Investigating Effect of Planet Migration Speed On Gap Opening in Protoplanetary Disks

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Brief Review of Star Formation

- Stars are born in dense molecular clouds
- Result of Gravitational collapse
- A cloud with $M > M_{Jeans}$ will collapse
- The free-fall timescale τ_{ff}
- Effect of rotation
- A protostar is formed with a protoplanetary disk around the star

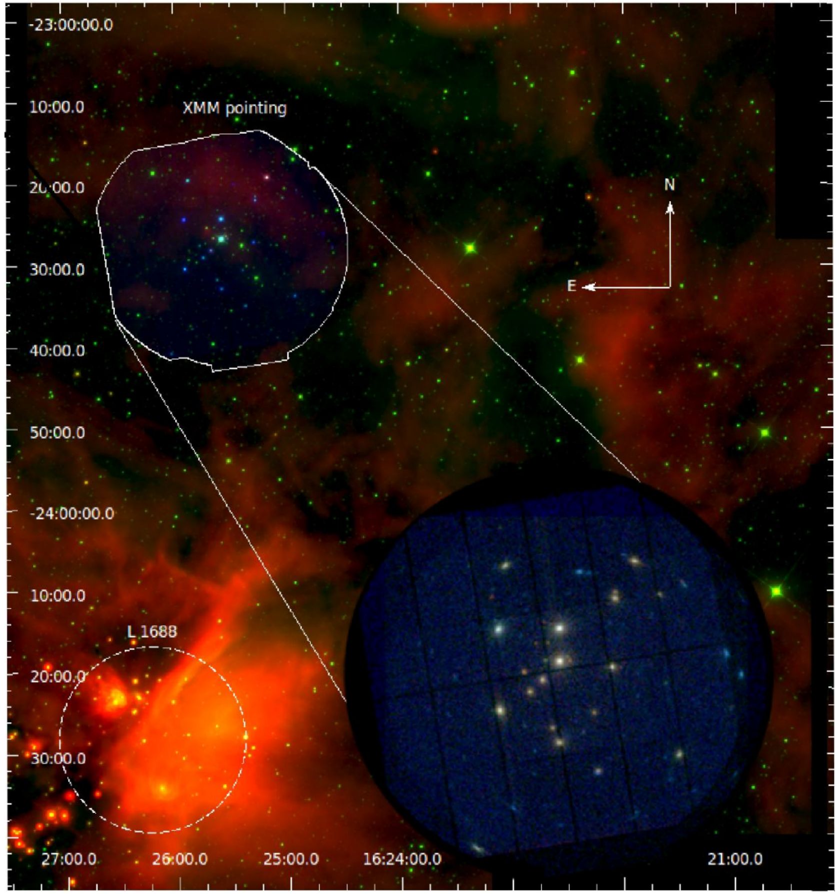

Fig 1: A composite RGB image from Wide-field Infrared Survey Explorer (WISE) images shows stars in ρ Ophiuchi dark cloud.

Image Source: Pillitteri et al. First stars of the ρ Ophiuchi dark cloud. XMM-Newton view of ρ Oph and its neighbors. A&A, 592:A88, Aug 2016

Structure of Disks

- Vertical structure
- Consider Hydrostatic equilibrium
- Pressure gradient:

$$\frac{dP}{dz} = -\rho g_z$$

- Solution is:

