Evolution of Protoplanetary Discs with Magnetically Driven Disc Winds

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Nov. 29th, 2017

Movies are available at

http://ea.c.u-tokyo.ac.jp/astro/Members/stakeru/research/movie/index.html

Life Time of Protoplanetary Discs (PPDs)

Near IR Obs. ⇔ Small (hot) dusts

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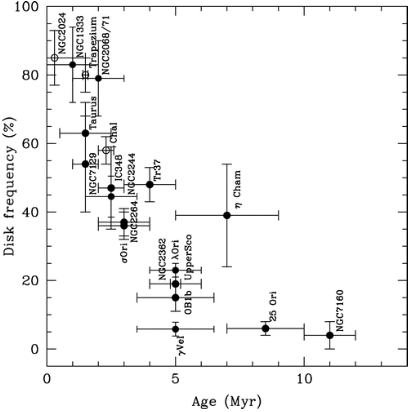

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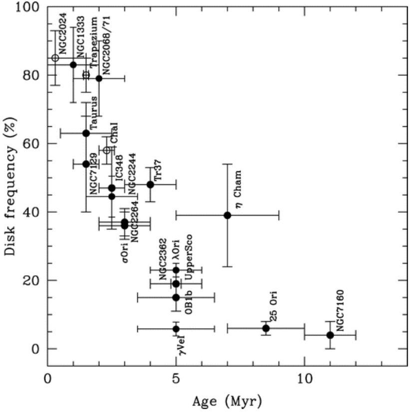
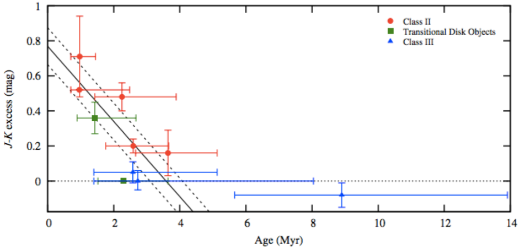


Individual Stars (Taurus)

Takagi+ 2014



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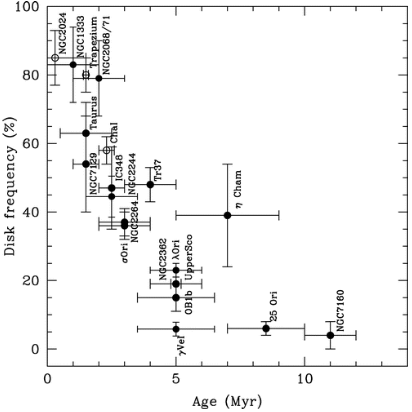

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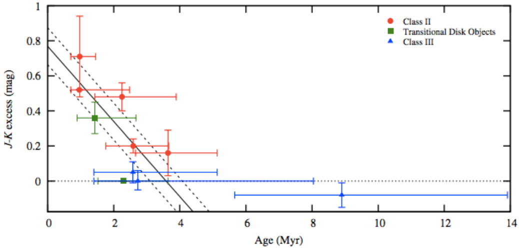

- $\tau_{\mathrm{life}} \sim$ 1-10Myr

  (metallicity dependence Yasui+ 2009; 2010)

Dispersal of PPDs

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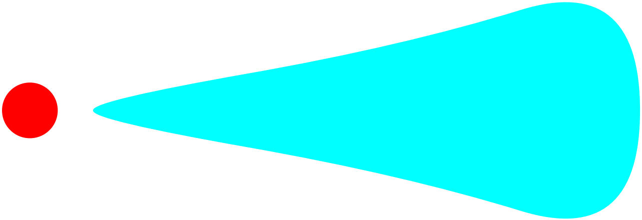

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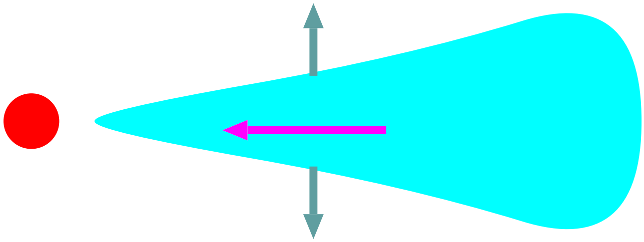

- Viscous Accretion to the Central Star
- Escape from the Surfaces

- Others: Stellar Winds

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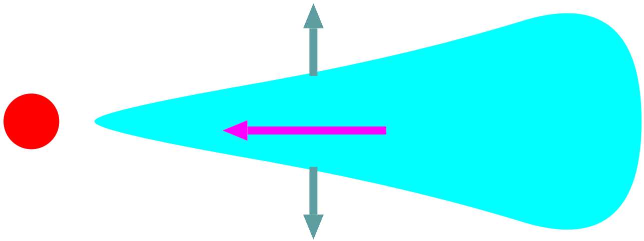

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    Shu+ 1993; Hollenbach 2000; Alexander+ 2006; Ercolano+ 2009; Owen+ 2010l; Kimura+ 2016
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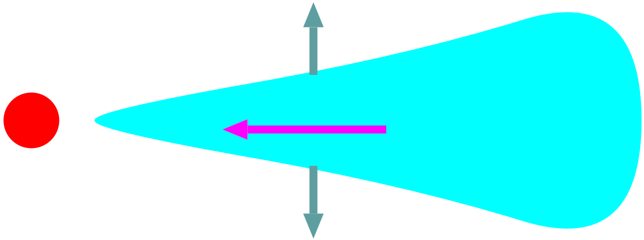

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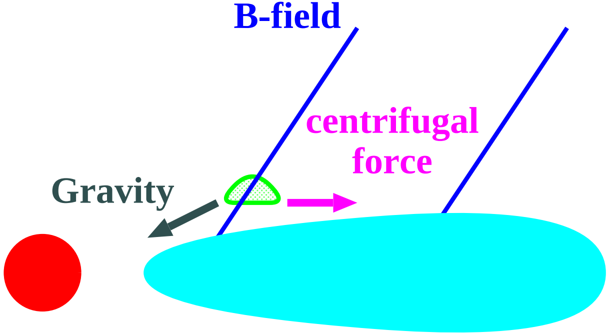
  - Magnetically Driven Disc Winds
    Blandford & Payne 1981; Shibata & Uchida 1986; Suzuki & Inutsuka 2009; 2014, Suzuki+ 2010; Flock+ 2011; Bai & Stone 2013; Fromang+ 2013; Lesur+ 2013
- Others: Stellar Winds

Accretion Disc Winds

Magneto-centrifugal driven winds by global $\boldsymbol{B}$ field

(Blandford & Payne 1982; Pelletier & Pudritz 1992; Kudoh & Shibata 1998; Ramsey & Clarke 2011; Salmeron+ 2011)



