Hydrodynamic processes in protoplanetary disks

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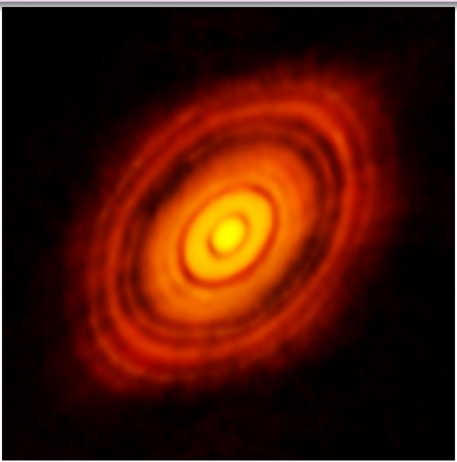
A new era for planet formation

Planets form in protoplanetary accretion disks around young stars



(ALMA Partnership, 2015, HL Tau)

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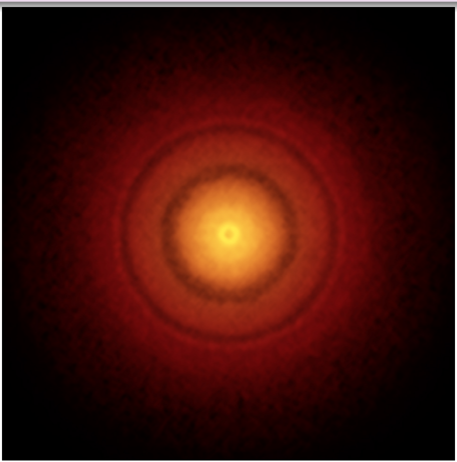
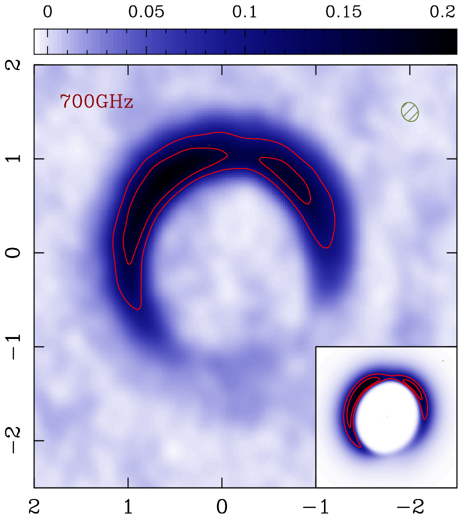


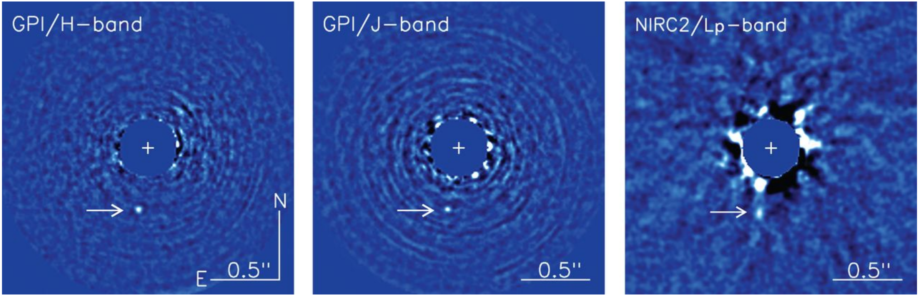
(TW Hydrae, Andrews et al., 2016)

Asymmetric transition disks



(HD142527, Casassus et al., 2015)

Directly imaged planets



(51 Eridani, Macintosh et al., 2015)

Planet formation through accretion disk theory

Fundamental gas dynamics of protoplanetary accretion disks

- How do disks transport angular momentum and accrete?
  - Turbulent transport?
  - Spiral arms from self-gravity?
  - Magnetic winds?

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- What are the sources of turbulence in disks?
  - Hydrodynamic, gravitational, or magneto-hydrodynamic?
  - Where and when do these operate?

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  - Planet induced?
  - Fluid instabilities?

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  - Planet induced?
  - Fluid instabilities?
- How do large-scale structures affect planet formation?
  - Dust-trapping mechanisms (enhance planetesimal formation)?
  - Dynamical interaction with planets?

Hydrodynamic activities in all stages of PPD evolution

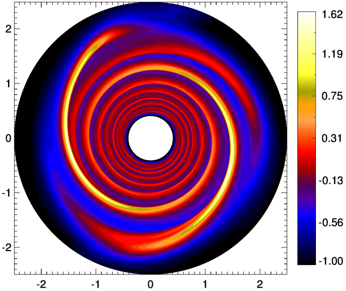
Protostellar disks: gravitational instabilities

disk evolution

MMSN disk: vertical shear instability

planet formation

Planet-induced vortices/dust-traps



(Lin, Fargo sims.)

