Disk winds driven by MRI –some aspects and applications–

Takeru K. Suzuki

Dept. Physics, Nagoya Univ., Japan

Aug. 4th, 2014

Suzuki & Inutsuka 2009, 691, L49
Suzuki, Muto, & Inutsuka 2010, ApJ, 718, 1289
Io & Suzuki 2014, ApJ, 780, 46
Suzuki & Inutsuka 2014, 784, 121

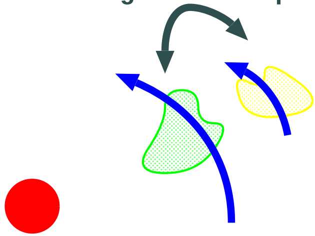
Thanks to PC clusters(Ta lab.), HITACHI SR16000(Yukawa inst.), Cray XT4 & XC30 (NAOJ)

Turbulence in Accretion Disks

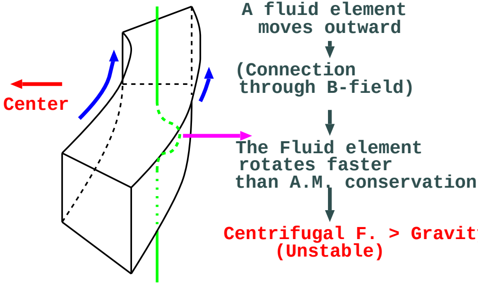
Turbulence ⇒ Macroscopic (effective) Viscosity

- Outward Transport of Angular Momentum
- Inward Accretion of Matters

Exchange fluid elements by ''stirring with a spoon''



Magneto-Rotational Instability (MRI)



Unstable under

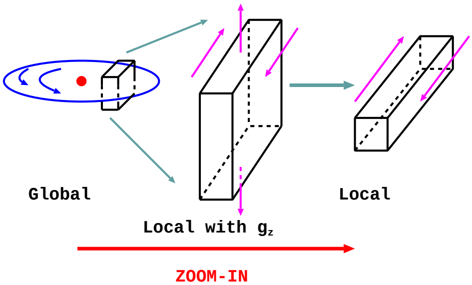
- Weak B-fields
- (inner-fast) Differential Rotation

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

▸ Local at Midplane

Theoretical Attempts on MRI in Disks

- Analytic Works
  Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; & many others
- Simulations



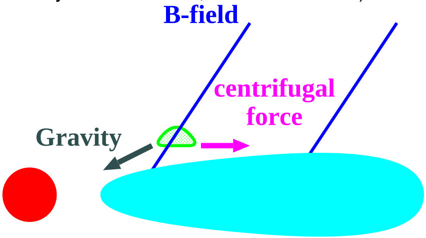
▸ Local at Midplane ▸ Local with vertical stratification ▸ Global

- Local Simulations in Shearing Box: "Zoom-in"
  Hawley+ 1995; Matsumoto & Tajima 1995; Brandenburg+ 1995; Stone+ 1996; Sano+ 2004; Hirose+ 2009; Simon+ 2009; Davis+ 2010; Shi+ 2010 & more
- Global Simulations Machida+ 2000; Hawley 2000; Papaloizou & Nelson 2003; Machida & Matsumoto 2003; Kato+ 2004; Fromang & Nelson 2006; Beckwith+ 2009; Flock+ 2011, 2012, 2013; Fromang+ 2011, 2013; Hawley+ 2011, 2013; Parkin & Bicknell 2013; Parkin 2014 & more

But, not so many works with B_z from the beginning.

Accretion Disk Winds

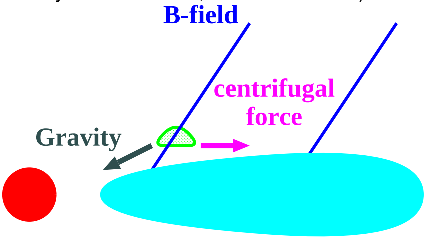
Magneto-centrifugal driven disk winds
(Coherent field lines)
(Blandford & Payne 1982; Kudoh & Shibata 1998; Ramsey & Clarke 2011; Salmeron+ 2011)



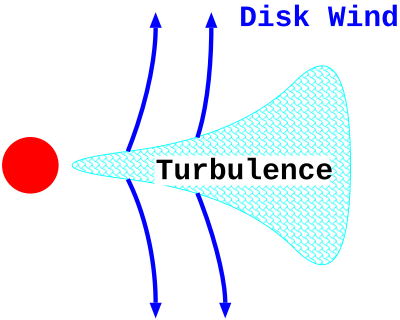
But the mass loading mechanism to wind is necessary.

Accretion Disk Winds

Magneto-centrifugal driven disk winds
(Coherent field lines)
(Blandford & Payne 1982; Kudoh & Shibata 1998; Ramsey & Clarke 2011; Salmeron+ 2011)



But the mass loading mechanism to wind is necessary.



Suzuki & Inutsuka 2009 (modified)

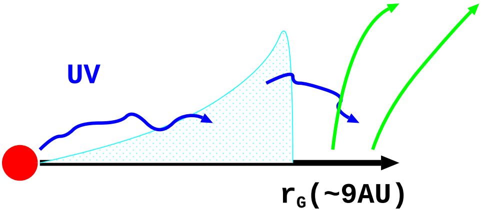
- Turbulent-driven vertical outflows as a mass loading mechanism

Recent works:
Bai & Stone 2013; Fromang+ 2013; Lesur+ 2013

Dispersal of Protoplanetary Disks

Current Major Scenario:
Photo-evaporating wind
+ Accretion

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



Difficult to explain some transitional disks

Calvet+ 2005; Espaillat+ 2008, Hughes+ 2009

Other mechanisms

- Stellar Winds
  - Limitted contribution ?
    Matsuyama et al.2009
  - Significant contribution with a boundary layer ?
    Schnepf et al.2014
- Disk Winds –Today's talk
- Recent Review
  Armitage 2011