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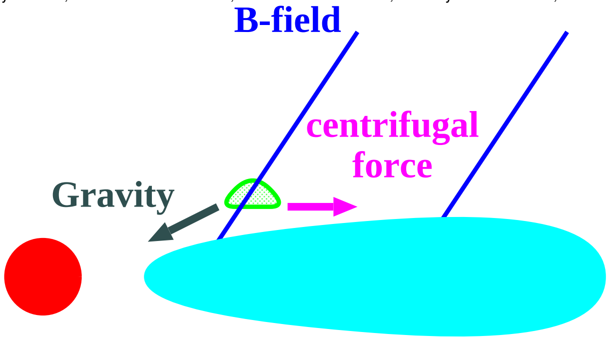

- Direct Mass Loss

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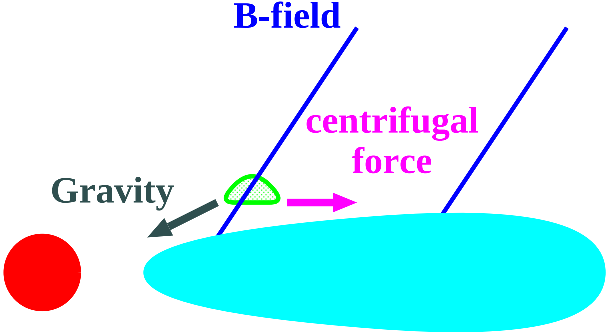

- Direct Mass Loss
- Angular Momentum Loss (Magnetic Braking)
  $\Rightarrow$ Accretion

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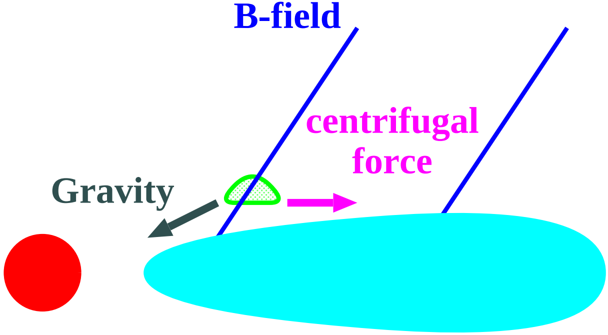


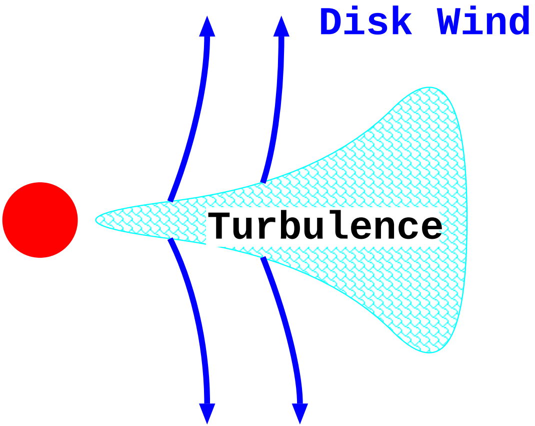
- Direct Mass Loss
- Angular Momentum Loss (Magnetic Braking)
  ⇒ Accretion

How mass is loaded to the wind footpoint?

Mass Loading

Mass Loading

A possible mechanism – Uplift by MHD turbulence

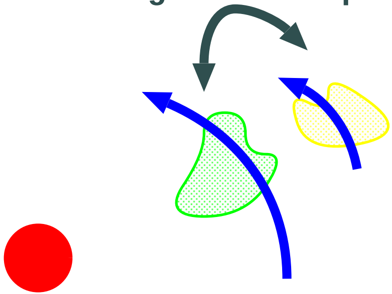


Suzuki & Inutsuka 2009; Bai & Stone 2013; Fromang+ 2013; Lesur+ 2013

Turbulence in Accretion Discs

Turbulence ⇒ Macroscopic (effective) Viscosity

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



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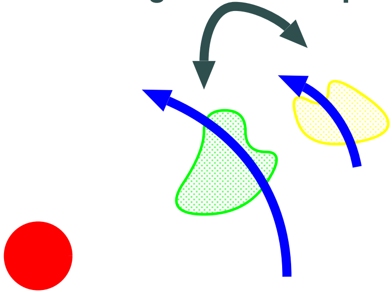

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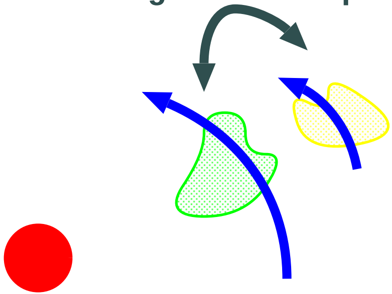

- Outward Transport of Angular Momentum
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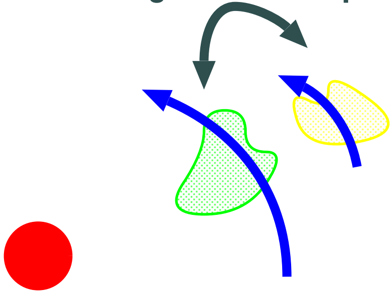

- Outward Transport of Angular Momentum
- Inward Accretion of Matters
- MRI (MagnetoRotational Instability)
  – a reliable process

Local Shearing Box Simulations

Hawley et al. 1995

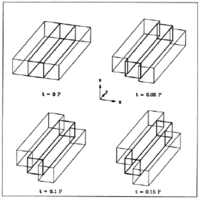

FIG. 1a

Suzuki & Inutsuka 2009

(Two Movies here)

Characteristics of Turbulence

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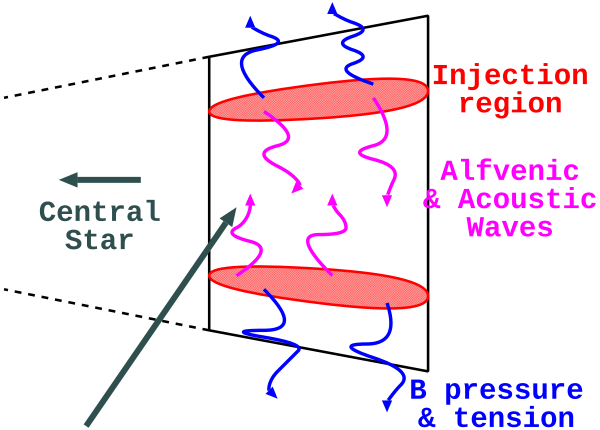

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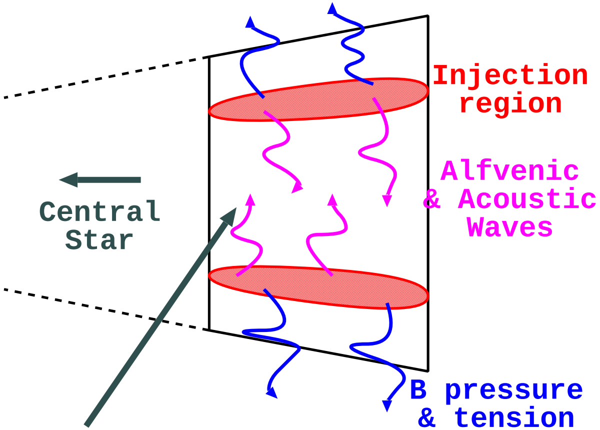