- Going beyond Toomre and Lin-Shu analyses (Lin & Kratter, 2016)

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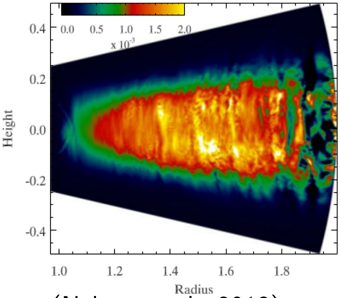


(Nelson et al., 2013)

- Does it occur in realistic PPDs? (Lin & Youdin, 2015)

Hydrodynamic activities in all stages of PPD evolution

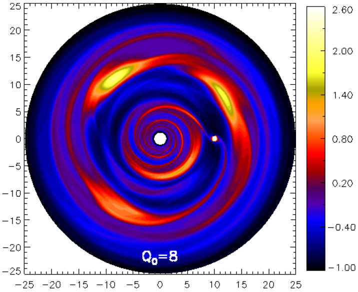
Protostellar disks: gravitational instabilities

↓ disk evolution

MMSN disk: vertical shear instability

↓ planet formation

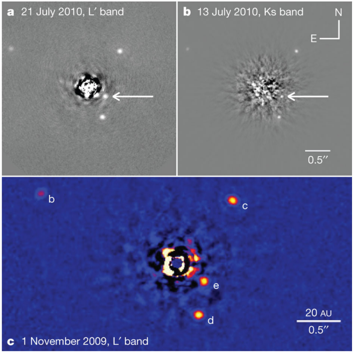
Planet-induced vortices/dust-traps



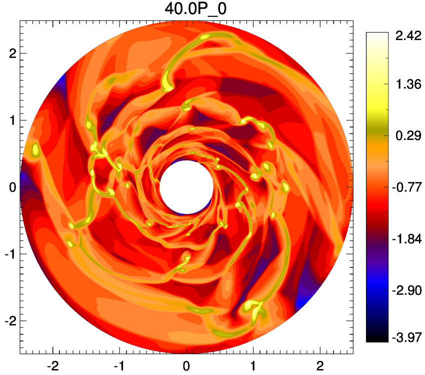
(Lin, 2012b)

- 3D effects on vortex evolution (Lin, in prep.)

Wide orbit planets/brown dwarfs & disk instability theory



(HR8799 Marois et al., 2010)



(Lin, Fargo sims., log dens.)

- Young, massive PPDs can fragment by self-gravity

Fragmentation conditions

- Massive disk

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \lesssim 2 \text{ or } M_{\rm disk} \gtrsim 0.1 M_*$$

- Fast cooling

$$t_{\rm cool}\Omega \lesssim 3$$

The cooling criterion is empirical!

WARNING
Critical cooling depends on the numerical simulation!

(resolution, 2D/3D, local/global, particle-based or grid-based simulations)

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Motivation 1:

Assess disk fragmentation without input from hydrodynamic simulations

Beyond classical gravitational instability

Modern simulations (c. 2010)

- Cooling physics, e.g.

$$\frac{\partial E}{\partial t} = -\frac{E}{t_{\mathrm{cool}}}$$

- Turbulent/viscous, e.g.

$$\nu = \alpha \frac{c_s^2}{\Omega}$$

Analytic toolbox (c. 1960)

- Isothermal/adiabatic (no cooling)

$$\frac{\partial E}{\partial t} = 0$$

- Laminar (inviscid)

$$\nu = 0$$

Lin-Shu dispersion relation, Toomre Q

$$\omega^2 = \kappa^2 - 2\pi G\Sigma|k| + c_s^2 k^2$$

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma}$$

Beyond classical gravitational instability

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- $\omega^2(k; Q) = \kappa^2 - 2\pi G\Sigma|k| + c_s^2 k^2$

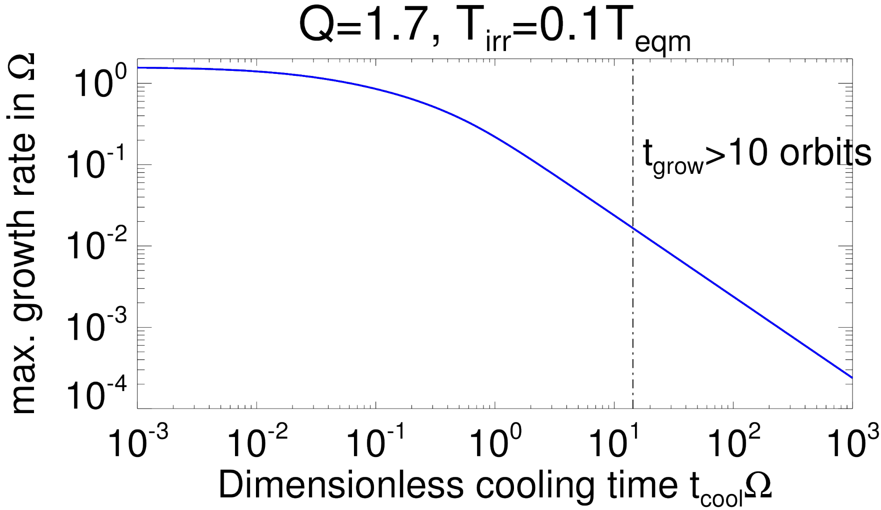
Motivation 2:

Generalize analytic treatment of GI to include cooling, irradiation and viscosity

$$\omega = \omega(k; Q, t_{\mathrm{cool}}, \alpha)$$

Cooling/viscosity $\rightarrow$ can be unstable even for $Q > 1$ (cf. $Q < 1$ for classic GI)

Cooling-driven gravitational instability

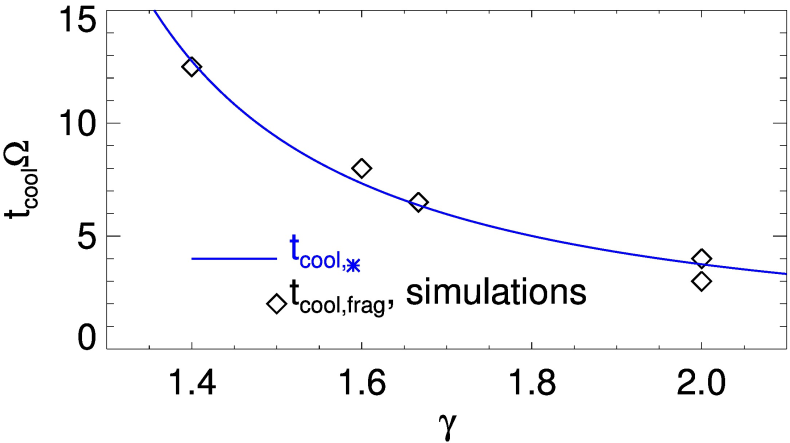


(Lin & Kratter, 2016) $T_{\rm irr}$: irradiation temp.