$$\rho(z) = \rho_o \exp\left(-\frac{z^2}{2H^2}\right)$$

- Gaussian profile
- Vertical Scale height : H
- Disks are geometrically thin

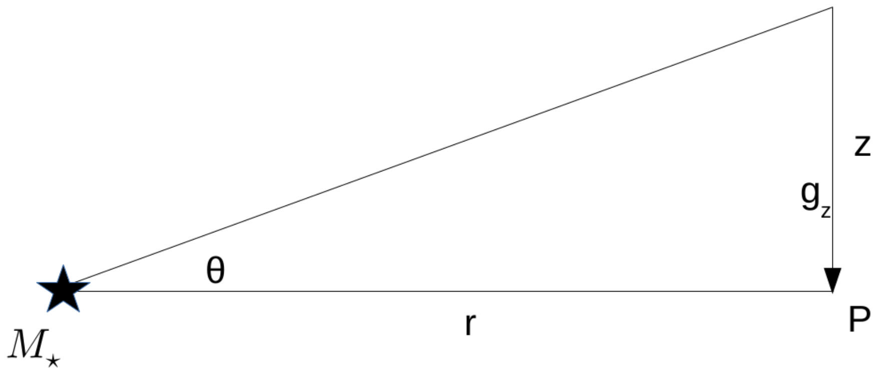

Fig 2: Geometry for calculation of the vertical hydrostatic equilibrium of a protoplanetary disk.

Planet-Disk Interactions

- **Hot-Jupiters**
- Low-mass planets: **Type I migration**
    - Planet-disk interaction negligible, disk structure unaltered
    - Net torque changes planet’s semi-major axis
    - Migration quite rapid
- Jupiter-mass planets: **Type II migration**
    - Gas is repelled from resonances
    - Surface density drops forming a **gap**
- **Gap**: annular region in the surface density
- Torque balance criterion (Crida et al. (2006))

Ref: Crida et al. On the width and shape of gaps in protoplanetary disks. Icarus, 181:587–604, Apr. 2006

What do Observations tell us?

