Hydrodynamic activity in planet-forming disks

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November 2019
An over-simplified picture of planet formation

well-mixed dust in young disk

dust settles to disk midplane

dust grains

planetesimals

protoplanet

gravity/pebble accretion
Complications from gas dynamics

\[ \log\left(\frac{\rho_d}{\rho_g}\right), \ t=0P_0 \]
Fundamental role of gas dynamics

- Mass accretion
  - Disk evolution
- Angular momentum transport
- Structure formation
- Planet formation/evolution
- Gas dynamics/instabilities
- Dust evolution
Instabilities in planet-forming disks

Hydrodynamic
- Zombie vortices
- Radial convection
- Vertical shear
- Rossby wave
- Subcritical baroclinic
- Elliptic instability

Magnetic fields

Self-gravity
- Gravitational instability
- Secular GI

Dust-gas interaction
- Kelvin-Helmholtz
- Streaming instability
Instabilities in planet-forming disks

- Zombie vortices
- Radial convection
- Vertical shear

Faster cooling

few AU

~100 AU
Hydrodynamic stability: Solberg-Hoiland criteria

- **Sufficient** stability conditions for **infinitesimal, axisymmetric, adiabatic** perturbations

\[
\kappa^2 + N_R^2 + N_z^2 > 0
\]

\[
- \frac{\partial P}{\partial z} \left[ \kappa^2 \frac{\partial S}{\partial z} - \frac{\partial (R\Omega^2)}{\partial z} \frac{\partial S}{\partial R} \right] > 0.
\]

(Tassoul 1978, Ogilvie 2016)

- Epicyclic frequency \( \kappa \)
- Radial and vertical buoyancy frequencies \( N_R, N_z \):

\[
N_R^2 \equiv - \frac{1}{C_p\rho} \frac{\partial P}{\partial R} \frac{\partial S}{\partial R}, \quad N_z^2 \equiv - \frac{1}{C_p\rho} \frac{\partial P}{\partial z} \frac{\partial S}{\partial z}.
\]

- Specify entropy \( S \):

\[
S \equiv C_p \ln \frac{P^{1/\gamma}}{\rho}.
\]
Keplerian disks are quite stable

- $\kappa^2 \gg \mathcal{N}_R^2, \mathcal{N}_z^2$
- $\Omega = \Omega(R)$
- Solberg-Hoiland conditions:
  
  $\kappa^2 > 0$ (Rayleigh criterion ✓)
  $\mathcal{N}_z^2 \kappa^2 > 0$ (Convectively stable ✓)

- Keplerian disks have specific angular momentum increasing outwards
- Second condition satisfied for stably stratified disks
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Destabilize disks by violating SH assumptions
(infinitesimal, axisymmetric, adiabatic perturbations)
Zombie vortex instability
(Barranco & Marcus, 2005; Marcus et al., 2013, 2015, 2016; Barranco et al. 2018)

- **Finite-amplitude, non-axisymmetric** perturbations

(adapted from Marcus et al. 2013)
Zombie vortex instability
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- **Finite-amplitude, non-axisymmetric** perturbations
ZVI: physical mechanism

Resonance between vortex-emitted Rossby waves and fluid buoyancy (Umurhan et al., 2016)
ZVI: physical mechanism

Critical layers roll up

New vortex forms

Next critical layers excited

(adapted from Marcus et al., 2015)
ZVI: physical requirements

- Minimum **vorticity** perturbations: $|\delta \omega| \gtrsim 0.4 \Omega$
- Nearly adiabatic gas: slow cooling $t_{\text{cool}} \gtrsim 10 \Omega^{-1}$ or heat diffusion: $\text{Pe} \gtrsim 10^4$

(adapted from Lesur & Latter et al., 2016)
Can ZVI occur in realistic disks?

No clear answer

- Depends on how $t_{\text{cool}}$ is estimated
- Lesur & Latter (2016): no ZVI for $R \gtrsim 0.3\text{AU}$
- Barranco et al. (2018): widespread ZVI
- Need realistic (cf. parameterized) thermodynamics in simulations
Convective overstability
(Klahr & Hubbard, 2014; Lyra, 2014; Latter, 2015)

- Need **radial buoyancy**, e.g. entropy decreasing from star
- Non-adiabatic perturbations, need **cooling**

(Lyra 2014)
Convective overstability
(Klahr & Hubbard, 2014; Lyra, 2014; Latter, 2015)

- Need radial buoyancy, e.g. entropy decreasing from star
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\[
growth \ rate \propto \frac{-N_R^2 t_{\text{cool}}}{1 + (\kappa^2 + N_R^2) t_{\text{cool}}^2}.
\]

(Lyra 2014)

- Maximum growth rate \(-\frac{N_R^2}{4\Omega}\) occurs for \(t_{\text{cool}} \sim \frac{1}{\Omega}\)
COV: physical mechanism

(a) $S_0$

Hotter → Colder

lower entropy

(b) epicyclic motion

heat exchange with outer disk

$S_1 < S_0$

buoyant acceleration

(c) $S_2 > S_0$

heat exchange with inner disk

(d)

(adapted from Latter 2015)
Can COV occur in realistic disks?

