The disk-planet connection: theory

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If you are interested in protoplanetary disks:

**What causes these features?**

If they are caused by planets, can we use these features to constrain the properties of young planets?
If you are interested in exoplanets

Kepler Orrery III by Daniel Fabrycky

Credit: NRC/HIA, C. Marois, and Keck Observatory
If you are interested in exoplanets

- How planets’ architecture evolves to current exoplanets demographics?
Outline

- The traditional interests in planet-disk interaction (Tin age interests)
  
  Migration
  
  Gap opening

- New interests in planet-disk interaction
  
  1. The imprints on the circumstellar disks
     
     Spiral Wakes
     
     Gaps/rings
     
     Vortices
  
  2. Circumplanetary disks
Migration

**Wave torque**
(Lindblad Resonances)

migration timescale for both Earth and Neptune \(\sim 10^5\) years

**Corotation torque**
(horseshoe drag or corotation resonances)

Baruteau+ 2014
Corotation torque

Depends on the vortensity/entropy gradient, viscosity, energy diffusivity


No viscosity

Viscous
Circular coplanar planets in a viscous disk

Bitsch et al. 2013
Gap opening in viscous disks

When planetary torque > viscous torque, a gap is opened

$0.1 \, M_J$ in $\alpha=0.01$, $H/R=0.05$ disks

Goldreich & Tremaine 1979, Lin & Papaloizou 1986, Crida et al. 2006

de Val-Borro et al. 2006
For planets in viscous disks, theories are quite robust!
More realistic disks

MRI turbulent

Laminar Region

~0.1-1 AU

Armitage 2011
Planets in laminar Disk

Gaps can be opened by any mass planets


Zhu et al. 2013
Planets in laminar Disk

Gap opening and migration feedback will stall the planet (>~3 M⊕)


Vortex generation at the gap edge

Yu et al. 2010
Planets in Turbulent Disks

Low mass planets: random walk (“diffusion process”)
The diffusion timescale does not depend on the planet mass.

Nelson & Papaloizou 2004, Baruteau et al. 2011,
Yang et al. 2009, Nelson & Gressel 2010

At 5 AU:
- <100 m: radial drift due to gas drag
- 10 km to Mars: turbulent diffusion
  ($\alpha=0.04$, 5 AU, 5 Myrs)
- >Mars: Type I

High mass planets:
  gap depth depends on magnetic field geometry

Zhu et al. 2013
Summary on migration and gap opening

- Viscous disks: relatively well understood, quantified
- Laminar disks: small viscosity and 0 viscosity are dramatically different
- Turbulent disks: statistical theory developed, but lacks confirmation by numerical simulations
- Other developments:
  - Magnetic resonances: Terquem 2003, Fromang et al 2005
  - Migration torque: Paardekooper 2014, McNally et al. 2017
  - Planet heating: Benitez-Llambay et al. 2015, Eklund & Masset 2017

The Disk Property is Crucial!
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Driven by observations

### Optical/Near-IR
- **Gaps/rings**
  - Debes+ 2013
  - Mayama+ 2012

### Radio
- ALMA Partnership+ 2015
- Andrews+ 2016
- Isella+ 2016

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### Nonaxisymmetric

### Vortices
- Avenhaus+ 2014
- De Boer+ 2016
- van der Marel+ 2013
- Casassus+ 2013

### Spirals
- Garufi+ 2015
- Benisty+ 2015
- Pérez+ 2016
Spirals Wakes

MWC 758

Benisty+ 2015

Ogilvie & Lubow 2002

See talk by J. Bae
Sound waves in disks

The pitch angle $\beta$

$$\tan \beta = \frac{c_s}{R|\Omega - \Omega_p|}$$
Explaining observations is difficult

1. Fitting the pitch angle suggests a too hot disk

MWC 758

At 50 AU, T~300 K

Benisty et al. 2015

2. Planet-induced spiral arms are too weak

Juhasz et al. 2015
Grand design

What if the planet is outside the spirals?
(Dong et al. 2015, Zhu et al. 2015)

M51

Benisty et al. 2015
When the planet mass increases:

- **The pitch angle increases**
- The secondary arm becomes apparent and the **separation** between two arms increases
- **Amplitude of shocks** becomes larger

Use spiral arms to estimate planet mass

\[
\tan \beta = \frac{c_s}{R|\Omega - \Omega_p|}
\]
The pitch angle increases towards the planet
New Observations: Reggiani+ 2017

New developments:
How to test the theory?

1. Use binaries as a test

2. Use spiral’s pattern speed
   - Planets at 30 AU, 10 years, rotates 30°
   - Planets at 150 AU, 10 years, rotates 2.7°

Wagner et al. 2015

Benisty et al. 2017

Wagner et al. 2018
Gaps/Rings: dust dynamics

Theory: dust particles drift to gas pressure maximum due to aerodynamic drag

Combining Gas+Dust simulations with MCRT:

See talks by S. Facchini, G. Dipierro

Dong et al. 2015
Dipierro et al. 2016


De Juan Ovelar et al. 2013, Dong et al. 2013, Picogna & Kley 2015, Dipierro et al. 2016, Dong & Fung 2017
Degeneracy:

- Uncertain particle size distribution
- Time dependent

Scatter light observations
$\alpha = 0.001$

Rosotti+ 2016
Including dust-to-gas feedback

- Particle filtration efficiency is significantly reduced.
- Gas is accumulated at the inner gap edge.

Yang & Zhu in prep.
Vortex

Casassus+ (2013)

van der Marel+ (2013)

Talks by P. Cazzoletti, M. Hammer
Gap edge instability

Papaloizou & Pringle 1984, 1985

Gas

Dust particles

Par. a
Par. c
Par. d
Par. e

Zhaohuan Zhu
Compared with observations

Analytical Model

Simulation+post processing

Lyra & Lin 2013

Barge et al. 2017

van der Marel+ 2013

Zhu & Stone 2014
Ring or vortex?

