Dust dynamics in (3D) protoplanetary disks

Min-Kai Lin

Sayantan Auddy (ASIAA), Somdeb Bandopadhyay (NTU), Jiaqing Bi (UVic), He-Feng Hsieh (NTHU)

December 2019
From dust to planets

well-mixed dust in young disk

dust settles to disk midplane

dust grains → Streaming instability? → planetesimals → gravity/pebble accretion → protoplanet

$\mu \text{m} \rightarrow \text{mm} - \text{cm}$

Secular GI? → $\sim \text{km}$

$\geq 10^3 \text{km}$
Streaming instability

- **Idealized setup**: no turbulence, unstratified disk
Streaming instability in a turbulent disk

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

\[ \alpha_{\text{visc}} \approx 10^{-3} \]

\[ \Sigma_{\text{dust}} = 0.1 \Sigma_{\text{gas}} \]

- \( \rho_{\text{dust}} > \rho_{\text{gas}} \)

K. Chen & Lin, in prep.

- SI is easily killed by viscosity
Rapid planetesimal formation requires high dust-to-gas ratios

\[ \rho_d \sim 0.01 \rho_g \text{ in ISM} \quad \text{HOW?} \quad \rho_d \sim \rho_g \text{ for SI} \]
Dust settling?

Yes... if the disk is laminar
Turbulence and particle stirring

\[ \log\left(\frac{\rho_d}{\rho_g}\right), \ t=0P_0 \]
Vertical shear instability
(Nelson et al., 2013; Lin & Youdin, 2015; Barker & Latter, 2015; Latter & Papaloizou, 2018)

- A centrifugal instability that feeds off vertical shear: $\partial_z \Omega \neq 0$
- Requires rapid cooling; applicable to 10s to 100 AU in protoplanetary disks
Effect of metallicity (Lin, 2019; one-fluid approx.)

\[ M_{\text{dust}} = 0.01M_{\text{gas}} \]
\[ M_{\text{dust}} = 0.1M_{\text{gas}} \]

More dust settles to thinner layers
How much dust can overcome the VSI?

\[ \Sigma_{\text{dust}} \gtrsim \frac{H_{\text{gas}}}{R} \Sigma_{\text{gas}} \]

- Compare destabilizing effect of vertical shear, \( \partial_z \Omega \propto H_{\text{gas}}/R \) with
- Stabilizing effect of dust-loading, \( \Sigma_{\text{dust}}/\Sigma_{\text{gas}} \)
Full two-fluid treatment with FARGO3D

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

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

\[ M_{\text{dust}} = 0.05M_{\text{gas}} \]

protoplanet
Planet gaps and dust rings
Planet gaps and dust rings

Gap profiles depend on: planet mass, viscosity, temperature, particle size, metallicity...

(Credit: S. Auddy)
Planet gaps and dust rings

S. Auddy & Lin, in prep.: application of machine learning to many-parameter surveys
Oscillatory torques in dusty disks

$$T_s = 0.001$$

- $\Sigma_d = 0.01\Sigma_g$
- $\Sigma_d = 0.5\Sigma_g$
- $\Sigma_d = 1.0\Sigma_g$

Chen & Lin, 2018
Planet migration in dust-rich disks

Hsieh & Lin, in prep.
What happens in 3D?

$log(\rho_d/\rho_g), \ t=200P_0$
Observational motivation: dust settling vs. gap opening

(Pinte et al. 2016)
- Well-defined rings ⇒ settled dust
Fake planet-disk simulations
(Lin & Tong, in prep.)
Full 3D simulations

(Bi, Lin, & Dong, in prep.)
Simplified setup with pressure bumps
(Lin & Tong, in prep.)
Summary

- Dust-enrichment helps settling (Lin, 2019)
- Streaming instability in turbulent disks (Chen & Lin, to submit)
- Dusty disk-planet interaction:
  - Planet migration (Chen & Lin, 2018; Hsieh & Lin, in prep.)
  - Application of machine learning (Auddy & Lin, in prep.)
- Dust settling around planet gaps:
  - Fake planet and artificial pressure bumps (Lin & Tong, in prep.)
  - Full 3D models (Bi, Lin, & Dong, in prep.)

Thank you

@linminkai
mklin@asiaa.sinica.edu.tw
minkailin.wixsite.com/minkailin
Back to basics: streaming instability

with Pin-Gao Gu (ASIAA), Yueh-Ning Lee (NTNU), Chien-Chang Yen (FJU)

- Classic SI analysis assumes a uniform background disk
- Real disks have vertical structure

\[ \rho_d \rightarrow \rho_d(z) + \delta \rho_d(z) \exp(\sigma t + ik_x x) \]
Stratified streaming instability: linear growth

\[ k_x H_g = 10^3 \]

\[ D = 10^{-7} c_s H_g \]

\[ \tau_s \Omega = 10^{-3} \]

growth rate = 0.27\Omega