Winds, jets and outflows

AST 541 Seminar - Fall 2012

Ai-Lei Sun

Outline

- Terminology
- Observation
- Theories
  - X-wind model
  - Disk-wind model (simulation)
- Summary

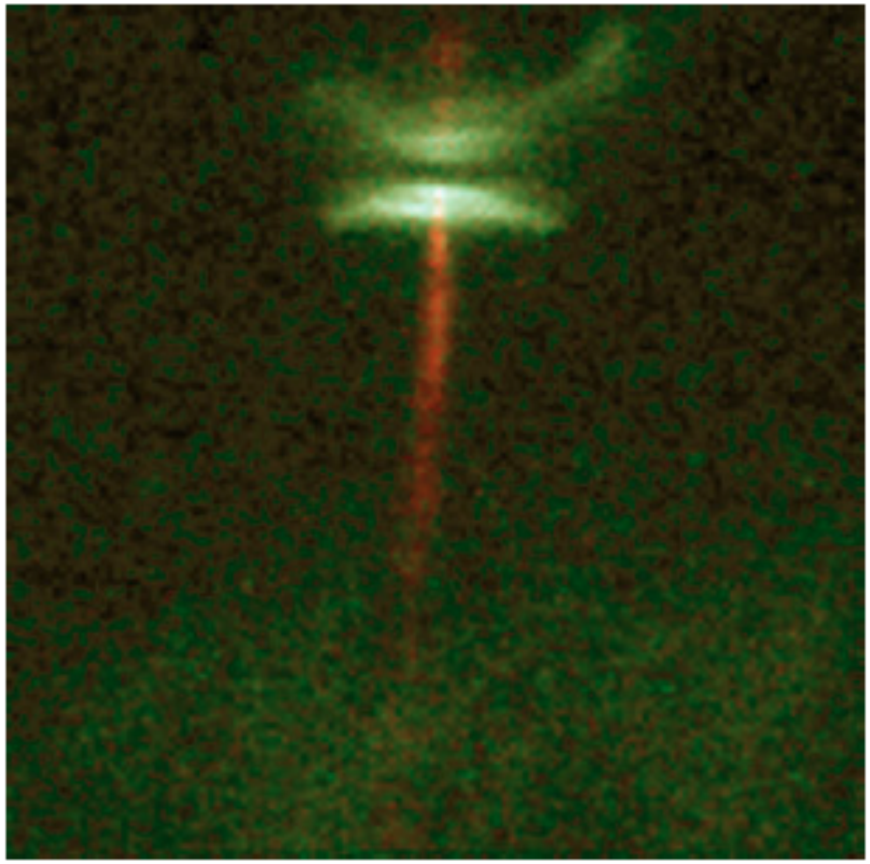
Terminology

- Wind
  - Named from the theory side
  - Mostly bipolar and collimated outflow launched from the disk
  - Ex: X-wind, disk-wind.

- Jet
  - Named from the observation side
  - Bipolar highly collimated outflow, or a series of knots along the polar axis – HH objects, observed in optical lines.
  - High velocity and small scale, corresponding to the inner region of the wind
    v ~ 100 – 300 km/s on 100 AU scale

- Outflow
  - Interstellar medium blown outward by the wind
  - Observed by radio molecule lines, ex: CO.
  - Slower, and on larger scale
    10 – 20 km/s on parsec scale