- Vertical outflows from Injection Regions at $z \approx \pm(1.5-2)H$ with $\beta \sim 1$–10

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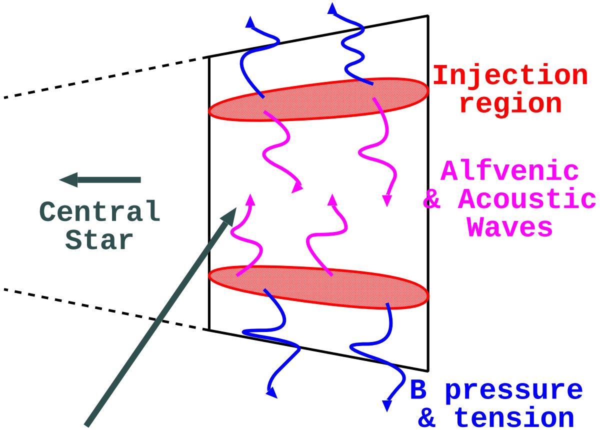

- Vertical outflows from Injection Regions at $z \approx \pm(1.5-2)H$ with $\beta \sim 1$–10
- Momentum flux to midplane ⇒ Dust

Turner et al.2010

Time dependency: $t - z$ diagrams

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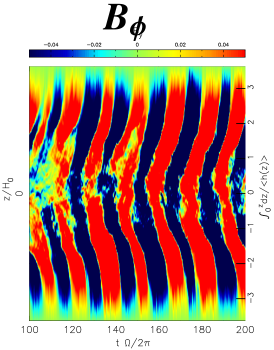

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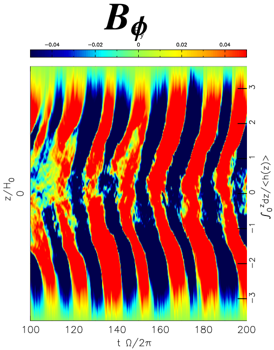

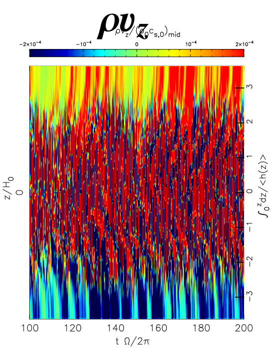

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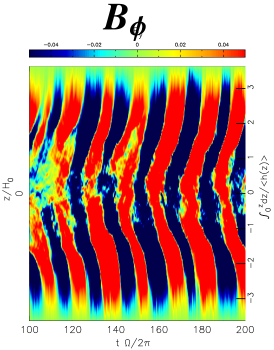
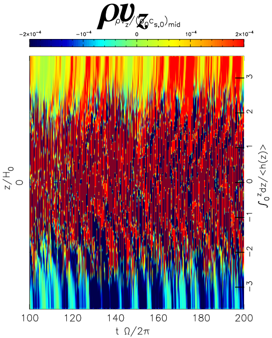


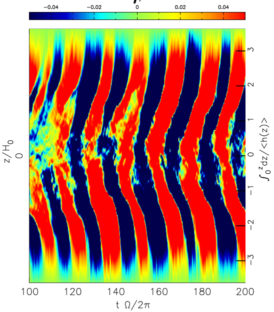


- quasi-periodic inversion of B_ϕ

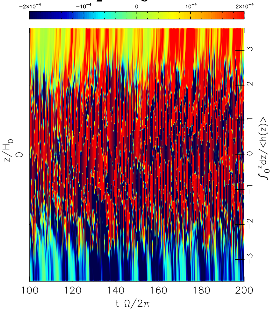
e.g. Davis et al.2010; Shi et al.2010

Time dependency: $t - z$ diagrams

B_ϕ



ρv_z



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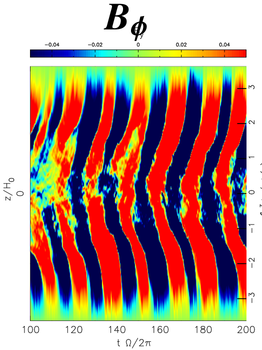

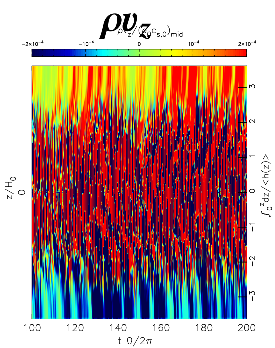

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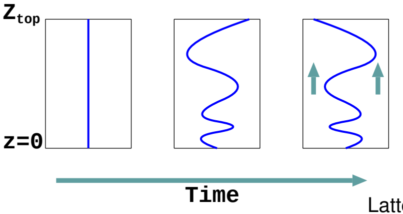
Upper half of the local box



Latter+ 2010

Application to PPDs

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- $T < 1000$ K except a very inner region
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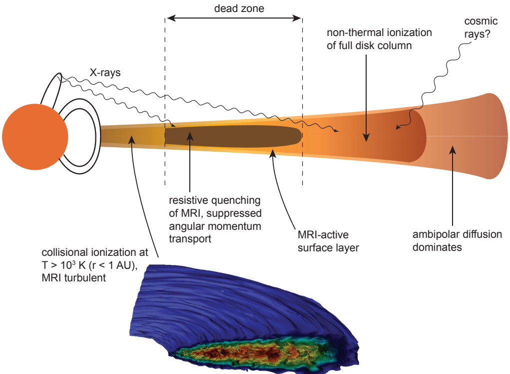
- Ionization sources

  Galactic cosmic rays, Stellar UV & X-rays, Radioactive nuclei



Armitage (2011)

Magnetic Diffusion

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Low ionization degree

⇒ Weak coupling between $\boldsymbol{B}$ & Gas

"Non Ideal MHD" effects

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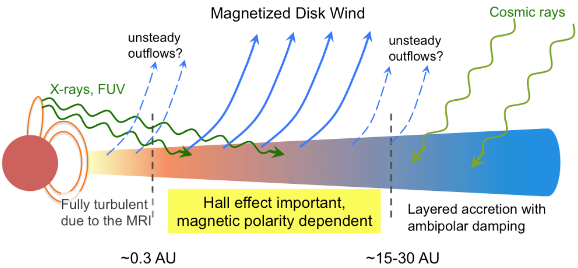

Bai (2013)

