Outflows & Jets: Theory & Observations

Lecture winter term 2008/2009

Henrik Beuther & Christian Fendt
Outflows & Jets: Theory & Observations

**10.10** Today: Introduction & Overview ("H.B." & C.F.)
**17.10** Definitions, parameters, basic observations (H.B.)
**24.10** Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
**31.10** Basic theoretical concepts & models II (C.F.)
**07.11** Observational properties of accretion disks (H.B.)
**14.11** Accretion disk theory and jet launching (C.F.)
**21.12** Outflow-disk connection, outflow entrainment (H.B.)
**28.12** Outflow-ISM interaction, outflow chemistry (H.B.)
**05.12** Theory of outflow interactions; Instabilities (C.F.)
**12.12** Outflows from massive star-forming regions (H.B.)
**19.12** Radiation processes - 1 (H.B. & C.F.)
**26.12** and **02.01** Christmas and New Years break
**09.01** Radiation processes - 2 (C.F.)
**16.01** Observations of AGN jets (C.F.)
**23.01** Some aspects of AGN jet theory (C.F.)
**30.01** Summary, Outlook, Questions (H.B. & C.F.)
Outflows & Jets: Theory & Observations

Summary – astrophysical jets

- **Definition:** collimated beam of matter of high velocity
- **Sources:** young stars, active galactic nuclei, μ–quasars, gamma-ray bursts, planetary nebulae, pulsars
- velocity > escape speed: 
  -> jets launched close to central object
- jet sources host accretion disks
- indication for magnetic field:
  \[ B_{jet} \sim \mu G \ (YSO) \ ... mG \ (AGN) \]
  \[ B_{source} \sim kG \ (YSO) \ ... 10^9 G \ (MQ) \]
- young stars: dipolar magnetosphere (?)
  black holes: disk magnetic field (?)
- Jets are huge: \[ R_{jet} \sim 10^3 \ ... 10^4 \ R_{source} \]

**Conclusion:**

- jets seen over wide range of energy output & central mass:
  -> mass \( M \sim 1 \ ... 10^{10} M_\odot \)
  -> luminosity \( L \sim 10^{33} \ ... 10^{43} \ erg \ s^{-1} \)
- i) jets launched from accretion disks
  ii) not relativistic but magnetic phenomenon -> same launching mechanism for all jets ! (?)
MHD model of jet formation:

-> jets are collimated disk/stellar winds, launched, accelerated, collimated by electro-magnetic forces

-> 5 basic questions of jet theory:

- collimation & acceleration of a disk/stellar wind into a jet?
- ejection of disk/stellar material into wind?
- accretion disk structure?
- generation of magnetic field?
- jet propagation / interaction with ambient medium
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Standard model of jet formation

Hypothesis: **common model** of jet formation:

**However:** understanding of different jet/outflow sources not yet complete:

**Low mass young stars:** standard model best investigated -> “approved”;
- detailed model geometry under debate: density contrast to ISM, magnetic field structure/origin
- time scale problem: Keplerian time scale of inner disk (days) << distance between knots (10-100 yrs)
- MHD simulations ongoing (all 5 questions)

**High mass young stars:** no model yet:
- few data & parameters available: mass flow rates?; magnetic field?; velocities?
- short evolution time scale -> different “mode” of jet formation?
- radiation pressure important (?)

**Old stars (PN, pulsars):** are there jets??
Magnetic pulsar wind model: strong field -> high (relativistic) speed
(-> magnetization ~ asymptotic velocity )
Hypothesis: common model of jet formation:

However: understanding of different jet/outflow sources not yet complete:

AGNs: unified model of AGN:
- jets launched by MHD or ED process?
- leptonic or hadronic matter?
- collimation mechanism of relativistic jets (?)

Micro-quasars: relativistic jets (synchrotron):
- binary systems w/ accretion disks surrounding a compact object
- 3D / non-axisymmetric effects
- collimation mechanism of relativistic jets (?)

GRBs: collapsing star produces outflow; SN connection approved
- “fireball” model of GRB from thin shock
- indirect evidence for “jetted emission”
- how to get Lorentz factors of 1000?
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Jets from low mass stars

Why magnetic jet formation?

