Magnetized Disk Wind from Protostellar Disks

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Magneto-centrifugal Wind

(Blandford & Payne, 1982)

Rigid rotation:
Centrifugal acceleration

$B^2_p/8\pi \gg \rho v_p^2/2$

B field winds up (develop $B_\phi$)

Alfvén surface

(Spruit 1996)

Intensive (analytical) study in the 80s-90s.
Numerical simulations in late 90s onward.

Missing ingredient: realistic disk physics

(Stepanovs & Fendt, 2014)
Microphysics in protostellar disks

The bulk of the protostellar disk is extremely weakly ionized: gas and magnetic fields are poorly coupled => 3 non-ideal MHD effects.

Magnetorotational Instbility (MRI) is largely suppressed in the inner disk.

Presence of external magnetic flux is essential to drive disk accretion and evolution, launching of magnetized disk wind is inevitable.

(cf. Bai & Stone 13, Bai 13,14,15, Lesur+14, Gressel+15, and PPVI review by Turner+14)
A toy model for protostellar disk wind

Axisymmetric, steady state wind theory:

Properties of disk wind are fully determined given the field line geometry and thermodynamics.

The gas at the wind base ($z = z_0$) is poorly ionized, largely decoupled with $B$

The hot gas is well ionized by an external source (UV), well coupled to $B$

The cold gas is poorly ionized, largely decoupled with $B$
Parameters and expected ranges (for class II)

**Poloidal B field strength:**

\[ B \gtrsim 0.1 \dot{M}_{-8}^{1/2} R_{AU}^{-5/4} \text{G} \]

Translating to \( v_{A0} \sim 0.03 - 0.1 v_K \)

*(weak field)*

**Wind temperature:**

\( \sim \) a few thousand K

Translating to \( c_s \sim 0.1 v_K \)
A representative wind solution (~1 AU)

\[ v_{A0} = c_s = 0.1v_K, \theta = 45^\circ, z_0 = 0.15R_0 \]

(chosen from expected wind launching conditions)

We solve time-dependent MHD equations restricted to a prescribed poloidal field line.

The system will relax to the steady state wind solution.
A representative wind solution (~1 AU)

\[ v_{A0} = c_s = 0.1v_K, \quad \theta = 45^\circ, \quad z_0 = 0.15R_0 \]

(chosen from expected wind launching conditions)

Alfvén point is not far from the wind base \((R_A \sim 1.5R_0)\).

From standard wind theory:

\[ \frac{\dot{M}_{\text{wind}}}{\dot{M}_{\text{acc}}} \approx \frac{R_0^2}{R_A^2 - R_0^2} \]

\sim \text{unity!} \quad \text{(for } R_A/R_0 = 1.5) \]

Protostellar disks lose mass very quickly!
Dependence on B field strength (class 0/I)

Black: fiducial
Blue: strong B

Accretion rate in early phases of SF (e.g., class 0/I) is much higher => stronger B

Accretion rate

\[
\frac{\dot{M}_{\text{wind}}}{\dot{M}_{\text{acc}}} \approx \frac{R_0^2}{R_A^2 - R_0^2}
\]

Stronger B field
Reduced ejection/accretion ratio
Summary

- Magnetized disk wind is likely the primary way to drive accretion and evolution of protostellar disks.
- Disk wind is launched from the externally heated, much-better-ionized disk surface.
- Wind kinematics strongly depends on disk magnetization:
  - Strong magnetization: large accretion rate, but small $\dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$
  - Weak magnetization: small accretion rate, but large $\dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$
- Disk magnetization drops with protostellar disk evolution: the disk lose more mass per mass accreted towards late evolutionary stages.
Observed accretion-ejection correlation

- Observations 20(!) yrs ago suggested that for the HVC (jet):
  \[ \dot{M}_{\text{out}} \sim 0.1 \dot{M}_{\text{acc}} \]

- Inferring wind mass rate from line profiles is highly difficult. For LVC, very rough estimates give
  \[ \dot{M}_{\text{wind}} \sim (0.1 - 1) \dot{M}_{\text{acc}} \]
  (e.g., Pontopidan+11, Natta+14)

- Measured accretion rate also have uncertainties of \(~0.5\) dex.

(Hartigan et al. 1995, adopted from L. Hartmann’s book)