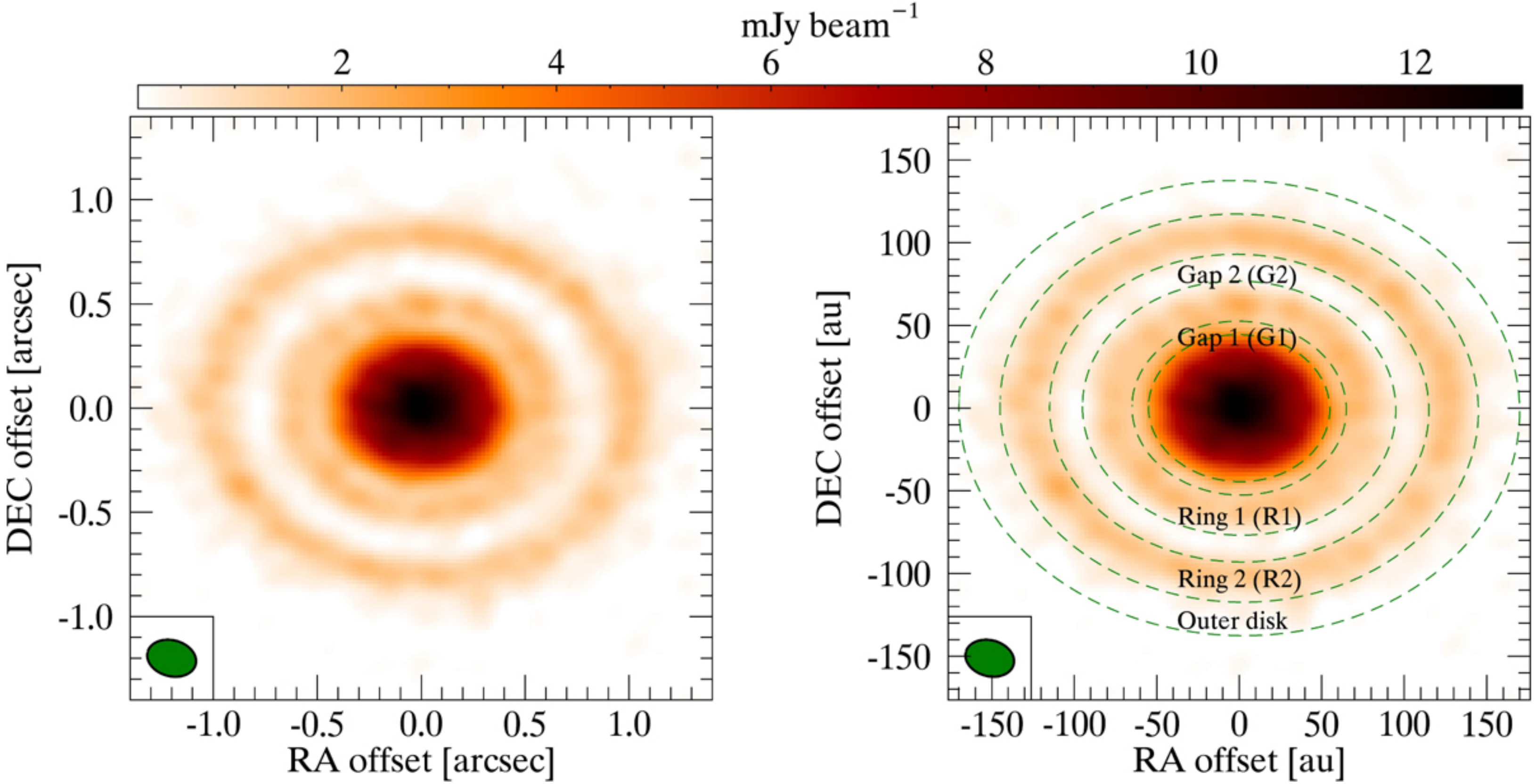

Fig 3: ALMA 1.3 mm dust continuum image of protoplanetary system AS 209.

Image Source: Fedele et al. ALMA continuum observations of the protoplanetary disk AS 209. Evidence of multiple gaps opened by a single planet. A&A, 610:A24, Feb 2018.

What do Observations tell us?

