Spirals in protoplanetary disks

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Plan

1. Overview of observed spirals in protoplanetary disks

2. Theory and simulations of spiral arms
   2.1. Gravitational Instability
   2.2. Planet-disk interaction
   2.3. GI + planet
   2.4. Shadows casted by the inner disk
   2.5. Stellar fly-by

3. For a given spiral observation, how to untangle the origin?

4. Observational perspectives
   4.1. Re-observations of HD 142527 spirals with ALMA
Global picture of observed spirals in disks in Near-IR

a) Grady+01 (HST); b) Clampin+03 (HST); c) Fukagawa+04 (HiCiao); d) Fukagawa+06 (HiCiao); e) Muto+08 (HiCiao); f) Casassus+12 (NICI); g) Grady+13 (HiCiao); h) Boccaletti+13 (NICI); i) Benisty+15 (SPHERE); j) Wagner+2015 (SPHERE)
Global picture of observed spirals in disks in sub-mm

- In view of the diversity of spirals in protoplanetary disks, there must be different ways to launch them. What are these processes?
- What are the implications on disk evolution?
Gravitational Instability

If the disk is massive enough, the influence of its own gravity is non-negligible compared to the star's gravity alone.

Toomre parameter: \[ Q = \frac{c_s \Omega}{\pi G \Sigma} \approx \frac{M_* h}{M_d} \]

- \( Q > 2 \): grav. stable
- \( Q \lesssim 2 \): grav. unstable

The evolution of a GI disk depends on its cooling timescale:

a/ \( \tau_{\text{cool}} \Omega \leq 3 - 5 \) => disk **fragmentation** and possible inward clump migration (e.g. Paardekooper+11); typically outer part of large primordial disks

b/ \( \tau_{\text{cool}} \Omega > 3 - 5 \) => no fragmentation, but creation of **spirals**, whose pattern depends on the disk mass and elapsed time:

(Forgan+11)
Gravitational Instability

\[ q = \frac{M_d}{M_*} \]

- \( q = 0.125 \)  \( \Rightarrow m \sim 8 \) (Di Pierro+ 15)
- \( q = 0.25 \)  \( \Rightarrow m \sim 4 \) (Dong+ 15)
- \( q = 0.5 \)  \( \Rightarrow m \sim 2 \) (Dong+ 15)

\[ m \sim \frac{1}{q} \]
Gravitational Instability

\[ q = \frac{M_d}{M_*} \]

- \( q = 0.125 \)
- \( q = 0.25 \)
- \( q = 0.5 \)

\( m \sim \frac{1}{q} \)

**OBSERVATIONS**

- SAO 206462
- MWC 758

(Di Pierro+ 15)

(Dong+ 15)
Gravitational Instability

Caveats of the theory:

• $q$ has to be $> 0.25$ to be prominent in NIR scattered images, and $q \sim 0.5$ to have $m=2$ spirals! This is contrary to most observations

• Requires high stellar accretion rates ($\sim 10^{-6} \, M_\odot \, \text{yr}^{-1}$)

• The disk fragments with GI beyond a certain radius (typically $\sim 100\text{au}$)
Planet-disk interaction

• Lessons from Zhu+15 (2D+3D hydro-simulations):
  • The more massive the planet, the larger the pitch angle.
  • A secondary spiral (or even tertiary) is excited. The more massive the planet, the larger the azimuthal separation between primary and secondary.
  • Using 3D hydro-simulations, one can re-create more prominent spirals as can be observed in NIR, than with 2D hydro-simulations assuming hydrostatic equilibrium.
  • Inner spirals (to the planet) usually appear more prominent than outer spirals, due to: 1/ enhanced vertical motion, 2/ sharper edges.

• Lessons from Dong+15 (radiative transfer of Zhu+15):
  • \( m = 2 \) symmetry
  • Inner spirals appear to have pitch angle between 10° and 15°
  • The spirals subtend 180° to 270°
  • \(~150\%\) brightness enhancement
Planet-disk interaction

• Dong+15 (radiative transfer of Zhu+15):

=> VERY SIMILAR TO SOME OBSERVED SPIRALS:

MWC 758

HD 100543
Planet-disk interaction

“The more massive the planet, the larger the azimuthal separation between primary and secondary.”

