

MAGNETIC FLUX TRANSPORT
through
A TURBULENT ACCRETION DISK

Dmitri A. Uzdensky¹ & Hendrik Spruit²

¹ Princeton University – CMSO

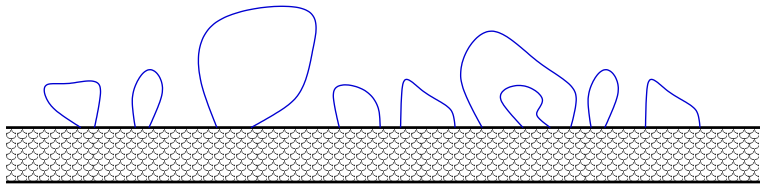
² MPA

Chicago, August 4, 2006

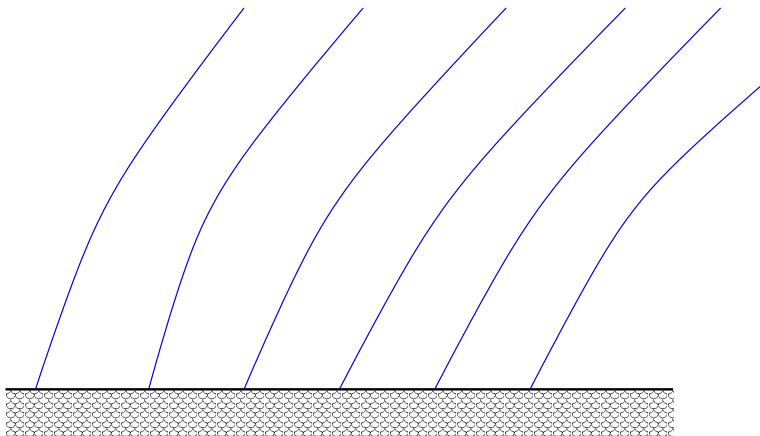
Accretion–Disk Magnetic Fields: Two Kinds

Two Kinds of Magnetic Fields in Accretion Disks :

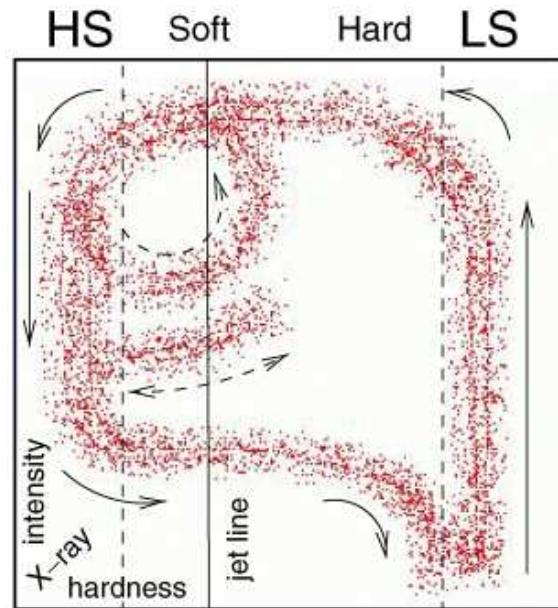
- **small-scale** ($l < R$):
generated by the disk turbulent MHD dynamo — no external source needed — determined locally by disk parameters, e.g., \dot{M}



- **large-scale** ($l > R$):
ambient flux trapped from the environment — depends on the external magnetic field \Rightarrow a second parameter (in addition to \dot{M}) characterizing accretion!