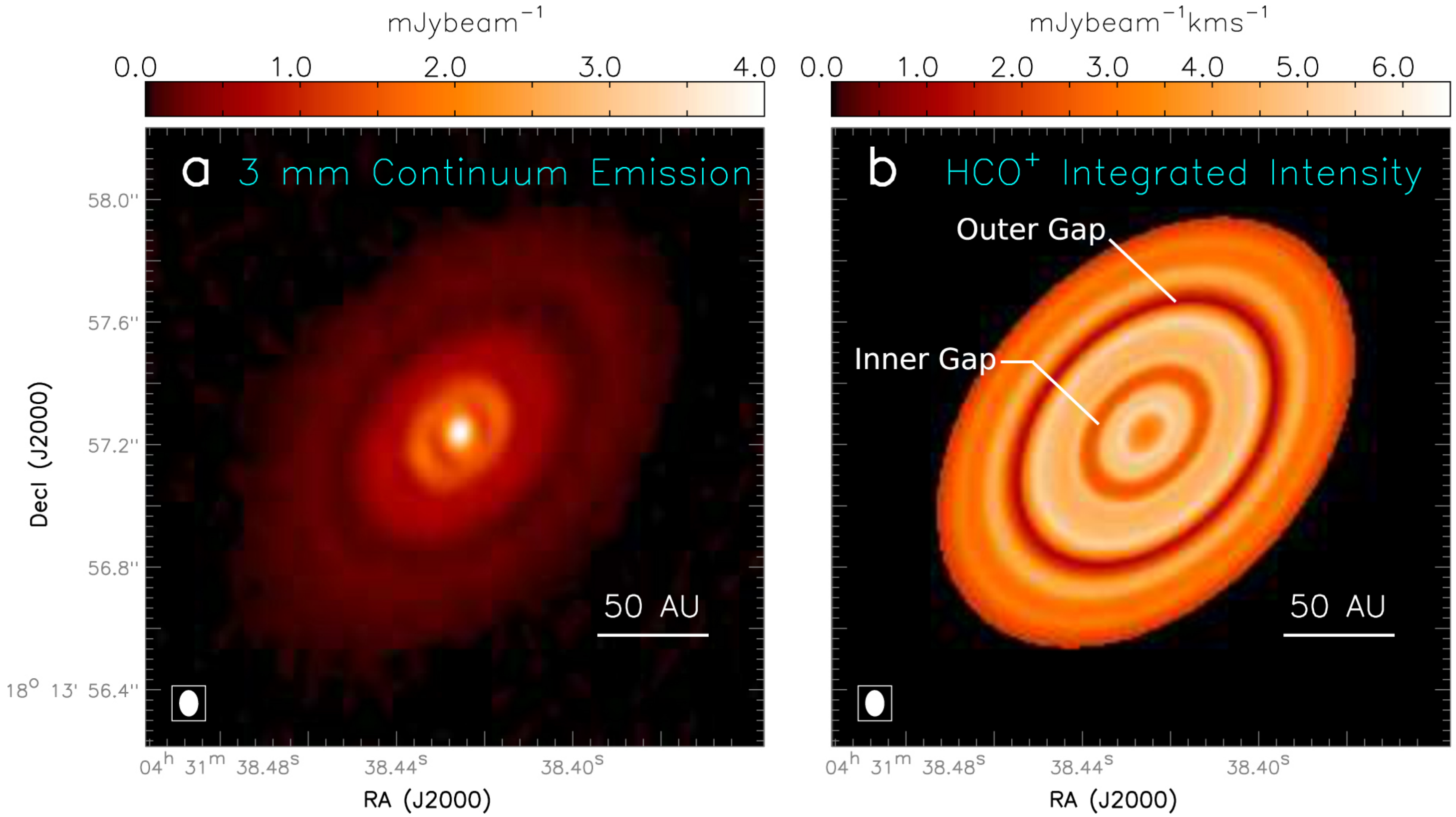

Fig 4: Left: 3 mm continuum image of disk around HL Tau. Right: High resolution image of HCO+ integrated intensity of the disk with distinct gaps.

Image Source: The 2014 ALMA Long Baseline Campaign: First Results from High Angular Resolution Observations toward the HL Tau Region. ApJ, 808:L3, Jul 2015.

What do Observations tell us?