• From $1M_{\text{Nep}}$ to $16M_{\text{Jup}}$ planetary companions:

$$\phi_{\text{sep}} = 102^\circ \left(\frac{q}{0.001}\right)^{0.2}$$

• For brown dwarf companions:

$$\phi_{\text{sep}} = 180^\circ$$

• Application to SAO 206462 $\Rightarrow M_{\text{pl}} \sim 6 M_{\text{Jup}}$
Lessons from Juhasz+15 (2D hydro-simulations+ rad. transfer):
- A surface density relative change of a factor 3.5 is necessary to be detectable
- A pressure scale height variation of only 0.2 is enough to be detectable

Lessons from Pohl+15 (2D hydro-simulations+ rad. transfer):
- Scale height perturbations due to either 1/ accretion heating of the planet or 2/ local heating by GI can create enough spiral contrast to be detectable
- A large variety of planetary gap + spiral morphologies can be created depending on planet and disk mass
- The disk is not GI itself, but the massive planet is working as a trigger for GI
Inner disk casting shadows on the outer one

- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 2D hydrodynamical simulations show it can create spiral arms as well (Montesinos+ almost subm.):

L = 100L_{Sun}

250 orbits

500 orbits

3500 orbits

4000 orbits

L = L_{Sun}
Inner disk casting shadows on the outer one

- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 2D hydrodynamical simulations show it can create spiral arms as well (Montesinos+ almost subm.):
Inner disk casting shadows on the outer one

- Periodical density and temperature perturbations created by the shadows cast on the outer disk
- 3D RT hydrodynamical simulations ALSO show it can create spiral arms as well (Perez+ in prep.):
Stellar fly-by

- Tidal interaction by a past stellar encounter?
  (e.g. Larwood+ 01, Augereau+ 04, Quillen+ 05)

  > Transient spirals (a few dynamical timescales ~ 10^3 years)
  > Requires the perturber star to still be found in the neighbourhood
  > Can excite very large scale spirals

Quillen+ 05
What is the effect of spirals on the disk itself?

- Linear theory of spiral waves have trouble to match observations:
  - Predicted disks are too hot
  - They require too large $h$

- Non-linear propagation of tidal waves: (Goodman & Rafikov 01, Rafikov 02)
  - Tidal interactions between planet and disk generate density waves.
  - Density waves carry angular momentum (AM)
    => 1/ Planet migration or clump migration
    2/ Evolution of the disk itself, but how is the AM transferred to the disk?
      - Linearly? Viscosity does not seem efficient enough
      - Non-linear dissipation (shock formation) seems inevitable
  - Consequences on the evolution of the disk (Rafikov 16)
    - Spirals drive significant mass accretion (> than the one due to viscous stress)
    - Shock AM transport drives significant and quick surface density evolution
    - It could proceed in an inside-out fashion, first clearing the inside cavity
    => naturally explain the transition morphology of many spiral-bearing systems
For a given spiral observation, how to untangle the origin?

**Diagnostics:**

1. Estimate either the global Q (e.g. with rad. transfer modelling to get $M_d$) or local Q under the spirals (with sub-mm continuum or line observations for the surf. density)
   - $Q \lesssim 2$: strong indicator of GI
   - $Q \sim 2$: could still be the case of marginal stability+massive planet
2. Small or large scale?
   - < 100au: GI or planet
   - > 100au: Stellar fly-by, external companion, late envelope infall
3. Get kinematics/dynamics of the disk (e.g. velocity map/dispersion of line observations):
   - Non-keplerian speeds under the spirals: late-envelope infall
4. Number of spirals and their symmetry:
   - m = 1: single low-mass sub-stellar companion
   - m = 2: stellar fly-by, (sub-)stellar companion within or external to the disk, GI, or shadows
     - Apply Fung&Dong15 empirical relation to estimate the mass of the possible companion
   - m > 2: GI or shadows
5. Pitch angle of the spirals:
   - Pitch angle $\sim 10$-15°: compatible with GI, planets or shadows
   - Pitch angle $\sim 15$°-30°: compatible with external companions or fly-by
6. Check surroundings:
   - Within a few arcsec: low-mass bound companion external to the disk?
   - Within a few arcmin: star with similar proper motion?
Observational perspectives

- Waiting for ALMA cycle 3 data on the spirals of HD 142527:
  - Confirm the temperature of 10-15K under S2 (below freeze-out)
  - Observe at better continuum sensitivity to confirm the lack of dust under S2 that could explain T below freeze-out.
  - More stringent constraints on the origin of these spirals; test of the shadows theory.

![CO J=2-1 Image](image_url)