Resistivity

- “Standard” Galactic cosmic rays + stellar X-rays at 1AU
- Ohmic diffusion

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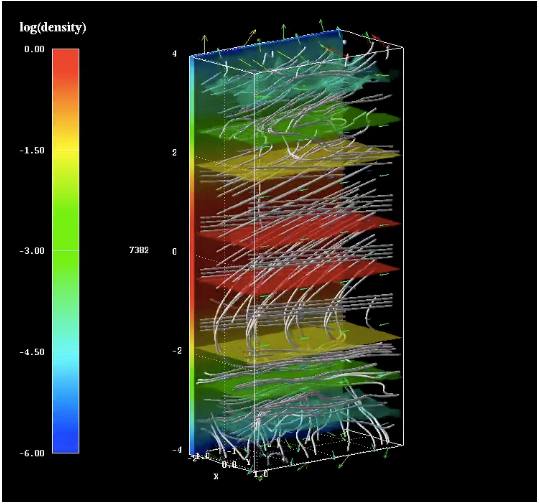
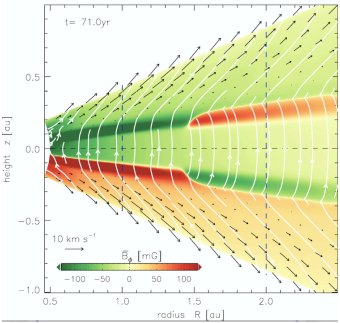
- ρv_z decreases (1/2-1/3), but $\neq \mathbf{0}$
- Dynamics is controlled by thin surface active layers



but, other non ideal MHD effects ?

e.g., Bai 2013; Gressel+ 2015

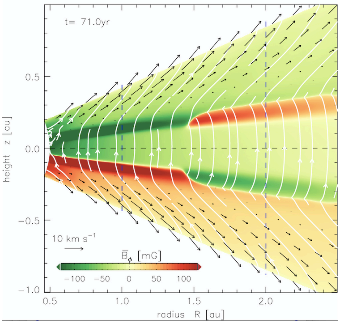
+ Ambipolar Diffusion



Gressel+ 2015

(Ohmic+Ambipolar Diffusion)
Magneto-centrifugal Winds even WITHOUT Ionization.

+ Ambipolar Diffusion



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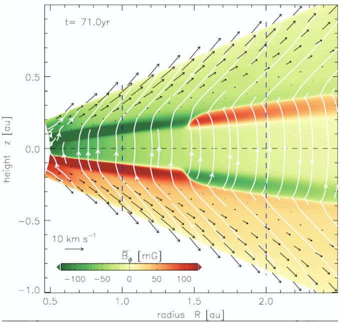

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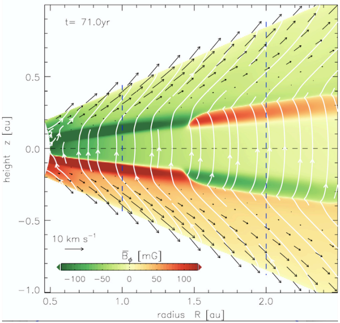

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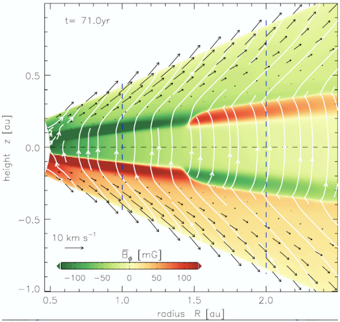

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Roles of Disc Winds

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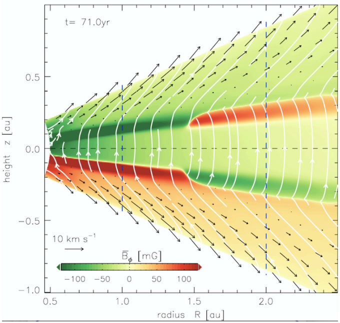

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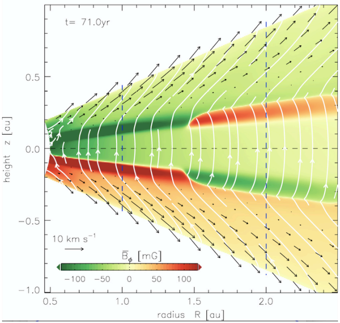

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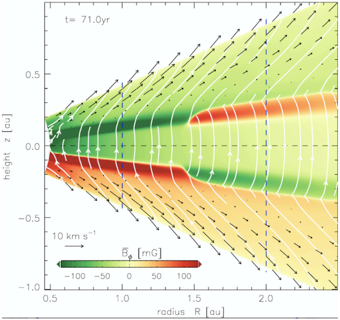

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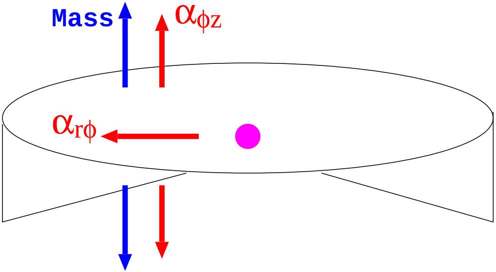
But Mass & Ang.Mom. loss rates are uncertain.

Evolution of PPDs –$t + r$ Model–



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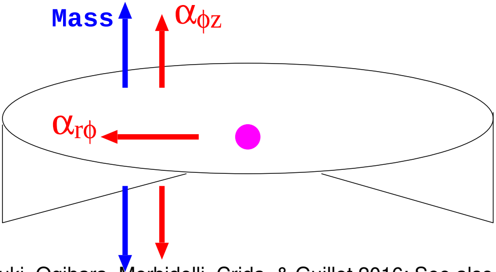

Suzuki, Ogihara, Morbidelli, Crida, & Guillot 2016; See also Hasegawa+ 2017

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

$\Sigma(=\int \rho dz)$: Surface density; Ω: Keplerian freq.

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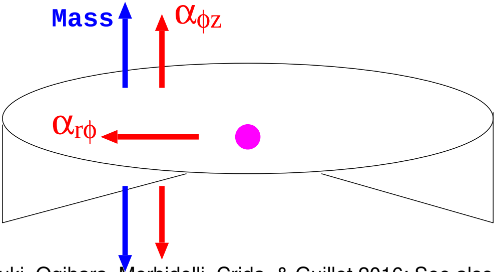

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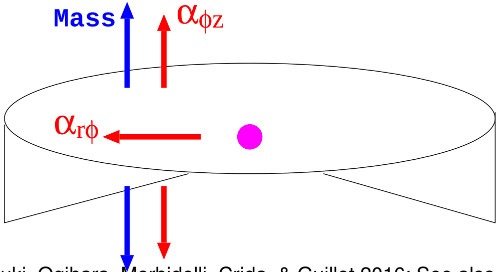
α & $(\rho v_z)_{\rm w}$ $\Leftarrow$ Local Simulations

- Turbulent Viscosity: $\alpha_{r\phi} = (v_r \delta v_\phi - B_r B_\phi / 4\pi\rho)/c_s^2$
- Wind Torque: $\alpha_{\phi z} = (\delta v_\phi v_z - B_\phi B_z / 4\pi\rho)/c_s^2$ Bai 2013
- Mass Loss Rate: $(\rho v_z)_{\rm w}$