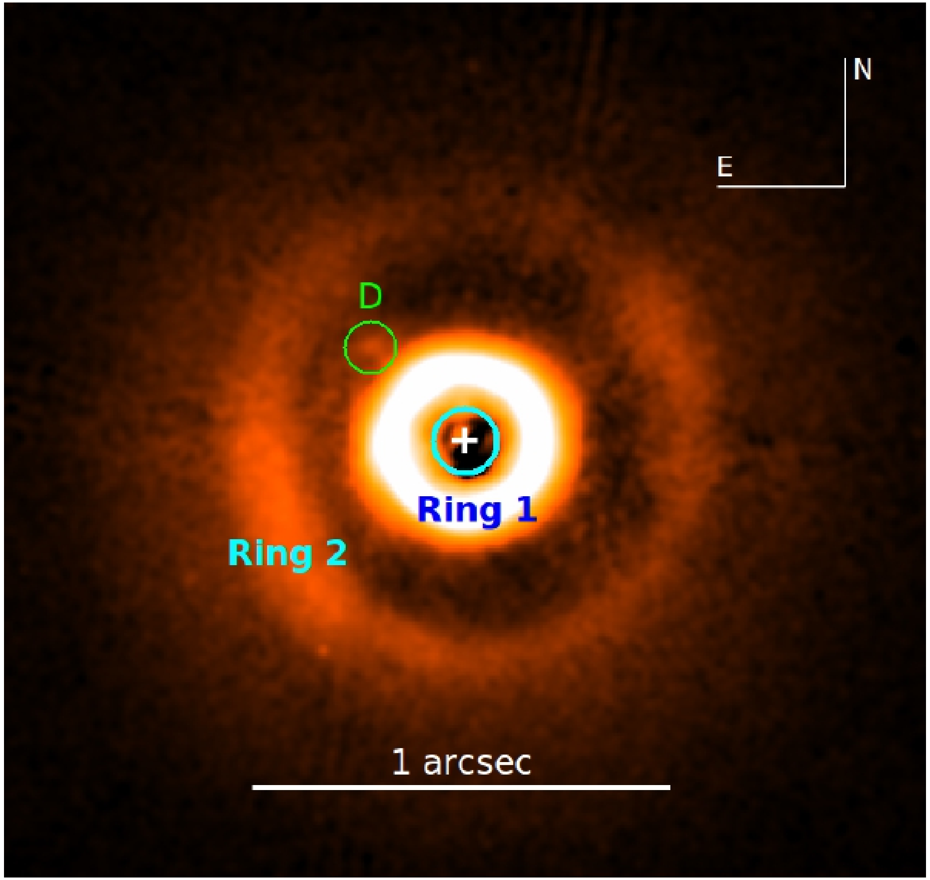

Fig 5: Polarimetric observation of the disk surrounding HD 169142 shows rings and faint structures.

- The central circle - mask used in imaging
- Circle labelled “D” - may be linked to planet formation

Image Source: Gratton et al. Blobs, spiral arms, and a possible planet around HD 169142. arXiv e-prints, Jan 2019

Physical Model

- How **fast** should planet **migrate** so that **gap is <u>not</u> opened**?
- Vertically averaged state variables
- 2D model : Using cylindrical coordinates (r,φ,z)
- Assume: two-dimensional, inviscid, isothermal disk
- Rotating frame of reference
- Hydrodynamic equations for continuity and momentum
- Surface density: $\Sigma \propto \frac{1}{r}$
- *Pyrodeo* : Dimensionless units, Planet at (r, φ) ≡ (1, 0)

