A rocky road from dust to planets

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Academia Sinica

- Governmental research institute
- ~ 1000 Research Fellows (equiv. professors); ~ 1000 post-docs
- No teaching duties, but plenty of research students
- Additional grants available from the Ministry of Science and Technology

MOST
Ministry of Science and Technology
AS Institute of Astronomy and Astrophysics

- Physical location in National Taiwan University; office in Hilo, Hawaii
- Total ~ 200 people
- International staff, English working environment
Academia Sinica's Institute of Astronomy and Astrophysics (ASIAA) is searching for an outstanding scientist with international experience and research credentials to become its next Director, starting on 1 September 2020 for renewable three-year terms. The Director is responsible for the overall scientific leadership and administrative management of the Institute including its laboratories, facilities, and a staff of about two hundred people.
Long story short

  Simplified model of dust-gas dynamics in protoplanetary disks

  Application to disk-planet interaction

  Application to dust settling in turbulent disks
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
Planets form in accretion disks around young stars

The result is readily observed, what about earlier stages, e.g. ‘e’ or even ‘d’?
HL Tau is so 2015

(Andrews et al 2018; DSHARP program)
Asymmetric protoplanetary disks

(Elias 2-27, Pérez et al., 2016)
Asymmetric protoplanetary disks

(HD 135344B, van der Marel et al., 2016)
Observing planet formation?

V1094 Sco (van Terwisga et al. 2018)

Elias 24 (Dipierro et al. 2018)
Observing planet formation?

Fedele et al., 2017
Structures from disk-planet interaction?

First planet detected inside protoplanetary disk gap?

(PDS 70, Müller et al. 2018)
The disk-planet connection

- How do protoplanetary disks accrete onto their stars?
- What are the sources of turbulence in protoplanetary disks?
- Origin of rings, gaps, asymmetries?

Dust dynamics

- How do planetesimals form from tiny dust grains?
- Dust-gas interaction
- Interpreting observations of PPDs, inferring disk structure/conditions
Importance of dust

- Protoplanetary disks are $\sim 99\%$ gas, $\sim 1\%$ dust
- Planets form from the solids (at least in core accretion)
- Need to understand how dust grains evolve in the gaseous disk
Dusty gas in protoplanetary disks

Gas and dust don’t always correlate

AB Aurigae, (Tang et al. 2017)
Dusty-gas dynamics in protoplanetary disks

1. Turbulent Mixing (radial or vertical)
2. Vertical Settling
3. Radial Drift
4. a) Sticking
   b) Bouncing
   c) Fragmentation with mass transfer
   d) Fragmentation

(Testi et al., 2014)
Modeling dust-gas dynamics is complicated

- State-of-the-art: gas+solid dynamics

(Simon et al., 2017)

- Intellectually & computationally demanding

Is there a simpler way?
A dust-free description of dusty gas

Lin & Youdin (2017)

dust + isothermal gas + drag equivalent for small particles hydrodynamics + cooling
A dust-free description of dusty gas

Lin & Youdin (2017)

Model equations

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} &= -\frac{1}{\rho} \nabla P - \nabla \Phi, \\
\frac{\partial P}{\partial t} + \mathbf{v} \cdot \nabla P &= -\Gamma P \nabla \cdot \mathbf{v} + P \mathbf{v} \cdot \nabla \ln c_s^2 \\
&\quad + \frac{\Gamma P}{\rho_{gas}} \nabla \cdot (f_{dust} t_{stop} \nabla P).
\end{align*}
\]

Looks like gas dynamics

(see also Fromang & Papaloizou, 2006; Laibe & Price 2014)
Physical interpretation

- Drag forces $\rightarrow$ ang. mom. exchange with gas $\rightarrow$ dust drifts to high pressure
Physical interpretation

- Drag forces → ang. mom. exchange with gas → dust drifts to high pressure

Thermodynamic view

- Dust particles ~ cold, pressureless fluid

+ve particle flux  ←  -ve heat flux
Model applications and predictions

- Thermodynamic interpretation of dusty phenomena
- Dusty analogs of thermodynamic processes
- Example: dusty edges are unstable ($\rightarrow$ entropy edges)
Dust rings and traps at planet gaps

- Pressure gradient at gap edges $\rightarrow$ radial dust ring
- PLUTO code doesn’t know about dust
Dust rings and traps at planet gaps

- Gap edge unstable to vortex formation $\rightarrow$ azimuthal dust trap
Dust rings and traps at planet gaps

van der Marel et al 2013: Observed dust trap

An unseen planet?

