Magnetic fields in accretion disks

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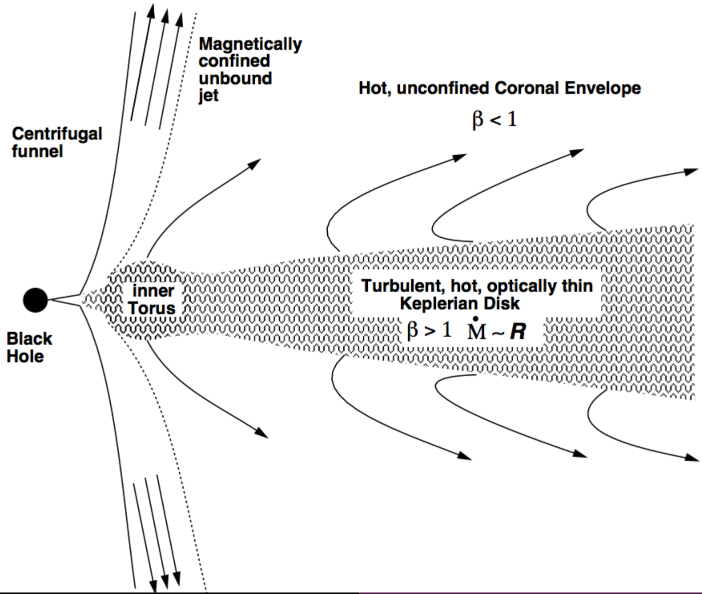
  - The magnetorotational instability - accretion disk turbulence and viscosity (Balbus & Hawley 1991)

Accretion disk - jet: schematic from Hawley & Balbus 2002



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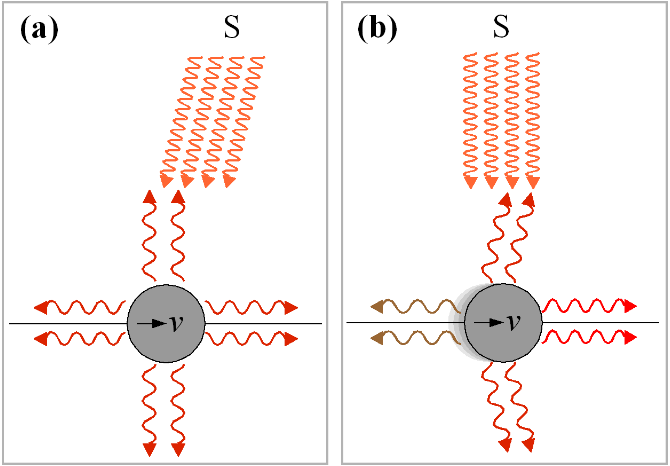
Poynting-Robertson drag

- What is it?

Poynting-Robertson drag



- Credit: Michael Schmid/Wikipedia

Poynting-Robertson drag

- Why is the drag force on a proton $(m_e/m_p)^2$ times smaller than that on an electron?

Poynting-Robertson drag

- The key is the Thomson scattering cross-section $\sigma_{\mathrm{T}} \equiv 8/3\pi r_0^2$ r_0 is the classical particle radius, $\equiv e^2/mc^2$

Poynting-Robertson drag

- Equivalently, angular distribution of power (Thomson) scattered by a charged particle $dP/d\Omega \propto$ the double derivative of the dipole moment: $\ddot{\mathbf{d}}^2$, and $\mathbf{d} \equiv e\mathbf{r} \propto m^{-1}$

Accretion disk battery - further details (Contopulos et al 2015)

- Poloidal magnetic fields “open up” due to differential rotation of footpoints, separate into an “inner” (radius) component and an outer one,

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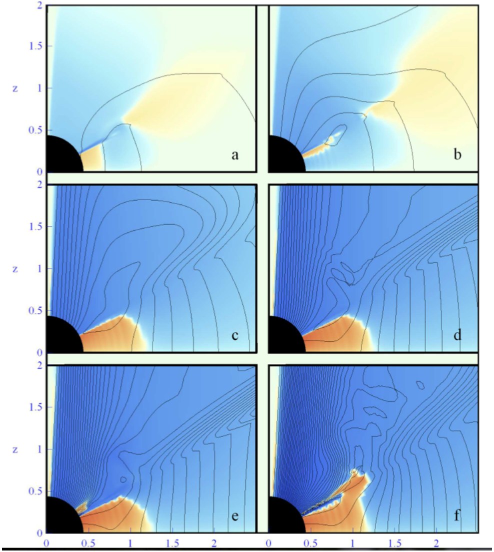

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- Inner field continuously advected inward, outer (return) field diffuses outward;

Accretion disk battery - further details (Contopulos et al 2015)

- This proceeds all the way to equipartition, generating astrophysically relevant fields on (astrophysically relevant) timescales (Contopoulos et al 2015)

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- You can also understand it via the induction equation $\dot{\mathbf{B}} = -c\,\nabla \times \mathbf{E} = \nabla \times (\mathbf{v} \times \mathbf{B})$

How to get the Poynting flux point $\hat{z}$-wards?