Evolution of PPDs $-t + r$ Model–



Suzuki, Ogihara, Morbidelli, Crida, & Guillot 2016; See also Hasegawa+ 2017

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

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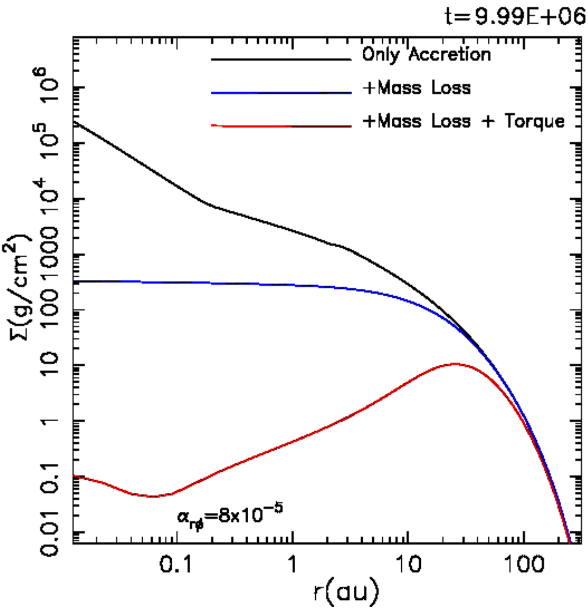
Viscous heating (Nakamoto+1994; Oka+ 2011) also included

Evolution of Σ_{gas}

- $\alpha_{r\phi} = 8 \times 10^{-5}$
  Dead Zone Level
  - w/o or w/ DW
  - w/o or w/
    Wind Torque

Suzuki+ 2010; 2016

Evolution of $\Sigma_{\rm gas}$



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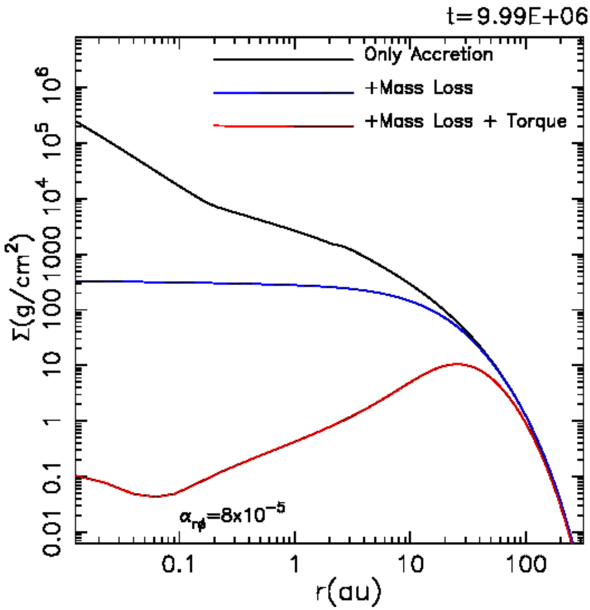

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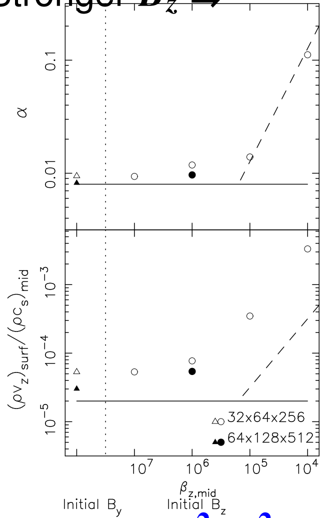
  $\Rightarrow$ Accretion

Suzuki+ 2010; 2016

Ambiguity

Ambiguity

Stronger $B_z \Rightarrow$



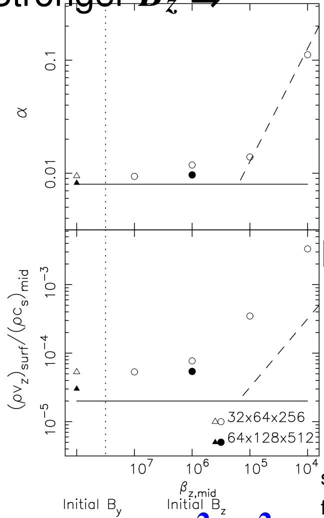
Suzuki, Muto, & Inutsuka 2010

- Turbulent viscosity, $\alpha_{r\phi}$ (upper panel)
- DW mass flux, $C_{\rm w}$ (lower panel)

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

Ambiguity

Stronger B_z ⇒



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- Turbulent viscosity, $\alpha_{r\phi}$ (upper panel)
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Both $\alpha_{r\phi}$ & $(\rho v_z)_\mathrm{w}$

- are constant for weak B_z ($\beta_{z,\mathrm{mid}} \gtrsim 10^6$)
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  Pessah+ 2007; Okuzumi & Hirose 2011

see Ogilvie (2012); Bai & Stone (2013) for stronger $\langle B_z \rangle$

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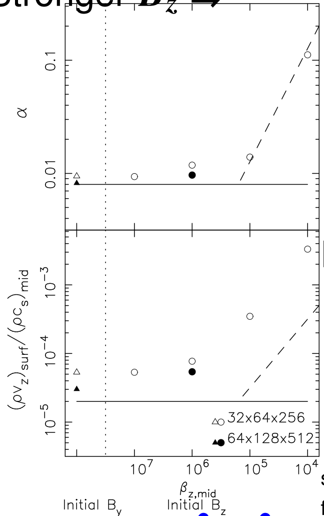

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Evolution of B_z is critical.

Evolution of B_z ??????

Suzuki & Inutsuka 2014

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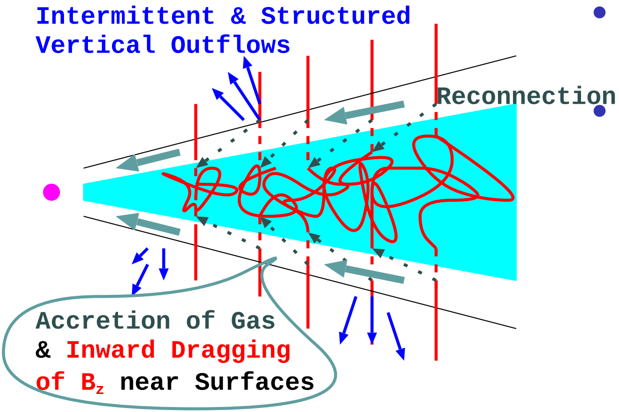
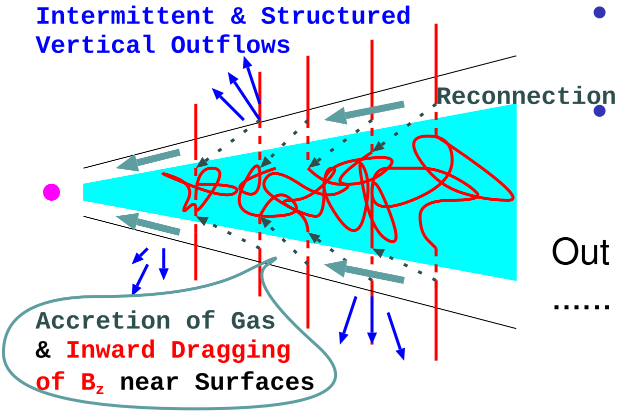


Our findings for B_z

- Inward dragging near the surfaces
- Stochastic outward & inward motion near the midplane

Evolution of B_z ??????