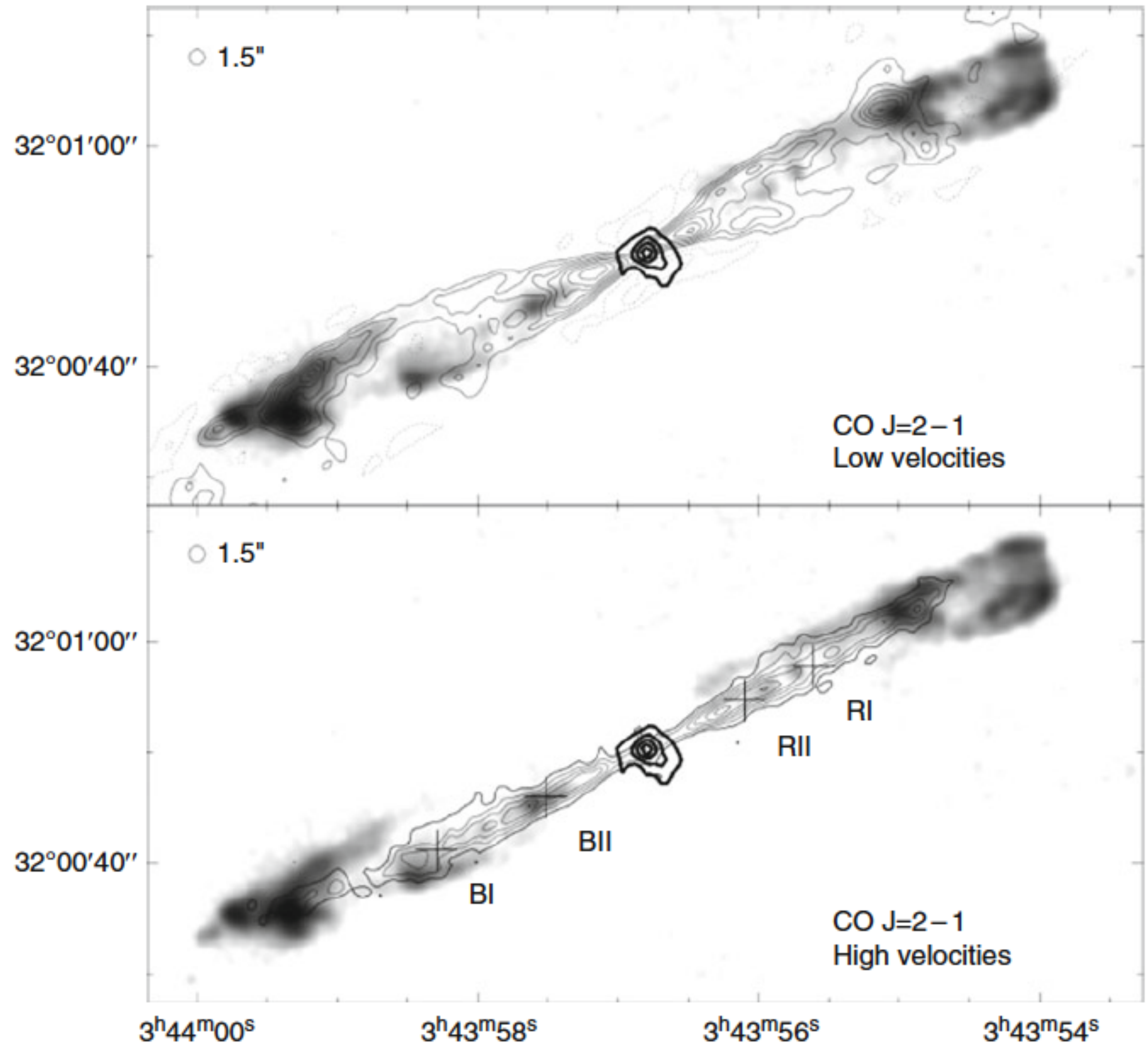
Observational examples of Jet



HH30: edge-on disk, bipolar jet, and scattered light (bright *regions)* from the obscured central star.

NASA, Space Telescope Science Institute, ESA, Bodenheirmer

Molecular Outflow



F. Gueth and S. Guilloteau, 1999

Evidence of Jet Herbig-Haro Objects

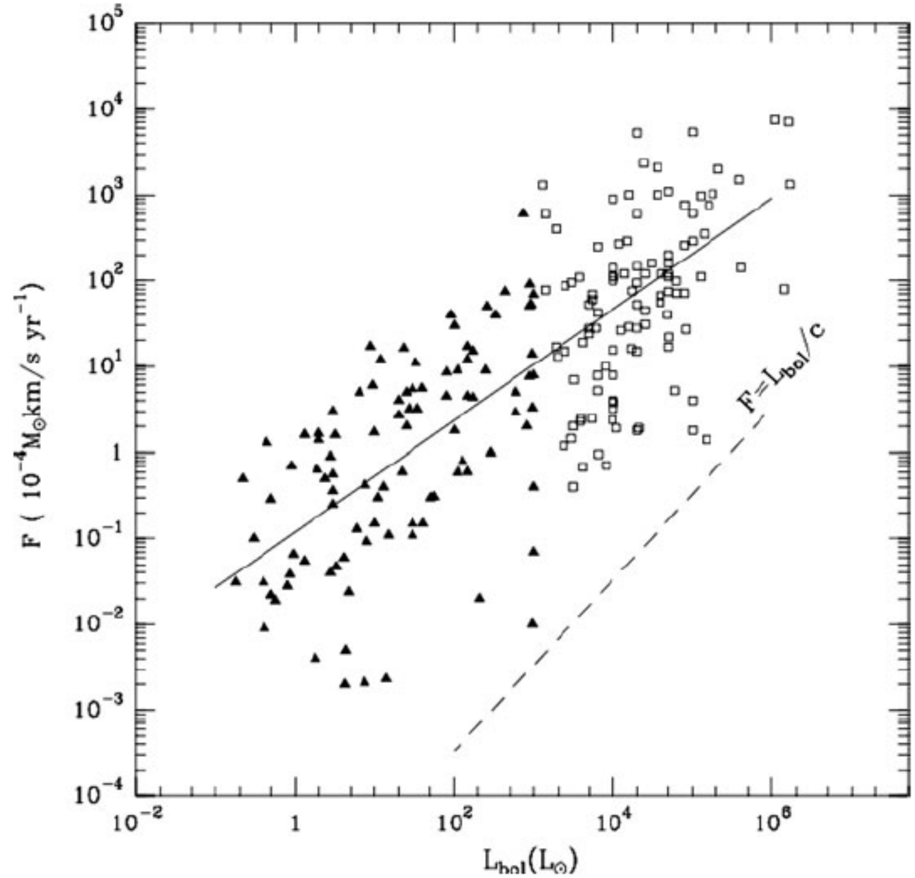
- HH 34 Jet; Slow movie(Color and B&W, 0.7Mb)
- 34 Bow; Slow movie (Color, 3.8Mb)
- Herbig-Haro objects
  - The excitation of the gas is caused by shock waves while jet collides with ISM or other jet materials moving at lower speed.
  - Here Red is [S II], and green is H-alpha line emission.