- If a gap edge is optically thick, a vortex will not show up.
- For a shallow gaseous gap edge, it is more likely to be a ring!
- If you have turbulence/viscosity, it forms a ring!

The vortex only appears when turbulence/viscosity is weak!

Turbulence is strong
\( \alpha \sim 0.01 \)

Turbulence is weak
\( \alpha \sim 0.001 \)

Zhu & Stone 2014
Fu et al. 2014
Hammer et al. 2017
Ring or vortex?

- Gas self-gravity suppresses instability (Lovelace & Hohlfeld 2013)

\[ Q \frac{h}{R} < 1 \]

\[ Q \frac{h}{R} \]

15

1.5

0.6

0.3

The vortex only appears when disk self-gravity is weak! (Zhu & Baruteau 2015, Mittal & Chiang 2015)

van der Marel+ 2013

Q~4000

ALMA Partnership+ 2015

Q~1
Gravity from gas to dust

No gravity from gas to dust

With gravity from gas to dust

Bigger particles shift away from the vortex center more

Baruteau & Zhu 2015
Including dust-to-gas feedback

- Locally, dust can have higher density than gas
- Signs of instability (Lesur & Papaloizou 2009, Chang & Oishi 2010, Railton & Papaloizou 2014)

Fu et al. 2014
Crnkovic-Rubsamen et al. 2014
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Circumplanetary Disks (CPD)

- **Viscous model:**

- **Wind, non-ideal MHD:** Turner et al. 2014, Fujii et al. 2014, Keith & Wardle 2015, Gressel et al. 2015

- **Shock driven accretion:** Zhu et al. 2016

**Poster by Cheng Chen**
CPD should be bright

If Jupiter is accreting at $\dot{M} = 10^{-5} \, M_{\text{Jupiter}} / \text{yr}$

$L_{\text{accretion}} = 0.5 \, G M_{\text{Jupiter}} \dot{M} / R_{\text{Jupiter}} = 1.5 \times 10^{-3} \, L_{\odot}$

As bright as M type brown dwarfs!

Reggiani et al. 2014
Biller et al. 2014
Quanz et al. 2014
Follette et al. 2017

Sallum+ 2015

Zhu 2015, Eisner 2015
CPD should be bright at submm


submm flux from CPDs at 20 AU, assume dust-to-gas ratio 0.01

Zhu, Andrews & Isella, 2018
Detection of dust emission in CPD by ALMA

OTS 44, 12 M_J

\( \alpha = 0.1 \)
\( \alpha = 0.01 \)
\( \alpha = 10^{-3} \)
\( \alpha = 10^{-4} \)

0.03 lunar mass of dust

\( \log_{10} F_{0.85\text{mm}} / \mu\text{Jy} \)

\( \log_{10} M_{\text{disk}} / M_J \)

\( M \dot{M} = 10^{-5} \)
\( M \dot{M} = 10^{-6} \)
\( M \dot{M} = 10^{-7} \)
\( M \dot{M} = 10^{-8} \)

\( \dot{M} \sim 10^{-7} M_J^2/\text{yr} \)

\( F = 100 \mu\text{Jy} \)

HD 142527

Bayo+ 2017

Boehler+ 2017

50 AU, 0.8 mJy
Dust drifts very fast in CPDs

Dust drift timescale in circumstellar disks

• CPDs should be bright at submm assuming dust-to-gas mass ratio of 0.01
  • But if we consider dust radial drift, it may not be observable except under certain conditions
  • Jet/Wind from CPD can be detected by ngVLA

In order to be detected at mm:
1) dust are micron sized
2) high gas surface density
3) substructures in CPD (HL Tau in HL Tau)

CPDs can also be compact (poster by Ya-Lin Wu)
Summary

- Migration and gap opening depend on the disk property.
- Planet-disk interaction can explain a lot of disk features (spirals, vortices, gaps/rings).
- Spirals to estimate planet mass/position.
- Dust dynamics is the key for gaps/rings. Dust-to-gas feedback starts to be considered.
- Vortices imply disk viscosity, mass, particle size.
- CPD should be bright at near-IR to submm. We don’t see many. Maybe radial drift, too compact?
- Where are the planets in protoplanetary disks?
Before ALMA

Prediction for ALMA:

Wolf & D’Angelo 2005
Planet-disk interaction affects solid accretion

When a low mass planet opens a gap, it stops particles at the gap edge, preventing the planet’s continuous growth.

(Morbidelli & Nesvorny 2012, Lambrechts et al. 2014)
Planet-disk interaction affects gas accretion

Disk material will enter the planet’s Hill sphere from the top and leave it from the midplane. Brings fresh high entropy material, preventing run-away accretion.

Fung et al. 2015, Ormel et al. 2015ab, Cimerman et al. 2017, Lambrechts & Lega 2017
Circumplanetary disks

Spiral shocks excited by the star can transport angular momentum

Larson 1990: semi-analytically derived

\[ \alpha \sim 0.013 \left[ \left( \frac{c_s}{V} \right)^3 + 0.08 \left( \frac{c_s}{V} \right)^2 \right]^{1/2} \]

(for a steady, self-similar shock)  

Rafikov 2016

Thermal Dynamics is extremely important!
Circumplanetary disks

\[ \dot{M} = 10^{-5} \, M_J/yr \]
\[ \dot{M} = 10^{-9} \, M_J/yr \]

SPH

Ayliffe & Bate 2009

Zhu+ 2016

Szulagyi & Mordasini 2017,
Szulagyi et al. 2014, 2016