Outline

- Simulation in Local Shearing Box

  Suzuki & Inutsuka 2009; Suzuki, Muto & Inutsuka 2010

  - Wave activity
  - Effect of the z box size
  - Effect of a dead zone
  - Preventing Type I migration

  ▸ Local with vertical stratification

- Simulations in Global Accretion Disk

  Suzuki & Inutsuka 2014

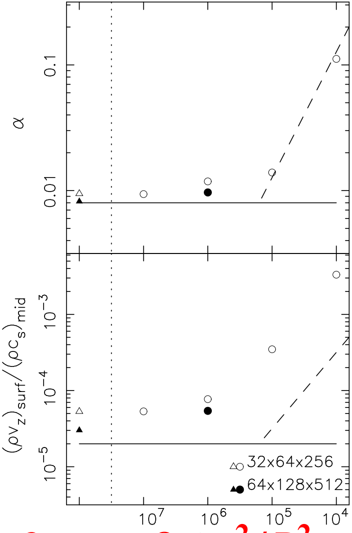
  - Effect of vertical shear (differential rotation)
  - Structured vertical outflows
  - Radial motion of the net $\boldsymbol{B}_z$

Assuming (locally) isothermal gas

Scheme: MHD Godunov (with only $\boldsymbol{B}_\perp$) (Sano+ 1999)
+ CMoC(Clarke 1996) + CT(Evans & Hawley 1988)

Dependence on NET B_z (ideal MHD)

Stronger B_z ⇒



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

- Upper panel

  $$\alpha = \left[\delta v_\phi v_r - \frac{B_\phi B_r}{4\pi\rho}\right] / c_s^2$$

  (Reynolds + Maxwell stresses)

- Lower panel

  $$C_\mathrm{w} \equiv \left[(\rho v_z)_\mathrm{surf}\right] / (\rho c_s)_\mathrm{mid}$$

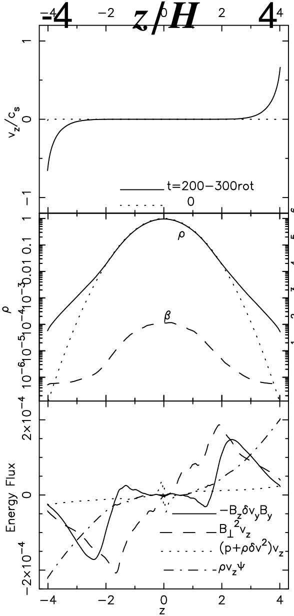
  (normalized disk wind mass flux)

Both α & $(\rho v_z)_\mathrm{w}$

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

Suzuki, Muto, & Inutsuka 2010
see also Pessah+ 2007; Okuzumi & Hirose 2011

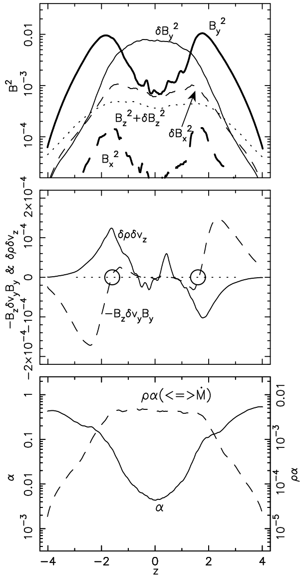
Poynting flux-driven disk winds



- Wind Onset:
  $\beta = 8\pi p/B^2 \lesssim 1$
- Energetics Argument
  - Energy Flux (z-direction):
    $$v_z\left(\frac{1}{2}\rho v^2 + \rho\Phi + \frac{\gamma}{\gamma-1}p\right)$$
    $$+v_z\frac{B_r^2+B_\phi^2}{4\pi} - \frac{B_z}{4\pi}(v_r B_r + v_\phi B_\phi)$$
    where, $\Phi = z^2\Omega_0^2/2$
  - Poynting Flux-driven
    Both Pressure & Tension contribute

Suzuki & Inutsuka 2009, ApJ, 691, L49

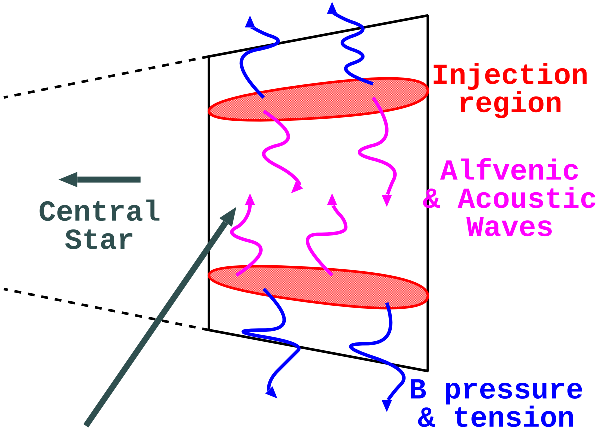
Characteristics of Turbulence



Imbalanced with waves in the vertically stratified background.