Understanding simulations

Cooling timescale to remove pressure over a lengthscale $\sim H$

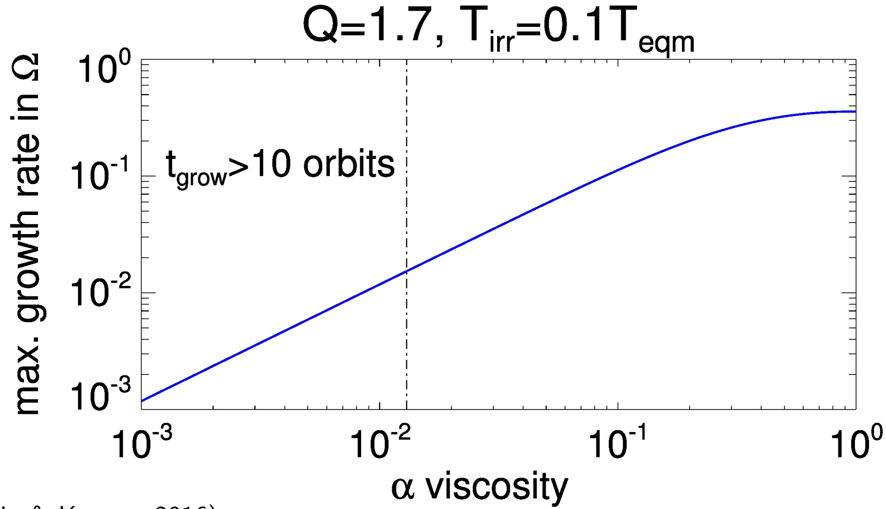
$$t_{\mathrm{cool},*} = (\sqrt{\gamma} - 1)^{-3/2}\,\Omega^{-1}$$ (Lin & Kratter, 2016)



Simulations: Gammie (2001); Rice et al. (2005, 2011); Paardekooper (2012)

Viscous gravitational instability

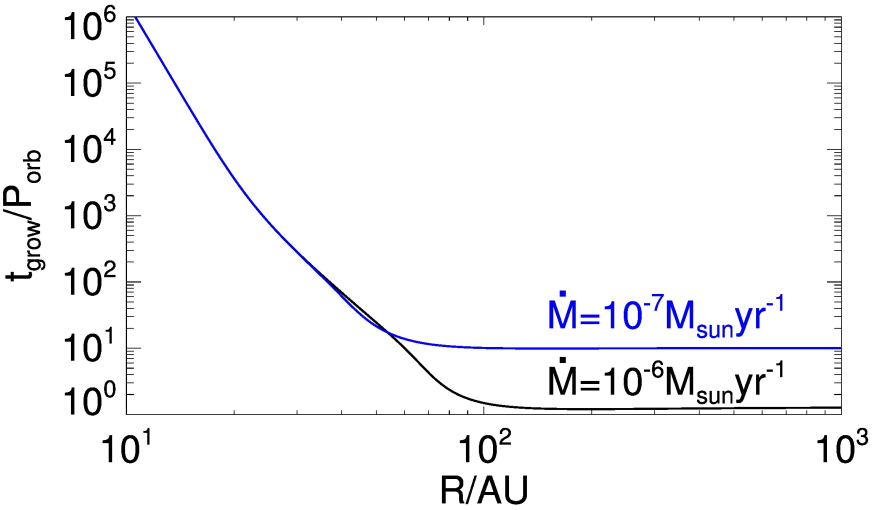
- Viscosity/friction can remove rotational stabilization (Lynden-Bell & Pringle, 1974)



(Lin & Kratter, 2016)

Putting it all together

- Input physical disk model with cooling and viscosity — get growth timescales



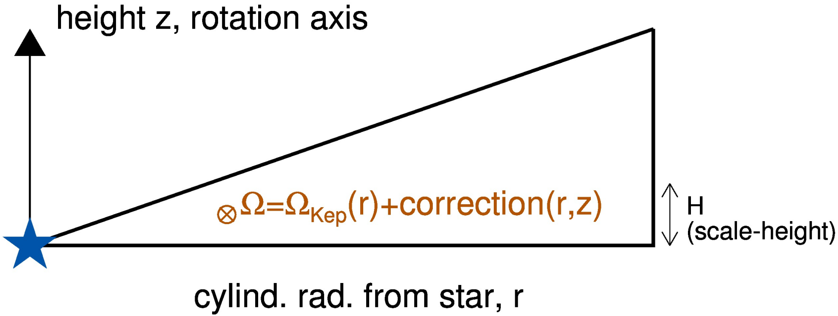
(Lin & Kratter, 2016)

- High $\dot{M}$ disk fragments $\gtrsim$ 60AU, growth times $\sim$ one orbit

What's next for disk GI theory?