Evidence for Large-Scale Fields in Disks: Two Spectral States of Accreting Black Holes



(Fender *et al.* 2004, *MNRAS*, 355, 1105)

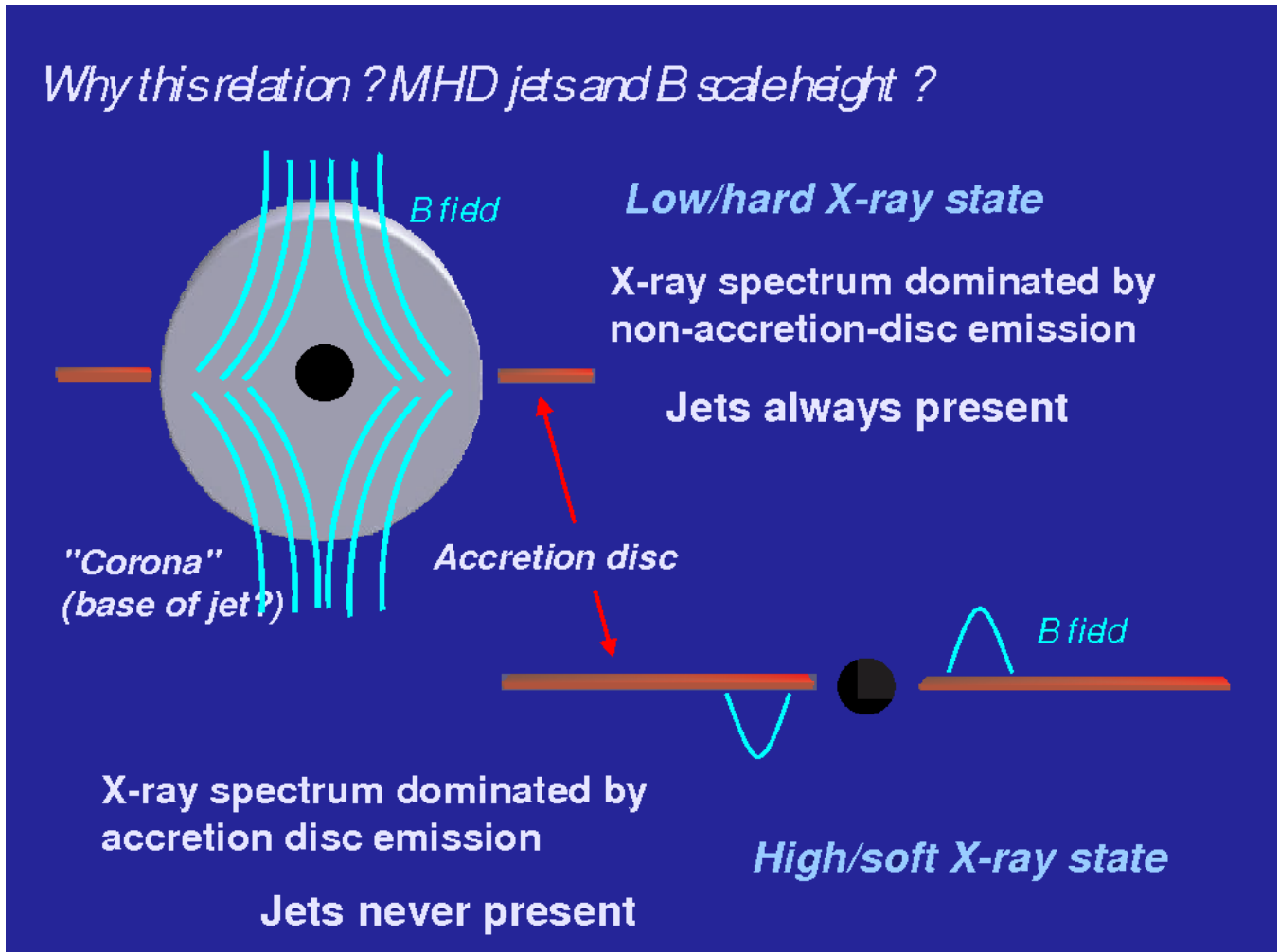
Two (or more!) spectral states (high/soft and low/hard) in black-hole X-Ray binary sources (e.g., GRS 1915):

- Hard state (truncated accretion disc plus strong corona) – jets
- Soft state (full accretion disc, weak corona) – no jets

rapid transitions between the two states

a second (apart from \dot{M}) physical parameter?