Suzuki & Inutsuka 2014



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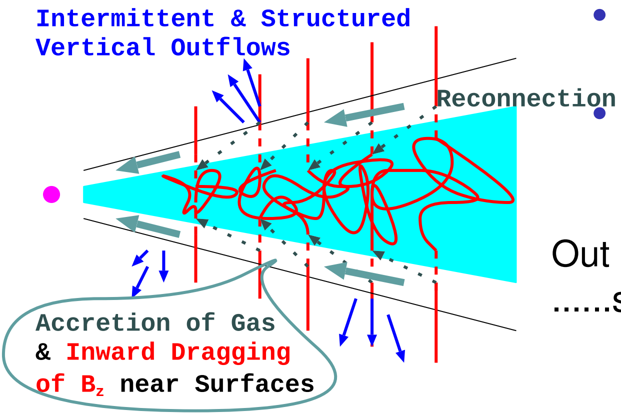

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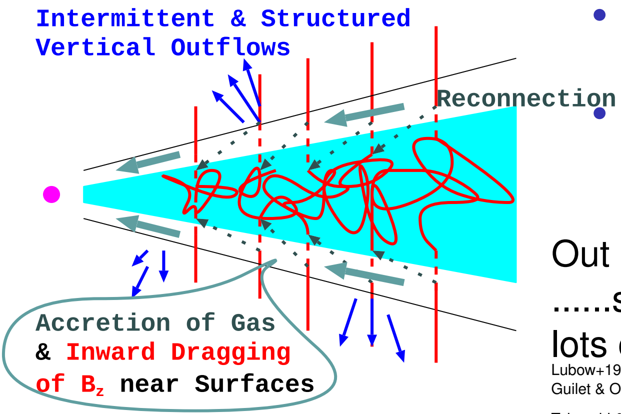

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Out understating is

......super poor

lots of analytic models:

Lubow+1994; Rothstein & Lovelace 2008;
Guilet & Ogilvie 2012; 2014; Okuzumi+ 2014;

Takeuchi & Okuzumi 2014; Bai 2017

Other Applications

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- Slow down / Reverse radial infall of boulders
  Suzuki+ 2016
  - Application to CAIs in the Solar system Desch+ 2017

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- Creating an inner hole ⇔ Transitional discs?
  Suzuki+ 2010

Floating Grains in Vertical Outflow

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Dust grains in the fixed background gaseous upflow (1D in z direction)

- $\frac{\partial \rho_d}{\partial t} + \frac{\partial}{\partial z}(\rho_d v_d + J) = 0$

  where $J \propto \frac{\partial}{\partial z}\left(\frac{\rho_d}{\rho_g}\right)$:

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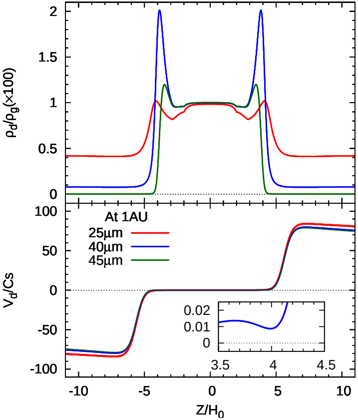
Miyake, Suzuki, & Inutsuka 2016



at 1 au from $1M_{\odot}$ star

- 25μm
- 40μm
- 45μm

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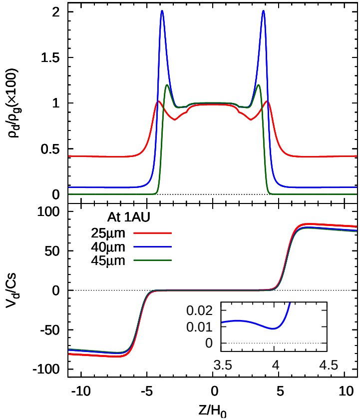
ρ_d/ρ_g peaks
⇐ Force balance btw
Upward gas drag
& Downward gravity

Miyake, Suzuki, & Inutsuka 2016



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Dust Grains: Radial Dependence

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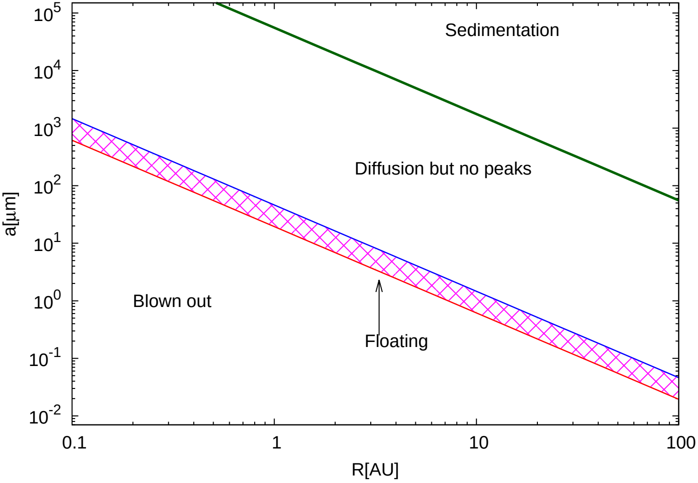
(MMSN:$\Sigma = 2400 \mathrm{g/cm^{-3}} \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2}$) Miyake, Suzuki, & Inutsuka 2016



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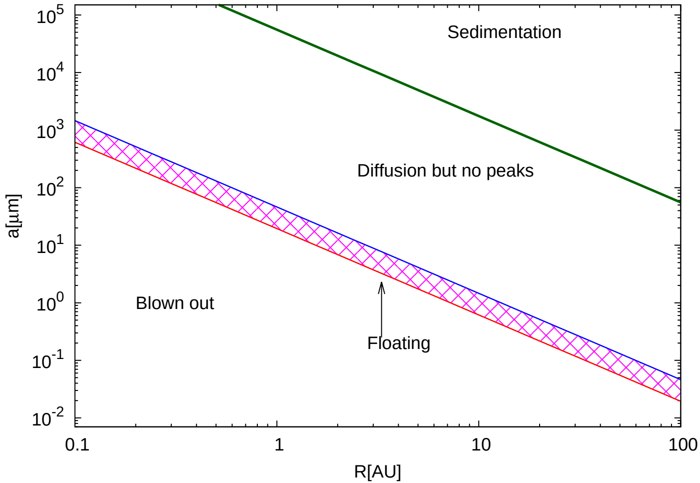

- Smaller grains are blown out

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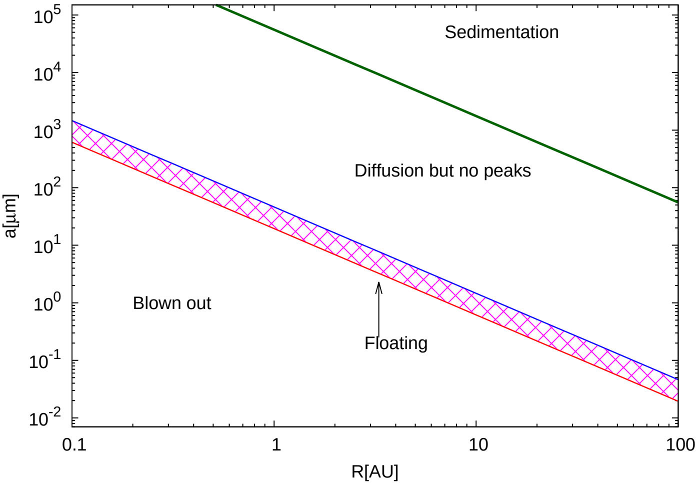

- Smaller grains are blown out
- Larger grains stay in a disc.