- Global effects with cooling and viscosity
  - Mass infall
  - Disks with radial structure
  - Large-scale spiral instabilities
- Magnetic effects: good or bad for stability?
  - Extend Lin (2014) to include cooling/viscosity
- Direct simulations: include actual turbulence (cf. viscosity)
  - Hydrodynamic turbulence due to VSI? Next topic!

Astrophysical disks have vertical shear



$$\frac{\partial \Omega}{\partial z} \neq 0$$

(Because $\nabla P \times \nabla \rho \neq 0$)

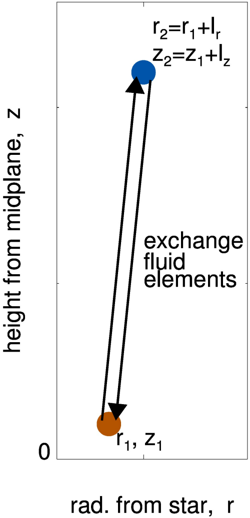
- Vertically isothermal thin-disk with $T \propto r^q$,

$$r\frac{\partial \Omega}{\partial z} \simeq \left(\frac{qz}{2H}\right) \times \frac{H}{r}\Omega_{\mathrm{Kep}}$$

- $H/r \sim 0.05$ in PPDs

Vertical shear instability

$\partial_z \Omega \neq 0 \Rightarrow$free energy$\rightarrow$instability?



- Change in kinetic energy:

$$\Delta E \sim l_r^2 \left(\Omega^2 + \frac{l_z}{l_r} \cdot r \frac{\partial \Omega^2}{\partial z} \right)$$

- Vertical shear is weak, **BUT**

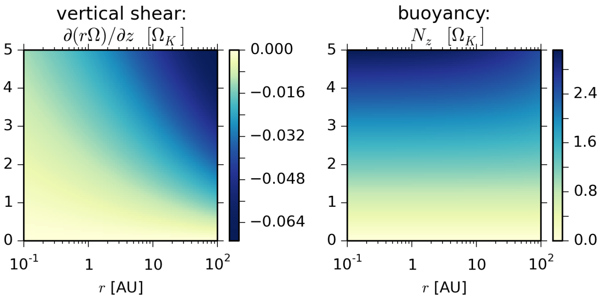
$$\Delta E < 0 \quad \text{if} \quad |l_z| \gg |l_r|$$

$\Rightarrow$ **INSTABILITY**

- Energy released for vertically elongated disturbances.

VSI needs to fight buoyancy in real disks

$$\underbrace{r\partial_z\Omega}_{\text{destabilizing vert. shear}} \quad \text{v.s.} \quad \underbrace{N_z}_{\text{stabilizing vert. buoyancy}}$$



- Vertical shear is weak, $\boxed{r\partial_z ln\Omega \sim O(h) \ll 1}$ (so need $l_z/l_r \gg 1$)
- Vertical buoyancy is strong, $\boxed{N_z/\Omega \sim O(1)}$

Ultra-fast cooling can overcome buoyancy forces

(Lin & Youdin, 2015): quasi-global analyses of the VSI

- Including energy equation with finite cooling timescale t_{cool}

For $T \propto r^q$ PPD, find that VSI requires:

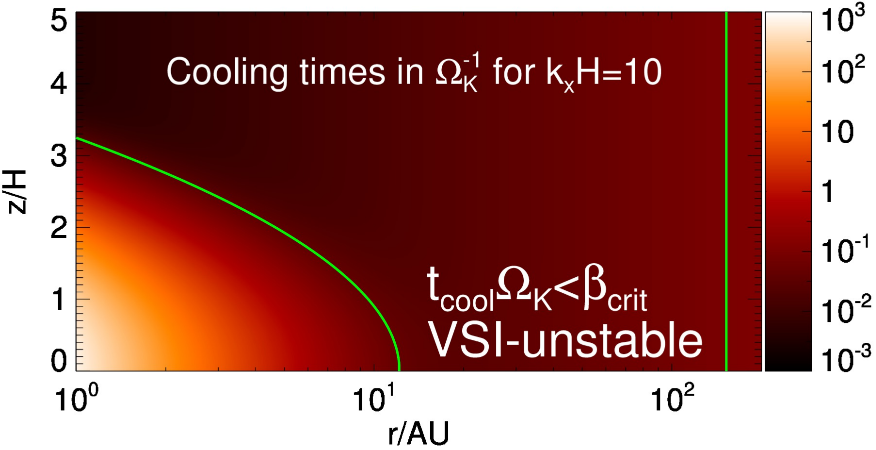
$$\boxed{t_{\mathrm{cool}}\Omega_{\mathrm{K}} < \frac{h|q|}{\gamma - 1} \ll 1}$$

- $h|q|$: vertical shear ($h \equiv H/r \ll 1$) — destabilizing
- $\gamma - 1$: vertical buoyancy — stabilizing
- As seen in high res. numerical simulations
  e.g. Nelson et al. (2013) find VSI only for $t_{\mathrm{cool}}\Omega_{\mathrm{K}} \lesssim 0.06$

Do protoplanetary disks actually develop VSI?

Cooling via dust-opacity ($\propto T^2$) in the Minimum Mass Solar Nebula

$$\beta_{\rm crit} \equiv \frac{h|q|}{\gamma - 1}$$



What's next for VSI theory?

Vertical shear in dusty disks

$$r\frac{\partial \Omega^2}{\partial z} = \frac{c_s^2}{\left[1+\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right)\right]^2}\left[\frac{\partial \ln \rho_{\mathrm{gas}}}{\partial z}\frac{\partial}{\partial r}\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right) - \frac{\partial \ln \rho_{\mathrm{gas}}}{\partial r}\frac{\partial}{\partial z}\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right)\right]$$

Is there a 'dusty VSI'?