Simulation Results

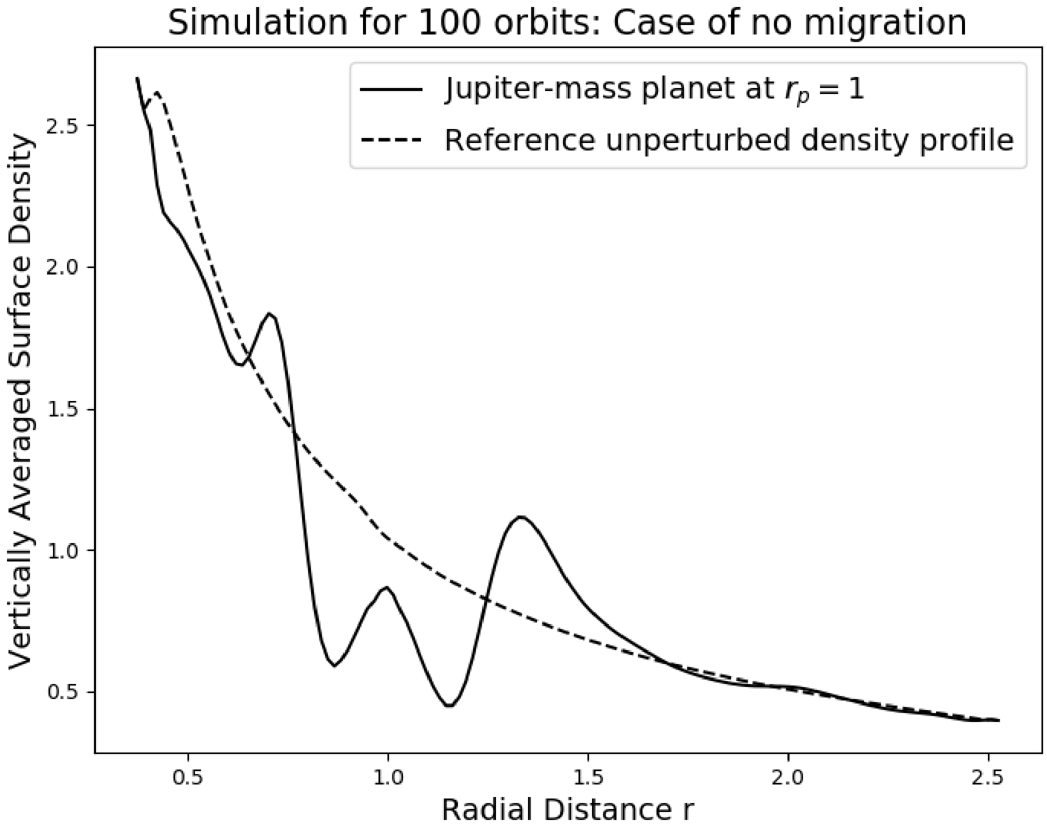

Fig 6: **Surface density** plot for a Jupiter-mass planet at r = 1 after 100 orbits and **no migration**.
Clear gap opens around $r = r_{planet} = 1$.

Simulation Results

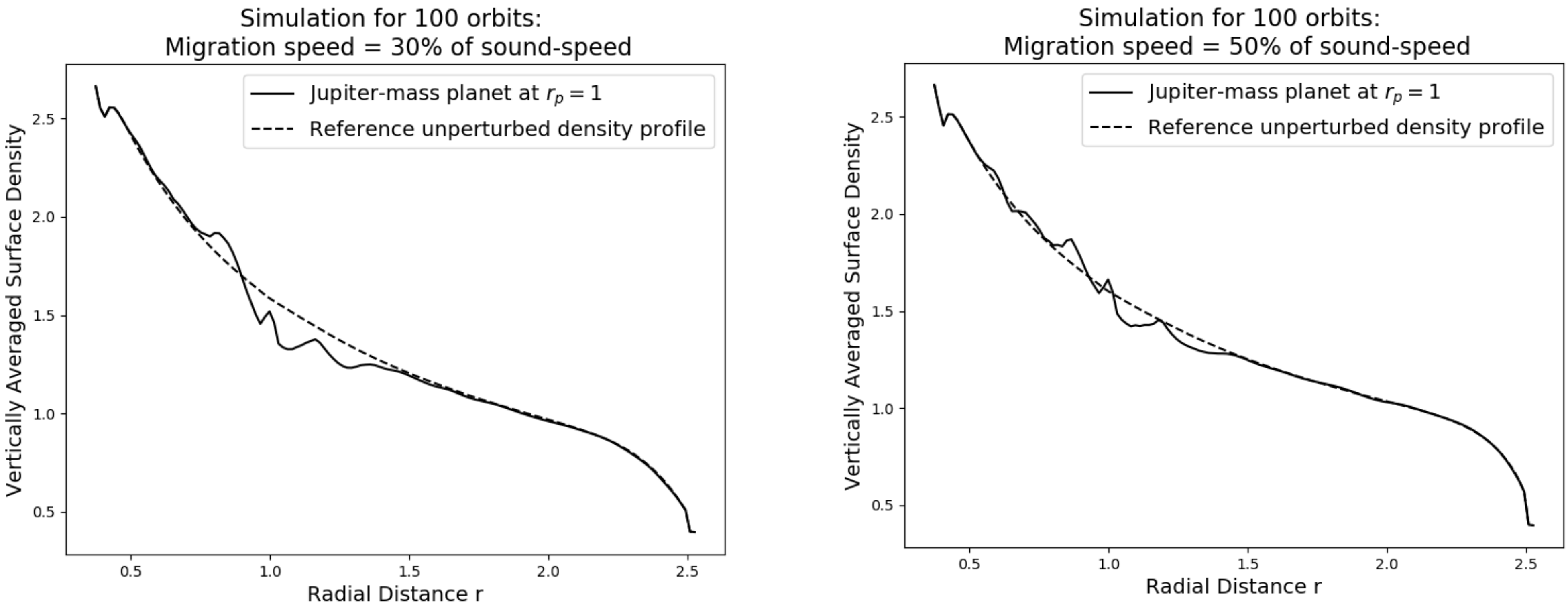

Fig 7: Simulation result for a Jupiter-mass planet at r = 1 after 100 orbits and at migration speed of (a) **30% of sound-speed**, and (b) **50% of sound-speed**. **No clear gap** opens.