Evidence for Large-Scale Fields in Disks: Two Spectral States of Accreting Black Holes



(from Rob Fender's talk at the XXII Texas Symposium on Relativistic Astrophysics, Dec. 15, 2004)

Evidence for Large-Scale Fields in Disks: JETS

- **Jets** are observed in many accreting systems (BH and NS XRBs, AGNs, YSOs).
- Most popular mechanism of jet launching:
magneto-centrifugal mechanism
(Blandford & Payne 1982)
— employs a large-scale ordered open magnetic field.
- A large-scale magnetic field is believed to be responsible for **jet collimation**.

What's the Problem?

Q:

Is it possible to concentrate external large-scale magnetic flux in the inner disk?

Ideal MHD \Rightarrow no problem:

flux is frozen into the disk and just accretes with the gas.

However:

A theoretical obstacle to trapping external flux:

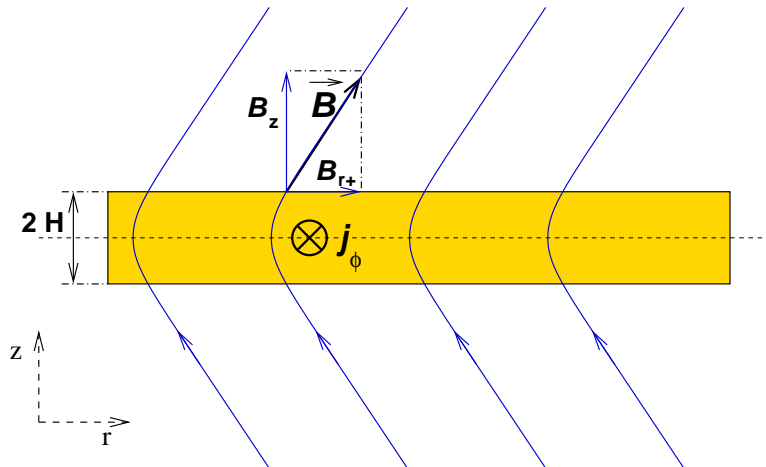
effective magnetic diffusivity due to **disk turbulence!**

Turbulent Magnetic Diffusivity

(e.g., van Ballegoijen 1989; Lubow et al. 1994; Heyvaerts et al. 1996; Agapitou & Papaloizou 1996; Livio et al. 1999; Uzdensky et al. 2002)

- Unless $\beta \leq 1$, the disk is unstable to MRI \Rightarrow MHD turbulence.
- This is **good** news for the angular-momentum transport (needed for accretion)
Turbulence \Rightarrow effective viscosity: $\nu = \alpha c_s H$
- But this is **bad** news for concentrating external flux:
effective **turbulent magnetic diffusivity**:

$$\eta \sim \nu \sim \alpha c_s H \quad (1)$$



- radial resistive slippage velocity:

$$\Delta v_r = v_r^B - v_r^{\text{accr}} \sim \eta j_\phi / B_z \sim \frac{\eta}{H} \frac{B_{r,+}}{B_z} \sim \alpha c_s \frac{B_{r,+}}{B_z} \gg v_r^{\text{accr}} \sim \alpha c_s \frac{H}{R} \quad (2)$$

flux diffuses outward faster than it is advected by accretion flow!

- steady state: $B_{r,+}/B_z \sim H/R \ll 1$

Proposed Solution: Intermittency of Disk Turbulence

- **Turbulent Diamagnetism:**
magnetic field is expelled from regions of strong turbulence and is concentrated between turbulent cells
(Zeldovich 1956; Parker 1963)
- Numerical Simulations of Magnetoconvection
(Weiss 1966; Proctor & Weiss 1982)