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Is there a 'dusty VSI'?

Not for perfectly coupled dust particles in an isothermal disk

Isothermal, well-coupled dusty gas $\equiv$ adiabatic pure gas

Isothermal dusty gas

- Small dust particles follow gas

$$\frac{D}{Dt}\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right) \simeq 0$$

- RHS$\equiv$ 0 for $t_{\mathrm{stop}} \to 0$

Textbook hydrodynamics

- Entropy follows gas

$$\frac{DS}{Dt} \simeq 0$$

- RHS $\equiv 0$ for $t_{\mathrm{cool}} \to \infty$

Exploit this analogy to

- Provide thermodynamical interpretations of known results in dusty fluids
  - E.g. streaming instabilities
- Explore dusty analogs of known phenomena in standard hydrodynamics
  - E.g. dusty Solberg-Hoiland criterion $\Rightarrow$ a limit on dust edges
- Study asymmetric dust-trapping, next topic!

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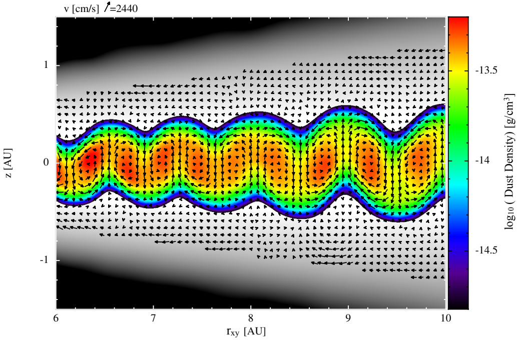

- Dusty-gas sims. from Lorén-Aguilar & Bate (2015)
- What is this?

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Isothermal dusty gas

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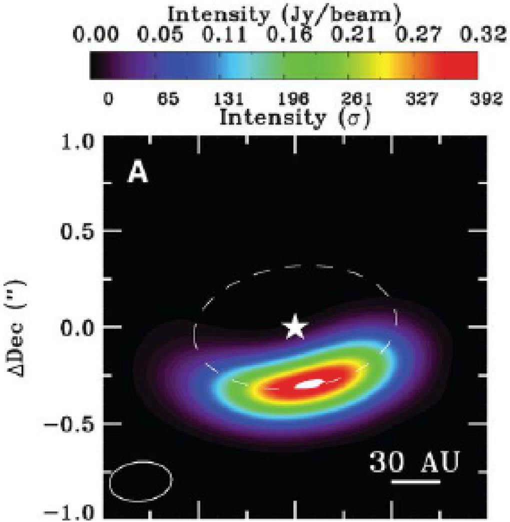
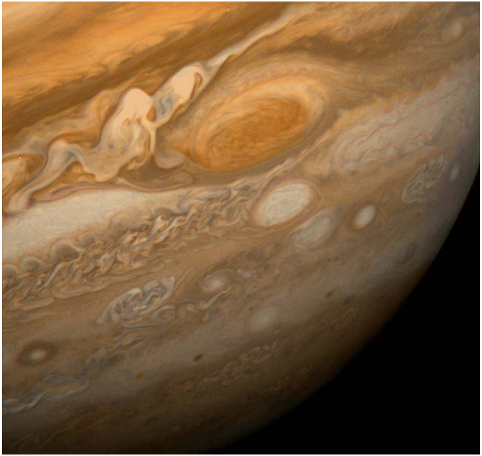
Transition disk asymmetries: vortices?



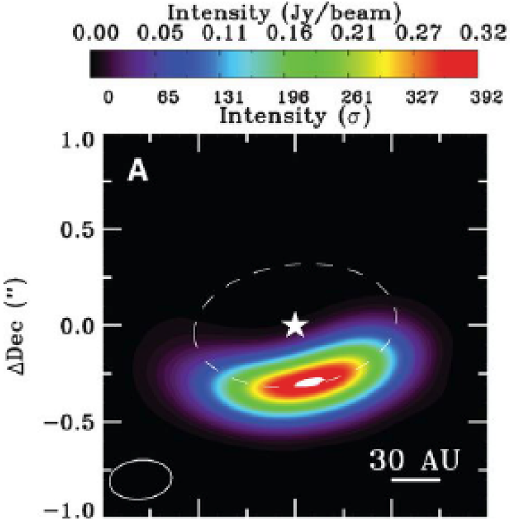
(Oph IRS 48, van der Marel et al., 2013)

Transition disk asymmetries: vortices?



Jupiter's Great Red Spot

Transition disk asymmetries: vortices?



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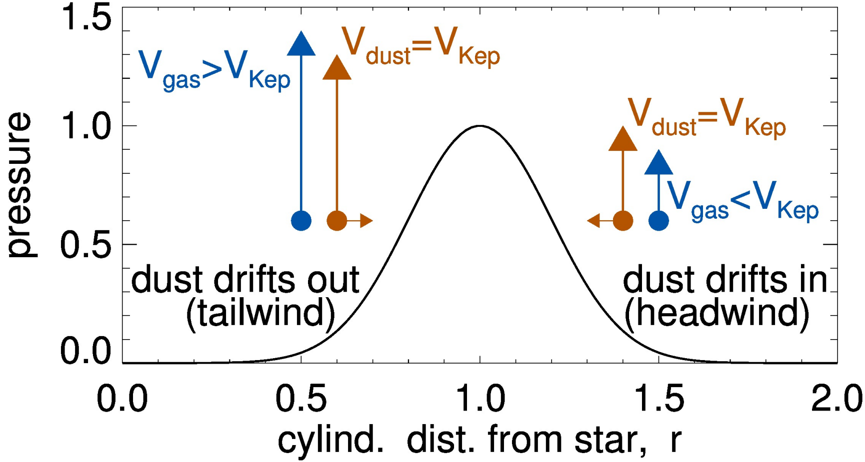
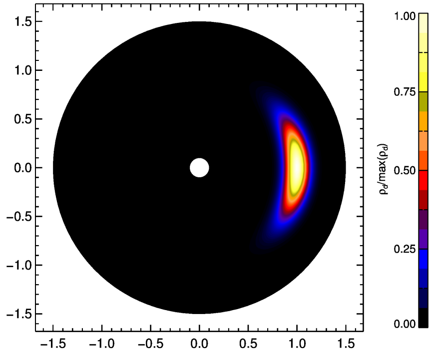
Dust-trapping at pressure maxima



