A rocky road from dust to planets

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Research interests

- Astrophysical fluid dynamics
- Accretion disks
- Fluid instabilities
- Structure formation and evolution
- Disk-planet interaction
- Stability analyses
- Numerical simulations

\[ \sim 10^{-6} \text{m} \quad \rightarrow \quad \sim 10^{7} \text{m} \]
Promotion


- Simplified model of dust-gas dynamics in protoplanetary disks


- Application to disk-planet interaction

Lin (2019, MNRAS)

- 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)
HL Tau is so 2015

(Long et al 2018)
Asymmetric protoplanetary disks (rare)

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

(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)

polytropic gas with dust ≈ pure gas with cooling

(for small particles)
A dust-free description of dusty gas

Lin & Youdin (2017)

\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_{\text{gas}}} \nabla \cdot (f_{\text{dust}} t_{\text{stop}} \nabla P).
\end{align*}

(see also Fromang & Papaloizou, 2006; Laibe & Price 2014)
Particle drift in protoplanetary disks

Drag forces → ang. mom. exchange with gas → dust drifts to high pressure
Thermodynamic view of particle drift

- Dust particles \(\sim\) cold, pressureless fluid
- \(T \propto c_s^2 \sim P_{\text{gas}} / (\rho_{\text{dust}} + \rho_{\text{gas}})\)

\[
\begin{align*}
\text{positive particle flux} & \approx \text{negative heat flux}
\end{align*}
\]
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

Observed dust trap

(van der Marel et al 2013) 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

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

\( z/H_0 \)

0.010
0.005
0.000
-0.005
-0.010

\( t=0.0P_0 \)

\( t=3.0P_0 \)

\( t=4.0P_0 \)

\( t=5.0P_0 \)

\( (R-R_0)/H_{g0} \)

-0.04
-0.02
0.00
0.02
0.04

\[ \begin{array}{c|c|c|c|c}
0.00 & 0.02 & 0.04 & 0.06 & 0.08 \\
0.00 & 0.02 & 0.04 & 0.06 & 0.08 \\
\end{array} \]
Planetesimal formation requires high dust-to-gas ratios

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

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

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

How?

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

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, Lin & Youdin, 2015)
Hydrodynamic turbulence in protoplanetary disks

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- Vertical shear instability (Nelson et al., 2013, Lin & Youdin, 2015)

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

\[ \Omega = \Omega_{\text{Kep}}(R) + \Omega_{\text{corr}}(R, z) \]

(Lin, 2019)

What happens to dust?
Lifting dust particles by the VSI

Moderately turbulent disk
Lifting dust particles by the VSI

Strongly turbulent disk
Effect of particle size

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

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

- Dust-on-gas drag neglected
- What about solid abundance?
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

- Dust loading → system becomes ‘heavy’ → more difficult to stir up
Effect of metallicity ($\Sigma_{\text{dust}}/\Sigma_{\text{gas}}$)

More dust settles to thinner layers
Effect of metallicity ($\frac{\Sigma_{\text{dust}}}{\Sigma_{\text{gas}}}$)

- Self-stabilized dust layer, similar to ‘dead zones’
Active dust settling in turbulent disks

- Dust settles<br>- Induces buoyancy<br>- Weakens turbulence<br>- Increase particle size<br>- Decrease vertical shear<br>- Increase metallicity<br>- Particle back-reaction<br>- Stabilize VSI

\[ \Sigma_{\text{dust}} \gtrsim (H_{\text{gas}}/R)\Sigma_{\text{gas}} \]

- Settling via dust-loading:
- Dust rings should be thinner than dust gaps
Full two-fluid treatment with FARGO3D

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

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

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

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

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 & Robin Dong, UVic)
- Axisymmetric disk-planet simulations (Simin Tong, Jilin University)

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 University)

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

- ‘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 Pin-Gao Gu (ASIAA)
- VSI turbulence and self-gravity, with Wei-Ting Liao (UIUC) and Hsi-Yu Schive (NTU)
- Planet-induced dusty vortex instabilities, with Arnaud Pierens (Bordeaux)
Opportunities at ASIAA

- Undergraduate research, summer student program
- Graduate research, visiting students
- Postdoctoral research

Ask me!
Thank you

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