大局円盤での磁気乱流と円盤風

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名大 理 物理

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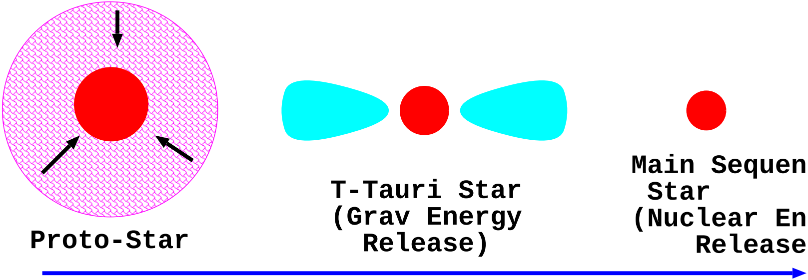
Protoplanetary Disks
–as an example of accretion disks–



Proto-Star

**T-Tauri Star
(Grav Energy
Release)**

**Main Sequence
Star
(Nuclear Energy
Release)**

Time

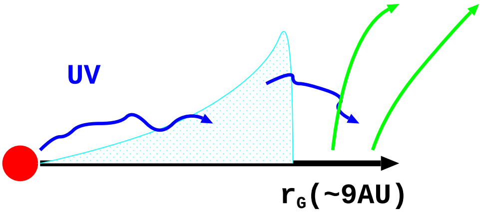
$10^{5-6} \sim 10^{7}$yr

3×10^{7}yr

Disk Dispersal –Current Major Scenario–

Shu+ 1993; Matsuyama+ 2003; Takeuchi+ 2005; Alexander+ 2006; Ercolano+ 2009

- Outer Region: Photo-evaporation by UV & X-rays



- Inner Regions: Viscous Accretion

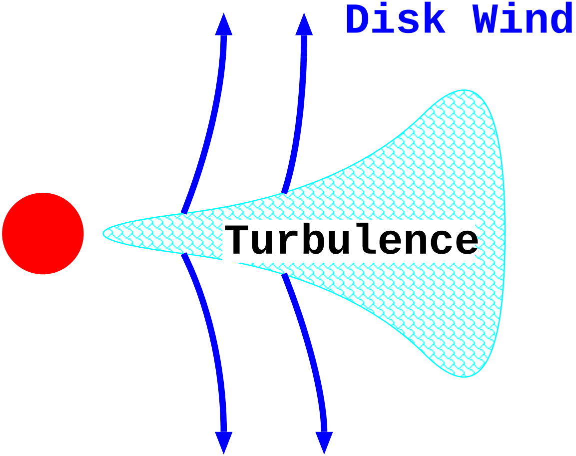
Some transitional disks seems inconsistent?

Calvet et al 2005; Espaillat et al.2008, Hughes et al.2009

- Stellar Winds: Limited Contributions

Matsuyama et al.2009

Turbulent-driven Disk Winds

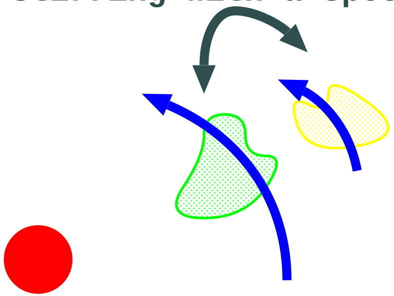


- Turbulent-driven Winds
  → Dispersal of Gas Disks ?
- Simple Extension from solar/stellar winds?

Turbulence in Accretion Disks

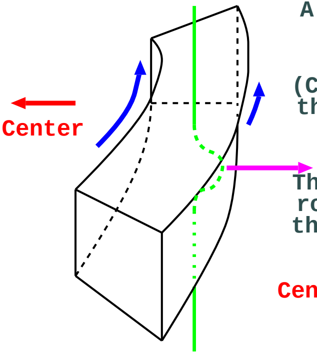
Turbulence ⇒ Macroscopic (effective) Viscosity

- Outward Transport of Angular Momentum
- Inward Accretion of Matters



`Exchange fluid elements by`
`‘‘stirring with a spoon’’`

Magneto-Rotational Instability (MRI)



A fluid element
moves outward

(Connection
through B-field)

The Fluid element
rotates faster
than A.M. conservation

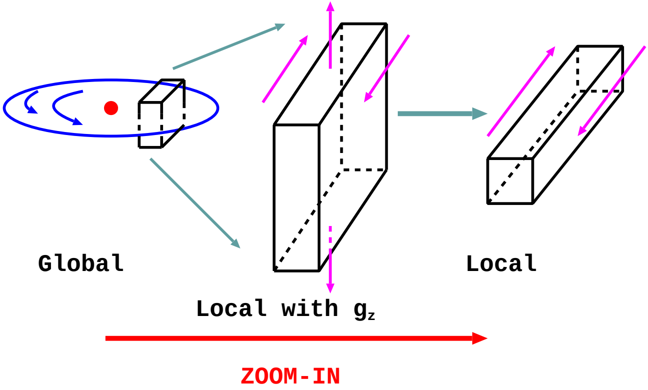
Centrifugal F. > Gravity
(Unstable)

