Footprints of planet formation

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About me

Topics

- Astrophysical fluid dynamics applied to planet formation theory
  - (Protoplanetary) accretion disks: structure and evolution
  - Fluid dynamical instabilities
  - Dust dynamics
  - Disk-planet interaction, orbital migration

Tools

- ‘Pen & paper’, small-scale semi-analytical calculations
- Large-scale numerical simulations
We are not alone

As of October 2017:

- Over 3600 extra-solar planets detected
- Over 2700 planetary systems
- Wide range of orbital configurations
Diversity of planetary systems

TRAPPIST-1 system

Credit: NASA/JPL/CalTech
Diversity of planetary systems

Wide-orbit multi-planets around HR 8799

Credit: NRC-HIA/C. Marois/Keck Observatory
Diversity of planetary systems

Triple-star planetary system around HD 131399

(Wagner et al. 2016)
Planet semi-major axis \( \sim 80 \text{au} \)
Questions

- Why are some planets found close to their stars (e.g. Hot Jupiters)? Did they form there, or moved there?
- Can planets form far away from the star?
- Eccentricity and inclination of exo-planets?
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- Why are some planets found close to their stars (e.g. Hot Jupiters)? Did they form there, or moved there?
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We need to understand planet formation and evolution
Planet formation in the past

Planets form in protoplanetary accretion disks around young stars

The result is readily observed, what about earlier stages (e.g. ‘e’ or even ‘d’)?
Birthsites of planets: protoplanetary disks

Are we observing the signatures of planet formation?

(ALMA Partnership, 2015)
Asymmetric protoplanetary disks

Spiral arms

(MWC 758, Benisty et al. 2015)

(HD 100453, Benisty et al. 2016)

(MWC 758, Benisty et al. 2015)
Asymmetric protoplanetary disks

Lopsided disks

(HD142527, Casassus et al., 2015)

(CARMA - 1.3 mm, LkHα, Isella et al., 2013)
How do protoplanetary disks accrete onto their stars?
- Turbulent transport of angular momentum?
- Magnetic winds?
Protoplanetary disk dynamics

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- What are the sources of turbulence in disks?
  - Hydrodynamic, gravitational, or magneto-hydrodynamic?
Protoplanetary disk dynamics

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- Rings, gaps, spirals, lopsidedness
  - Planet induced?
  - Fluid instabilities?
Gaps and rings in protoplanetary disks

(HL Tau, Yen et al., 2016)
Gaps and rings in protoplanetary disks

(HD 169142, Fedele et al., 2017)

- Planetary candidate: did it make the gap?
Disk-planet interaction

Planet launches spiral density waves
- Outer wave deposits +ve ang. mom. → gas moves out
- Inner wave deposits −ve ang. mom. → gas falls in

Disk-planet interaction → gap formation

(Lin, M-K., PLUTO simulation.)
Gas and dust moves differently

(AB Aurigae, Tang et al. 2017)
Dust particles drift relative to gas

\[
\frac{v_{\text{gas}}^2}{r} = \frac{v_{\text{Kep}}^2}{r} + \frac{1}{\Sigma} \frac{dP}{dr}
\]

Dust particles accumulate at pressure bumps
Dust traps at planet gaps

(Lin, M-K., PLUTO simulation.)

- Pressure bump at gap edges $\rightarrow$ radial dust trap
Application to HL Tau

Dust-gas simulation with 3 planets: 0.2, 0.27, and 0.55 Jupiter-masses

(Dipierro et al. 2015)
Other ring-forming mechanisms

- Condensation fronts (ice/snow lines)
- Secular gravitational instability, dust-induced instabilities
- Zonal flows from non-ideal MHD instabilities
Asymmetric disks: vortices?

(IRS 48, van der Marel et al., 2013)
Asymmetric disks: vortices?

IRS 48

Jupiter
Asymmetric disks: vortices?

- Disk vortices: pressure bumps in radius and azimuth
- Lyra & Lin (2013) model for dust-trapping by a gas vortex

\[
\rho_{\text{dust}}(a) \propto \exp \left( -\frac{a^2}{2H_v^2} \right)
\]

- \(a\): distance from the vortex center
- \(H_v\): vortex shape, turbulence level, particle size
Modeling observations with a vortex

(SAO 206462, Pérez et al., 2014)
Vortices in planet formation theory

- Concentrate dust particles
  → accelerated planetesimal formation
  → planet formation
- Angular momentum transport
  → disk accretion
Where to vortices come from?

Fluid (gas) instabilities:

- Rossby wave/Kelvin-Helmholtz instabilities (Li et al., 2000)
- Sub-critical baroclinic instability (Lesur & Papaloizou, 2010)
- Convective overstability (Lyra, 2014)
- Zombie vortex instability Marcus et al. (2015)
- Vertical shear instability (Richard et al., 2016)

Vortices should be common in protoplanetary disks
Where to vortices come from?

Fluid (gas) instabilities:

- Rossby wave/Kelvin-Helmholtz instabilities (Li et al., 2000)

(http://www.brockmann-consult.de/CloudStructures/kelvin-helmholtz-instability-description.htm)
Where to vortices come from?