Hartigan et al.

Observational evidence of connection between outflow and disk / accretion

Radiation is insufficient in driving outflow as its momentum flux is 2 magnitudes lower

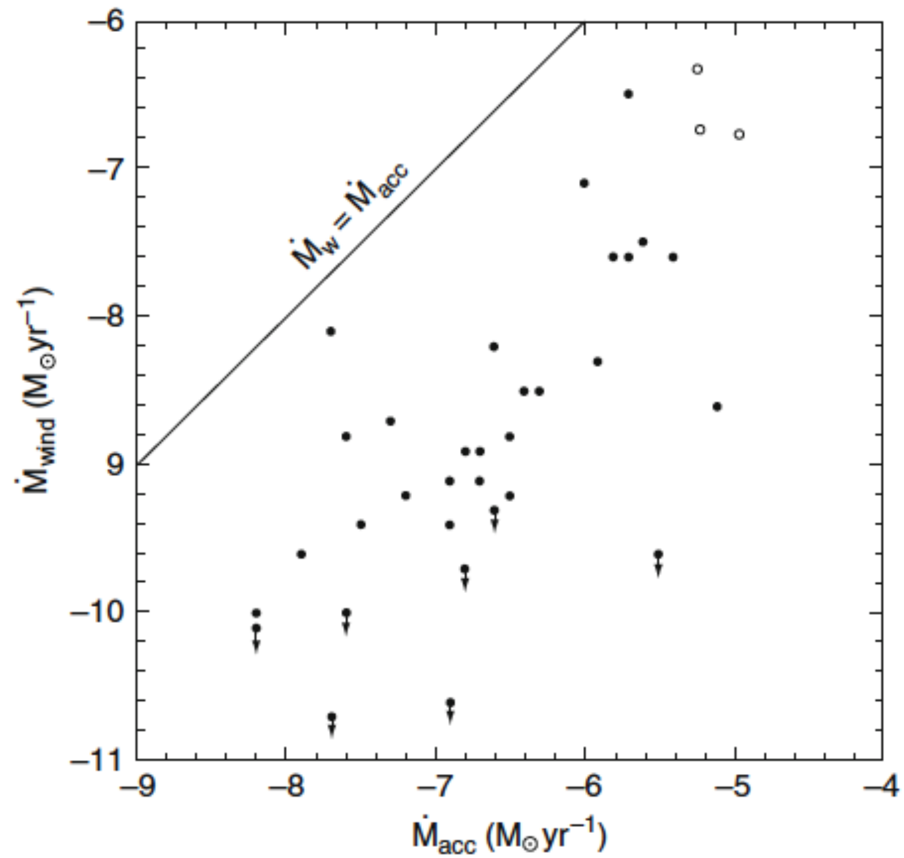
Correlation between **outflow momentum transfer rate** and **bolometric luminosity** suggests outflow is related to accretion



Y. Wu et al., 2004

Observational evidence of connection between outflow and disk / accretion

dM_{acc}/dt is an upper limit of dM_w/dt



Rate of disk accretion onto T Tauri stars plotted against rate of mass loss in the outflow

Hartigan et al. 1995

Goals for wind theory

- Should predict wind/high velocity jet
- Should explain the connection between accretion and outflow
- Should be able to cover a wide range of stellar mass
- Solve the angular momentum problem of star formation

- All the theory are using magnetic field, and are classified by where the field originates
  - Either external and through the disk
  - Or generated in the star and interacting with disk
  - Generated in the disk
- MHD equations

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) &= 0 \\
\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v}\right) + \nabla p + \rho \nabla \Phi - \frac{\mathbf{j} \times \mathbf{B}}{c} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) &= 0 \\
\rho\left(\frac{\partial e}{\partial t} + (\mathbf{v}.\nabla) e\right) + p(\nabla.\mathbf{v}) &= 0 \\
\nabla.\mathbf{B} &= 0
\end{aligned}$$

General Predictions for MHD Flow

- From conservation of angular momentum

  Specific angular momentum $l(a) = \Omega_0 r_A^2 = (r_A/r_0)^2 l_0$

  - A particle in the flow can carry away angular momentum ten times of a particle in the disk

- From conservation of Energy

  Terminal speed of the wind $v_\infty \simeq 2^{1/2}\Omega_0 r_A = (r_A/r_0)v_{esc,0}$

  - Terminal speed is larger than the escape velocity
  - Wind velocity is higher in small radius
  - The velocity scale with the potential. Therefore, it can be universal.