- Drag forces cause dust to accumulate at pressure bumps

Dust distribution in disk vortices



$$\rho_d(a) \propto \exp\left(-\frac{a^2}{2H_v^2}\right),$$

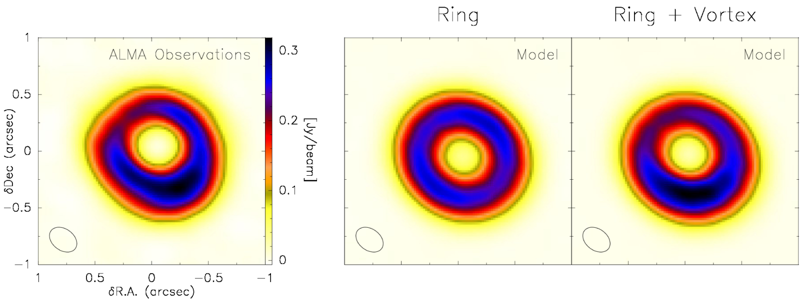
- a: distance from the vortex center

(Lyra & Lin, 2013)

$$H_v(\chi, \delta, \mathrm{St}) = \frac{H_g}{f(\chi)}\sqrt{\frac{\delta}{\delta + \mathrm{St}}}.$$

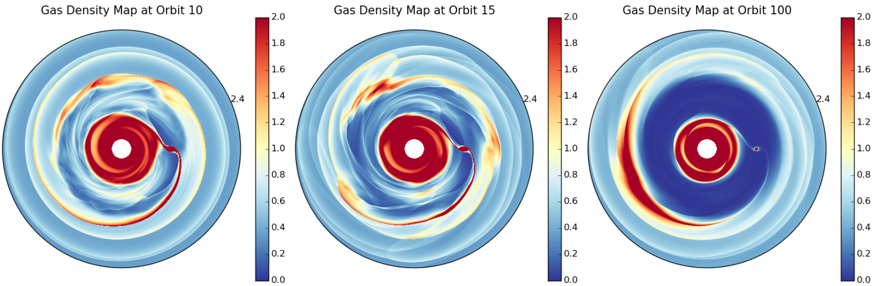
- χ: vortex aspect-ratio
- δ: turbulence in the vortex
- St: Stokes number (dust-gas friction)
- H_g: gas scale height

Application to observations



(SAO 206462, Pérez et al., 2014)
$\chi_{\rm obs} \sim 7$, model+ data $\rightarrow v_{\rm turb} \sim 0.22 c_s$.

Gap edges as sites for vortex formation

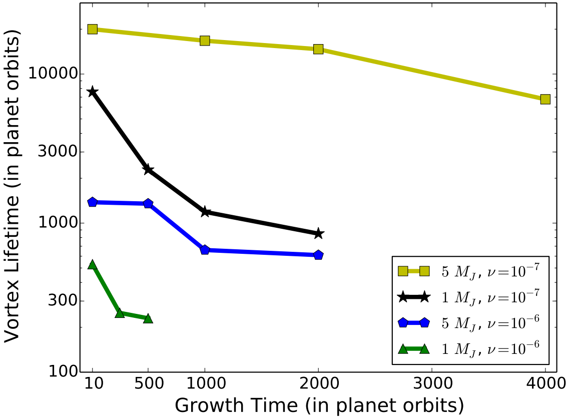


(Credits: UA grad. student M. Hammer, 'Vortices and orbital migration')

- Disk-planet interaction $\rightarrow$ gaps
- Surface density maxima at gap edges, or PV minima due to strong shear
- Rossby wave instability $\rightarrow$ edges 'roll up' into vortices (Li et al., 2001)

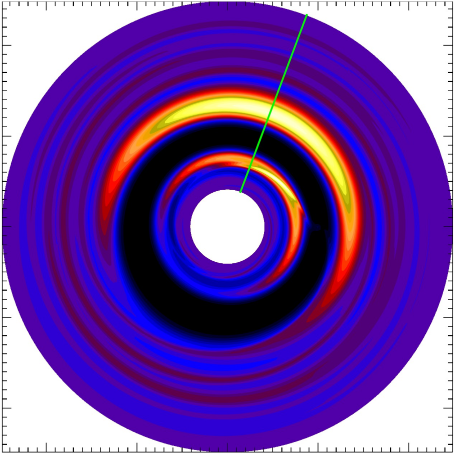
Slowly-growing planets make weaker vortices

(Hammer, Kratter & Lin, 2016, in prep.)



