Planet-driven Spiral Waves in Protoplanetary Disks

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Why would you go back to the past?
Spiral waves have been studied for many decades...

THE EXCITATION AND EVOLUTION OF DENSITY WAVES*

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THE EXCITATION OF DENSITY WAVES AT THE LINDBLAD AND COROTATION RESONANCES BY AN EXTERNAL POTENTIAL¹

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Six Decades of Spiral Density Wave Theory

Frank H. Shu

ARAA, 2016
In most of the cases, we see multiple spiral arms.
Planet-disk interaction simulations generally show that one planet launches multiple spiral arms.
exoplanets (NASA exoplanet archive, https://exoplanetarchive.ipac.caltech.edu/)

- confirmed exoplanets
- solar system planets
See Figure 1 of Bae, Pinilla & Birnstiel (2018) for the full reference list.

- confirmed exoplanets
- solar system planets

- HL Tau
- MWC 758
- HD 163296
- Elias 2–27
- Elias 2–24
- SAO 206462
- AS 209
- HD 100546
- TW Hya
- AB Aur
- HD 169142
- HD 97048
- DSHARP
- LkCa 15
- RX J1615
- GY 91
- V4046 Sgr
- PDS 70

exoplanets (NASA exoplanet archive, https://exoplanetarchive.ipac.caltech.edu/)
DSHARP data (GW Lup, HD 142666, HD 143006, SR 4) from Zhang et al. (2018).
Outline

1. How does a planet excite multiple spiral arms?

2. What are the implications?

3. Effects of disk thermal properties on the planet-driven spiral arm formation.
How does a planet excite multiple spiral arms?
A simulated J band scattered light image of SAO 206462 based on the model presented in Bae, Zhu & Hartmann (2016).

\[ \Phi_p (r, \phi) = -\frac{G M_p}{|\vec{r} - \vec{r}_p|} \]

\[ \Phi_p (r, \phi) = \sum_{m=0}^{\infty} \Phi_m (r) \cos (m \phi) \]
The $m$th Fourier component of the planet’s potential excites $m$ axisymmetric spiral wave modes at the Lindblad resonance (Goldreich & Tremaine 1978a,b,1979).
The propagation of waves depends on their azimuthal wavenumber $m$ such that constructive interference becomes available.
\[ \Phi_p(r, \phi) = \sum_{m=0}^{\infty} \Phi_m(r) \cos(m\phi) \]

\[ \Phi_p(r, \phi) = -\frac{GM_p}{|\vec{r} - \vec{r}_p|} \]

Bae & Zhu (2018a)
\[ \Phi_p(r, \phi) = -\frac{GM_p}{|\vec{r} - \vec{r}_p|} \]

Bae & Zhu (2018a)
• A more massive planet creates stronger spiral shocks (= faster propagation), so the spirals have more opened shapes (Bae & Zhu 2018b; see also Zhu et al. 2015, Fung & Dong 2015).

• This may explain why we need multi-Jupiter-mass planets to reproduce the observed grand-design m=2 spiral arms.
Q: What can a spiral arm do?

A: It transports angular momentum as it shocks the disk gas, opening a gap (Goodman & Rafikov 2001, Rafikov 2002).
Q: What happens when a planet excites multiple spiral arms?

A: The planet can open multiple gaps!
Multiple rings/gaps formed by “one” planet

Bae, Zhu & Hartmann (2017)
Gaps open at the radial locations each spiral arm shocks the disk gas.
A 0.1 Jupiter-mass planet at 99 AU can explain many of the observed continuum gaps and rings in the AS 209 disk (Zhang et al. 2018).

Secondary spiral arm formation prefers a low disk viscosity ($\alpha \lesssim 10^{-3}$ for a Jupiter-mass planet; Bae, Zhu & Hartmann 2017).
Summary

- **One planet can launch more than one spiral** through constructive interference among wave modes having different azimuthal wavenumbers.

- **One planet can create multiple rings and gaps** as its spiral arms shock the disk gas.
  - Number of observed gaps ≠ number of planets
  - We need more direct, localized evidence of planets in order to link disk substructures to planets.