- Transverse (≈ Alfvén) waves to both directions
  $w_{\pm} = (v_{\perp} \mp B_{\perp}/\sqrt{4\pi\rho})/2$
  $-B_z v_{\perp} B_{\perp}/4\pi = \rho v_{\mathrm{A}}(w_+^2 - w_-^2)$
  (Elsässer variables)
- Sound waves to midplane
  $u_{\pm} = (\delta v_z \pm c_{\mathrm{s}}\delta\rho/\rho)/2$
  $\delta\rho\delta v_z = \rho c_{\mathrm{s}}(u_+^2 - u_-^2)$

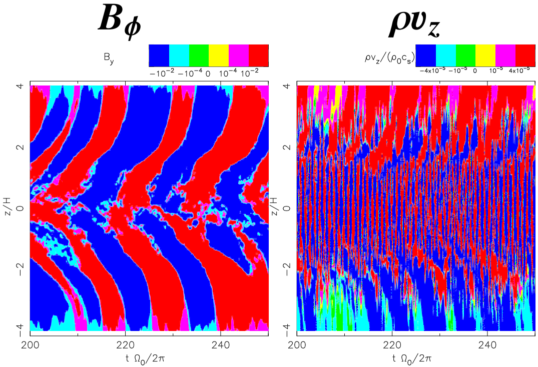
Characteristics of Turbulence



- Vertical outflows from Injection Regions at $z \approx \pm(1.5-2)H$ with $\beta \sim 1$–10
- Momentum flux to midlplane $\Rightarrow$ Dusts

Turner et al.2010

Time dependency: $t - z$ diagrams

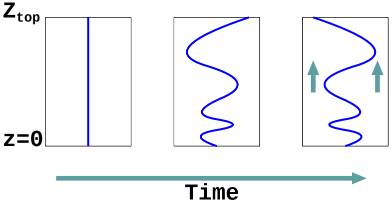


- quasi-periodic inversion of B_ϕ

  e.g. Davis et al.2010; Shi et al.2010

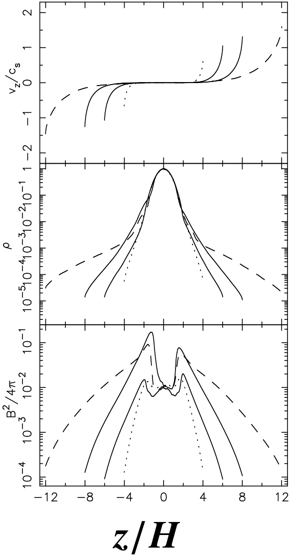
- The vertical outflows are also quasi-periodic.

Upper half of the local box



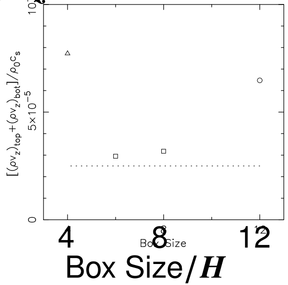
Dependence on z Box Size

z-gravity: $g_z = \Omega^2 z \frac{r^3}{(r^2+z^2)^{3/2}}$

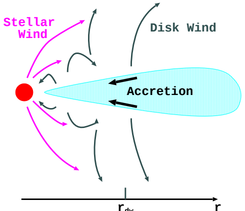


ρv_z

Suzuki, Muto & Inutsuka 2010



- ρ & v_z structures depend severely on the z box size. (Fromang et al.2013)
- But, ρv_z shows weak dependence.

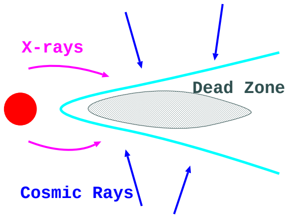


Effect of a Dead Zone

- Disk winds are not so affected by a dead zone with resistivity.
  The mass flux slightly decreases to 1/2-1/3.

  see Gressel+ (2013) & Bai (2013) for ambipolar diffusion
- Quasi-periodic inversion of B_ϕ. (e.g. Nishikori et al.2006)

Overall dynamics is controlled by the thin active layers near the surfaces.



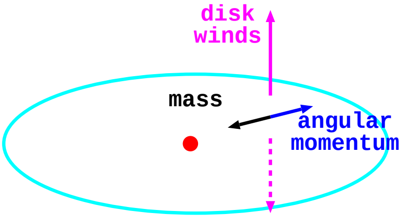
Most of ionization sources from the surfaces

Movie

Evolution of Surface Density

$$\frac{\partial \Sigma}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left[\frac{2}{r\Omega}\frac{\partial}{\partial r}(\Sigma r^2 \alpha c_s^2)\right] + (\rho v_z)_{\rm w} = 0$$

$\Sigma(=\int \rho dz)$: surface density; Ω : Keplerian Freq.

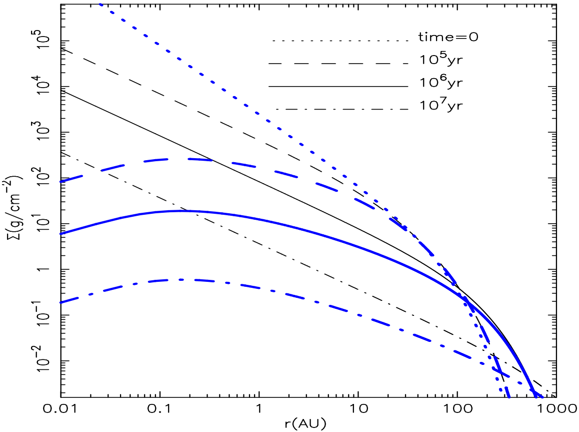


- α & $(\rho v_z)_{\rm w}$ $\Leftarrow$ local simulations
  - turbulent viscosity: $\alpha = (v_r \delta v_\phi - B_r B_\phi / 4\pi\rho)/c_s^2$
  - disk wind flux from top & bottom surfaces: $(\rho v_z)_{\rm w}$
- Initial Cond.: Min.Mass Sol.Neb. (Hayashi 1981)

$$\Sigma = \Sigma_0 \left(\frac{r}{1\ \rm AU}\right)^{-3/2} \exp(-r/r_{\rm cut})$$

$(\Sigma_0 = 2400$ g cm^{-3}; $r_{\rm cut} = 50$AU$)$

Evolution of Surface Density



- blue : With Disk Winds
- Black : Without Disk Winds

Suzuki, Muto, & Inutsuka 2010

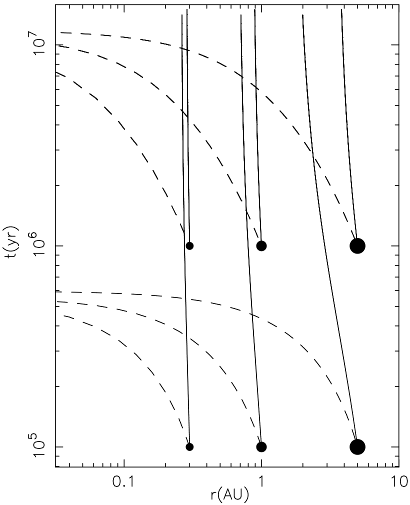
Movie!