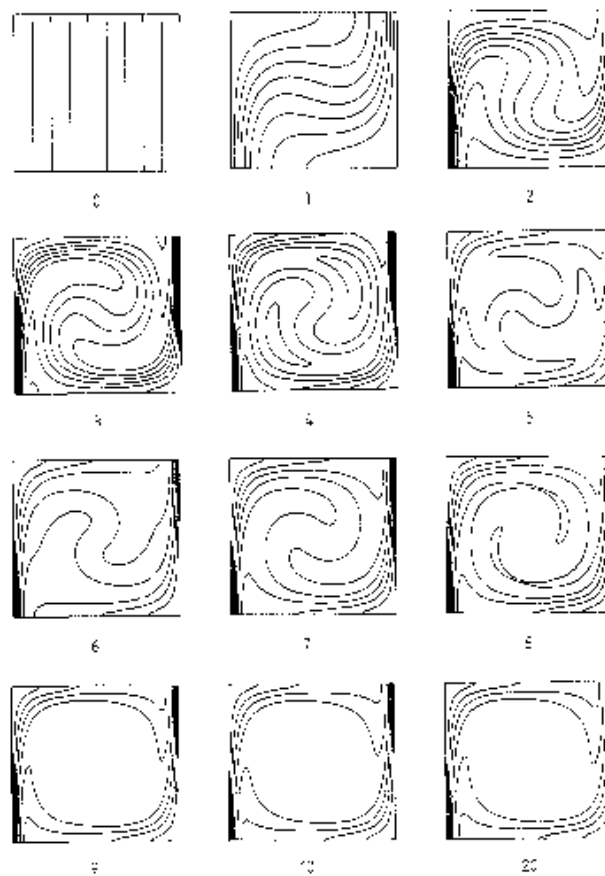
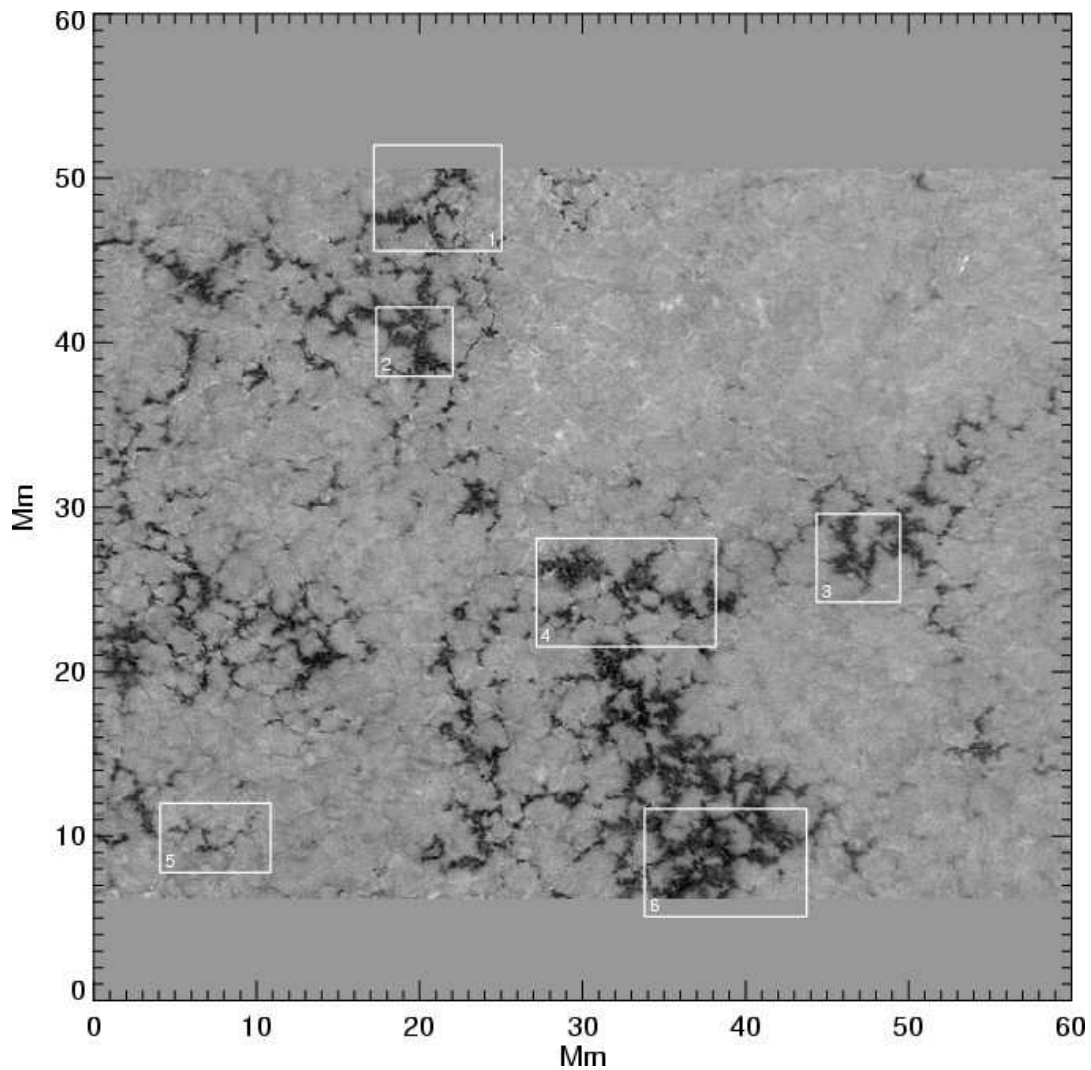


