Thermal Structure of Magnetized PPDs and Its Implications for Planet Formation

Abstract

Understanding the temperature structure in protoplanetary disks is essential for developing a comprehensive theory of planet formation. The thermal profile governs the dust composition, which in turn affects the bulk composition of forming planets. In addition, both the growth and orbital migration of protoplanets are strongly regulated by the temperature structure of the disk. Accurate modeling of the thermal structure requires capturing the underlying disk dynamics, including accretion and energy transport. We present our latest global MHD simulations with full non-ideal MHD effects and radiation transport. We show that accretion heating is generally inefficient across a wide range of disk parameters. We also discuss the long-term thermal evolution of magnetized disk models, based on MHD simulation results. Compared to viscously heated disks, MHD disk models more readily lead to the formation of both rocky super-Earths and volatile-rich sub-Neptunes, highlighting the crucial role of MHD disks in shaping planetary systems.

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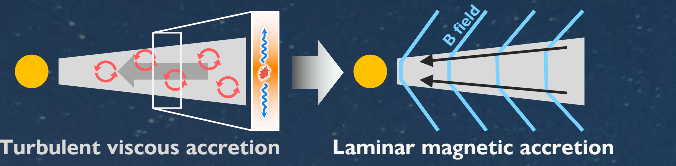
1 Dynamics & Thermal Structure

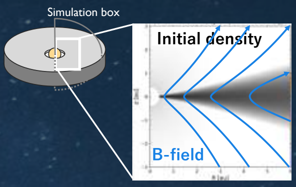
- Temperature in inner au region impacts planet formation processes
  - Snowlines, streaming instability, pebble isolation mass, planet migration …
- Heat source: Irradiation heating + Accretion heating
- Viscous heating is efficient
  - Blanketing effect: heat is released around midplane and accumulated
- MRI is suppressed by nonideal MHD effects (Bai & Stone13; Gressel+15)
  - Global magnetic field drives the accretion on disk surface



2 Radiative nonideal MHD simulation

for thermal structure of Magnetized PPDs

- Global 2D, *Athena++* (Bai17, Stone+21)
- *Full* nonideal MHD effects
  (Ohm diff, Hall effect, ambipolar diff)
  - calculate column density, ion rate, and ion frac



- Radiative transfer model

Energy eq — Optically thin term — Optically thick term

$$\frac{\partial \rho u}{\partial t} \mathrel{+}= \boxed{\exp(-\tau_\theta) Q_{\rm thin}} \quad \boxed{-\nabla\cdot\left[\exp\left(-1/\tau_\theta\right) F_{\rm thick}\right]}$$

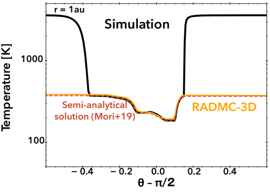
Relaxing to target temperature

$$Q_{\rm thin} = -4\rho\kappa_{\rm P}\sigma\left(T^4 - T_{\rm thin}^4\right) \quad T_{\rm thin}^4 = \left(T_{\rm opt}(r)\exp(-\tau_r)\right)^4 + T_{\rm re}^4$$

$T_{\rm re}^4$: reemitted radiation T, $\sigma T_{\rm re}^4 \equiv J$

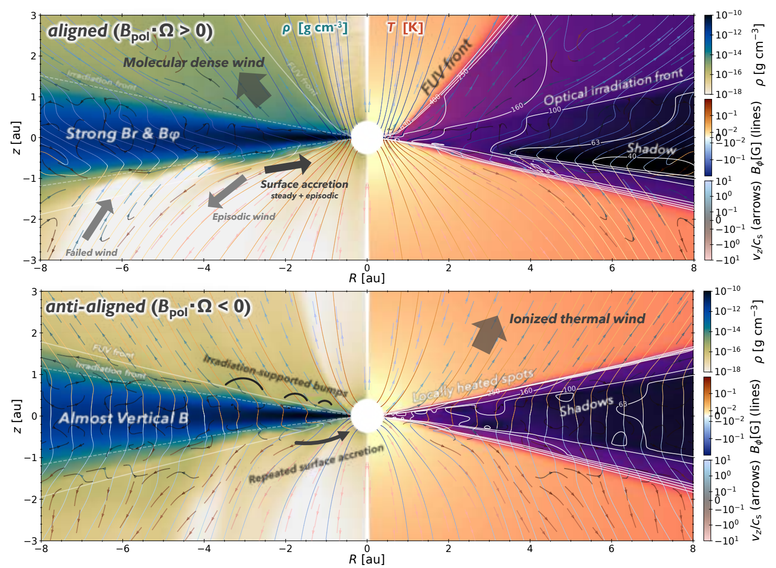
To get this, calculate θ-integration of RT eq

$$\mu\frac{\partial I(\tau,\mu)}{\partial \tau} = I(\tau,\mu) - S(\tau)$$ with two-stream approximation