Unstable under

- Weak B-fields
- (inner-fast) Differential Rotation

Velikov (1959); Chandrasekhar (1960); Balbus & Hawley (1991)

Simulations –Global & Local–



Global

Local with g_z

Local

ZOOM-IN

Local Simulations in Shearing Box: “Zoom-in”

▸ MRI in local shearing box

- Shearing boundary in radial (x) direction

  Hawley et al.1995; Matsumoto & Tajima 1995; Sano et al.2004; Hirose et al.2009 ...

Thanks to PC clusters(Ta lab.), HITACHI SR16000(Yukawa inst., Kyoto), Cray XT4 (NAOJ)

Local Simulations with g_z

z-component of gravity by a central star:

$$g_z = \frac{GM_\star z}{(r^2+z^2)^{3/2}} \approx \Omega^2 z$$

- Density Stratification
- Flowing-out disk winds can by handled.

Local simulations in a shearing box

$\Rightarrow$ High Resolution

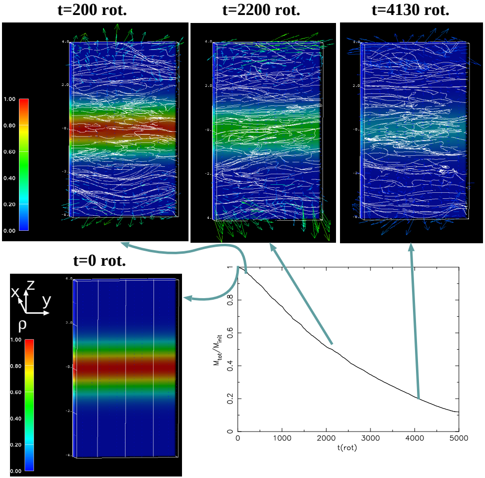
- can determine Shakura-Sunyaev $\alpha(= (v_r \delta v_\phi - B_r B_\phi / 4\pi\rho)/c_s^2)$ parameters more precisely.

α: transported angular momentum

local simulation with vertical stratification

Long Time Simulation

Suzuki, Muto, Inutsuka 2010



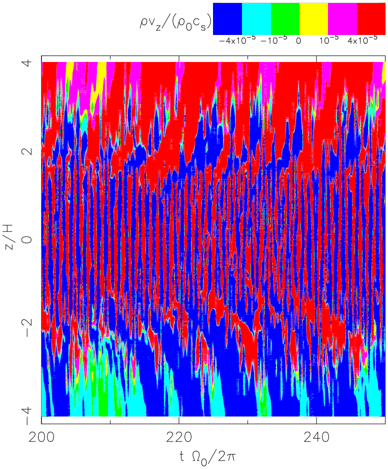
Disk mass is lost by turbulent-driven disk winds.

(Caution! No Accretion)

Intermittency

Mass Flux t-z diagram

Suzuki & Inutsuka 2009



Intermittency with 5-10 rotations

⇔ (probably) Breakups of Channel Flows

Dead Zone

Insufficient ionization ⇒ B-field is decoupled with gas ⇒ MRI-inactive ⇒ Dead Zone

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Disk winds are not so affected by dead zones

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Disk winds are not so affected by dead zones

- Disk winds are driven from surface regions.
- Surface regions are active because of ionization by X-rays from a central star and cosmic rays

▸ Movie!

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However,
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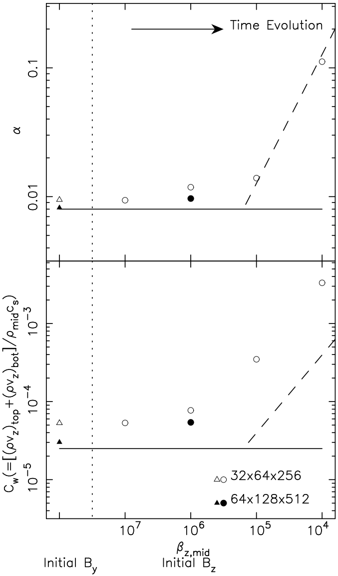
- Disk winds are driven from surface regions.
- Surface regions are active because of ionization by X-rays from a central star and cosmic rays

▸ Movie!

- Quasi-periodic inversion of B_ϕ around the midplane. (e.g. Nishukori et al.2006)
  ⇐ Breakups of Channel flows.