Pudritz et al., 2006

General Predictions for MHD Flow

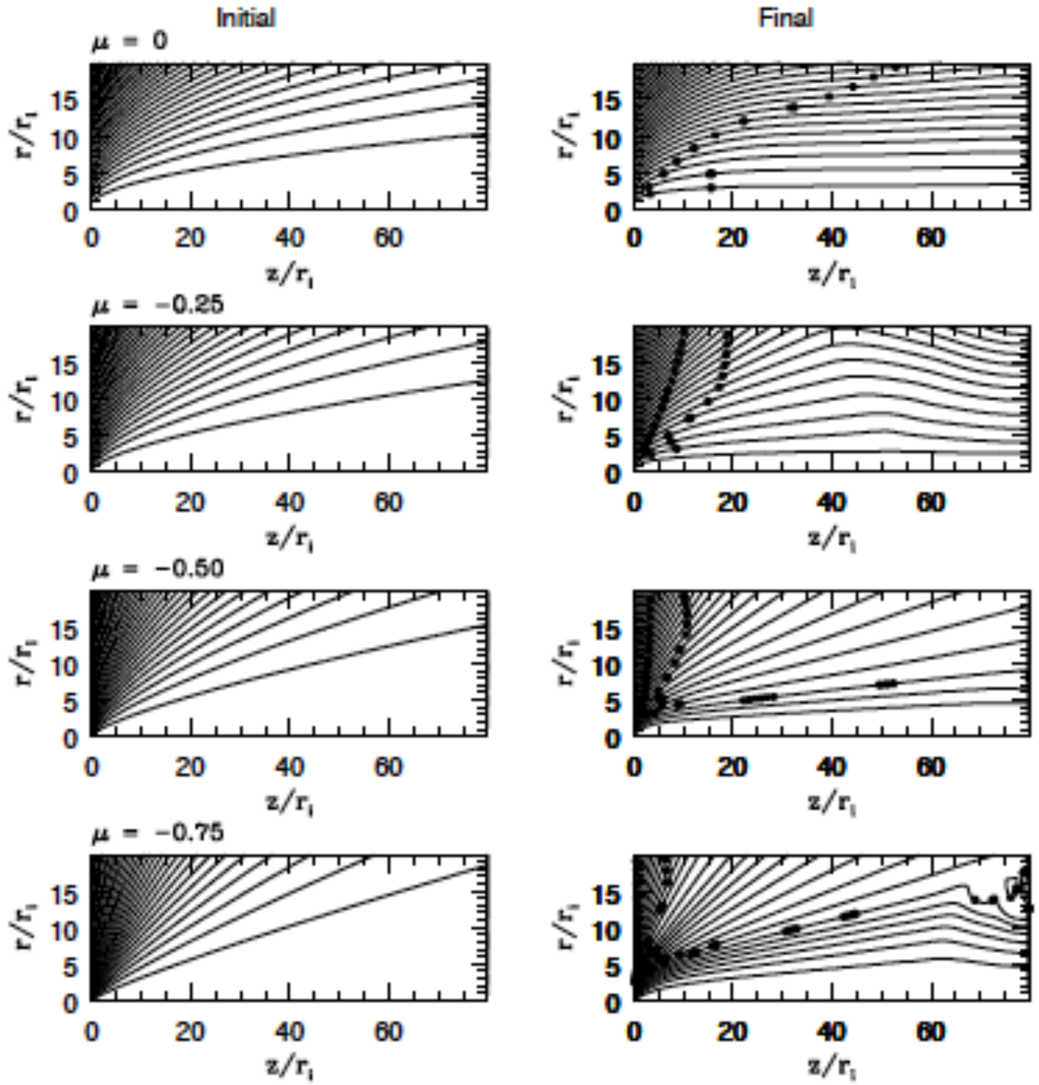
- Mass outflow rate is related to disk accretion rate
  - Via the relationships $\dot{M}_a \simeq (r_A/r_0)^2 \dot{M}_w$

  outflow <-> poloidal field <-> toroidal field <-> rotation of disk

Koenigl & Pudritz. 2000

- Mass load has effect on jet collimation
  - Jet can be collimated by toroidal field $f_r = -J_z B_\phi$
  - Collimation depends on radial distribution of B_ϕ
  - The more centrally concentrated the field strength is, the less collimated the wind is.