Simulation Results

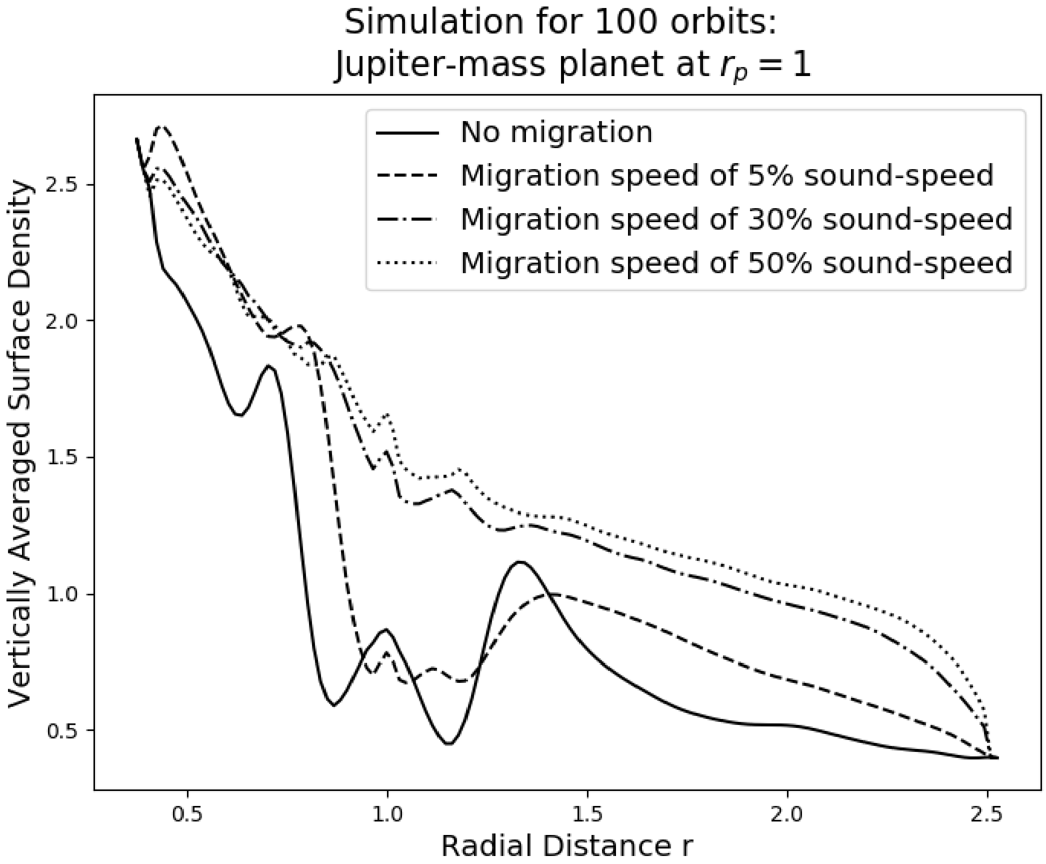

Fig 8: A **comparison of surface density** for all Jupiter-mass planet migration cases ($r_{planet} = 1$) after 100 orbits.