Dependence on B_z (ideal MHD)



$(\beta_{z,\mathrm{mid}} \equiv 8\pi\rho c_s^2/B_z^2)$

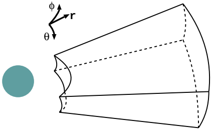
Both α & $(\rho v_z)_{\mathrm{w}}$ show

- Constant for weak B_z $(\beta_{z,\mathrm{mid}} \gtrsim 10^6)$
- Increase with B_z

Suzuki, Muto, Inutsuka 2010

Global Simulation –Set-up–

- Simulation Region:
  $(r, \theta, \phi) = (1 \sim 20, \pm 0.5, 2\pi)$ resolved
  by (192,64,128) mesh points
- Initial Conditions
  - ~Keplerian rotation
  - $p \propto r^{-3}$
  - weak $B_z \propto r^{-3/2}$, $\beta (= \frac{8\pi p}{B_z^2}) = 2 \times 10^4$
- up to 1000 rotations at r_{in}



Model 1

- T =const.
  No Differential Rotation
  along z direction

▸ Movie!

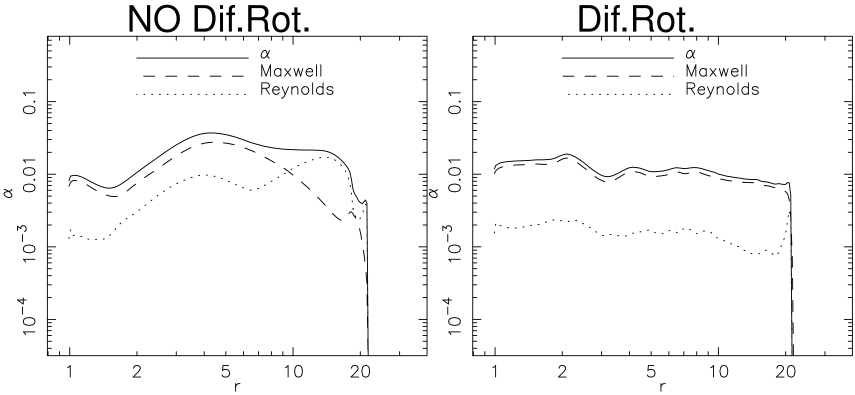
Model 2

- $T \propto r^{-1}$
  Differential Rotation
  along z direction

▸ Movie!

Takeuchi & Lin 2002

Angular Momentum Transport

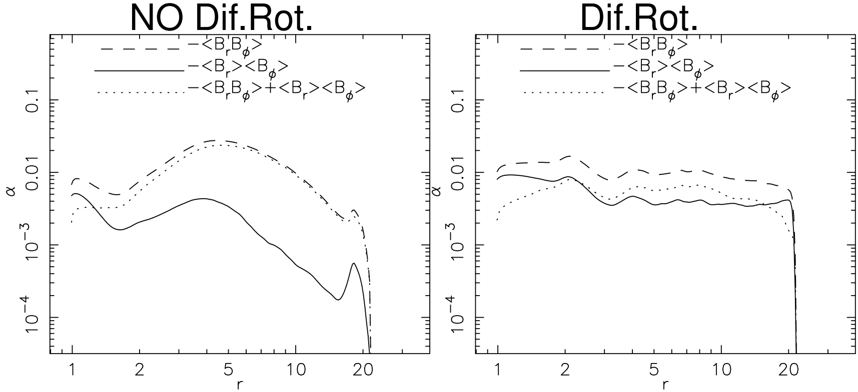


NO Dif.Rot.

Dif.Rot.

$$\alpha = (v_r \delta v_\phi - B_r B_\phi / 4\pi\rho)/c_s^2$$

Coherent α vs. Turbulent α



NO Dif.Rot.

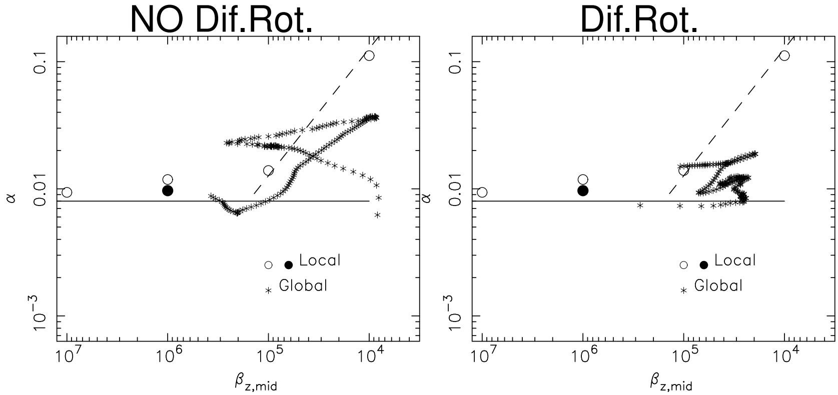
Dif.Rot.