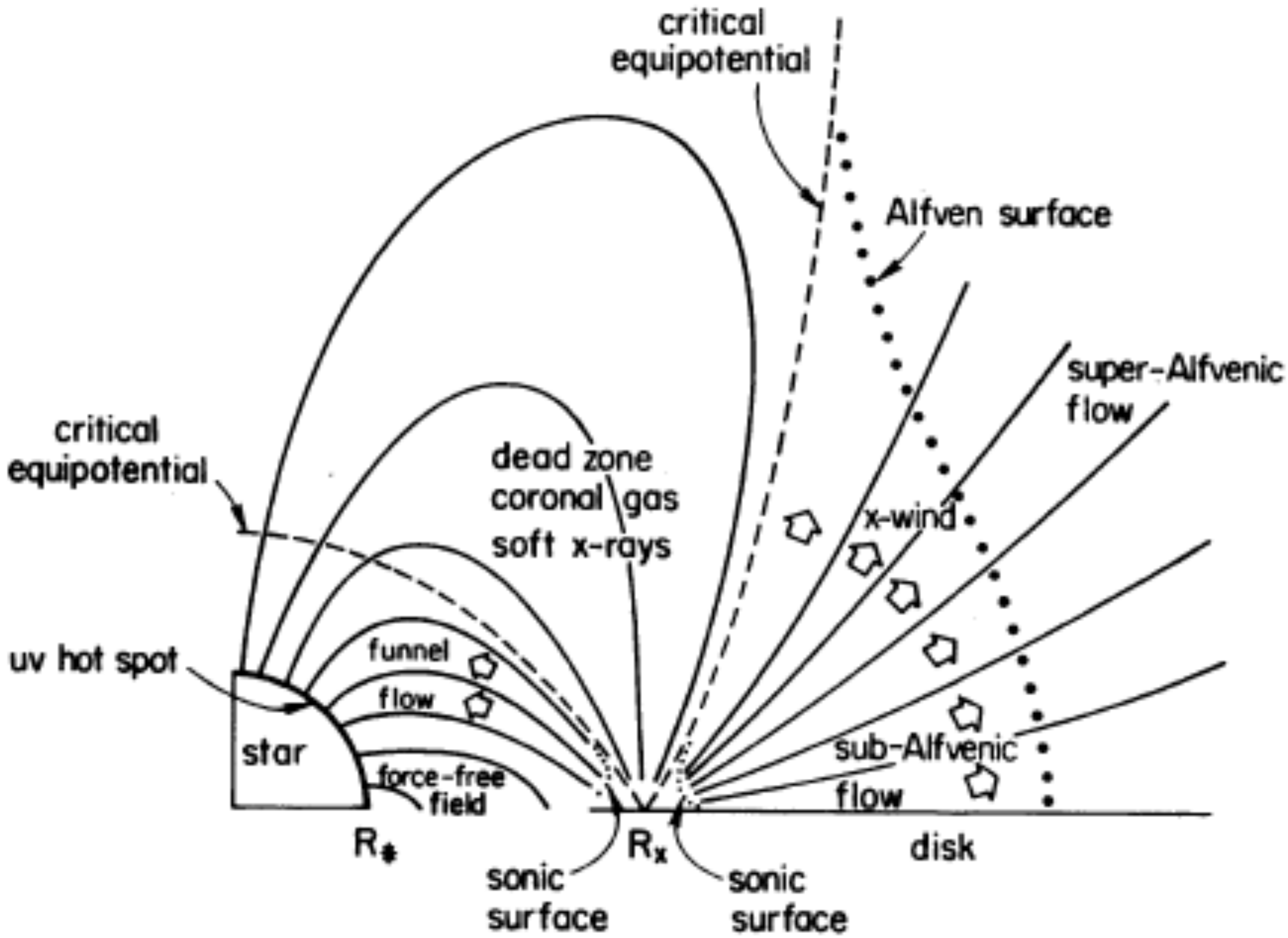
$$B_z(r_0, 0) \propto r_0^{\mu - 1}$$



– The more centrally concentrated the field strength is, the less collimated the wind is.

Pudritz et al., 2006

X-wind model [Shu et al. 1994]



X-wind model for typical T Tauri Star (Shu 1994)

X-wind model

Inside the corotating radius (T-region)

- The dipole magnetic field of the star is connected with the inner part of the disk
  - Because of shielding current on the surface of the disk, the magnetic field of the star cannot penetrate through the disk, except for the inner edge of the disk. For those magnetic lines not to be wrapped up, the inner edge of the disk and the star must be corotating.
  - If there is disk accretion and magnetic diffusivity, then the inner edge of the disk R_t and the corotating radius R_x will differ by a finite amount and become a region. Here, the dominating magnetic field force the materials to be corotating through the whole region.