1) magnetic field is there ... : in jets, jet sources, surrounding medium
2) magnetic field is needed:

-> compare terms in e.o.m.: gravity, thermal / radiation pressure, magnetic forces

-> **kinematics**: kinetic energy of molecular outflows: $10^{45-48}$ ergs
(with $10^{-4} - 10^{-3} \ M_\odot / \text{yr}$ for 1000-10000 yrs, 20km/s)
kinetic energy of asymptotic jet: $10^{37}$ ergs
(with $10^{-8} \ M_\odot / \text{yr}$ for 10000 yrs, 300km/s)

in general: kinematic thrust of outflow / bolometric thrust of star:

$$\frac{P_{\text{kin}}}{P_{\text{rad}}} = 250 \left( \frac{L_{\text{bol}}}{10^3 L_\odot} \right)^{0.3}$$

(observed for 390 flows up to $10^6 \ L_\odot$, Cabrit & Bertout 1992)

-> thermal & radiation pressure too low for observed momentum:
   "jets are cold" << T~$10^6$ K (missing UV, X-rays)
-> acceleration by Lorentz force (utilizes stellar rotational energy)
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-> **kinematics:**

\[
P_{\text{kin}} \over P_{\text{rad}} = 250 \left( \frac{L_{\text{bol}}}{10^3 L_\odot} \right)^{0.3}
\]

(observed for 390 flows up to \(10^6 L_\odot\), Cabrit & Bertout 1992)
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Jets from low mass stars

Why magnetic jet formation?

1) magnetic field is there ... in jets, jet sources, surrounding medium
2) magnetic field is needed:
   -> compare terms in e.o.m.: gravity, thermal / radiation pressure, magnetic forces

-> **collimation:** occurs on distances ~ 50 AU from star
   -> compare outflow ram pressure ~ \((dM/dt \cdot v) / (4\pi z^2)\) to collimating forces
      (ambient thermal pressure, ambient magnetic pressure)
   - no ambient thermal pressure collimation ~ \(P_{\text{ext}}\)
   - YSO jets are over-dense/pressured, propagate in cavities;
   - ambient pressure ~ ram pressure of wind would be required
     -> high extinction not observed (density 1/600 smaller) in case of cool matter
     -> nor hot ambient gas with ~6000K
   - no external magnetic pressure collimation ~ \(B_{\text{ext}}^2 / 8\pi\)
     -> 10 mG required to balance ram pressure (observed is 10-100 \(\mu\)G in cores)

-> no external pressure collimation:
-> **self-collimation by MHD Lorentz force**
Magnetic De Laval nozzle: launches super-(magneto)sonic flow
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Jets from low mass stars

Magnetic De Laval nozzle: launches super-(magneto)sonic flow

(HH34 proper motion, Patrick Hartigan)

(aircraft pics from airliners.net)
Outflows & Jets: Theory & Observations

Brief introduction to MHD

MHD concept: ionized, neutral, single fluid: average quantities:

\[ \vec{j} = q_e \vec{v}_e \rho_e + q_i \vec{v}_i \rho_i \]

Ideal MHD: “frozen-in” field lines:

- mass flux couples to magnetic flux
- matter moves “along” the field lines

**MHD Lorentz force:**

\[ \vec{F}_L \sim \vec{j} \times \vec{B} \]

**MHD equations** (can only be solved numerically):

\[
\begin{align*}
\partial_t \rho + \nabla \cdot (\rho \vec{v}) & = 0 \\
\rho (\partial_t \vec{v} + (\vec{v} \cdot \nabla) \vec{v}) + \nabla P + \rho \nabla \Phi - \vec{j} \times \vec{B} & = 0 \\
\rho (\partial_t e + (\vec{v} \cdot \nabla) e) + P (\nabla \cdot \vec{v}) - \eta_D |\vec{j}|^2 / c^2 & = 0 \\
\partial_t \vec{B} & = \nabla \times (\vec{v} \times \vec{B} - \eta_D \vec{j} / c) \\
\nabla \cdot \vec{B} & = 0, \quad \nabla \times \vec{B} = 4\pi \vec{j} / c
\end{align*}
\]

(note non-ideal MHD resistive term of magnetic diffusivity)
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Brief introduction to MHD

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Ideal MHD: “frozen-in” field lines

**MHD Lorentz force:**

\[ \vec{F}_L \sim \vec{j} \times \vec{B} \]

**Axisymmetric jets:**

-> poloidal, toroidal field components: \( B = B_p + B_\phi \)