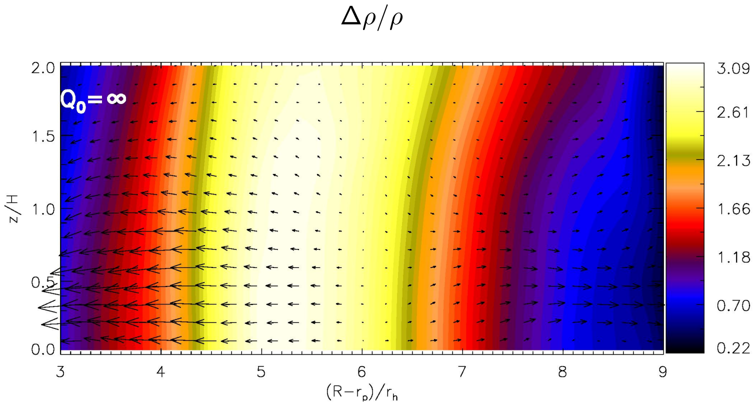
- Vortex lifetime/observability depends on planet formation time-scale

Basic theory is 2D, but PPDs are 3D



Take a look in the (r, z) plane through the vortex

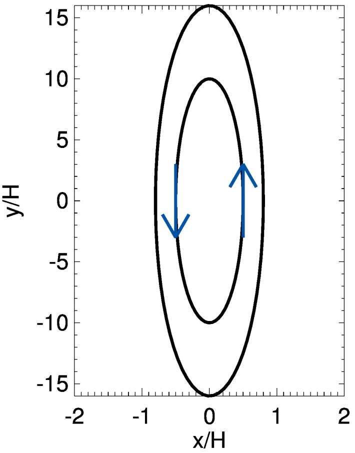
Rossby vortices are vertically global



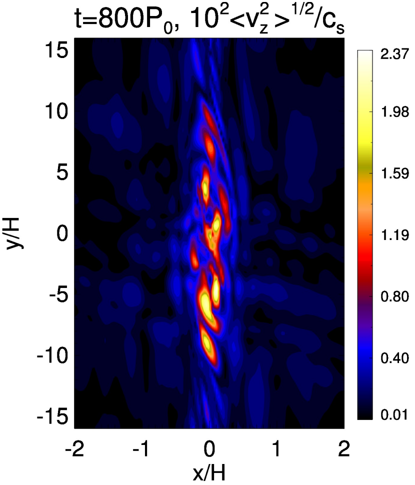
- Global 3D Zeus simulations (Lin, 2012b)
- Consistent with 3D linear theory (Lin, 2012a, 2013a,b)
- Vortex evolution is sensitive to disk vertical structure (Lin, 2014)

Elliptic instability of 3D vortices

- A 3D instability that weakens/destroys vortices (Lesur & Papaloizou, 2009)
- In plane ($v_z = 0$) elliptical flow about the vortex center



- Instability $\rightarrow$ small-scale 3D turbulence ($v_z \neq 0$)

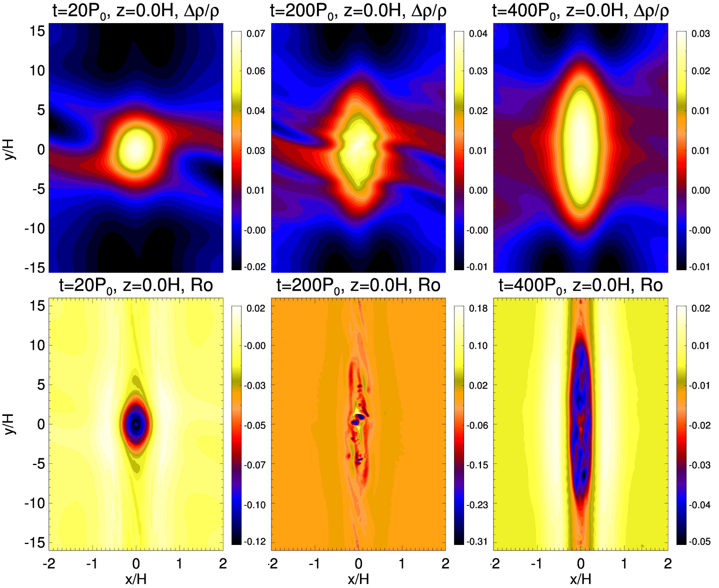


Athena sims. (Lin, in prep.)

Elliptic instability of 3D vortices

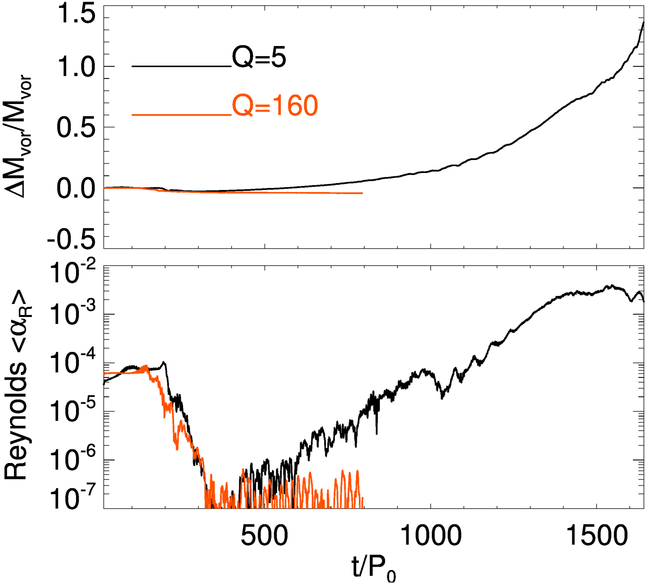
Density pert.