Consequences

- Materials between R_t and R_x flows inward along the field line and accrete onto the star. The disk is truncated here.
  - The materials are forced to rotate in sub-Keplerian velocity
  - Field is dominating
- The trailing spiral of magnetic field transfers angular momentum from the star to the disk

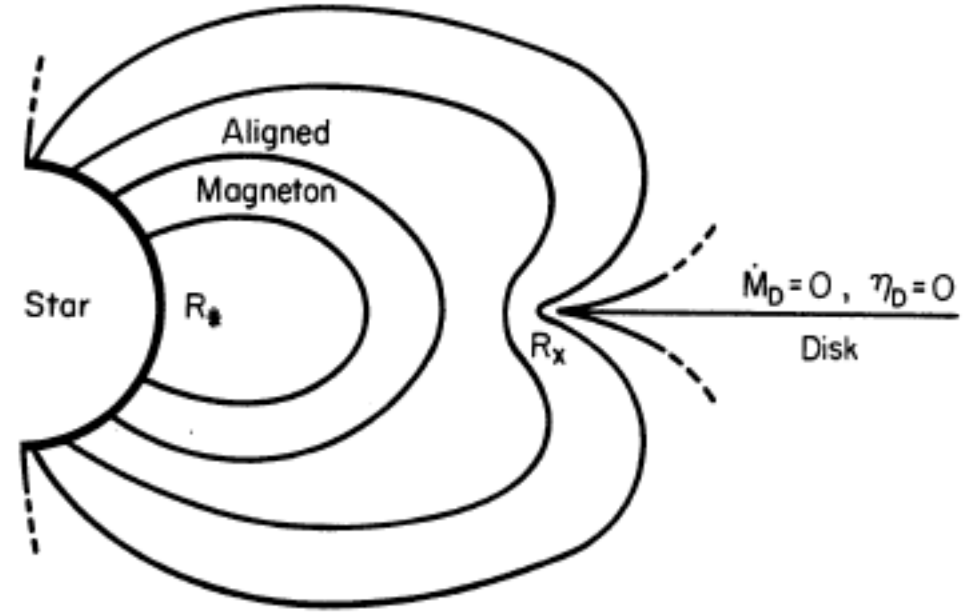

Aligned
Magneton
Star
R_*
$\dot{M}_D = 0$, $\eta_D = 0$
R_x
Disk

FIG. 2*a*

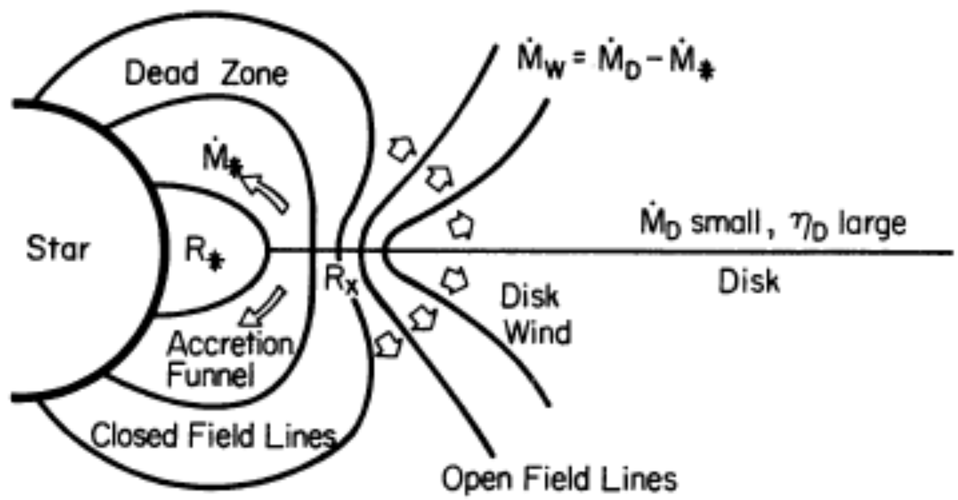

Dead Zone
$\dot{M}_W = \dot{M}_D - \dot{M}_*$
$\dot{M}_*$
Star
R_*
$\dot{M}_D$ small , η_D large
R_x
Disk
Disk
Wind
Accretion
Funnel
Closed Field Lines
Open Field Lines

FIG. 2*b*

X-wind model

Slightly outside the corotating radius (X-region)

- The magnetic field lines are open and bends outward
  - They are anchored in place because of the inward motion of the disk accretion
  - The material on the surface of the disk rotates at super-Keplerian velocity and is accelerated centrifugally outward, dragging the field lines outward as well.
  - Lines which are originally closed can be open by the ram pressure of the out going gas

  Consequence
  - Wind !!!
  - The trailing spiral of the magnetic lines transfer momentum from this part of the disk out
  - The material on the midplane of the disk can still accrete inward because of high magnetic diffusivity

- Between the X-region and T-region, angular momentum is transferred outward mainly by the internal mechanism in the disk, ex: viscosity.