Dispersal Time by Disk Wind:

$$\tau = \Sigma/(\rho v_z)_w \propto r^{-3/2}$$

"Dynamically Evaporate" Inside-Out

Type I Migration with Disk Winds



Put

- $\mathbf{0.3}M_\oplus$ at 0.3 AU
- $\mathbf{1}M_\oplus$ at 1 AU
- $\mathbf{5}M_\oplus$ at 5 AU

with Tanaka+ 2002 formula

- Solid: With Disk Winds
- Dashed: Without Disk Winds

Migrating planets

Outline

- Simulation in Local Shearing Box

  Suzuki & Inutsuka 2009; Suzuki, Muto & Inutsuka 2010

  - Wave activity ▸ Local with vertical stratification
  - Effect of the z box size
  - Effect of a dead zone
  - Preventing Type I migration

- Simulations in Global Accretion Disk

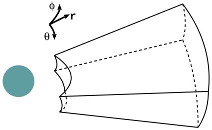
  Suzuki & Inutsuka 2014

  - Effect of vertical shear (differential rotation)
  - Structured vertical outflows
  - Radial motion of the net B_z

Assuming (locally) isothermal gas

Scheme: MHD Godunov (with only $B_{\perp}$) (Sano+ 1999)
+ CMoC(Clarke 1996) + CT(Evans & Hawley 1988)

Global Simulations –Set-up– (1/2)



- Simulation Region: Suzuki & Inutsuka 2014
  - Low resolution: $(r, \theta, \phi) = (1 \sim 20, \pm 0.5, 2\pi)$ resolved by (192,64,128) mesh points.
  - High resolution:
    $(1 \sim 20, \pm 0.5, \pi)$ by (512,128,256)
    $(1 \sim 300, \pm 0.5, \pi)$ by (1024,128,256)
- Ideal MHD with local isothermal EoS

  (⇒ next page)
- Initial Conditions
  - ~Keplerian rotation
  - $p \propto r^{-3}$ & weak $B_z \propto r^{-3/2}$ ($\beta = \frac{8\pi p}{B_z^2} = 10^5$)
- Boundary Conditions
  - outgoing at $\pm\theta$
  - accretion at $r_{\rm out}$ & $r_{\rm in}$: $v_r \approx -\alpha c_s^2 / r\Omega$
- up to 2000 rotations at $r_{\rm in}$

Global Simulations –Set-up– (2/2)

Assuming locally isothermal gas

Case I

- T =const.
  $\Rightarrow \frac{\partial \Omega}{\partial z} = 0$
  (good for MRI studies)
  $H/R \propto R^{1/2}$
  (not good for disk winds)
  No Vertical Shear

cT+L.R. cT+H.R.

Case II

- $T \propto r^{-1}$
  $\Rightarrow \frac{\partial \Omega}{\partial z} \neq 0$
  (not good for MRI studies)
  H/R =const.$(z < 4H)$
  (good for disk winds)
  Vertical Shear

rT+L.R. rT+H.R.

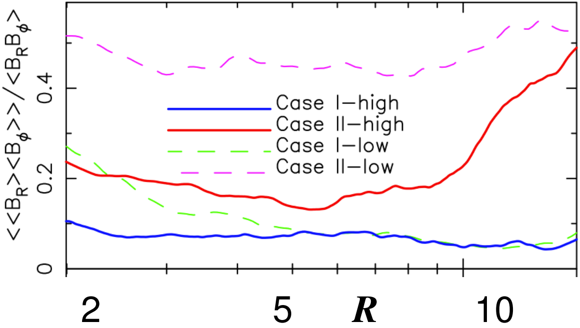
$\frac{d\Omega}{dz} = 0$ only if $p = p(\rho)$

von Zeipel 1924; Kozlowski 1978; Takeuchi & Lin 2002; McNally & Pessah 2014

Vertical shear seems important even without B.(Nelson+ 2013)

- Simulations:spherical coordinates (r, θ, ϕ)
- Data Analyses:cylindrical coordinates(R, ϕ, z)

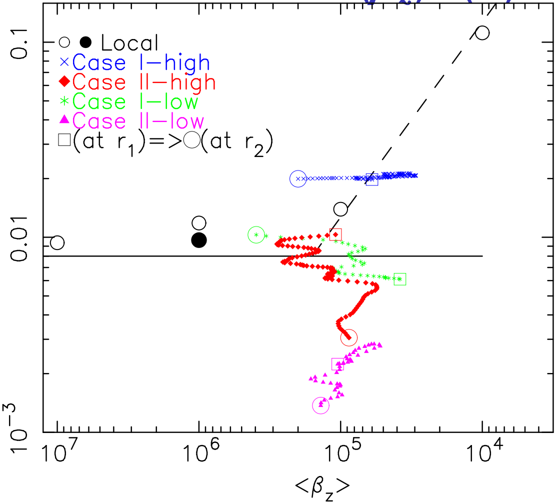
Turbulent vs. Coherent $B_R B_\phi$



(Not converged with resolution yet,)

- Case I (No Vertical shear):
  Turbulent component dominates
- Case II (Vertical shear): Coherent Maxwell stress (magnetic braking) is not negligible