Figure 1. Flux expulsion in two dimensions. Successive stages in the distortion of an initially uniform magnetic field at times t/τ_1 (values given for each diagram), where $\tau_1 = 5\pi/8$ (from Galloway and Weiss 1981).

Photospheric Magnetic Field Intermittent Structure

- Observational Example: **Solar Photosphere:**
convective flow concentrates emerging magnetic flux into vertexes
between convective cells ($B \sim 1$ kG, $l \sim 100$ km)

Solar Magnetogram using the Swedish Solar Telescope
(*Berger et al. 2004*)



D. Uzdensky

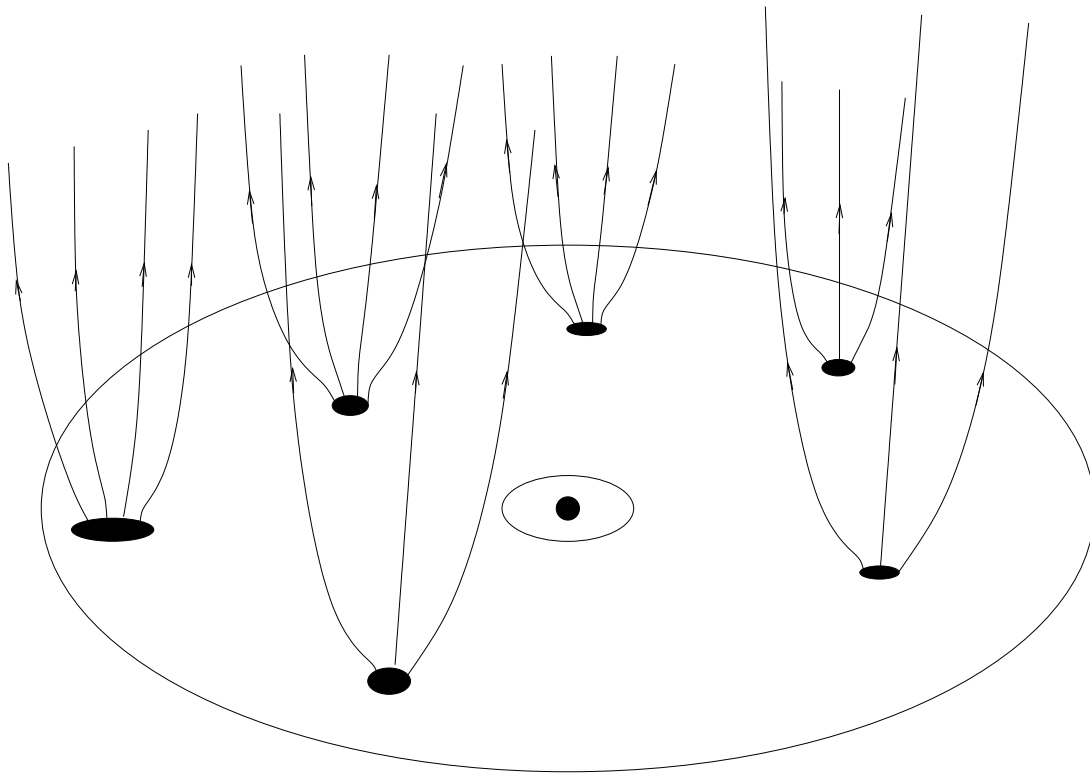
Analogy with Superconductors

- Consider superconducting material in external magnetic field B_0 at $T > T_c(B_0)$. Start lowering the temperature.
- When $T < T_c(B_0)$, the medium separates into two phases:
 - superconducting regions without magnetic flux (flux expulsion)
 - normal regions with concentrated strong magnetic field that suppresses superconductivity
- Turbulence plays the role of superconductivity

Small Patches of Strong Field

Conjecture:

Weak external vertical field is concentrated into many small patches of strong field where MRI is suppressed.

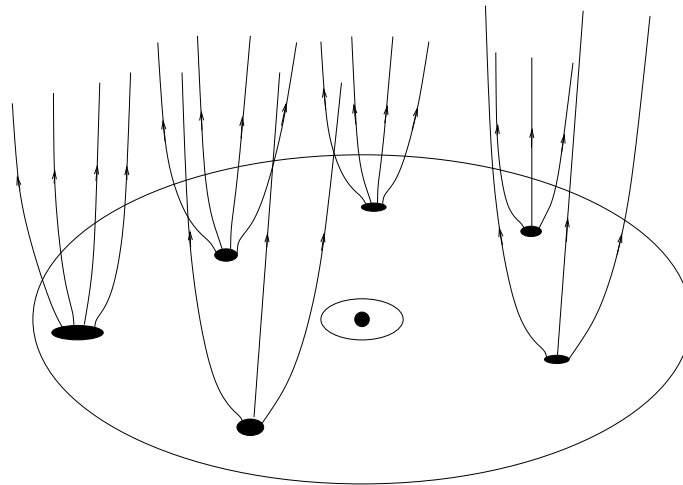


