Is the Dust-to-Gas ratio constant in molecular clouds?

Terrence Tricco
Canadian Institute for Theoretical Astrophysics
ttricco@cita.utoronto.ca
http://cita.utoronto.ca/~ttricco

Daniel Price, Monash (Australia)
Guillaume Laibe, Lyon (France)
Dust as a Measure of Gas Mass

- $\text{H}_2$ effectively invisible
- Dust distribution correlates well with molecules
- Use dust or molecular tracers to infer cloud mass
- Requires understanding of the dust properties to have accurate mass measurements
Anomalous extinction laws:

- $R_v = A_v / (A_B - A_v) = 3.1$ in diffuse clouds (fairly “universal”), but $R_v \sim 5$ in molecular clouds (Cardelli+ 1989; Weingartner & Draine 2001)
- Implies molecular clouds have a different grain size distribution

Coreshine phenomenon:

- higher abundance of large grains (>1 micron) in dense filaments (Pagani+ 2010; Steinacker+ 2010; Lefevre+ 2014)

- e.g., Evans et al 2009 dust re-calibration of c2d data resulted in 40% change of cloud mass

Weingartner & Draine (2001)
Dust is not gas!

• Dust behaves dynamically different than gas
• But would it have a noticeable effect?
• Let’s do some simple napkin math
  • $\rho \sim 10^{-20}$ g/cm$^3$ (gas density)
  • $c_s \sim 0.2$ km/s, (sound speed)
  • $s_{\text{grain}} \sim 0.1$ micron (grain size)
  • $\rho_{\text{grain}} \sim 3$ g/cm$^3$ (intrinsic grain density)

  ➢ Drag stopping timescale, $t_s \sim \rho_{\text{grain}} s_{\text{grain}} / \rho \sim 10^3$ yrs
  ➢ Expect well-mixed and coupled mixture of dust and gas (High drag regime.)

• But this assumes cloud is homogenous and ignores turbulence!
• Could supersonic turbulence cause dynamical variations in the dust-to-gas ratio?
“dust filaments can exist where there is no gas filament at all”

“exhibit dramatic (exceeding factor $\sim 1000$) fluctuations in the local dust-to-gas ratio”

Hopkins & Lee (2016); Lee, Hopkins & Squire (2017)
Dust & Gas Mixtures in High Drag

• **Timestep criterion**: drag stopping timescale, $t_s$
• **Spatial criterion**: resolve ‘stopping length’ of dust grains to be in the gas, $l_s \sim c_s \times t_s$ (Price & Laibe 2012)
  - For $\sim 0.1$ micron dust grains in cold, dense molecular clouds, require $\sim 1600^3$ gas elements (even stricter in dense filaments!)

• Tracer particles in compressible turbulence are known to suffer from numerical artefacts (Price & Federrath 2010; Genel et al 2013)

“it is notable that a dense shock structure appears in the [tracer particles] that is completely absent from both SPH and grid density fields”

“the resulting [density] PDFs show a strong deviation from a lognormal distribution, particularly in the high density tail”

“the velocity field tracers display structures that do not exist in the gas distribution”
One fluid approach (Laibe & Price 2014a,b; Price & Laibe 2015)

- Change of variables; each element is mixture of dust and gas

\[
\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \mathbf{v}_g) = 0
\]

\[
\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \mathbf{v}_d) = 0
\]

\[
\rho_g \left( \frac{\partial \mathbf{v}_g}{\partial t} + \mathbf{v}_g \cdot \nabla \mathbf{v}_g \right) = \rho_g \mathbf{f} + K(\mathbf{v}_d - \mathbf{v}_g) - \nabla P_g
\]

\[
\rho_d \left( \frac{\partial \mathbf{v}_d}{\partial t} + \mathbf{v}_d \cdot \nabla \mathbf{v}_d \right) = \rho_d \mathbf{f} - K(\mathbf{v}_d - \mathbf{v}_g)
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = - \nabla P_g \rho - \frac{1}{\rho} \nabla \cdot \left( \frac{\rho \rho_d}{\rho} \Delta \mathbf{v} \right)
\]

\[
\frac{\partial \Delta \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \Delta \mathbf{v} = \frac{\nabla P_g}{\rho} - \frac{\Delta \mathbf{v}}{t_s} - (\Delta \mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{2} \nabla \left( \frac{\rho \rho_d - \rho \rho_g}{\rho} \Delta \mathbf{v}^2 \right)
\]

- Ideal when dust and gas well coupled
- No spatial resolution criterion since gas/dust are combined
- Accurate for stopping time short when gas/dust move together


**Dust/Gas: Barycentric Point of View**

One fluid approach (Laibe & Price 2014a,b; Price & Laibe 2015)