-> magnetic flux surfaces: \( \Psi(R, Z) \sim \int \vec{B}_P \cdot dA \)

**Lorentz force components 1:**

projected on \( \Psi \):

\[ \vec{F}_L \equiv \vec{F}_{L,\|} + \vec{F}_{L,\perp} \]

-> (de/) accelerating:

\[ \vec{F}_{L,\|} \equiv \vec{j}_\perp \times \vec{B}_\phi \]

-> (de-) collimating:

\[ \vec{F}_{L,\perp} \equiv \vec{j}_\| \times \vec{B} \]
Outflows & Jets: Theory & Observations

Brief introduction to MHD

Interpretation of Lorentz force 2:

\[ \vec{F}_L = \nabla \left( \frac{|\vec{B}|^2}{8\pi} \right) + \frac{1}{4\pi} (\vec{B} \cdot \nabla) \vec{B} \]

composed of: magnetic pressure gradient & magnetic tension

\[ \Rightarrow \] both pressure gradient and tension have accelerating & collimating components
Understanding jet collimation:

... remember high school experiment:

-> take two wires
-> apply electric current $j$

(remember Ampere's law / right hand rule $I_p = c/2 \cdot r \cdot B_\phi$)

-> Result:
  1) wires of parallel electric current attract each other
  2) wires of anti-parallel current push off each other

==> attractive Lorentz force $j \times B_\phi$

-> jets represent bundle of wires, carrying a net electric current
Magneto-centrifugal acceleration: (Blandford & Payne 1982)

- magnetic field lines frozen-in and co-rotate with disk
- matter moves along the field (imagine beads on a wire)
- if field line inclination $< 60^\circ$:
  - unstable equilibrium
  - acceleration outwards -> sling-shot mechanism
Self-collimation of MHD jets: (Blandford & Payne 1982)

beyond critical radius: Alfven radius:

-> kinetic energy of fluid > magnetic energy

-> matter inertia dominates magnetic field

-> field cannot hold matter in co-rotation

-> poloidal field -> toroidal field

-> self-collimation by toroidal field tension
  (requires net electric current, Heyvaerts & Norman 1989)
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MHD jet collimation & acceleration

**Blandford & Payne (1982):**

**Result 1)** jet acceleration mechanism:

-> **magneto-centrifugal slingshot:**

- field line anchored at footpoint $r_0$
  - rotating with Keplerian velocity
- strong field dominates inertia
- total potential (gravity + centrifugal forces) along a field line:

$$\Phi(r, z) = -\frac{GM}{r_0} \left( 0.5 \left( \frac{r}{r_0} \right)^2 + \frac{r_0}{\sqrt{r^2+z^2}} \right)$$

- if field inclination towards disk $< 60^\circ$, equilibrium is unstable
  - small disturbance leads to centrifugal acceleration
    - outwards / inwards along the field line
- stable equilibrium for field inclinations $> 60^\circ$
- note: $60^\circ$ limit for “cold” wind;
  - if gas pressure included $\rightarrow \sim 78^\circ$ (Pelletier & Pudritz 1992)
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MHD jet collimation & acceleration

Blandford & Payne (1982):

Result 2): self-similar MHD structure of disk jets

-> magnetohydrodynamic self-collimation

BP solved self-similar, axisymmetric, stationary, cold, ideal MHD equations:

-> self-similarity: quantities scale with spherical radius along a given direction:

\[ r = [ r_0 \xi(\chi), \phi, r_0 \chi ] \]

\[ \mathbf{v} = [\xi'(\chi) f(\chi), g(\chi), f(\chi)] \mathbf{v}_{\text{Kep}}(r_0) \]

-> disk surface: \( \chi = 0, \xi(\chi) = 1 \)

-> power law for all variables \( Q(r) \sim (r/r_0)^{\alpha} \)

-> find "regular" solutions at critical points:

- flow velocity at fast-magnetosonic point
  = fast magnetosonic speed
- flow velocity at Alfven point
  = Alfven speed

PLEASE read this most fundamental paper on jet theory

Field structure: axisymmetric magnetic field lines

Dynamical parameters along a field line: \( v_\phi (=U), B_\phi/B_p, \text{Alfven-Machnumber (=m)} \)
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MHD jet collimation & acceleration