Vort./2Ω



Athena simulations (Lin, in prep.)

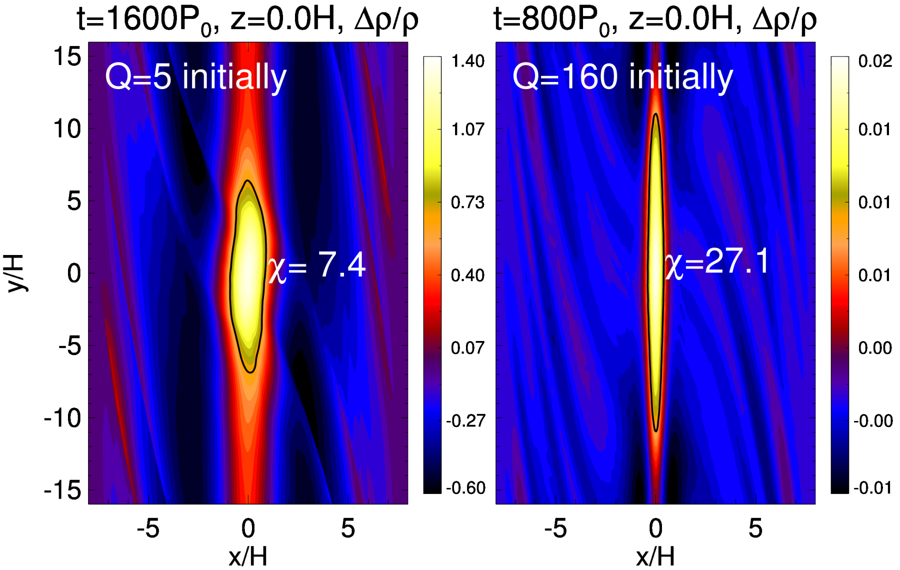
3D vortex evolution with self-gravity (Lin, in prep.)



- Vortex collapse correlates with increasing internal turbulence

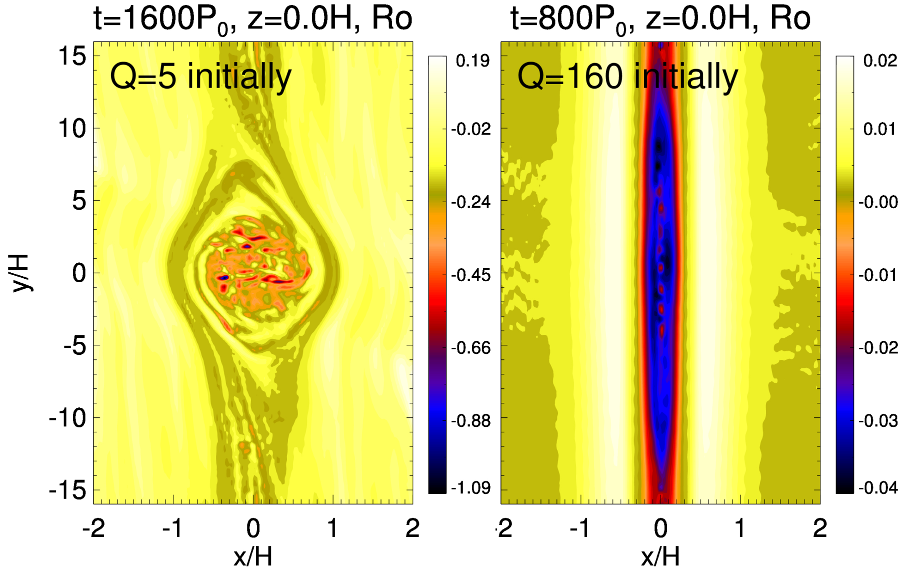
3D vortex evolution with self-gravity (Lin, in prep.)

Density perturbation



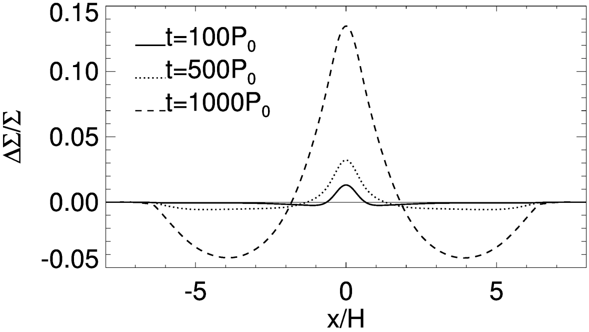
3D vortex evolution with self-gravity (Lin, in prep.)

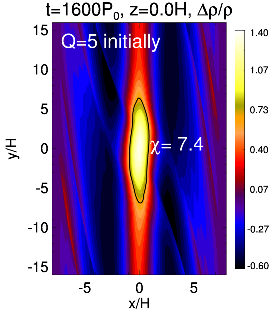
Vorticity/2Ω



What's next on disk vortex dynamics?

- Accretion onto ellipsoidal density distributions
- Gap-opening by vortices





- Dust dynamics in elliptical flows
  - Explicit 3D sims. to study the effect of hydro. turbulence

Summary

Generalized gravitational instability

- Cooling: reduces thermal support
- Viscosity: reduces rotational support
- Fragmentation: GI due to cooling and/or turbulent stresses (viscosity)

Vertical shear instability

- Feeds off free energy in $\partial_z \Omega \neq 0$
- Enabled by ultra-fast cooling in PPDs
- VSI possible in the outer PPD between 10—100AU

Vortices in 3D PPDs

- Can moderate self-gravity enhance vortex stability?
- How can we use the observed structure of vortices to infer disk properties?

References

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