<tr>
<th></th>
<th>R2-rand</th>
<th>R1-rand</th>
<th>R2-lin</th>
<th>R1-lin</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{\text{Si}} ) (Gyr)</td>
<td>0.35</td>
<td>0.50</td>
<td>0.23</td>
<td>0.36</td>
</tr>
<tr>
<td>( \tau_{\text{C}} ) (Gyr)</td>
<td>0.44</td>
<td>0.64</td>
<td>0.29</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Comparing to the single SN results

Applying the results of single SN to the SNe in the multi-phase ISM, destruction times become ~ 40% lower than the actual values.

SNe that occur in preexisting bubbles do not destroy dust as efficiently since **there is little dust left**
- Effectively reduce the SN rate by 0.4
DGR spatial variations

Dust destruction + incomplete turbulent gas mixing

25% DGR deficit in the volume-filling warm phase (10^4K) relative to the cold clouds (10^2K)
Summary

First attempt in following the dust destruction directly in 3D hydro simulations:
- nonthermal sputtering dominates for typical SN environments
- $\tau \sim 0.4$ Gyr for solar-neighborhood conditions (slightly faster for silicate dust)
- SN correction factor $\sim 0.4$ comes out naturally from simulations
- DGR deficit $\sim 25\%$ in the warm phase ($10^4$K) relative to the cold phase ($10^2$K)

Future directions:
- dust growth in the ISM, AGB dust
- evolution of size distribution
- applications to dwarf galaxies, high-z galaxies
Backup slides
Dust destruction by single SN in a uniform medium

\[
\frac{dm_{\text{dust}}}{dt} = \frac{3n_H m_{\text{dust}}}{a} Y_{\text{tot}}
\]

Small grains destroyed via nonthermal sputtering

Large grains destroyed via thermal sputtering

Non-thermal

Grain size

destroyed dust mass

\( n_H = 0.1 \text{ cm}^{-3} \)

\( M_{\text{dust}}^a [M_{\odot}] \)

\( a [\mu m] \)

Grain size

\( 10^{-2} \)

\( 10^{-1} \)

\( 10^0 \)

\( 10^{-2} \)

\( 10^{-1} \)
SN environments
Convergence study for single SN sputtering

![Graphs showing convergence study for single SN sputtering](image)