Dust settling in turbulent protoplanetary disks

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Diversity of planetary systems

As of September 2018:
- Over 3700 extra-solar planets detected
- Over 2800 planetary systems
- Wide range of orbital configurations, sizes
Planets form in accretion disks around young stars

M. Liu (IfA/Hawaii)
A new era for planet formation

V1094 Sco

Elias 24

(van Terwisga et al. 2018)

(Dipierro et al. 2018)
Dusty gas in protoplanetary disks

**Dust**

Dusty gas dynamics

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**Gas**

HL Tau (Yen et al., 2016)
Dusty gas in protoplanetary disks

Disk-planet interaction?

(Chen & Lin, 2018)
Dusty gas in protoplanetary disks

Gas and dust don’t always correlate

AB Aurigae, (Tang et al. 2017)
Protoplanetary discs are $\sim 99\%$ gas, $\sim 1\%$ dust
Planets form from the solids (at least in core accretion)
From dust to planets

Disk of gas and dust spinning around young Sun

Dust grains

Dust grains clump into planetesimals

Planetesimals collide and collect into planets
From dust to planets

μm grains

mm-cm grains

sticking

km planetesimals

protoplanets

gravity

Disk of gas and dust spinning around young Sun

Dust grains

A

mm-cm grains

Dust grains clump into planetesimals

B

Planetesimals collide and collect into planets

μm grains
From dust to planets

- From dust to planets
- μm grains
- mm-cm grains
- sticking
- km planetesimals
- protoplanets
- gravity
- HOW?

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From dust to planets

- Dust-trapping by gas vortices (Barge 1995, Lyra & Lin, 2013)
- Secular gravitational instabilities (Youdin 2011; Takahashi & Inutsuka, 2014)
- **Streaming instability** (Youdin & Goodman, 2005)
Planetesimal formation by the streaming instability

\[
\frac{\rho_{\text{dust}}}{\rho_{\text{gas}}}
\]

Two-phase instability driven by dust-gas friction

- Subtle physics \(\rightarrow\) see Lin & Youdin (2017) for a recent interpretation

(Chen & Lin, 2018)
Planetary formation by the streaming instability

(SI with self-gravity, Simon et al., 2017)
Strong clumping by SI requires \( \rho_{\text{dust}} \sim \rho_{\text{gas}} \) to begin with
Planetesimal formation by the streaming instability

Strong clumping by SI requires $\rho_{\text{dust}} \sim \rho_{\text{gas}}$ to begin with

$\frac{\rho_d}{\rho_g} \sim 0.01$ in ISM

HOW?

$\frac{\rho_d}{\rho_g} \sim 1$ for SI
Enhancing the dust-to-gas ratio in protoplanetary disks

Dust settling?

- Yes... if the disc is laminar
Instabilities in protoplanetary disks

Classic sources of turbulence

- Magneto-rotational instability (Balbus & Hawley 1991)
  - Needs enough ionization
- Gravitational instability (Gammie, 2001)
  - Needs a massive disk
Instabilities in protoplanetary disks

Newly (re)discovered sources of turbulence

- Zombie vortex instability (Marcus et al., 2015)
- Convective overstability (Klahr & Hubbard, 2014)
- Vertical shear instability (Nelson et al., 2013)

(Malygin et al., 2017; Lyra & Umurhan, 2018)
Vertical shear instability

\[ \Box \Omega = \Omega_{\text{Kep}}(r) + \text{correction}(r, z) \]

\[ \frac{\partial \Omega}{\partial z} \neq 0 \]

(Because \( \nabla P \times \nabla \rho \neq 0 \))
Vertical shear instability

$\partial_z \Omega \neq 0 \Rightarrow$ free energy $\rightarrow$ instability?

- Change in kinetic energy:

$$\Delta E \sim l_r^2 \left( \Omega^2 + \frac{l_z}{l_r} \cdot r \frac{\partial \Omega^2}{\partial z} \right)$$

- $\Delta E < 0 \Rightarrow$ unstable
  - Possible for vertically elongated disturbances.
  - Essentially a Rayleigh-type instability
  - Needs rapid cooling to overcome buoyancy forces $\rightarrow$ most unstable for isothermal gas
Vertical shear instability

\[ \partial_z \Omega \neq 0 \Rightarrow \text{free energy} \rightarrow \text{instability?} \]

- VSI \rightarrow \text{large-scale up/down motions}
  
  (Lin, in prep.)