$\langle\beta_z\rangle$–$\langle\alpha\rangle$

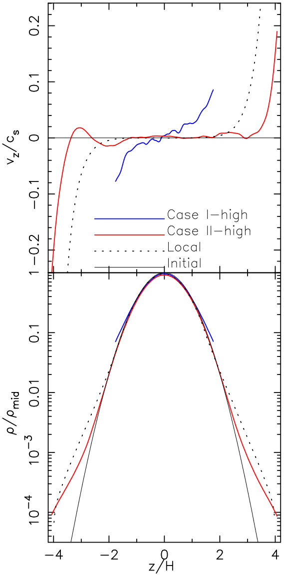


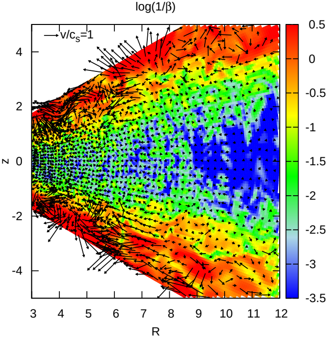
- Black/White: Local Simulations
- Colors: Global simulations

- $\langle\beta_z\rangle_{t,\phi,z}(R) = \dfrac{8\pi\langle p_{\rm mid}\rangle_{t,\phi}(R)}{\langle\langle B_z\rangle_{t,\phi}^2\rangle_z(R)}$ (β from the only net B_z flux)
- $\langle\alpha\rangle_{t,\phi,z}(R) = \dfrac{\langle\rho v_R \delta v_\phi\rangle_{t,\phi,z}(R)}{\langle p\rangle_{t,\phi,z}(R)} - \dfrac{\langle B_R B_\phi\rangle_{t,\phi,z}(R)}{4\pi\langle p\rangle_{t,\phi,z}(R)}$

Disk Winds

Vertical Structure at $r = 5r_{\mathrm{in}}$





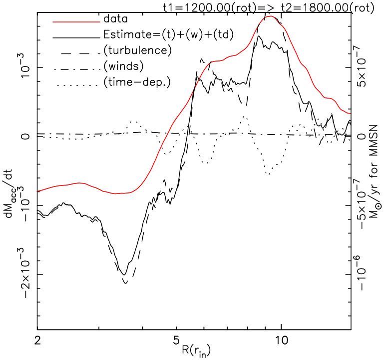
(Case I: insufficient vertical box size)

Disk Winds in Global Simulations (Case II)

- Structured & Intermittent
- Mass flux is slightly smaller (~1/2 of that of local sh.box.)

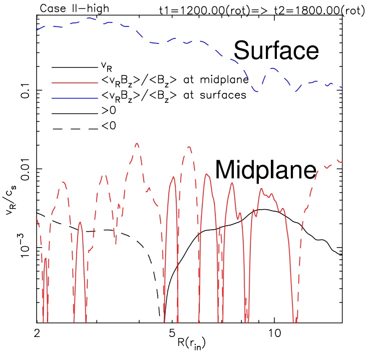
Radial motion of gas & net B_z (1/2)

Mass Accretion



v_R of Gas (black) & B_z (colors)

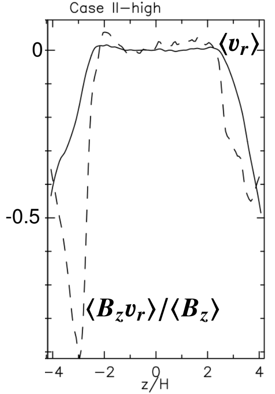
- Solid: $v_R > 0$
- Dashed: $v_R < 0$

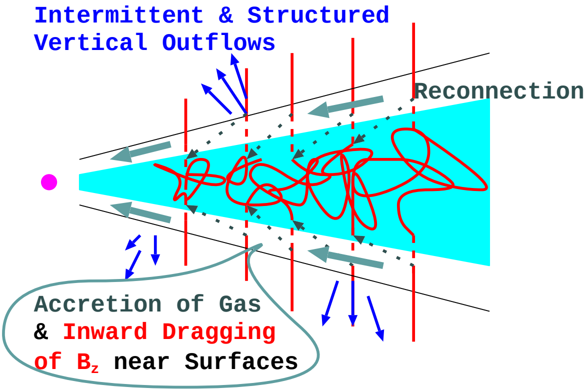


- Accretion in small R and Decretion in large R (Lynden-Bell & Pringle 1974) by the Maxwell stress
- $\langle v_R B_z\rangle/\langle B_z\rangle$ (radial motion of net B_z) is different from that of the gas.

Radial motion of gas & net B_z (2/2)

v_r on z





Lobow et al.1994; Rothstein & Lovelace 2008; Guilet & Ogilvie 2012, 2013, 2014; Okuzumi et al.2014; Hubbard et al.2014

Caution: The boundary condition at the disk surfaces might affect the result.

Summary

- Vertical outflows from the injection regions at $z \approx \pm(1.5-2)H$;
  Alfvénic & acoustic wave flux along z direction
  $\Rightarrow$ Dynamics of solid particles
- ρ & v_z structures are affected by the z box size, but ρv_z ($\Rightarrow \dot{M}_{\rm wind}$) is less affected.
- Vertical shear (differential rotation) $\Rightarrow B_r B_\phi$;
  Turbulent MRI vs. Coherent Magnetic Braking
- Layered accretion in the global ideal MHD simulations; $\langle B_z \rangle$ dragged inward in the surface regions ($\Leftarrow$ surface boundary condition??).