Floating Grains by Disc Winds ?

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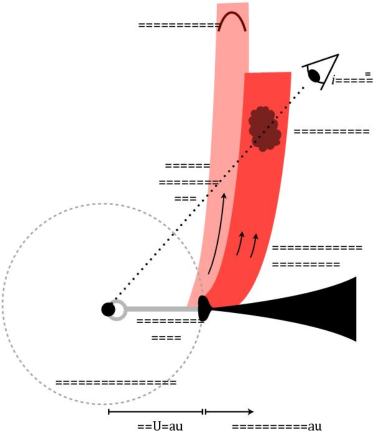
Ellerbroek+ 2014



Time-variable optical fadings and

IR brightenings

Floating Grains by Disc Winds ?

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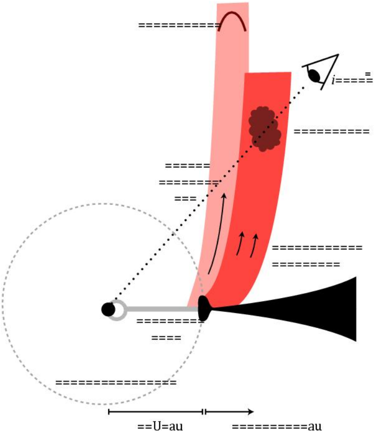
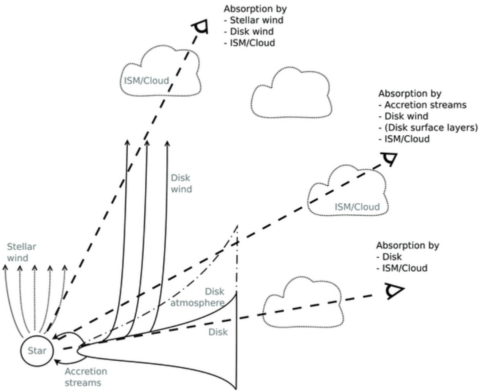


Time-variable optical fadings and IR brightenings

McJunkin+ 2014



Suggest large dust-to-gas ratio from Lyα ⇔ A_V

Summary

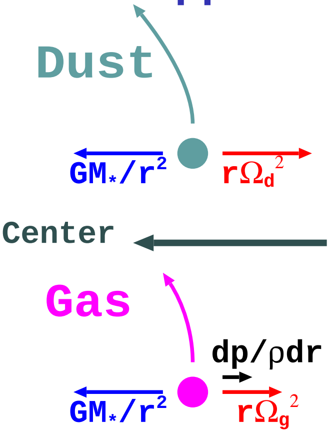
Magnetically Driven Disc Winds

- remove the gas component of PPDs
- remove the angular momentum
  ⇒ Drive Accretion
- list up small dust grains ⇒ IR observation ?
- could slow down / reverse inward drift of boulders & protoplanets

But very uncertain in a quantitative sense

- Mass Loss Rate?
- Magnetic Braking Rate?
- Evolution of net B flux?

Suppress Infall of Boulders



- Head-Wind from Gas ⇒ Slower Rotation of Solids ⇒ Inward Drift
- Typical situation at 1au Boulders infall with 100-1000 years

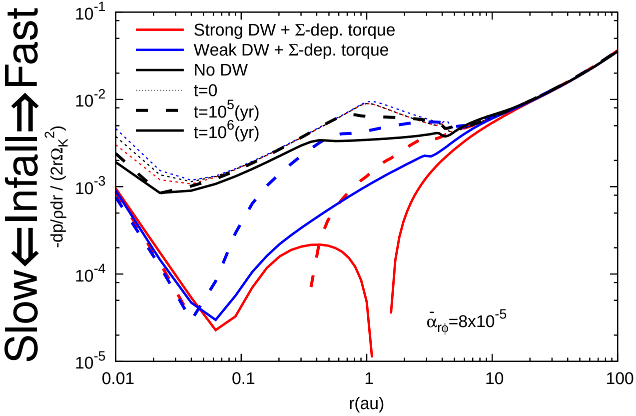
$\Omega_g < \Omega_d = \Omega_K$

Direction of P-gradient is a Key:

Inward P-grad. ⇒ Outward Drift

P-grad force

Suzuki, Ogihara, Morbidelli, Crida, & Guillot 2016



Min. infall time: $\tau_{\mathrm{dr,max}} \approx 1/\eta\Omega_{\mathrm{K}}$

where $\eta = -\frac{1}{\rho}\frac{\partial p}{\partial r}/(2r\Omega_{\mathrm{K}}^2)$

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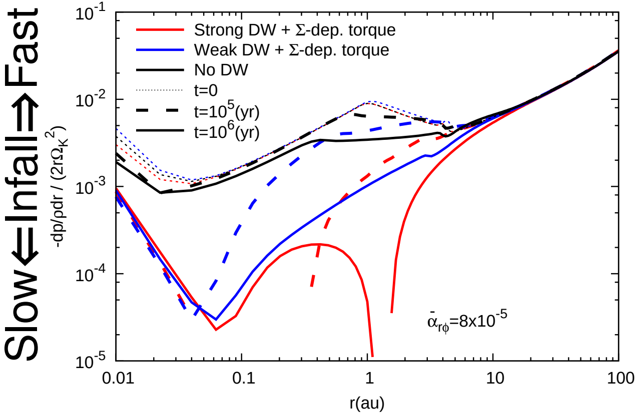

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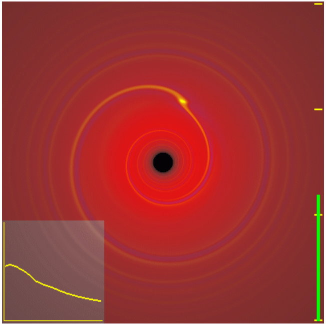
Outward Drift near 0.1 au (10^5yr) / 1 au (10^6yr)

Type I Migration



Armitage 2005

Gravitational Interaction of a Planet with Gas
⇒ Migration of Planet by tiny ± force Difference.