- Change of variables; each element is mixture of dust and gas

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\]

**Gas mass conservation**

\[
\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \mathbf{v}_d) = 0
\]

**Dust mass conservation**

\[
\rho_g \left( \frac{\partial \mathbf{v}_g}{\partial t} + \mathbf{v}_g \cdot \nabla \mathbf{v}_g \right) = \rho_g \mathbf{f} + K(\mathbf{v}_d - \mathbf{v}_g) - \nabla P_g
\]

**Gas momentum conservation**

\[
\rho_d \left( \frac{\partial \mathbf{v}_d}{\partial t} + \mathbf{v}_d \cdot \nabla \mathbf{v}_d \right) = \rho_d \mathbf{f} - K(\mathbf{v}_d - \mathbf{v}_g)
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**Dust momentum conservation**

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**Total mass conservation**

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{\nabla P_g}{\rho} - \frac{1}{\rho} \nabla \cdot \left( \frac{\rho_g \rho_d}{\rho} \Delta \mathbf{v} \Delta \mathbf{v} \right)
\]

**Total momentum conservation**

\[
\frac{\partial}{\partial t} \left( \frac{\rho_d}{\rho} \right) + \mathbf{v} \cdot \nabla \left( \frac{\rho_d}{\rho} \right) = -\frac{\rho}{\rho^2_g} \nabla \cdot \left( \frac{\rho_g \rho_d}{\rho} \Delta \mathbf{v} \right)
\]

**Dust/gas ratio**

\[
\frac{\partial \Delta \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \Delta \mathbf{v} = -\frac{\nabla P_g}{\rho_g} \frac{\Delta \mathbf{v}}{t_s} - (\Delta \mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{2} \nabla \left( \frac{\rho_d - \rho_g}{\rho^2} \Delta \mathbf{v}^2 \right)
\]

**Differential velocity**
Supersonic Dusty Turbulence

Modelled turbulent dynamics of dusty molecular clouds using the Phantom SPH code (Price et al, 2017; phantomsph.bitbucket.io)

- Not concerned with grain growth or destruction
- No self-gravity (not trying to make stars) or magnetic fields

Initial Conditions:
- $L = 3$ parsec, $\rho = 10^{-20}$ g/cm$^3$ (peak $\rho \sim 10^{-17}$ g/cm$^3$)
- Isothermal gas with $T= 11.5$ K, $c_s = 0.2$ km/s
- Mach 10 turbulence driven on large scales for $\sim 14$ Myr

Dust:
- 0.1, 1 and 10 micron dust grains (3 separate simulations)
- Initially uniform 1% dust-to-gas mass ratio
- Includes back-reaction of dust on gas

http://phantomsph.bitbucket.io
• Large-scale column dust density traces gas column density for all grain sizes
• For 10 micron, local variations in dust column density relative to gas column density
• Almost no variation in dust-to-gas ratio for 0.1 micron grains
• Large, 10 micron grains typical variations of ∼2-3x (max ∼10x)
Slices through midplane of cloud
• ~0.1 micron grains:
  • Sharply peaked PDF of dust-to-gas ratios at 1%
  • Dust density distribution matches gas (well-coupled throughout cloud)
• 1-10 micron grains:
  • PDFs broaden with increasing grain size due to ‘size-sorting’
  • Turbulence causes dynamical transfer of dust mass into high density filaments

Gas and Dust Density Distributions

• ~0.1 micron grains:
  • Sharply peaked PDF of dust-to-gas ratios at 1%
  • Dust density distribution matches gas (well-coupled throughout cloud)
• 1-10 micron grains:
  • PDFs broaden with increasing grain size due to ‘size-sorting’
  • Turbulence causes dynamical transfer of dust mass into high density filaments
Is the Dust-to-Gas Ratio Constant?

**Yes!** For ~0.1 micron grains, turbulence almost no effect since dust is well-coupled to gas throughout the cloud.

**No!** For ≥ 1 micron grains, turbulence causes typical variations ~2-3x.
• We find that **0.1 micron dust grains remain well-coupled to the gas** throughout a molecular cloud

• We **do not find orders of magnitude fluctuations** for \( \sim 0.1 \) micron dust grains, contrary to Hopkins & Lee (2016)

• Local, small-scale variations of dust-to-gas ratio for large grains (>1 micron) can occur, with typical increases of \( \sim 40\% \) up to 2-3x

• **A maximum of 10x increase for 10 micron** dust grains (max dust-to-gas ratio of 1:10)

• ‘**size-sorting’**: preferential concentration of large grains into filaments due to changes in dust-stopping times between filaments and lower density gas
  ➢ May be relevant for coreshine

• These are dynamical effects – **not grain growth**!