1) magneto-centrifugal slingshot
2) self-similar MHD structure

magneto-centrifugal instability (close to disk)

\[ f = f_0 \chi + \frac{1}{2} f''_0 \chi^2 + \ldots, \]

\[ \xi = 1 + \xi' \chi + \frac{1}{2} \xi'' \chi^2 + \ldots, \]

where

\[ f_0 = \frac{(3 \xi'^2 - 1)^{1/2}}{[k^2 (\lambda - 1)^2 + (1 + \xi'')]}^{1/2}, \]

\[ f''_0 = -9 \kappa \xi'^2 - \frac{1}{4} [3 k^2 (\lambda - 9) \lambda (\lambda - 1) + 5 (1 + \xi'')] \xi f_0 + \kappa (2 + 3 \xi'^2) f_0^2 + 2 \xi' f_0^3 + 2 k f_0^4, \]

\[ \xi'^2 = -1 - \frac{1}{4} (1 + \xi'') + \kappa (1 - 3 \xi'^2) \xi f_0 - \frac{1}{4} \kappa^2 (\lambda - 9) (\lambda - 1). \]

regularity condition at Alfvén point

\[ m S^2 (2 m^2 \chi (\xi^2 - \lambda) J - (m - 1) (5/4 T + \xi^2 - S) \chi (\chi + \xi')) \]

\[ m' = \frac{\xi T (m - 1)}{(t - 1)} \left[ \chi (\xi^2 + T) - f^2 (\chi + \xi') \right] J. \]

\[ \alpha \xi + \beta \xi'' + \gamma = 0, \]

where

\[ \alpha = \xi (m f^2 J - \xi T) \]

\[ \beta = \chi m (m - 1) \xi f^2 \]

\[ \gamma = m \left[ \frac{5}{4} \xi T \xi' - (m - 1) f^2 D \xi' + \chi m \xi J S^3 + (1 - S^3) \xi \xi' - \chi \xi^2 \xi' \right], \]

with the differential form of the quartic for \( f(\chi) \), equation (2.12),

\[ \delta m' + \varepsilon \xi'' + \theta = 0, \]

where

\[ \delta = (m - 1) (m f^2 U - T) \xi J \]

\[ \varepsilon = m (m - 1)^2 (\chi + \xi') \xi f^2 \]

\[ \theta = 2 m^3 (\xi^2 - \lambda) J \xi' - m (m - 1)^2 J \left[ T \xi' + (1 - S^3) \xi \xi' - \chi \xi S^2 \right], \]

to obtain a second-order differential equation for \( \xi(\chi) \),

\[ \xi f^2 T (m - 1)^2 S^2 (m - 1)^2 \left[ \xi T + (n - m - 1) f^2 J \right] T \]

\[ + m (m - 1) \left[ (t - 1) \xi T S - \xi f^2 (\chi + \xi') \left( \xi \xi' - \chi \xi S^2 - \chi S^3 \right) \right] \]

\[ + (m - 1) \left[ m^2 (\xi \xi - m f^2 J) - S (n - 1) \xi T^2 + 2 m^3 (\xi^2 - \lambda) (m f^2 J - \xi T) \right] = 0 \]

where

\[ \frac{4 \pi \rho u T}{B^2} \]

\[ t = \frac{4 \pi \rho u T}{B^2} \]

\[ n = \frac{4 \pi \rho (u_T^2 + v_T^2)}{B^2} \]

\[ = \kappa \xi f^3 J U / T. \]
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Jet formation in low mass stars

Model szenarios for protostellar jet formation:

- Star-disk magnetosphere: Camenzind (1990)
- X-wind: Shu et al. (1994)

Common properties:
- consider MHD
- main jet component is launched from disk

Differences in model geometry:
- impact / interrelation of / between star / disk / magnetic field

Recent literature:
see reviews of the Protostar & Planets V conference 2005:
Bouvier et al.: “Magnetospheric accretion in Classical T Tauri stars”
Shang et al.: “Jets & bipolar outflows from young stars: theory and observational test”
Pudritz et al.: “Disk winds, jets, and outflows: theoretical and computational foundations”
Stellar jets as collimated disk winds:

- magneto-centrifugally driven disk winds (arise from molecular disk)
- two-component (ions, neutrals) treatment of MHD
- essential parameter $\beta = T_{ni} / T_{fl}$
  $T_{ni} \sim 1000$ yrs; ion-neutrals collision time
  $T_{fl} \sim 10000$ yrs; flow dynamical time
- strong matter-field coupling for $\beta << 1$, implying ionisation degrees $\chi > 10^{-7}$
- wind removes angular momentum from disk, carries it out to large distances

Pelletier & Pudritz (1992):
- application to MHD jets
- solution to the MHD equations for separate outflow regimes ($B, v, \rho, ..$); see BP82 above
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Jet formation in low mass stars

Stellar jets as collimated disk winds:

MHD simulations:

-> first proof of jet MHD self-collimation:
   Ouyed & Pudritz (1997)
   Ustyugova et al. (1996)

-> 3D MHD simulations prove jet stability:
   Ouyed et al. (2003)

-> more simulations, adding:
   - magnetic diffusivity
   - time-dependent mass loss
   - diff. mass loss profiles
   - central dipolar field
   - disk evolution
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Jet formation in low mass stars

Stellar jets as collimated disk winds:

MHD simulations:
-> proof of jet MHD self-collimation:

Colors: mass density, Lines: magnetic field lines; movie @ www.mpio.de/homes/fendt/research.html

Numerical simulation following Ouyed & Pudritz (1997) model setup:
- Keplerian disk w/ given disk wind mass loss rate and disk magnetic field profile
- initial condition: hydrostatic state, force-free magnetic field (Lorentz force = 0)
Jet formation in low mass stars


-> stellar dipole magnetosphere disturbed by accretion pressure
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Jet formation in low mass stars

Star-disk-wind magnetosphere:

-> corotation radius:
\[ R_{\text{cor}} = \left( \frac{GM_\ast}{\Omega_\ast^2} \right)^{1/3} \]

-> stellar wind + disk wind
from \( R > R_{\text{cor}} \) (super Keplerian rotation)

-> accretion along dipole field:
  infall from \( R < R_{\text{cor}} \), proven by observed stellar hot spots

-> disk dynamic pressure:
\[ P(R) = \frac{1}{I_{N+1}} \frac{\dot{M}}{4\pi \alpha R^2} \left( \frac{GM_\ast}{R} \right)^{1/2} \left( \frac{H}{R} \right)^{-1} \]

-> inner disk radius defined by
  - accretion pressure – magnetic field pressure equilibrium (Camenzind 1990)
  - angular momentum removal by stellar field (Königl 1991)

\[ R_{\text{in}} = 2.4 \ R_\ast \left( \frac{\alpha I_{N+1}}{2} \right)^{2/7} \left( \frac{B_{\ast,3} R_\ast}{3R_\odot} \right)^{4/7} \left( \frac{H}{M_{\text{-7}} R} \right)^{2/7} \left( \frac{R_\ast c^2}{10^6 GM_\ast} \right)^{1/7} \]
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Jet formation in low mass stars

**X-wind:** Shu et al. (1994a,b,c; 1995a,b):

- derived from model (Shu et al. 1988) of rapidly rotating young star
  (at equatorial break-up speed)
- **X-point:** X- radius = corotation radius
  - magnetic flux & energy concentration
  - energy released into X-wind
    (magneto-centrifugally) which becomes collimated into jets
  - X-point corresponds to Lagrange point in Roche lobes

- recent change of view (Shang et al. 2007):
  
  “... X-winds and disk winds are not mutually exclusive. Both are driven magnetocentrifugally from open field lines anchored on rapidly rotating circumstellar disks. Their main distinction lies in where the field lines are anchored: near the radius of magnetospheric truncation on the disk – the X-point – for X-winds and over a wider range in disk radii for disk winds.”

MHD solution for sub-Alfvenic X-wind
(Shu et al. 1994c)
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Jet formation in low mass stars

MHD simulations of star-disk interaction:

Example 1: Miller & Stone (1997)

-> dipole inflates,
   potentially being broken-up
-> sporadic outflow activity, no "jet"
-> disk structure included in simulation
   - disk structure becomes instable
   - short lifetime of simulations
     ~ < 10 inner orbits
     (disk model too simple)

-> Additional literature:
   Hayashi etal. 1996
   Goodson etal 1997
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Jet formation in low mass stars

MHD simulations of star-disk interaction:

Example 2: Fendt & Elstner (2000): long time evolution essential

movie @ www.mpia.de/homes/fendt/research.html

-> disk structure not included in simulation  
-> long-term evolution ~2500 rotations 
-> dipole inflates, breaks up (differential rot.) 
-> steady state outflow activity, two components: disk & stellar wind 
-> no collimation: dipole field too weak, does not provide net electric current
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Jet formation in low mass stars

MHD simulations of star-disk interaction:

Example 3: Romanova et al. (2003, 2004)

- dipolar accretion in 2.5D & 3D
- inclined dipole (diff. offset angle)
- stationary disk structure (high numerical viscosity)
- disk truncated, complex magnetospheric flow (supersonic)
- corotation radius 1.5 x truncation radius
- “disk locking”; star-disk angular momentumbalance not yet resolved:
  a.m. gain by accretion?
  a.m. loss by magnetic field?
  yet both net stellar spin-up & spin-down feasible

Additional literature:
Romanova group (1997-2008)
Küker et al. (2003)
Matt & Pudritz (2004-2007)
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Jet formation in low mass stars

The question of magnetic field origin:

1) Magnetic field of young star:
   Stellar dipole: dynamo mechanism:
   \[ \alpha \Omega - \text{dynamo (?:) } \]
   \[ \alpha: \text{turbulence: } B_{\phi} \rightarrow B_{\rho} \]
   \[ \Omega: \text{differential rotation: } B_{\rho} \rightarrow B_{\phi} \]

   -> needed: convective layer:
   low mass YSO are thought to be fully convective (on Hayashi track)

   -> dynamo estimates for YSO parameters
   -> 1 kG saturation field
   -> dynamo time scale ~ some years

   -> non-axisymmetric modes prefered in case of disk-less stars (Kueker et al. 1999)

   -> dipole mode most stable & long living

   -> observational indication for inclined dipolar fields (Bouvier et al 2007)
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Jet formation in low mass stars

The question of magnetic field origin:

2) Disk magnetic field: (see disk lecture)

   a) disk dynamo (see above): \( \mu G \) (seed) \( \rightarrow \) G (disk)

   b) disk advection of interstellar field: \( \mu G \) (ISM) \( \rightarrow \) G (disk)

\[ \rightarrow \text{upper limit: disk equipartition field strength:} \]
\[ \text{disk gas pressure } \sim \text{ disk magnetic pressure:} \]
\[ \rightarrow B_\phi < 50 \text{ G } \rightarrow B_z \sim 0.1 B_\phi \]

\[ \rightarrow \text{magnetic flux from protostellar disk: } \Psi \sim 10^{25} \text{ G cm}^2, \]
\[ \text{sufficient to power observed jets/outflows} \]

\[ \rightarrow \text{disk turbulence provided by magneto-rotational instability} \]
(Balbus & Hawley 1991)

\[ \rightarrow \text{differential rotation by Keplerian orbits} \]
Outflows & Jets: Theory & Observations

Jet formation in low mass stars

Summary: Essential parameters / variables:

- stellar radius: ~3 solar radii
  rotation period: 1 - 10 days
  magnetic field: 1 kG

- accretion disk: Keplerian rotation, accretion rate $10^{-6}$ Mo/yr
  magnetic field: unknown, ~10 G estimate from equipartition

- co-rotation radius: ~4 stellar radii
- truncation radius, inner disk radius: ~4 stellar radii
- Alfven radius: lever arm for torque: ~10 foot point radii

- slow / fast magnetosonic point:
  radius where wind/jet velocity reaches slow / fast magnetosonic speed

- jet: velocity 200-500 km/s, opening angle ~0°,
  mass flow rate $10^{-8}$ Mo/yr
Standard model of jet formation

Hypothesis: common model of jet formation:

However: understanding of different jet/outflow sources not yet complete:

**Low mass young stars:** standard model best investigated -> “approved”;
- detailed model geometry under debate: density contrast to ISM, magnetic field structure/origin
- time scale problem: Keplerian time scale of inner disk (days) << distance between knots (10-100 yrs)
- MHD simulations ongoing (all 5 questions)

**High mass young stars:** no model yet:

**Old stars (PN, pulsars):** are there jets??

**AGNs:** unified model of AGN:

**Micro-quasars:** relativistic jets (synchrotron):

**GRBs:** collapsing star produces outflow; SN connection approved
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