- Suzuki & Inutsuka 2009, ApJ, 691, L49
- Suzuki, Muto, & Inutsuka 2010, ApJ, 718, 1289
- Io & Suzuki 2014, ApJ, 780, 46
- Suzuki & Inutsuka 2014, ApJ, 784, 121

Shearing Box approximation

- Local Cartesian coordinate with co-rotating with Ω_0. (neglect curvature)
- $x = r - r_0$; $y \leftrightarrow \phi$-direction
- Basic equations for Keplerian rotation ($\Omega_0 = \sqrt{GM/r^3}$)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

$$\frac{\partial v_x}{\partial t} = -\frac{1}{\rho}\nabla_x\left(p + \frac{B^2}{8\pi}\right) + \frac{(B\cdot\nabla)B_x}{4\pi\rho} + 2\Omega_0 v_y + 3\Omega_0^2 x$$

$$\frac{\partial v_y}{\partial t} = -\frac{1}{\rho}\nabla_y\left(p + \frac{B^2}{8\pi}\right) + \frac{(B\cdot\nabla)B_y}{4\pi\rho} - 2\Omega_0 v_x$$

$$\frac{\partial v_z}{\partial t} = -\frac{1}{\rho}\nabla_z\left(p + \frac{B^2}{8\pi}\right) + \frac{(B\cdot\nabla)B_z}{4\pi\rho} - \Omega_0^2 z$$

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B - \eta \nabla \times B)$$

$$\nabla \cdot B = 0$$

- Steady-state solution
  - $B = (0, B_y, B_z)$ & $v = (0, -\frac{3}{2}\Omega_0 x, 0)$
  - $\rho = \rho_0 \exp(-z^2/H^2)$ ($H^2 \equiv 2c_s^2/\Omega_0^2$): hydrostatic equilibrium

Set up

- Simulation Region :
  $-0.5H < x < 0.5H, -2H < y < 2H, -4H < z < 4H$
  $(N_x, N_y, N_z) = (32, 64, 256) \& (64, 128, 512) \quad (H^2 = 2c_s^2/\Omega_0^2)$
- Boundary : x: shearing, y: periodic, & z: outgoing
  - outgoing boundary≠ 0-gradient boundary
- Initial Condition
  - Hydrostatic Equilibrium: $\rho = \rho_0 \exp(-z^2/H^2)$
  - Keplerian Rotation : $v_{y,0} = -(3/2)\Omega_0 x$
  - B-field : $B_{z,0}$ =const or $B_{y,0}$ =const
    $(\beta_0 \equiv 8\pi\rho_0 c_s^2/B_0^2 = 10^4 - 10^7)$
    - Base Model: net B_z with $\beta_0 = 10^6$ (@midplane)
  - v perturbation: $\delta v = 0.005c_s$
- miscellaneous
  - With/Without Resistivity (B diffusion)
  - Isothermal Equation of State

Turbulent Viscosity

Angular Momentum Eq. :

$$\frac{\partial}{\partial t}(\rho r v_\phi) + \nabla \cdot r\left[\rho v_\phi v - \frac{B_\phi}{4\pi}B + \left(p + \frac{B_r^2 + B_z^2}{8\pi}\right)e_\phi\right] = 0$$

Assuming $\partial_t = \nabla_z = \nabla_\phi = 0$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[\rho r^3 \Omega v_r + r^2 \rho\left(\delta v_\phi v_r - \frac{B_\phi B_r}{4\pi\rho}\right)\right]$$

$$\equiv \frac{1}{r}\frac{\partial}{\partial r}\left[\rho r^3 \Omega v_r + r^2 \rho w_{r\phi}\right] = 0,$$

where $v_\phi = r\Omega + \delta v_\phi$ (Kepler rot.+perturbation)

$w_{r\phi}$ = Reynolds stress$(\delta v_\phi v_r)$ + Maxwell stress$(-\frac{B_\phi B_r}{4\pi\rho})$

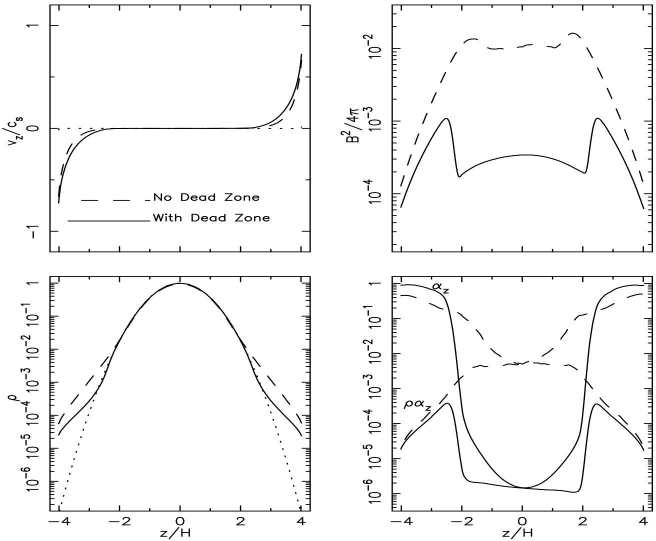
For accretion ($v_r < 0$), $w_{r\phi} > 0$.(Outward ang.mom. transport)

Note : $w_{r\phi} \equiv \alpha c_s^2$; α is the Shakura & Sunyaev parameter.

