Simulations of Relativistic Jet Formation In Microquasars

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Talk Outline

- Introduction: observed Lorentz factors
- Review of steady state simulations
- Pseudo-relativistic simulations and the "magnetic switch"
- General relativistic jet production and rotating black holes
- Possible scenarios for Microquasars

Acknowledgements

- Collaborators
  - General Relativistic simulations: S. Koide (Toyama University), K. Shibata, T. Kudoh (National Astron. Obs, Japan)
  - Pseudo-relativistic simulations: D. Payne (Intel), K. Lind (Silicon Graphics), S. Edgington (Caltech), P. Godon (Space Telescope)

Observed Lorentz Factors

- Component proper motions: $\Gamma \equiv (1 - v^2/c^2)^{-1/2} = 5\text{-}10$

  (NOTE: this may measure a pattern speed only)

- Brightness temperature measurements of Doppler boosting:

  $$\Gamma \geq 0.5\ T_{B,\text{measured}} / T_{B.\ \text{rest frame}}$$

  - $T_{B,\ \text{rest frame}} \approx 10^{11}$ K for an equipartition synchrotron plasma
  - Some measured brightness temperatures and inferred Lorentz factors:
    - Ground Radio VLBI: $T_{B,\text{measured}} \geq 10^{12}$ K $\Rightarrow$
    - Space VLBI (VSOP): $T_{B,\text{measured}} \geq 7 \times 10^{12}$ K $\Rightarrow$
    - Intra-day variable sources: $T_{B,\text{estimated}} \sim 5 \times 10^{14}$ K (?) $\Rightarrow$ (?)

Conclusions

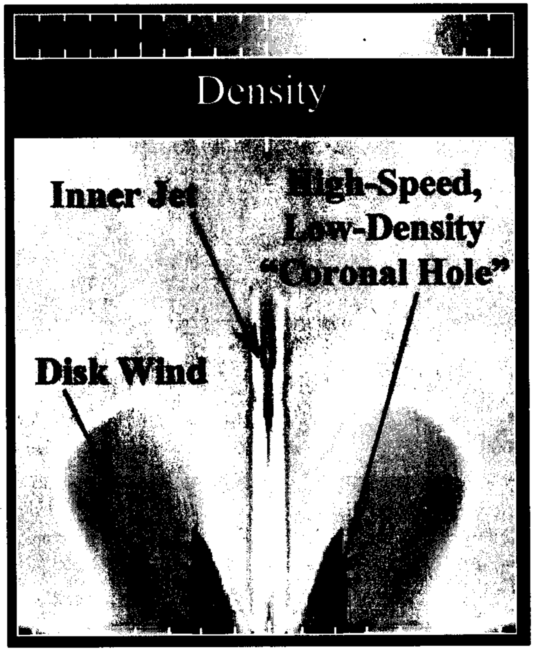
- The magnetically-driven outflow has two main components:
  - A slowly-collimating wind from the surface of the accretion disk
  - A highly-collimated jet from the inner edge of the disk or torus
- Both types of outflow are subject to “magnetic switching”:

  There exists a critical MHD power $L_{crit} \equiv E_{escape}/\tau_{free\text{-}fall}$ (analogous to the Eddington limit) such that
  - When the MHD power in the rotating magnetic field $L_{MHD} < L_{crit}$, gravity is ***im***portant, and the jet/wind speed is limited to $V_{jet} \sim V_{escape}$

$L_{MHD} > L_{crit}$

$$\dot{M} V_{jet}^2 \sim L_{MHD}$$

$$\Gamma_{jet} \dot{M} c^2 \sim L_{MHD}$$

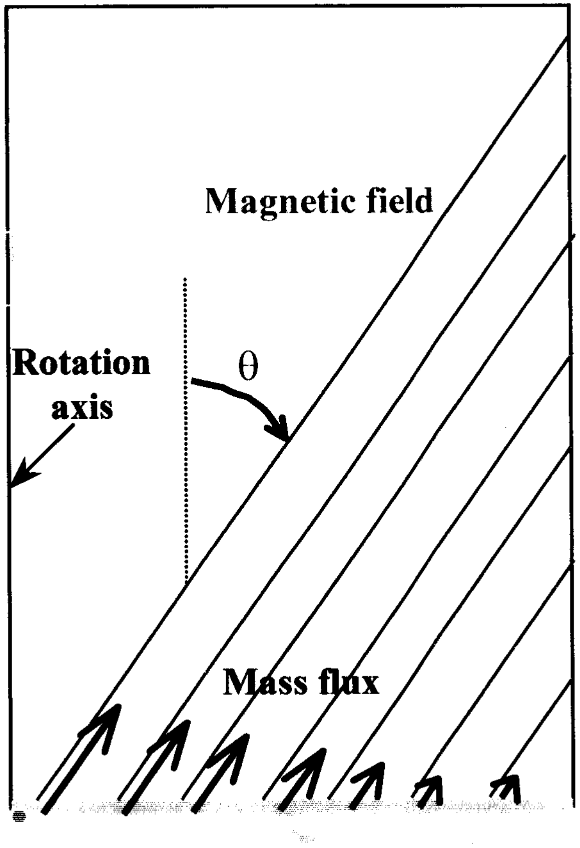


Conclusions (continued)