Maybe at special locations

To get $N_R^2 < 0$ at the midplane (for $\gamma = 1.4$):

$$\frac{\partial \ln \Sigma}{\partial \ln R} > 3 \left( \frac{\partial \ln T}{\partial \ln R} + \frac{1}{2} \right)$$

For $T \propto R^{-1/2}$: need density to increase with distance, e.g. gap edges

Instability condition may be more easily satisfied off-midplane (Lyra & Umurhan, 2019)
COV and the subcritical baroclinic instability
(Petersen et al., 2007; Lesur & Papaloizou, 2010; Lyra & Klahr, 2011; Barge et al. 2016)

- **Non-linear** version of COV: seed vortices amplified by buoyancy+cooling
- Same physical mechanism and requirements as COV \( N_R^2 < 0, t_{cool} \sim \Omega^{-1} \)
- Works in 2D: relevant profiles are vertically integrated density, pressure...etc

(Petersen et al. 2007b)
Vertical shear instability
(Nelson et al., 2013; Lin & Youdin, 2015; Barker & Latter, 2015; Latter & Papaloizou, 2018)

- A centrifugal instability that feeds off **vertical shear**: $\partial_z \Omega \neq 0$
- Requires **rapid cooling**

![Diagram showing $v_{gz}/c_s$, $t=1000P_0$](image)

Lin et al. in prep., FARGO3D sim.
VSI: physical mechanism

- Swap fluid elements, conserve specific angular momentum
- Change in energy:

\[
\Delta E \sim \frac{l_z^2}{l_R^2} \left( \frac{\Omega^2}{l_R} \cdot R \frac{\partial \Omega^2}{\partial z} \right)
\]

- $\Delta E < 0 \Rightarrow$ unstable
  - Possible for vertically elongated disturbances.

**BUT** in real disks:
- Buoyancy stabilizes vertical motion
VSI: cooling requirement (Lin & Youdin, 2015)

- Rapid cooling kills buoyancy
- For $T \propto R^q$:

$$t_{cool} \Omega < \frac{|q|}{\gamma - 1} \left( \frac{H}{R} \right) \ll 1$$
Can VSI occur in realistic disks? 

Probably at large radii

- Stoll & Kley (2014, 2016): radiation hydrodynamic simulations:
VSI in 3D

Vortex formation via RWI of VSI structure

(adapted from Richard et al., 2016)
Map of hydrodynamic instabilities

(adapted from Lyra & Umurhan, 2019; based on Maylgin et al., 2017)
Prevalence of vortices

Vortex formation/amplification

- Convective overstability/SBI
- Zombie vortex instability
- Dust-trapping
- Elliptic instability
- Gaps, DZ edges, snowlines
- Rossby wave instability
- Vertical shear instability
Elliptic instabilities disrupt 3D vortices

(Kerswell 2002; Lesur & Papaloizou, 2009; Lyra & Klahr, 2011)

Lin & Pierens, 2018: elliptic instability in self-gravitating disks
Role of hydrodynamic instabilities

- Weak angular momentum transport, $\alpha \lesssim 10^{-3}$
- **Particle trapping** by vortices
- **Particle stirring** by turbulence
Vortices and dust

(Chen & Lin, 2018)

- RWI: Li et al. (2000); Meheut et al. (2010); Lin & Papaloizou (2011)...etc.
- Vortex dust traps: Barge & Sommeria (1995); Lyra & Lin (2013); Zhu et al. (2014)...etc.
Vertical shear instability and dust

(Stoll & Kley, 2016; Flock et al., 2017; Picogna et al., 2018; Lin, 2019)
Effect of metallicity (Lin, 2019)

- $M_{\text{dust}} = 0.01M_{\text{gas}}$
- $M_{\text{dust}} = 0.1M_{\text{gas}}$

More dust settles to thinner layers
Can planetesimals form in turbulent layers?

Streaming instability in MMSN-like disk

\[ \rho_{\text{dust}} < \rho_{\text{gas}} \]

\[ \alpha_{\text{visc}} \approx 10^{-3} \]

\[ \Sigma_{\text{dust}} = 0.1 \Sigma_{\text{gas}} \]

Chen & Lin, in prep.
Planet-disk interaction

Auddy & Lin, in prep.: application of machine learning to many-parameter surveys
→ S. Auddy’s talk (Thursday)
Oscillatory torques on planets in dusty disks

\[ T_s = 0.001 \]

\[ \Sigma_d = 0.01 \Sigma_g \]
\[ \Sigma_d = 0.5 \Sigma_g \]
\[ \Sigma_d = 1.0 \Sigma_g \]

Chen & Lin, 2018
Planet migration in dust-rich disks

Hsieh & Lin, in prep., see *poster*
What happens in 3D?

\[ \log(\frac{\rho_d}{\rho_g}), \; t=200P_0 \]
Fake planet-disk simulations
(Lin & Tong, in prep.)
Full 3D simulations

(Bi, Lin, & Dong, in prep.)

age = 0 $P_0$
### Hardware - Overall Specifications
- 252 nodes / 9072 CPU cores
- **2016 GPUs**
- 193.5 TB memory
- 10 PB storage
- EDR InfiniBand 100 Gbps
- 1.2 PUE (Warm Water Cooling)

### Software Environment
- Slurm / Kubernetes
- Nvidia NGC Docker
- Ceph
- Spectrum Scale (GPFS)
- CentOS

### Hardware - Single Node Specifications
- Intel Xeon Gold CPU x 2
- **Nvidia Tesla V100 w/32GB x 8**
- 768 GB memory
- 240 GB SSD + 4TB NVMe

### AI Architecture
- Tensorflow
- Caffe / Caffe 2
- PyTorch / Torch
- ......and more

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Credit: NCHC.org.tw

- Seeking collaborations (zero wait times right now)
Summary & future

- Zombie vortices: least understood and explored
- Convective overstability: understood, somewhat explored
- Vertical shear instability: understood, most explored
- Need to verify **ZVI and COV with realistic thermodynamic treatment**
- Impact of non-ideal MHD? C. Cui’s talk on VSI+MHD
- **Important for dust dynamics**: particle stirring/trapping
  - Note: dust-gas heating needed when considering ZVI and COV
- Impact on planetesimal formation and planet migration
Summary & future

Thank you

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