Cosmological Simulations of Cosmic Dust

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Dust grains have little mass but big impact

Solid dust grains reradiate $\sim 30\%$ of stellar light in IR, but dust-to-gas mass ratio in ISM only $\sim 1\%$

Jessberger+ (2001)  
Perets+ (2006), NASA
Galactic extinction curves show significant variation

Extinction measured using sightlines to background stars

Fitzpatrick+ (2007)
Key points

1. Cosmological simulations can make predictions of the dust distribution in galaxies and on large scales

2. Models can self-consistently couple the dynamical motion and size evolution of ISM dust grains
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Dust in cosmological simulations

- My thesis aims to model dust physics in the code AREPO.

- Here, dust treated as a component of gas cells.

- Many models track dust in postprocessing, not on-the-fly.

Springel (2010)

Sources: dust injection from stars, accretion of metals in ISM
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Sinks: destruction of dust by SN shocks, thermal sputtering
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For now, only evolve dust mass; will address grain sizes later
First application: eight Milky Way-sized haloes

McKinnon+ (2016)
Benchmark model against low redshift scalings

Observed scalings connect dust mass to other quantities

\[ \log(M_{\text{dust}}/M_*) \]

\[ \log(D) \]

\[ \log(M_{\text{gas}}/(M_* + M_{\text{gas}})) \]

\[ \log(M_*/M_{\odot}) \]

Corbelli+ (2012)

McKinnon+ (2016)
Dust mass function evolves with redshift

Predicted dust mass function similar to observations at $z = 0$, but underproduction of dust-rich galaxies at high $z$.
Comoving dust density versus observations

Observations suggest dust density may peak near $z \sim 1 - 2$
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Dust density evolution may be less like stellar mass density, more like SFR density

McKinnon+ (2017)
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2. Models can self-consistently couple the dynamical motion and size evolution of ISM dust grains.
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Drag couples dust to hydrodynamic motion

Track dynamics of dust particles subject to drag (and gravity)
Drag couples dust to hydrodynamic motion

Track dynamics of dust particles subject to drag (and gravity)

Amounts to force in dust and gas equations of motion

\[
\begin{align*}
\frac{dv_d}{dt} &= - \frac{K_s(v_d - v_g)}{m_d} + a_{d,ext} \\
\frac{dv_g}{dt} &= - \frac{\nabla P}{\rho_g} + \rho_d K_s(v_d - v_g) \frac{1}{\rho_g m_d} + a_{g,ext}
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stopping time-scale \( t_s = \frac{m_d}{K_s} \propto a\rho_{\text{grain}}/\rho_g c_s \)
Drag induces variations in dust-to-gas ratio

Dust lags behind gas in Sedov blast wave

McKinnon+ (2018)
Drag induces variations in dust-to-gas ratio

Dust lags behind gas in Sedov blast wave

McKinnon+ (2018)
Stars, gas, and dust grains coevolve

number-conserving

accretion
sputtering
dust-gas

mass-conserving

shattering
coaagulation
dust-dust

SN shocks

stellar yields
dust condensation
dust production

Mckinnon+ (2018)
Model grain sizes using dust ensemble particles

Parallels star particles with masses following an IMF

Characterize individual dust particles by grain size distributions, which can evolve in time

McKinnon+ (2018)
Simulate idealized galaxy with grain size evolution

Track spatial and size distributions of grains self-consistently
Simulate idealized galaxy with grain size evolution

Track spatial and size distributions of grains self-consistently

McKinnon+ (2018)
Grain physics models predict different sizes

Model including grain-grain collisions produces small grains, rise in extinction from optical to UV

Comparison of grain size distributions

Mock extinction along line of sight

- Dust from stars only
- Dust from stars, dust-gas collisions
- Dust from stars, dust-gas collisions, dust-dust collisions

McKinnon+ (2018)
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