- So the Poynting flux $\mathbf{S} = (c/4\pi)\,\mathbf{E} \times \mathbf{B}$ becomes $\mathbf{S} = (1/4\pi)\,\mathbf{B} \times (\mathbf{v} \times \mathbf{B})$

How to get the Poynting flux point $\hat{z}$-wards?

- We saw how dipolar fields can be generated (think B_z), and how differential twisting of footpoints cause them to generate B_ϕ

How to get the Poynting flux point $\hat{z}$-wards?

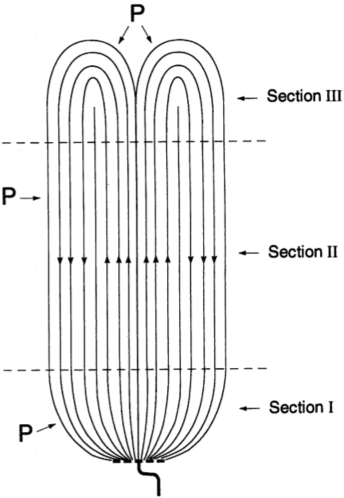

Figure 1. Conjectural structure of the static field with significant twist showing the splay in Section I, the cylindrical Section II and the turnover in Section III. Only the poloidal field is shown; the twists run around this structure. **P** is the pressure p.

How to get the Poynting flux point $\hat{z}$-wards?

- The fluid velocity is primarily azimuthal (v_ϕ)

How to get the Poynting flux point $\hat{z}$-wards?

- So $B_\phi \times (v_\phi \times B_z)$ gives rise to a z-component of $\mathbf{S}$ (not that there aren't other components of $\mathbf{S}$)

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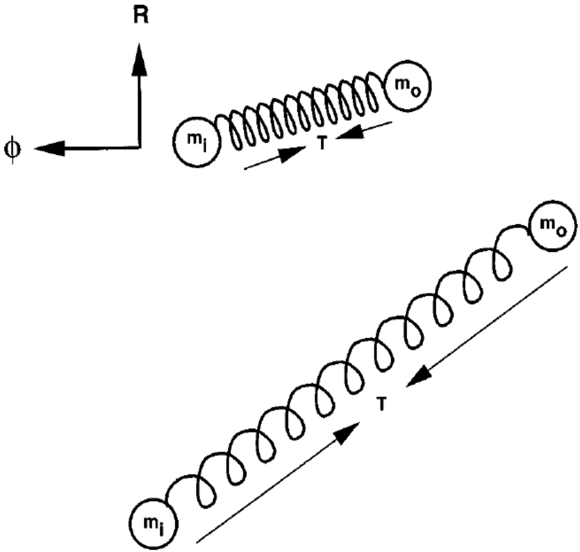
- ..and the instability saturates via magnetic reconnection, yielding a saturated state of tangled B fields
- Main motivation - generate viscous stress $w_{r\,\phi}$ from magnetic fields $\sim B_r B_\phi / 4\pi$ that will enable accretion to proceed

The instability



MRI: procedure

- Perturb the Euler equation

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References

- Accretion disk battery:
  - Contopoulos & Kazanas 1998, ApJ, 508, 859; Contopoulos et al 2006, ApJ, 652, 1451; Contopoulos et al 2015, arXiv:1501.05784
- Poynting flux jets:
  - Lovelace, 1976, Nature, 262, 649; Lovelace et al, 2002, ApJ, 572, 445; Lovelace & Kronberg, 2015, arXiv:1212.0577; Lynden-Bell, 1996, MNRAS, 279, 389; Blandford & Znajek, 1977, MNRAS, 179, 433
  - Magnetocentrifugal launching: Blandford & Payne 1982, MNRAS, 199, 883; Lovelace et al 1991, ApJ, 379, 696; Utsyugova et al 1999, ApJ, 516, 221
- Magnetorotational instability:
  - Balbus & Hawley, 1991, ApJ, 376, 214; Hawley & Balbus, 1992, ApJ, 400, 595; Balbus & Hawley, 1998, Rev. Mod. Phys., 70, 1
- General: Plasma Physics for Astrophysics, Kulsrud, 2005, Princeton University Press