Gravitational Instabilities in Protoplanetary Disks

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Outline

• Motivation of studying Gravitational Instabilities (GI) in protoplanetary disks

• Gravitoturbulence and locality of GI

• Fragmentation of disks due to GI

• FU Orionis outbursts and models of disk evolution
Motivation – Protoplanetary Disks

- Accretion disks are required:
  - Observation (Infrared and sub-mm)
  - Dynamical role in star formation: accretion
  - Site of planet formation

Credit: C. Burrows and J.Krist(STScI), K.Stapelfelt(JPL) and NASA
Properties of Protoplanetary Disks

- **Masses:** $10^{-3} - 10^{-1} \, M_{\text{sun}}$ in gas
- **Sizes:** 100 – 1000 AU
- **Lifetimes:** $10^6 - 10^7$ yr
- **Temperature:** cold, ~ several 100 K
- **Thickness:** $H/R \sim 0.03 - 0.05$
- **Opacity:** $\tau \sim 10^3 - 10^4$ (at 1 AU in optical, mainly due to dust)
- **Very low ionization fraction:** MRI couldn’t work in “dead zones”
Motivation – Gravitational Instability (GI)

• Alternative source of angular momentum transport in cold disks (Lin & Pringle 1987; Armitage, Livio & Pringle 2001).
  • Locally: gravitational turbulence → “viscosity”
  • Globally: bar structures, spiral arm structures

• Giant Planet Formation:
  • Limit of time:
    giant planets have to be formed within several million years from the star forming event
  • Difficulty with current planet formation theory (i.e. core instability models, Ida & Lin 2004; Rafikov 2010)
  • Giant planets might have formed by Gravitational Instability (disk fragmentation, Boss 2000).
When does GI work?

- Dispersion relation for density waves in gas disks in WKB limit (Binney & Tremaine 1987):
  \[ \omega^2 = c_s^2 k^2 - 2\pi G \Sigma |k| + \kappa^2. \]

- Similar to Jeans Instability:
  - Gravity \(\rightarrow\) Pressure + F\text{centri}
  - Small wavelengths: P
  - Long wavelengths: F\text{centri}
  - Intermediate: GI

- GI occurs when:
  1. \(\omega^2 < 0\)
  2. \(Q = \frac{c_s \Omega}{\pi G \Sigma} < Q_{\text{crit}} \approx 1\) (Toomre Parameter)
  3. \(M_{\text{disk}} \gtrsim \frac{H}{r} M_*\)
  4. \(\dot{M} \gtrsim \frac{3\alpha c_s^3}{G} = 7.1 \times 10^{-4} x \left(\frac{c_s}{1 \text{ km s}^{-1}}\right)^3 M_\odot \text{ yr}^{-1}\)

\[ \dot{M} = 3\pi \alpha c_s^2 \Sigma / \Omega. \]

Pre-assumption for 4: No external torques, no heating from external illumination.
Thermal processes are important to GI

\[ Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\text{crit}} \approx 1 \]

- Timescales:
  - Change of \( \Sigma \): accretion timescale \( \sim (r/H)^2 (\alpha \Omega)^{-1} \)
  - Cooling or heating: thermal timescale \( \sim (\alpha \Omega)^{-1} \)
  - \( r/H \gg 1 \)
Final Fate for GI Unstable Disks

- **Quasi-steady, long-lived state:**
  - Gravitational turbulences transport angular momentum out
  - Marginally stable $Q \sim Q_0$.
  - Self-regulated state cooling $\sim$ heating by GI

- **Rapid fragmentation:**
  - If cooling is much more efficient than heating
  - Formation of massive planets or substellar objects (Boss 1997).

- **Bursts of accretion (FU Ori bursts):**
  - If temperature becomes high enough to trigger MRI
1. GI as a specific form of “viscosity”: Controversy about locality of GI


**Locality**

- Evolution of viscous disks:

\[
\frac{\partial \Sigma}{\partial t} = \frac{3}{R} \frac{\partial}{\partial R} \left[ R^{1/2} \frac{\partial}{\partial R} (\nu \Sigma R^{1/2}) \right]
\]

\[\nu \sim \lambda \tilde{\nu}.\]

- \(\alpha\)-prescription:

\[\nu = \alpha c_s H \text{ (Shakura and Sunyaev, 1973 )}\]

**Lin & Pringle, 1987:**
Self-gravity could be treated as local, gravitoturbulent process, and thus could be described in a modified viscous \(\alpha\) framework.

**Balbus & Papaloizou, 1999:**
Self-gravitating disks could only be described as local process when the pattern speed \(\Omega_p\) matches the local angular velocity \(\Omega\). Otherwise, the energy equation cannot be put into the form of a diffusion equation as required in local viscous scenario.
Locality

- Gravitoturbulence:
  - Local Thermal Equilibrium:
    \[
    \alpha = \frac{4}{9\gamma(\gamma - 1)} \frac{1}{t_{\text{cool}}\Omega}
    \]
  - Assuming opacity to be power law of midplane temperature:
    \[
    \alpha \sim \frac{\sigma}{\kappa_0} \left( \frac{\mu m_p}{\gamma k_B} \right)^{4-\beta} (Q_0 \pi G)^{6-2\beta} \Sigma^{4-2\beta} \Omega^{2\beta-7}
    \]
    (Levin 2007)