Caveat:

Flux expulsion/concentration works for magnetoconvection, but will it work for MRI-driven turbulence?

– needs further exploration...

Angular Momentum Loss in Patches



- Disk is threaded by a weak large-scale vertical field, B_0 :

$$\beta_0 \equiv \frac{8\pi P}{B_0^2} \gg 1 \quad (3)$$

- In the disk, vertical flux is concentrated in small patches with field B_p that is just strong enough to suppress MRI:

$$\beta_p \equiv \frac{8\pi P}{B_p^2} \simeq \beta_{\text{MRI}} \sim 1 \quad (4)$$

- Surface covering fraction of patches: $f = \frac{B_0}{B_p} \ll 1$

- Magnetic torque on a patch of area a^2 :

$$\tau_p = \left| \frac{1}{4\pi} 2ra^2 B_p B_{\phi,p} \right| = \frac{\gamma}{2\pi} ra^2 B_p^2, \quad (5)$$

where we parametrized $|B_{\phi,p}| = \gamma B_p$

INWARD DRIFT

- Torque leads to inward drift, v_{dr} :

$$\tau_p = -\frac{dJ_p}{dt} = v_{\text{dr}} \frac{d}{dr} J_p(r), \quad (6)$$

where J_p is the patch angular momentum:

$$J_p(r) = M_p v_K r = a^2 \Sigma \sqrt{GM r}. \quad (7)$$

- **Inward drift velocity:**

$$v_{\text{dr}} = \frac{2\tau_p}{a^2 \Sigma v_K} = \frac{\gamma}{\pi} \frac{r B_p^2}{\Sigma v_K} \quad (8)$$