Fluid (gas) instabilities:

- Rossby wave/Kelvin-Helmholtz instabilities (Li et al., 2000)
Gap edges as sites for vortex formation

- Disk-planet interaction $\rightarrow$ gaps
- Gap edges are sites of strong shear $\rightarrow$ Rossby wave instability may develop
- Gap edges ‘roll up’ into vortices

(Credits: M. Hammer [U. Arizona]; FARGO simulations)
Dust-trapping by gap-edge vortices

- Gap edge unstable to vortex formation $\rightarrow$ azimuthal dust trap

(Lin, M.-K., PLUTO simulations)
Dust-trapping by gap-edge vortices

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(Lin, M.-K., *PLUTO* simulations)

(IRS 48, van der Marel et al, 2013)
Vortex evolution under realistic conditions

- Vortices must persist long enough if they are to explain observations
- Previous work: massive planet suddenly introduced into 2D disk
- What happens in 3D?
- What happens when a planet grows slowly over time?
Slowly-growing planets make weaker vortices

(Hammer, Kratter & Lin, 2017)
Slowly-growing planets make weaker vortices

(Hammer, Kratter & Lin, 2017)
Basic theory is 2D, but PPDs are 3D

Take a look in the \((r,z)\) plane through the vortex
Rossby vortices are vertically global

\[ \Delta \rho / \rho \]

- Global 3D Zeus simulations (Lin, 2012b)
- Consistent with 3D linear theory (Lin, 2012a, 2013a,b)
- Vortex evolution is sensitive to disk vertical structure (Lin, 2014)
Elliptic instability of 3D vortices

- A 3D instability that weakens/destroys vortices (Lesur & Papaloizou, 2009)
- In plane \( (v_z = 0) \) elliptical flow about the vortex center
- Instability \( \rightarrow \) small-scale 3D turbulence \( (v_z \neq 0) \)

Athena sims. (Lin, in prep.)

\( t = 800P_0, \ 10^2 <v_z^2>^{1/2}/c_s \)
3D vortex survival in self-gravitating disks

Vorticity \( = \left( \nabla \times \mathbf{v} \right)_z / 2\Omega \) (Lin, 2017, in prep.)
3D vortex survival in self-gravitating disks

Massive disk

Light disk

Density perturbation (Lin, 2017, in prep.)
Turbulent vertical motions inside vortices

\[ \langle V_z^2 \rangle^{1/2} / C_s \]

Massive disk
Light disk

(Lin, 2017, in prep.)
How do dust particles respond to disk turbulence?

(Testi et al., 2014)
How do dust particles respond to disk turbulence?

Vertical settling of dust particles, $100 \times \rho_{\text{dust}}/\rho_{\text{gas}}$ (Lin, in prep.)
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Laminar disk
How do dust particles respond to disk turbulence?

Vertical settling of dust particles, $100 \times \rho_{\text{dust}}/\rho_{\text{gas}}$ (Lin, in prep.)

Laminar disk

- $t=0.0P_0$
- $t=100.0P_0$
- $t=200.0P_0$
How do dust particles respond to disk turbulence?

Vertical settling of dust particles, $100 \times \rho_{\text{dust}}/\rho_{\text{gas}}$ (Lin, in prep.)

Laminar disk

Turbulent disk

$\frac{z}{R_0}$

$t=0.0P_0$

$1.15$ $1.00$ $0.83$ $0.67$ $0.50$ $0.50$ $0.33$ $0.17$ $0.00$

$t=100.0P_0$

$t=200.0P_0$

$1.15$ $1.00$ $0.83$ $0.67$ $0.50$ $0.50$ $0.33$ $0.17$ $0.00$

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Laminar disk

Turbulent disk

$z/R_0$

$t=0.0P_0$

$t=100.0P_0$

$t=200.0P_0$

$R/R_0$

$z/R_0$

$R/R_0$
How do dust particles respond to disk turbulence?

Vertical settling of dust particles, $100 \times \rho_{dust}/\rho_{gas}$ (Lin, in prep.)

Laminar disk

Turbulent disk

M-K. Lin (ASIAA)

Protoplanetary disks

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Inferring turbulence from observing dust layers

(ALMA Band 6+7)

no settling

$\Delta \text{Dec (')}$

$0.0$

$-0.5$

$0.5$

$\text{Distance from star (AU)}$

$\Delta \text{Ra (')}$

$-0.5$

$0.0$

$0.5$

$\text{ALMA Band 6+7}$

$\text{no settling}$

$h_{\text{1mm}} = 2.15 \text{ au}$

$\alpha_{SS} = 3 \times 10^{-3}$

$h_{\text{1mm}} = 0.70 \text{ au}$

$\alpha_{SS} = 3 \times 10^{-4}$

(HL Tau disk, Pinte et al., 2016)

The mm-size dust layer is consistent with a turbulent viscosity $\alpha \sim 3 \times 10^{-4}$

(consistent with vertical shear instability)
Protoplanetary disks contain rich sub-structures: gaps, rings, spirals, lopsidedness.

Disk-planet interaction may explain dust rings and lopsided dust distributions.

Vortices are effective dust traps, relevant to observations of theory, but their survival under realistic disk conditions needs to be checked.

Dust particles behave distinctly from the gas flow, stirring (or lack thereof) of particles may provide a way to measure the underlying disk turbulence.
Summary

- **Protoplanetary disks contain rich sub-structures**: gaps, rings, spirals, lopsidedness
- **Disk-planet interaction** may explain dust rings and lopsided dust distributions
- **Vortices** are effective dust traps, relevant to observations of theory, but their survival under realistic disk conditions needs to be checked
- Dust particles behave distinctly from the gas flow, stirring (or lack thereof) of particles may provide a way to measure the underlying disk turbulence.

Thank you @linminkai
References


