Dust settling in turbulent protoplanetary disks

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Research interests

- Astrophysical fluid dynamics
- Accretion disks
- Fluid instabilities
- Structure formation and evolution in protoplanetary disks
- Disk-planet interaction
- Dust dynamics
- Stability analyses
- Numerical simulations
Diversity of planetary systems

- $O(10^3)$ extra-solar planets detected
- $O(10^3)$ planetary systems, $O(10^2)$ multi-planet
- Wide range of orbital configurations
From dust to planets

\[ \sim 10^{-6} \text{m} \quad \to \quad \sim 10^7 \text{m} \]
From dust to planets

- Disk of gas and dust spinning around young Sun

- Dust grains

- mm-cm grains

- Sticking

- μm grains

- km planetesimals

- Protoplanets

- Gravity

- Streaming instability? (Youdin & Goodman, 2005)
Streaming instability

\( \rho_{\text{dust}} / \rho_{\text{gas}} \)

- One-fluid model of dusty gas (Lin & Youdin, 2017)
- PLUTO code
Streaming instability in protoplanetary disks

$\rho_{\text{dust}} < \rho_{\text{gas}}$

$\rho_{\text{dust}} > \rho_{\text{gas}}$

cm particles

$\alpha_{\text{visc}} \simeq 10^{-3}$

$\Sigma_{\text{dust}} = 0.1 \Sigma_{\text{gas}}$

SI is easily killed by viscosity
Rapid planetesimal formation require $\rho_{\text{dust}} \gtrsim \rho_{\text{gas}}$

$\rho_{d} \sim 0.01 \rho_{g}$ in ISM

HOW?

$\rho_{d} \sim \rho_{g}$ for SI
Dust settling?

Yes... if the disk is laminar.
Hydrodynamic turbulence in protoplanetary disks

- Vertical shear instability (Nelson et al., 2013)
  - $\frac{\partial \Omega}{\partial z} \neq 0 + $ rapid cooling $\Rightarrow$ unstable

$$\Omega = \Omega_{Kep}(R) + \Omega_{corr}(R, z)$$

What happens to dust?
Lifting dust particles by the VSI

Lin (2019), one-fluid approximation
Classic picture: passive particles

- Large particles and/or weak turbulence lead to dust settling.
- Small particles and/or strong turbulence lead to dust lofted.

What about particle feedback and solid abundance?
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

Lin (2019), one-fluid approx.

- Dust-loading $\rightarrow$ buoyancy $\rightarrow$ stabilizes VSI
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

Lin (2019), one-fluid approx.

- More dust settles to thinner layers

$\Sigma_{\text{dust}}/\Sigma_{\text{gas}} = 0.01$

$\Sigma_{\text{dust}}/\Sigma_{\text{gas}} = 0.03$

$\Sigma_{\text{dust}}/\Sigma_{\text{gas}} = 0.05 = \frac{H_{\text{gas}}}{R}$

$\Sigma_{\text{dust}}/\Sigma_{\text{gas}} = 0.1$
Active dust settling in turbulent disks

Settling via dust-loading: $\Sigma_{\text{dust}} \gtrsim (H_{\text{gas}}/R)\Sigma_{\text{gas}}$

Dust rings should be thinner than dust gaps
Lin & Youdin (2017); built upon Laibe & Price (2014), also Fromang & Papaloizou (2006)
Full two-fluid treatment with FARGO3D

$$\log(\rho_d/\rho_g), \ t=500P_0$$

\[ M_{dust} = 0.01M_{gas} \]

\[ M_{dust} = 0.05M_{gas} \]
Full two-fluid treatment with FARGO3D

\[ \log(\rho_d/\rho_g), \ t=500P_0 \]

- \( M_{dust} = 0.01M_{\text{gas}} \)
- \( M_{dust} = 0.05M_{\text{gas}} \)

protoplanet
Dusty disk-planet interaction

(Andrews et al 2018)
Dust settling and planet gaps

(Pinte et al. 2016)
- Well-defined rings $\Rightarrow$ settled dust
- Dust settling also implied by polarization observations (S. Ohashi)
Dust settling and planet gaps

(Pinte et al. 2016)

- Well-defined rings $\implies$ settled dust
- Dust settling also implied by polarization observations (S. Ohashi)

Is dust settling compatible with gap opening?
2019 ASIAA Summer Student Program

- Full 3D disk-planet simulations
  (Jiaqing Bi & Robin Dong, UVic)
Axisymmetric disk-planet simulations
(Simin Tong, Jilin → Leiden)
No settling at gap edges??
High performance computing (HPC) is the foundation of scientific research. As the only national laboratory that provides HPC services for interdisciplinary scientific research projects, the NCHC plans to establish a world leading computing and data storage environment and high performance PC cluster, as well as various engineering and scientific applications and databases, which will be provided to industries, academia, and research institutes. This will help users contribute with their high performance academic output. The NCHC built the largest open supercomputer “TAIWANIA 1” in Taiwan in 2018. The system has a total of 27,760 computing cores, a parallel file system with a total capacity of 3.4PB, OPA 100Gbps high speed network, and overall performance reaching 1.7 PFLOPS. The system is a general purpose supercomputer with a large number of compute nodes and an independent file system, high security mechanisms, and supports multiple fields of application, including physics, chemistry, mathematics, atmospheric, engineering and life sciences. In addition to commercial package software, the system also offers several compilers and MPI libraries for researchers to develop their own programs.

System specifications

| Compute node | Intel Xeon Gold 6148 2.40GHz CPU x 2 with 192/384GB memory |

- **Current credit:** ~ 4.3M CPU-hours or ~ 180K GPU-hours
Summary

Dust settling depends on solid abundance (Lin, 2019)

Some questions under investigation

- **Dust settling v.s. disk-planet interaction**
  with Jiaqing Bi (UVic), Simin Tong (→ Leiden)

- **Streaming instability v.s. physical disk conditions**
  with Kan Chen (→ Cambridge)

- ‘**Streaming instability’ in razor-thin disks?**
  with Sayantan Auddy (ASIAA)
Thank you

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