Can dust particles still settle?
Lin & Youdin (2017), built upon Laibe & Price (2014) found:

**Implicit modelling of dust-gas friction or drag:**

\[
\rho_d \frac{\partial v_d}{\partial t} |_{\text{drag}} = -\rho_g \frac{\partial v_g}{\partial t} |_{\text{drag}} = -\frac{\rho_d \rho_g}{\rho_{\text{tot}}} \frac{(v_d - v_g)}{t_{\text{stop}}}.
\]

- \( t_{\text{stop}} \propto \text{particle size} \)
Modeling dusty-gas without dust

Lin & Youdin (2017), built upon Laibe & Price (2014) found:

dust+polytropic gas+drag

equivalent for small particles

hydrodynamics+cooling

\[ \begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} &= -\frac{1}{\rho} \nabla P - \nabla \Phi, \\
\frac{\partial P}{\partial t} + \mathbf{v} \cdot \nabla P &= -\Gamma P \nabla \cdot \mathbf{v} + P \mathbf{v} \cdot \nabla \ln K \\
&+ \frac{\Gamma P}{\rho_{gas}} \nabla \cdot (f_{dust} t_{stop} \nabla P).
\end{align*} \]

- \( \rho \) = total density; \( \mathbf{v} \) = center of mass velocity
- **Dust-gas friction**, \( f_{dust} \): dust-fraction, \( t_{stop} \propto \) particle size
Lifting dust particles by the VSI

- \( c_s^2 \propto R^{-q}, \partial_z \Omega \propto q = 0.5 \)

Moderately turbulent disk
Lifting dust particles by the VSI

- \( c_s^2 \propto R^{-q} \), \( \partial_z \Omega \propto q = 1 \)

Strongly turbulent disk
Dust settling against VSI turbulence

- Particle size \( \propto T_{\text{stop}} \)
- Settling only occurs for \( \alpha_z < T_{\text{stop}} \) or \( \text{Particle size} > \text{turbulent stirring} \)

Consistent with theory (Dubrulle et al., 1995)
Effect of particle size ($T_{\text{stop}}$)

- Large particles settle faster ($t_{\text{settle}} \propto 1/T_{\text{stop}}$)
- Large particles settle to a thin layer and weakens subsequent VSI stirring
Particle back-reaction on the gas

- Dust-on-gas coupling *adds weight* (inertia) but *not pressure* (restoring force)
- Dust-loading induces a vertical buoyancy frequency $N_z$
- Buoyancy stabilize vertical motions of the VSI $\rightarrow$ reduced turbulence
Particle back-reaction on the gas

- Dust-on-gas coupling adds weight (inertia) but not pressure (restoring force)
- Dust-loading induces a vertical buoyancy frequency $N_z$
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$T_{\text{stop}} = 0.001$

$T_{\text{stop}} = 0.01$
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

- $\Sigma_d = 0.01\Sigma_g$
- $\Sigma_d = 0.03\Sigma_g$

Increasing the overall dust content makes the system ‘heavy’ → more difficult for VSI to stir up
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

- $\Sigma_d = 0.01\Sigma_g$
- $\Sigma_d = 0.1\Sigma_g$

Increasing the overall dust content makes the system ‘heavy’ $\rightarrow$ more difficult for VSI to stir up
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

- $\Sigma_d = 0.01\Sigma_g$
- $\Sigma_d = 0.1\Sigma_g$

Increasing the overall dust content makes the system ‘heavy’ → more difficult for VSI to stir up

- Dense particle layer is self-stabilized against VSI
Self-sustained settling

- Dust settles
- Weakens turbulence
- Induces buoyancy
- Increase particle size
- Decrease vertical shear
- Increase metallicity
- Particle back-reaction
- Stabilizes VSI

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Summary

- **Rapid planetesimal formation** require dust-to-gas ratios to be first enhanced by $\sim 100$ from the ISM value.
- Dust-settling is one way to enhance $\rho_d/\rho_g$.
- **Dust-settling is opposed by turbulence**, e.g. from the vertical shear instability.
- VSI turbulence can be circumvented by:
  - Increased particle size
  - Increased metallicity
- **Particle back-reaction** allows a feedback loop for self-sustained settling.
Near-future work

- Full 3D simulations to account for non-axisymmetric structures
- Mutual interaction with protoplanets
- VSI (or other hydro.) turbulence and self-gravity
- Influence of infall from external envelope
- Non-circular flows (eccentric disks, vortices)

Thank you

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