Mass accretion rate can be estimated as follows:

$$\dot{M} = -2\pi r v_r \int \rho dz \approx -2\pi w_{r\phi}/\Omega \int \rho dz$$

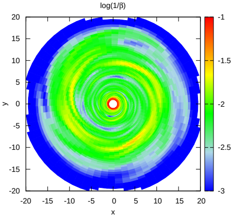
Time-averaged Vertical Structure

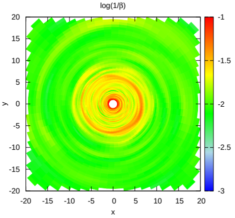


Inactive at midplane

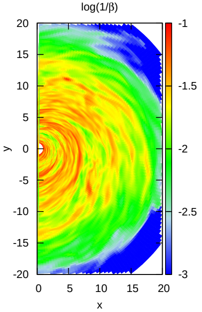
Face-on Views of $1/\beta$

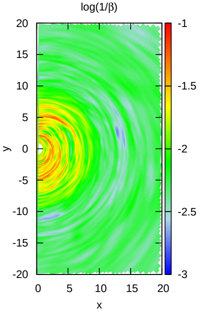
Case I-low ($250 t_{\mathrm{rot,in}}$) Case II-low ($1250 t_{\mathrm{rot,in}}$)





Case I-high ($250 t_{\mathrm{rot,in}}$) Case II-high ($1250 t_{\mathrm{rot,in}}$)

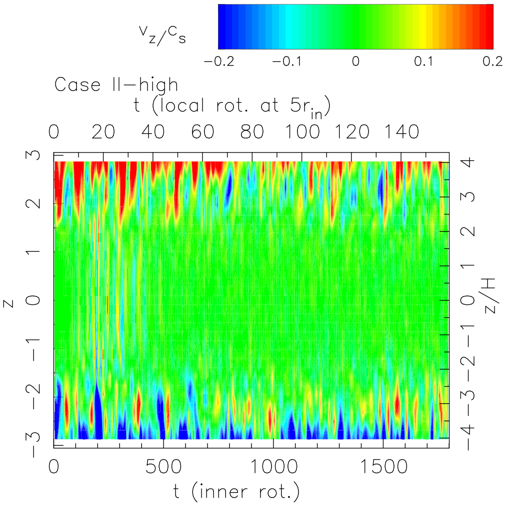




$$\frac{1}{\langle\beta\rangle_z(t,R,\phi)} = \frac{\langle B^2\rangle_z(t,R,\phi)}{8\pi\langle p\rangle_z(t,R,\phi)}$$

- Case I: More Turbulent
- Case II: More coherent by Winding

$t - z$ diagram of v_z at $R = 5r_{\rm in}$



The disk winds take a rest for a while. (The intermittency is more random)

MHD Simulations

in a shearing box

- Ideal MHD with isothermal eq. of state

  Suzuki & Inutsuka 2009, ApJ, 691, L49 ‣ Local with vertical stratification

- Ideal MHD with non-isothermal eq. of state

  Io & Suzuki 2014, ApJ, 780, 46 ‣ $\gamma = 1.4$

- Resistive MHD with isothermal eq. of state

  Suzuki, Muto, & Inutsuka 2010, 718, 1289 ‣ Dead Zone

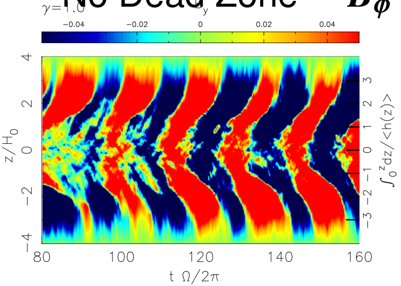
in a global box

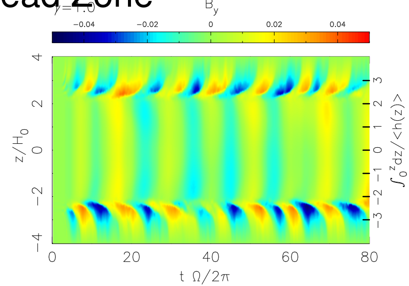
- Effects of large- / intermediate-scale flows on turbulent $\boldsymbol{B}$ field.

  Suzuki & Inutsuka 2014, ApJ, 784, 121

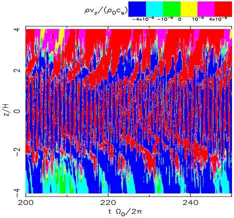
Quasi-periodicity: t–z diagrams

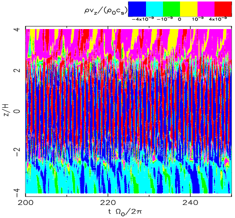
No Dead Zone B_ϕ Dead Zone





(ρv_z) (disk wind mass flux)

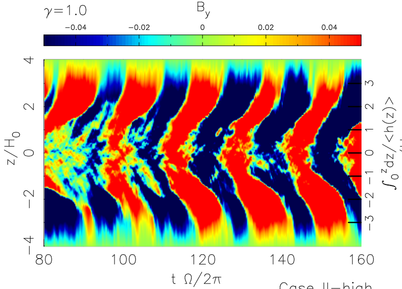


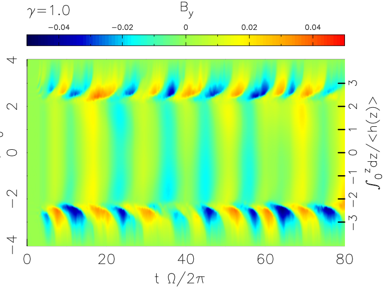


Quasi-periodicity with 5-10 rot time preserved

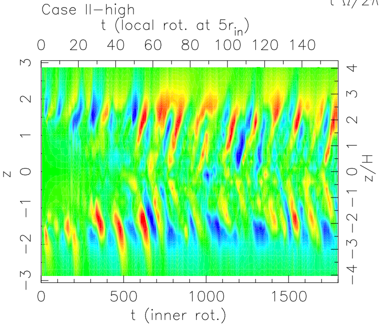
t–z diagram of B_ϕ

Local (Without Dead Zone) (With Dead Zone)





Global



Vertical Differential Rotation ?