3 Simulation Results

see Mori, Bai, Tomida (2025b) for details



- Σ = 500 g/cm² $R_{\rm au}^{-1}$
- $\beta_{\rm ini}$ = 10^4
- $f_{\rm dg}$ = 10^-4
- $\kappa_{\rm disk}$ = 1 cm²/g
- $\kappa_{\rm star}$ = 1 cm²/g
- $\kappa_{\rm FUV}$ = 33 cm²/g
- L = 2.7 $L_\odot$

Dynamics

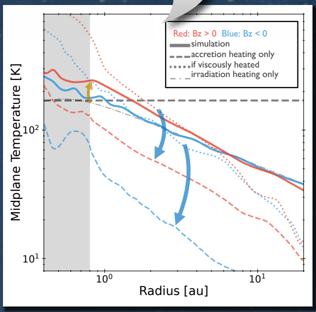
- Hall-amplified *strong B* (Bai17)
- Laminar ($\alpha_{\rm turb}$ ~ 10^{-4})
- Asymmetric strong wind
  - Monopolar outflow observations (e.g. HH30, Louvet+18)
  - Less asymmetric in weaker B
- Episodic accretion & wind
  - Time variable
  - Clumpy accretion surface
    Casting shadows in outer disks

- Hall-damped *weak B* (Bai17)
- Laminar ($\alpha_{\rm turb}$ ~ 10^{-4})
- Symmetric weaker wind
- Thermal-induced bumps
  - Higher P with local irradiation ⇄ increase ρ
- Repeated accretion of surface bumps

Accretion heating is weaker

but irradiation heating can be stronger

Thermal structure



Why efficient?
- ✓ Irradiation front lifted by wind

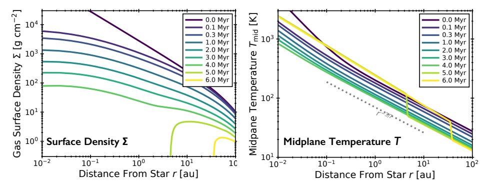
Why inefficient?
- ✓ Heating at surface
- ✓ Energy removal by wind

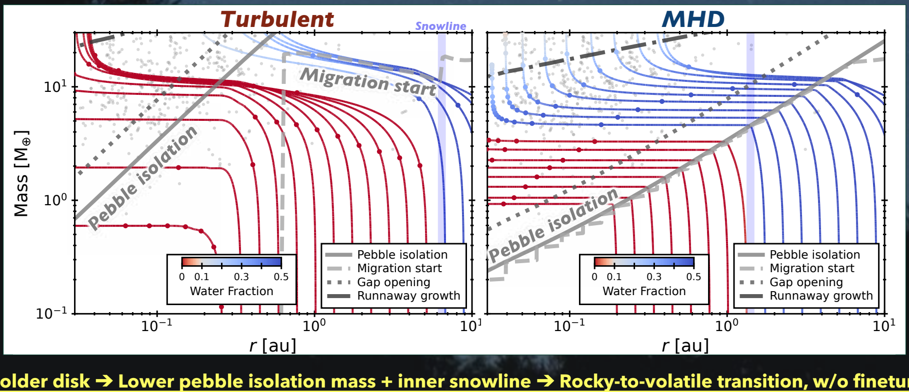
Simulation data is available!
Let's think about applications!

4 Impact of *Inefficient accretion heating* on planet formation

see Mori, Kunitomo, Ogihara (2025a) for details

- 1D-evolving disk simulation with winds (e.g., Suzuki+16)
  - Viscous and wind-driven accretion
  - Mass-loss by MHD and PE winds
- Inefficient accretion heating model (Mori+2021)
  - Heating height: depending on vertical ion frac profile
  - Dissipated energy fraction: 10% of accretion energy
- Growth and migration of planets





Colder disk ➔ Lower pebble isolation mass + inner snowline ➔ Rocky-to-volatile transition, w/o finetune

Summary

We have conducted 2D global radiative nonideal MHD simulations of the inner region of PPDs. We show that accretion heating is negligibly weak. Instead, when winds are strong, irradiation heating becomes efficient. In disks with inefficient accretion heating, the pebble isolation mass and snowline radius are small because of low T, producing compositions of super-Earths and sub-Neptunes.