X-wind model

What can X-wind explain

- Interaction between star and disk
  - Slow rotation of T Tauri stars
- Wind related to disk accretion
  - $M_W = f\ M_D$ of the same order
- Magnetic field is centrally concentrated
  - Radial flow and cylindrical collimation of density

- Problems - being an ideal model
  - The magnetic field of star in real case may not be as concentrated at corotating radius as assumed here
  - The observed velocity gradient in winds suggest that winds may originate from a range of radii

Disk-wind model (simulation)

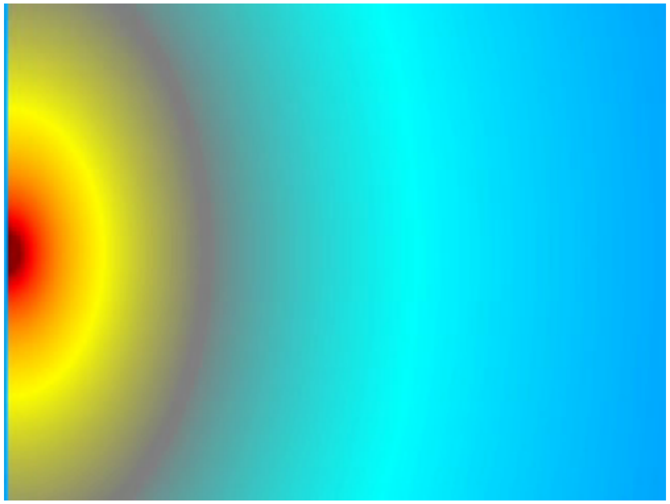
- Simulation can help us to understand
  - Time variability
  - Jet stability
  - Jet morphology
  - And how do they depends on disk / field configurations

2-D Simulation

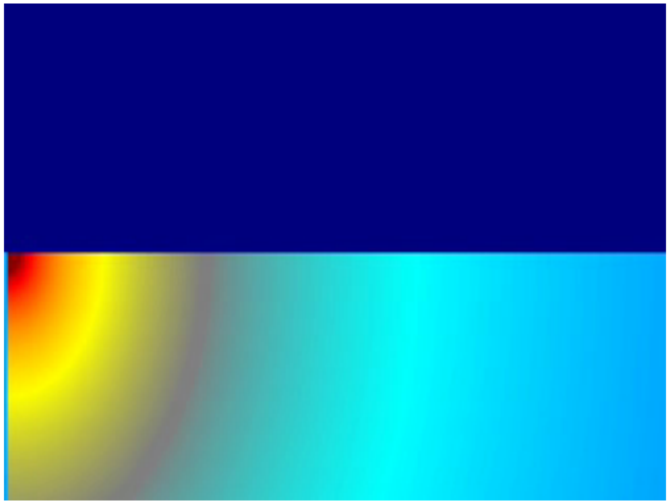
Ouyed and Pudritz, 1997b

Episodic Outflows-

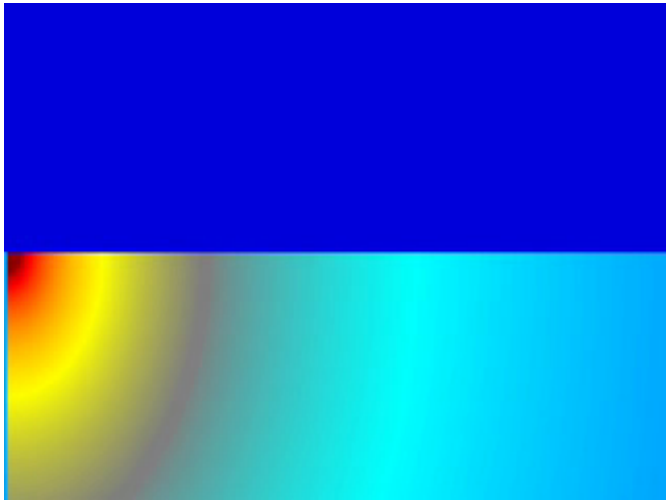
The periodic knots are generated by strong troidal field through MHD shock