Force Balance eqns.:

von Zeipel (1924); Kozlowski (1978)

$$-\frac{1}{\rho}\frac{\partial p}{\partial R} + R\Omega^2 - \frac{\partial \Phi}{\partial R} = 0, \qquad (1)$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{\partial \Phi}{\partial z} = 0, \qquad (2)$$

Ω: rot.freq.; Φ: External Potential

Differentiating Eq. (1) with z and Eq. (2) with R $\Rightarrow$

$$-\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial p}{\partial R}\right) + \frac{\partial}{\partial R}\left(\frac{1}{\rho}\frac{\partial p}{\partial z}\right) + \frac{\partial}{\partial z}(R\Omega^2) = 0. \qquad (3)$$

Globally $p = p(\rho)$ $\Rightarrow$ the 1st and 2nd terms are canceled out:

$$\frac{\partial \Omega}{\partial z} = 0 \qquad (4)$$

c.f. Taylor–Proudman state

Non-barotropic EoS $\Rightarrow \frac{\partial \Omega}{\partial z} \neq 0$

Global Simulations –Set-up– (2/2)

Assuming locally isothermal gas

Case I

- T =const.
  $\Rightarrow \frac{\partial v_\phi}{\partial z} = 0$
  (good for MRI studies)
  $H/R \propto R^{1/2}$
  (not good for disk winds)
  No Differential Rotation along z direction

cT+L.R. cT+H.R.

Case II

- $T \propto r^{-1}$
  $\Rightarrow \frac{\partial v_\phi}{\partial z} \neq 0$
  (not good for MRI studies)
  H/R =const.$(z < 4H)$
  (good for disk winds)
  Differential Rotation along z direction

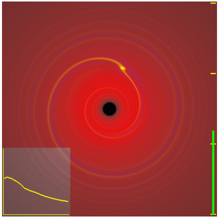
rT+L.R. rT+H.R.

von Zeipel 1924; Kozlowski 1978; Takeuchi & Lin 2002

- Simulations:spherical coordinates (r, θ, ϕ)
- Data Analyses:cylindrical coordinates(R, ϕ, z)

Type I Migration

Armitage 2005



Gravitational Interaction of a Planet with Gas

⇒ Migration of Planet by (tiny) ± force Difference.

Mostly inward migrate with :

$$\tau_{\mathrm{mig,I}}(r) \approx 5 \times 10^4 \mathrm{yr} \left(\frac{4.35}{2.7+1.1s}\right) \left(\frac{\Sigma(r)}{\Sigma_0}\right)^{-1} \left(\frac{M}{M_\oplus}\right)^{-1}$$

(Tanaka et al.2002)

Surface density is a key

Description of Time Evolution

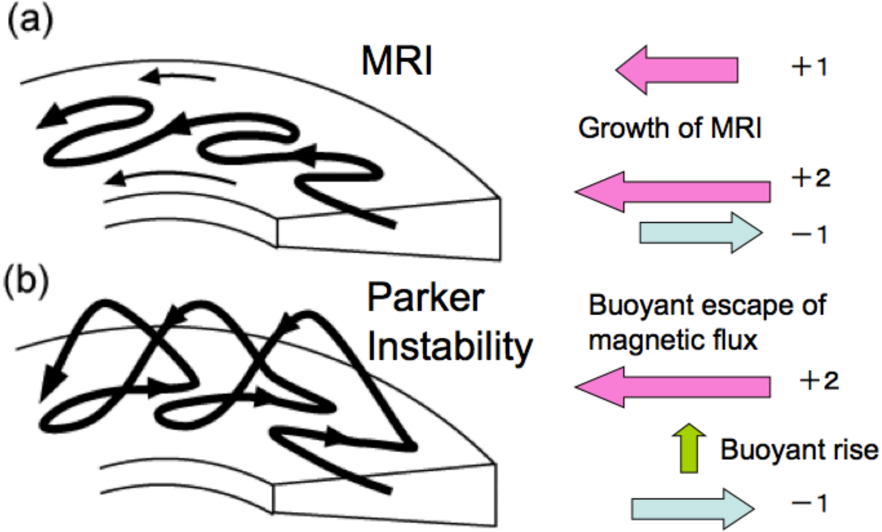
- No Disk Winds
  Approach to $\exp(-r/r_s)/r$. (Lynden-Bell & Pringle 1974)
- Disk Winds
  - Mass Flux:
    $$(\rho v_z)_w = C_w \rho_{mid} c_s \propto C_w \Sigma \Omega \propto \Sigma r^{-3/2}$$
    $\propto$ Keplerian Frequency
  - Dispersal Time (if no accretion) :
    $$\tau = \Sigma / (\rho v_z)_w \propto r^{-3/2}$$
    "Dynamically Evaporate" Inside-Out
    (controlled via τ_{dyn})
  - Switching-on accretion & disk winds
    $\Rightarrow$ an expanding inner hole

Disks with inner holes $\Leftrightarrow$ Transitional Disks ?

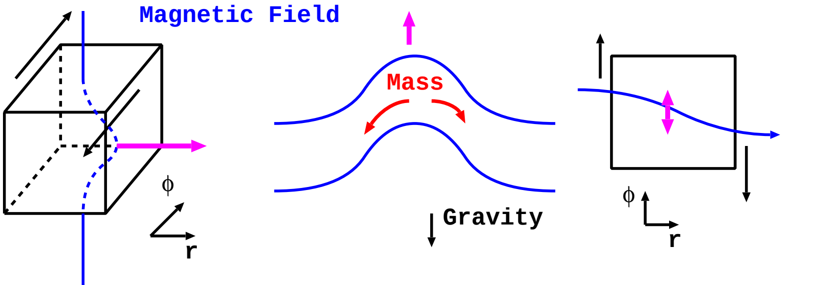
Time Evolution of B_ϕ –contd.–

From a viewgraph by Dr. R. Matsumoto

(Nishikori et al.2006; Machida et al.2013)



Amplification of *B*-field



MagnetoRotational Instability

Parker Instability (Magnetic Boyancy)

B_ϕ Generation by Differential Rotation

MRI: triggering MHD turbulence