Simulation Results

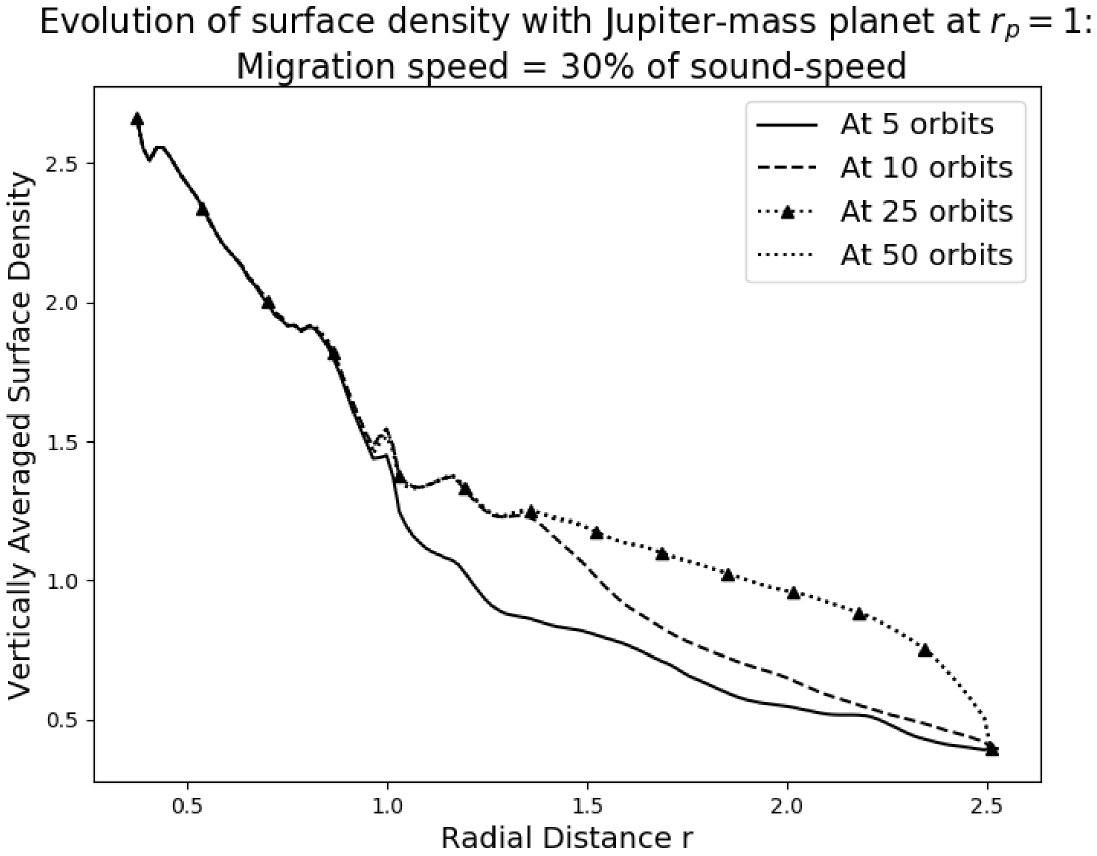

Fig 9: **Change in surface density** after simulating for **different number of orbits** for a Jupiter-mass planet (r_{planet} = 1) migrating at 30% of sound-speed.
Steady state after 25 orbits.

Conclusion

- Crida and Bitsch (2017) : “Migrating giant planets **always open gaps** in the disk”.
- Malik et al. (2015) : Torque balance criterion (Crida et al. (2006)) not sufficient.
- Our result : Jupiter-mass planet migrating at **speed > 30%** of speed of sound **does not open** a gap.
- Result agrees with Crida and Bitsch (2017) : used **low (< 5%)** migration speed.

Ref: Crida, A. and Bitsch, B. Runaway gas accretion and gap opening versus type I migration. Icarus, 285:145–154, Mar 2017.
Malik, M., Meru, F., Mayer, L., and Meyer, M. On the Gap-opening Criterion of Migrating Planets in Protoplanetary Disks. ApJ, 802:56, Mar 2015

Thank You!