Density



Toroidal Field

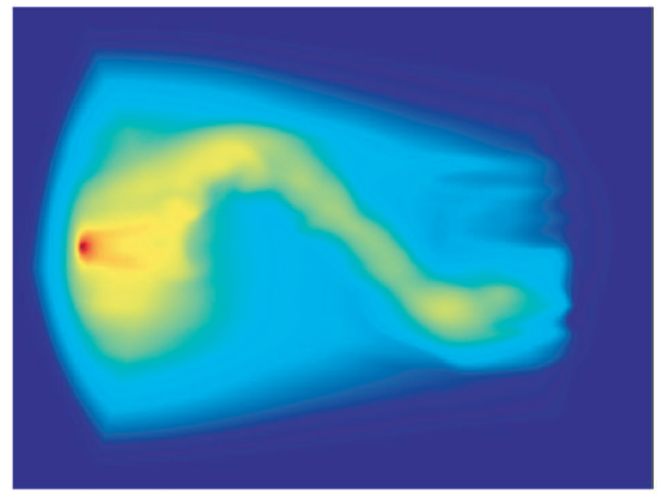


Axial-Velocity

3D Simulation

Oyued, Clarke, & Pudritz 2003

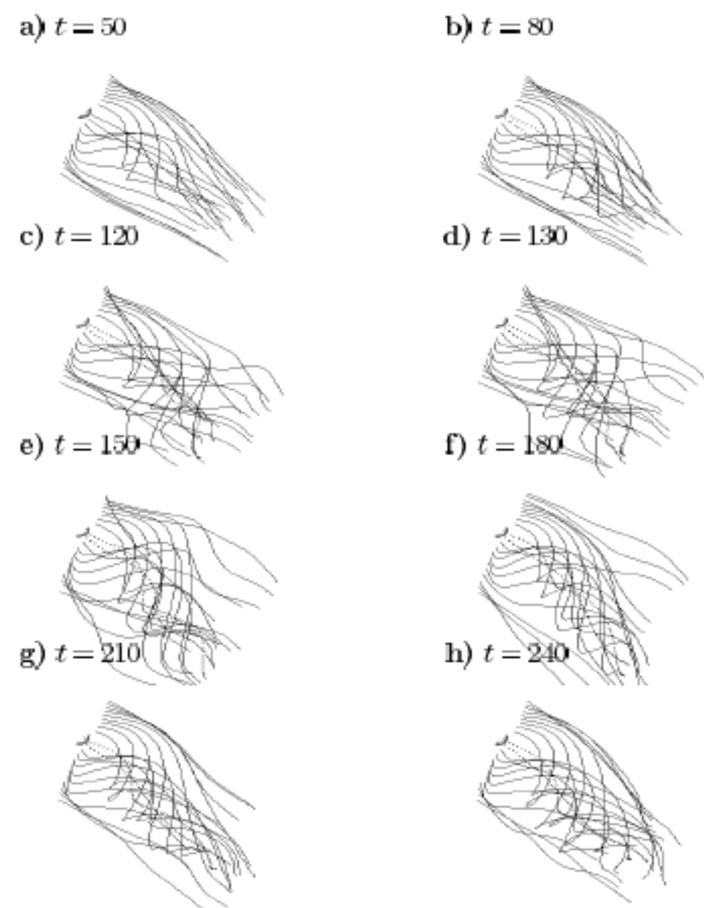
- Results
  - Jets can have either corkskew or wobbling morphology depending on the perturbation
  - Although Kelvin-Helmholtz plasma instability exists in this physical regime, the jet can still survive in the long term if the Alfvenic-Mach number is of order unity



3D Simulation

Oyued, Clarke, & Pudritz 2003

- Results
  - Jets can have either corkskew or wobbling morphology depending on the perturbation
  - Although Kelvin-Helmholtz plasma instability exists in this physical regime, the jet can still survive in the long term if the Alfvenic-Mach number is of order unity



What have we learned from simulations

- Simulations confirms that jets are megnetocentrifugal disk winds and are collimated by toroidal fields.
- Jet can be stationary or episodic depending on mass loading from the accretion disk (controversy).
- Jet can have different morphologies
  - ex: wobbling, cork-screw, etc.
- Both stellar and disk magnetic field can exit in real physical case
- Wind models can be constrained by molecular outflow observation. Ex: momentum flux distribution.

Conclusion

- Winds are driven by magnetocentrifugal force and originates from the circum-stellar disk
- Angular momentum can be transferred from star to disk and from disk to wind via the magnetic field and particles following the magnetic field
- Winds can be static or episodic with a wide range of collimation and morphology
- The wind helps to determine the mass of the star

References

- Peter Bodenheimer, *Principles of star formation*, Springer , 2011
- Shu, Najita, Ostriker , and Wilkin, ApJ 429:781-796, 1994
- Pudritz, Ouyes, Fendt, and Brandenburg, 2006
- Ouyed, Clarke, and Pudritz, ApJ, 582:292–319, 2003
- Ouyed and Pudritz, ApJ, 484:794-809, 1997
- Ostriker, ApJ 486:291 – 306, 1997