- $-\langle B_r B_\phi \rangle$: Turbulent α ⇔ MRI
- $-\langle B_r \rangle \langle B_\phi \rangle$: Coherent α ⇔ Magnetic Braking

Blandford & Payne 1982; Uchida & Shibata 1985

Magnetic braking is also as efficient as turbulent α in the z-differential rotation case.

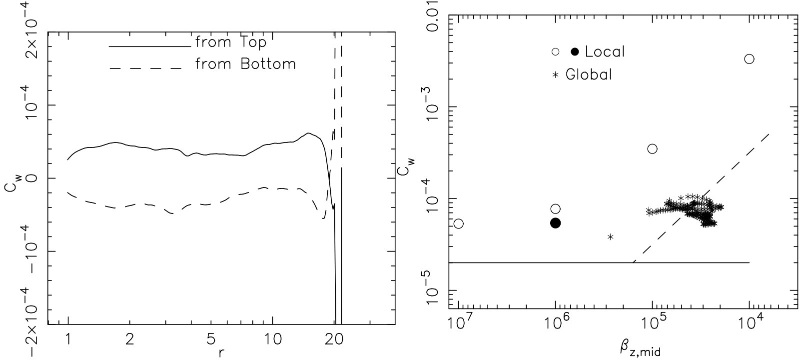
$\alpha - \beta_z$



$$\beta_z = \frac{8\pi p}{B_z^2}$$

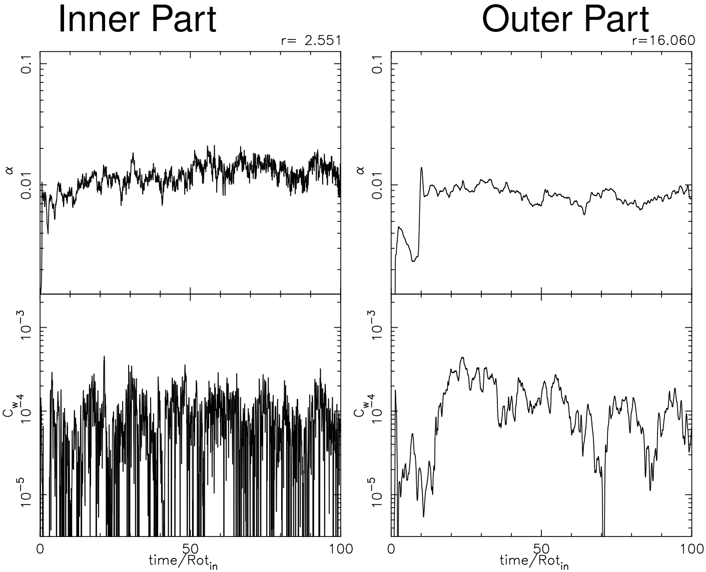
Disk Wind Flux

only Dif.Rot. case



$$C_w \equiv [(\rho v_z)_{\mathbf{top}} + (\rho v_z)_{\mathbf{bottom}}]/(\rho c_s)_{\mathbf{mid}}$$

Time-dependency



Inner Part

Outer Part

Intermittent disk wind with $\boldsymbol{\tau}$ ~ 5-10 local rotations

Summary

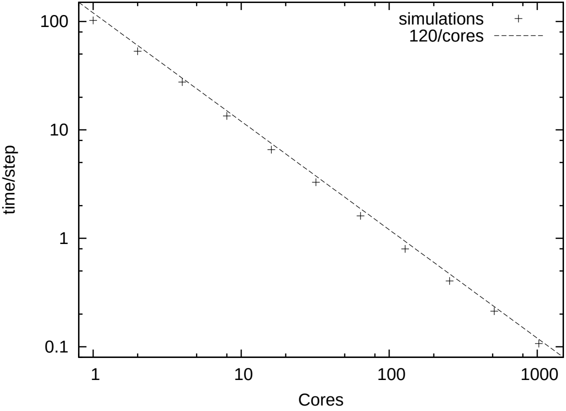
We are investigating basic properties on MRI-turbulence in accretion disks, with emphasis on drivining disk winds.

- Local simulations
    - quasi-periodic intermittency of disk winds & $\boldsymbol{B_\phi}$ reversal
      : more apparant with a dead zone
- Global simulations
    - Coherent $\boldsymbol{B}$ seems as important as turbulent $\boldsymbol{B}$.
    - Saturated level of α is comparable to the level by local simulations.

Scalability Test

メッシュ数 $(r, \theta, \phi) = (384, 128, 256)$

並列化は (r, ϕ) 方向のみ



1024 並列にすると 950-960 倍速くなる.