- Using $\Sigma = 2\rho H$, $B_p^2 = 8\pi P/\beta_{\text{MRI}}$, and $c_s \equiv \sqrt{P/\rho}$:

$$v_{\text{dr}} \simeq \frac{4\gamma}{\beta_{\text{MRI}}} c_s \gg v_{\text{accr}} \simeq \alpha c_s \frac{H}{r}. \quad (9)$$

Global Evolution of Large-Scale Magnetic Field

- Evolution equation for $B_0(r, t)$:

$$\frac{\partial B_0}{\partial t} = \frac{1}{r} \partial_r [r B_0(r, t) v_{\text{dr}}(r)] = \frac{4\gamma}{\beta_{\text{MRI}}} \frac{1}{r} \partial_r [r c_s(r) B_0(r, t)]. \quad (10)$$

- Steady state:

$$r c_s(r) B_0(r) = \text{const}. \quad (11)$$

Adopting $c_s/V_K \sim H/R = \text{const}$,

$$B_0(r) \sim \frac{1}{\sqrt{r}}. \quad (12)$$

- Magnetic field in patches, B_p ,
for a radially self-similar disk; (*e.g.*, Krolik 1999):

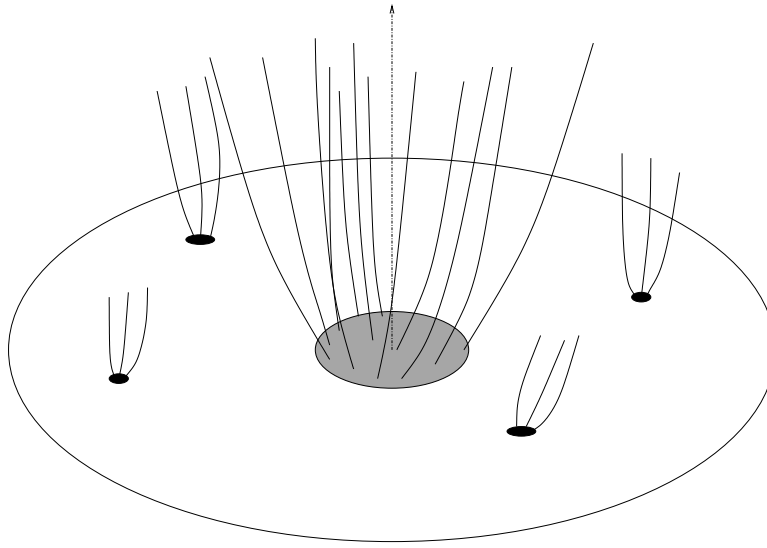
$$B_p \sim P^{1/2} \sim r^{-5/4}. \quad (13)$$

- Surface covering fraction:

$$f \sim B_0(r)/B_p(r) \sim r^{3/4} \quad (14)$$

– decreases inward.

CENTRAL FLUX BUNDLE



- Over time, vertical flux accumulates in a **central flux bundle**, aka Magnetically-Arrested Disk — MAD (*Narayan et al. 2003*).
- MRI turbulence is suppressed by the strong magnetic field
- Gas piles up outside the bundle until the configuration becomes unstable to MHD instabilities (e.g., interchange) — when magnetic support against gravity exceeds a few per cent (*Stehle & Spruit 2001*).
- The accretion flow character changes: accretion continues episodically, via blobs and streams (*e.g., Igumenshchev et al. 2003*).

SUMMARY

- **Large-scale, ordered magnetic fields** in central parts of accretion disks are desirable for explaining BH spectral-state transitions and jet production.
- Inward advection of vertical flux in a turbulent accretion disk is problematic if there is an effective **turbulent diffusivity**.
- We propose a **new mechanism** to resolve this problem:
 - turbulent flux expulsion leads to concentration of the large-scale vertical flux into small patches of strong magnetic field;
 - because of their large field strengths, the patches experience higher angular-momentum loss rate via magnetic braking/winds;
 - as a result, patches rapidly drift inward, carrying the vertical flux with them.
- The accumulated vertical flux aggregates in the **central flux bundle** in the inner part of the disk. Accretion flow through the bundle changes its character.