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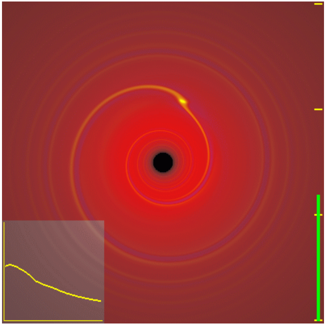

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$$\tau_{\mathrm{mig,I}}(r) \approx 5\times10^4\mathrm{yr}\left(\frac{4.35}{2.7+1.1s}\right)\left(\frac{\Sigma(r)}{\Sigma_0}\right)^{-1}\left(\frac{M}{M_\oplus}\right)^{-1}$$

Recent update: Paardekooper+ 2011; Baruteau+ 2011; Bitsch+ 2013; Lega+ 2014, ...

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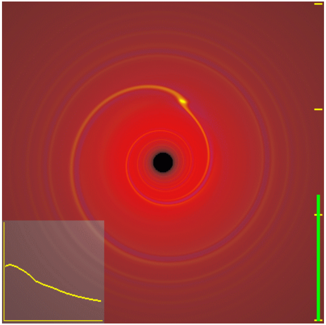

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Recent update: Paardekooper+ 2011; Baruteau+ 2011; Bitsch+ 2013; Lega+ 2014, ...

Surface density is a key

Type I Migration with Disc Winds

Initial Condition

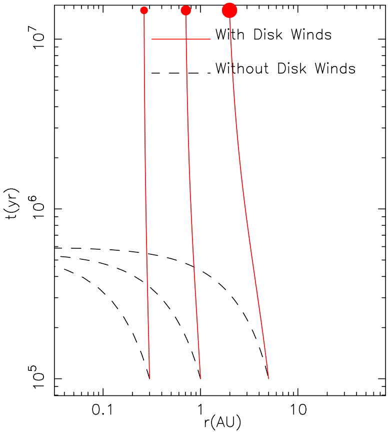
- $\mathbf{0.3}M_\oplus$ at 0.3 au
- $\mathbf{1}M_\oplus$ at 1 au
- $\mathbf{5}M_\oplus$ at 5 au

with Tanaka+ 2002 formula

- (Red)solid: w/ Disc Wind (No Wind Torque)
- (White)dashed: w/o Disc Wind

Migrating planets

Type I Migration with Disc Winds



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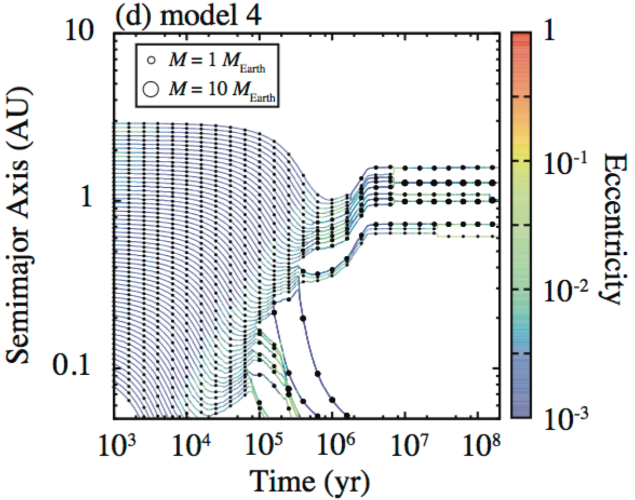
▸ Migrating planets

Cases with Wind Torque
⇒ Ogihara et al. in prep.

Type I Migration with Disc Winds

N-body simulation in a gaseous disc

Ogihara, Kobayashi, Inutsuka, & Suzuki 2015



Type I migration formula from Paardekooper+ (2011)

Recent paper by Ogihara, Morbidelli, & Guillot 2015

Inner Hole –moderately strong B_z–

Suzuki, Muto, & Inutsuka 2010

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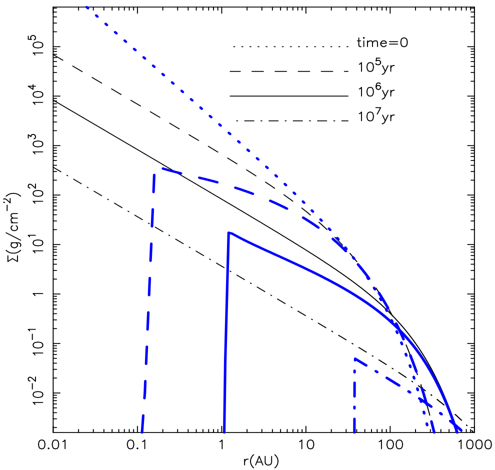

Runaway & inside-out evacuation

–"switch-on" $\alpha_{r\phi}$ & $C_{\rm w}$

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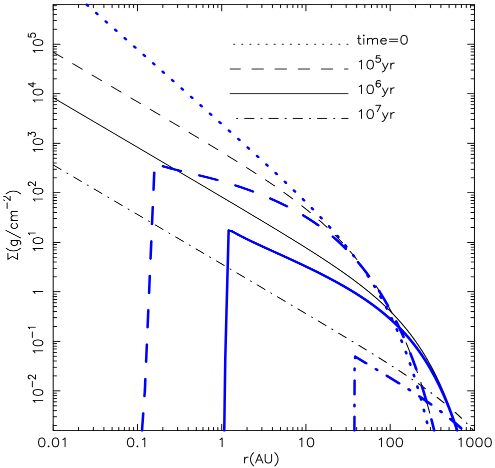


Runaway & inside-out evacuation

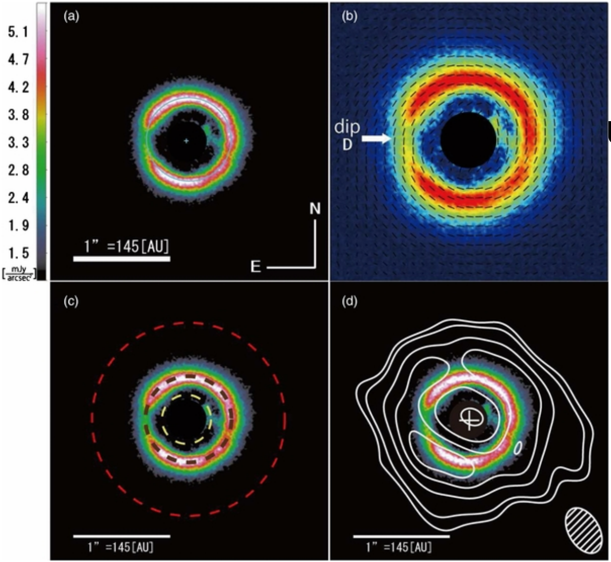
–"switch-on" $\alpha_{r\phi}$ & C_w

Gradual expansion of an inner hole

Connection with Transitional Discs ?

Mayama+ 2012

(many other works including Subaru/SEEDS project)



Upper Sco

- colours: Polarized Intensity of H band (Scattered stellar light via dust grains)
- (d) dust continuum (SMA)