- Locality is proved when:
  - \( M_{\text{disk}} / M_* < 0.25 \) (Lodato&Rice 2004)
  - \( M_{\text{disk}} / M_* = 0.1 \), departure is 10%  
    (Cossin, Lodato & Clarke, 2009)
  - \( M_{\text{disk}} / M_* < 0.5 \)  
    (including radiative transfer, Forgan et al. 2010)
2. Fragmentation due to GI
Disk Fragmentation

2D hydrodynamic simulation by Gammie 2001:
Disks will fragment when $t_{\text{cool}} \leq 3 \, \Omega^{-1}$

$t_{\text{cool}} = 50 \, \Omega^{-1}$, no fragmentation

$t_{\text{cool}} = 2 \, \Omega^{-1}$, fragmentation
Disk Fragmentation

3D hydrodynamic simulation by Rice et al. 2003:
Disks will fragment when $t_{\text{cool}} \leq 5 \Omega^{-1}$

$t_{\text{cool}} = 5 \Omega^{-1}$, no fragmentation

$t_{\text{cool}} = 3 \Omega^{-1}$, fragmentation
Disk Fragmentation

• If:
  • there’s no irradiation from central star;
  • angular momentum transport is totally dominated by gravitoturbulence

• Then:
  1. around a 1 M\(_{\odot}\) star,
  2. self-gravity acts as a local process whose efficiency is set by the requirement of thermal equilibrium (Clarke 2009, Rafikov 2009).
  3. The opacity includes contributions from water ice, amorphous carbon, silicates, and graphite

\[ \alpha = \frac{4}{9\gamma(\gamma - 1)} \frac{1}{t_{\text{cool}}\Omega} \]

\[ \dot{M} \geq \frac{3\alpha c_s^3}{G} \]

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\[
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\dot{M} \geq \frac{3\alpha c_s^3}{G}
\]

Figure 3

In a steady state disk whose heating is dominated by a central source, calculated assuming that self-gravity "turned on" in a natural way.

\[ T_{\text{eff}} = 20 \text{ K (no irradiation)} \]

\[ T_{\text{eff}} = 10 \text{ K (no irradiation)} \]

Self-gravity suppressed by hydrodynamic angular momentum transport

\( \alpha(\text{self-grav}) = 10^{-2} \)

\( \alpha(\text{self-grav}) = 10^{-3} \)

Fragmentation possible

\[ (\text{Armitage, 2011}) \]
Disk Fragmentation

- Two caveats:
  - **Background viscosity**: if background viscosity dominates, then the disk might be gravitationally stable;
  - **Stellar irradiation**: external heating source keeps the disk gravitationally stable
Disk Fragmentation

- **Background viscosity:**
  
  - $\alpha_v = 0.003$

- **Strong stellar irradiation:**
  
  - $T_0 = 35K$ due to irradiation, spatially constant

- **Opacity:**
  
  - $\kappa = \kappa_0 T^2$

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(Roikov, 2009)
3. Disk Evolution & FU Orionis Bursts
Phenomena

- Luminosity problem of protostars (Kenyon et al. 1990):
  Typical bolometric luminosity $\ll$ infall rate
- FU Orions outbursts (Hartmann & Kenyon 1996)
Models of Disk Evolution

- Rapid matter addition to the disk
  - Perturbations from companions.(Bonnell & Bastien 1992; Forgan & Rice 2010)


(Forgan & Rice 2010) (Vorobyov & Basu 2010)
Models of Disk Evolution

- Thermal Insabilities (TI, Bell & Lin 1994):
  - Opacity of the disk changes rapidly at $T \sim 10^4$ K due to ionization of hydrogen.
  - Problem: only works if angular momentum is extremely inefficient ($\alpha \sim 10^{-3} – 10^{-4}$).

![Graph showing opacity $\kappa(T)$ and local disk vertical structure](image)

(Armitage 2011)
Models of Disk Evolution

- Association with MRI:
  - Dead zone at \( r \sim 1 \text{ AU} \), where angular momentum transport is low in the midplane, and where materials pile up and heat up;
  - MRI triggered at \( T_M \sim 1200 \text{K} \) (Zhu et al. 2009), rapid accretion

\[ \alpha = 0.025 \]

\[ \alpha = 0.1 \]

Lasts 100yr at \( 2 \times 10^{-4} M_{\odot}/\text{yr} \)

(Zhu et al. 2009)
Models of Disk Evolution

2D simulation (Zhu et al. 2009):

\[ R_{\text{in}} = 0.06 \text{AU} \]
\[ N_R = 320 \]
\[ N_\theta = 224 \]

Observed FU Ori (Hartmann & Kenyon 1996):

\[ \text{B Magnitude} \]
\[ \text{Time (Years)} \]
Long-term evolution

- Layered accretion with infall (Zhu, Hartmann & Gammie, 2010):

Solves the luminosity problem!
Conclusions

• Gravitational instability could be common and so important to protoplanetary disks
• Locality of gravitational instability is plausible in low-mass disks
• Gravitational instability results in two outcomes depending on the cooling time:
  • Gravitoturbulence (steady angular momentum transport)
  • Fragmentation
• Irradiation and background viscosity constrain regimes where GI works:
  • Irradiation stabilizes disks against fragmentation at low mass accretion rates
  • Background viscosity could dominate angular momentum transport and stabilize the disk
• Heating up due to GI could trigger MRI and produce bursts of accretion, which explains FU Ori outbursts.
References

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