How to make the planet?
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)
Streaming instability: particle+gas simulations

- Streaming instability → dust clumping mediated by mutual dust-gas drag
Streaming instability: one-fluid model

\[ \frac{\rho_{\text{dust}}}{\rho_{\text{gas}}} \]
Planetesimal formation requires high dust-to-gas ratios

(SI in viscous disks; K. Chen & Lin, in prep.)

- SI needs $\rho_{\text{dust}} \gtrsim \rho_{\text{gas}}$ for strong clumping ($\rightarrow$ collapse into planetesimals)
Planetesimal formation requires high dust-to-gas ratios

\[ \rho_d \sim 0.01\rho_g \text{ in ISM} \]

**HOW?**

\[ \rho_d \sim \rho_g \text{ for SI} \]
Enhancing the dust-to-gas ratio in protoplanetary disks

Chiang E, Youdin AN. 2010.
Annu. Rev. Earth Planet. Sci. 38:493–522
Dust settling?

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

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

\[ \frac{\partial \Omega}{\partial z} \neq 0 + \text{rapid cooling} \Rightarrow \text{unstable} \]
Vertical shear instability

(Lin, 2019)

What happens to dust?
Lifting dust particles by the VSI
Effect of particle size

- Small particles remain well-mixed with gas: no settling
Classic picture: passive particles

- Large particles and/or weak turbulence → dust settles
- Small particles and/or strong turbulence → dust lofted

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

- Dust loading → system becomes ‘heavy’ → more difficult to stir up

$$M_{\text{dust}} = 0.01M_{\text{gas}}$$
$$M_{\text{dust}} = 0.1M_{\text{gas}}$$
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

- Dust loading → system becomes ‘heavy’ → more difficult to stir up

![Graph showing the effect of metallicity on system properties.](image-url)
Active dust settling in turbulent disks

- Dust settles induces buoyancy.
- Buoyancy weakens turbulence.
- Turbulence decreases vertical shear.
- Increased shear increases metallicity.
- Metallicity stabilizes vertical structure.

- Dust loading increases particle size.
- Increased particle size decreases vertical shear.

Settling via dust-loading: $\Sigma_{\text{dust}} \gtrsim (H_{\text{gas}}/R)\Sigma_{\text{gas}}$
Full two-fluid treatment with FARGO3D

\[
\frac{M_{\text{dust}}}{M_{\text{gas}}} = 0.01 \quad \frac{M_{\text{dust}}}{M_{\text{gas}}} = 0.05
\]
Full two-fluid treatment with FARGO3D

How do planets interact with dusty disks?

$M_{\text{dust}} = 0.01M_{\text{gas}}$

$M_{\text{dust}} = 0.05M_{\text{gas}}$

How do planets interact with dusty disks?
Dusty disk-planet interactions

- Disk material exerts a gravitational force on the planet → torques
- What happens in dusty disks?
Torque oscillations in dust-rich disks

- $\Sigma_{\text{dust}} = 0.5\Sigma_{\text{gas}}$ (2D disks)
- One-fluid approximation to treat dust using PLUTO code

(J.-W. Chen & Lin, 2018)

- Top: zero particle size (Stokes number $\rightarrow 0$)
- Bottom: finite particle size (Stokes number $\sim 10^{-3}$)
Full two-fluid treatment with FARGO3D

Credit: He-Feng Hsieh (NTHU)

- Planet fixed on a circular orbit; just measure torques
(Non-)migrating planets in dust-rich disks

Credit: He-Feng Hsieh (NTHU)

- Planet allowed to move, using FARGO3D
Planet-induced rings

What happens in 3D?
2019 ASIAA Summer Student Program

- Full 3D disk-planet simulations (Jiaqing Bi, University of Victoria)
- Axisymmetric disk-planet simulations (Simin Tong, Jilin University)
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No settling at gap edges??
Summary

- Dust is fundamental to planet formation and evolution
- A simple model for dust-gas dynamics (Lin & Youdin, 2017)
- Dust settling depends on solid abundance (Lin, 2019)
- Oscillatory torques affect planet migration in dusty disks (Chen & Lin, 2018)
Other topics

Vortices in protoplanetary disks

- Vortices in 3D self-gravitating disks (Lin & Pierens, 2018)
- Vortices in massive, non-isothermal disks (Pierens & Lin, 2018)
- Observational implications (Hammer, Pinilla, Kratter & Lin, 2019)

Ongoing

- Streaming instability in global 2D disks,
  with Sayantan Auddy (ASIAA)
- Streaming instability with particle diffusion and non-linear drag laws,
  with Kan Chen (Nanjing University)
- Stability of stratified, dusty disks,
  with Jack Ng (NTU) and Pingao Gu (ASIAA)
- VSI turbulence and self-gravity,
  with Wei-Ting Liao (UIUC) and Hsi-Yu Schive (NTU)
Thank you

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