- When the accreting object is a <u>rotating</u> black hole:
  - The jet is accelerated from the "frame-dragged" accreting matter inside the ergosphere
  - Recall:
    - The horizon is much smaller than one Schwarzschild radius (GM/c^2 for maximal Kerr)
    - All matter in the region $R < 2\ GM/c^2$ (the "ergosphere") must rotate with the black hole
  - The strongest and fastest jets occur when:
    - The black hole is rotating rapidly
    - The accreting material plunges rapidly into the ergosphere
      - ***E.g.*, when the accretion is an Advection-Dominated Accretion Flow [ADAF] or**
      - ***E.g.*, when the accretion disk counter-rotates relative to the black hole**

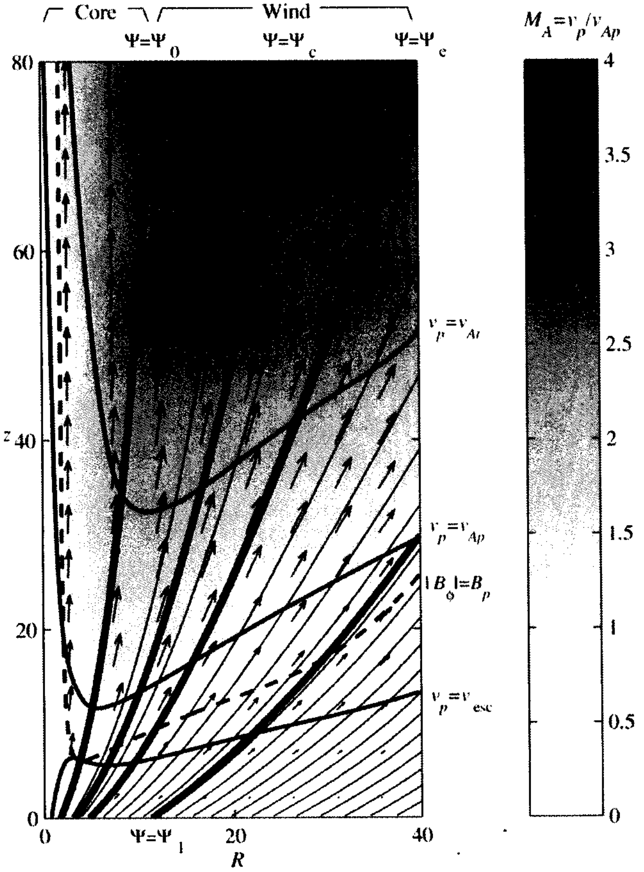
Review of Steady State Simulations

- Some numerical simulations have attempted to reproduce the Blandford & Payne solutions (Ustyugova et al. 1995, 1999; Ouyed et al. 1997; Krasnopolsky et al. 1999)
-
  - An infinitely-thin accretion R=0
  - A central mass gravitational potential with a small "smoothing radius"
  - Keplerian rotation
  - Fixed vertical magnetic field B_Z
  - Fixed mass flux along the field lines
  - : the following quantities on the boundary are allowed to : radial B_R and toroidal B_φ magnetic field strength, and radial velocity V_R



Review of Steady State Simulations (continued)

- (e.g., Krasnopolsky, Li, & Blandford 1999):
  - Simulations run out to late times to achieve a steady state
  - Results similar to Blandford & Payne's self-similar solutions are produced
  - For magnetically-driven outflow, the magnetic field polar angle ($\tan\theta = B_R/B_Z$) must be larger than $\theta > 30°$ at the disk boundary
  - Flow accelerates smoothly, reaching escape velocity and then the local Alfvén speed(s)
  - Collimation is slow but steady, reaching a jet-like state far away from the disk
  - Outflow speed is of order the escape velocity at the base of the flow



Pseudo-Relativistic Simulations of Black Hole Accretion Disks

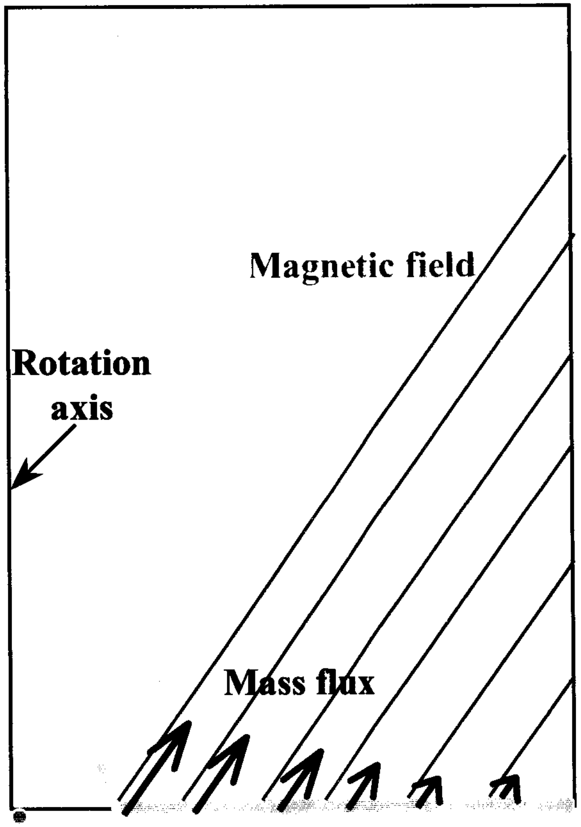
- When the disk coronal material is not a relativistic gas ($c_{sound} < c$; $V_{Alfvén} < c$), the non-relativistic MHD equations are nearly identical to the relativistic ones, IF we replace the velocity V with the proper velocity U

$$V \rightarrow U = \Gamma V$$

- In these simulations, 1

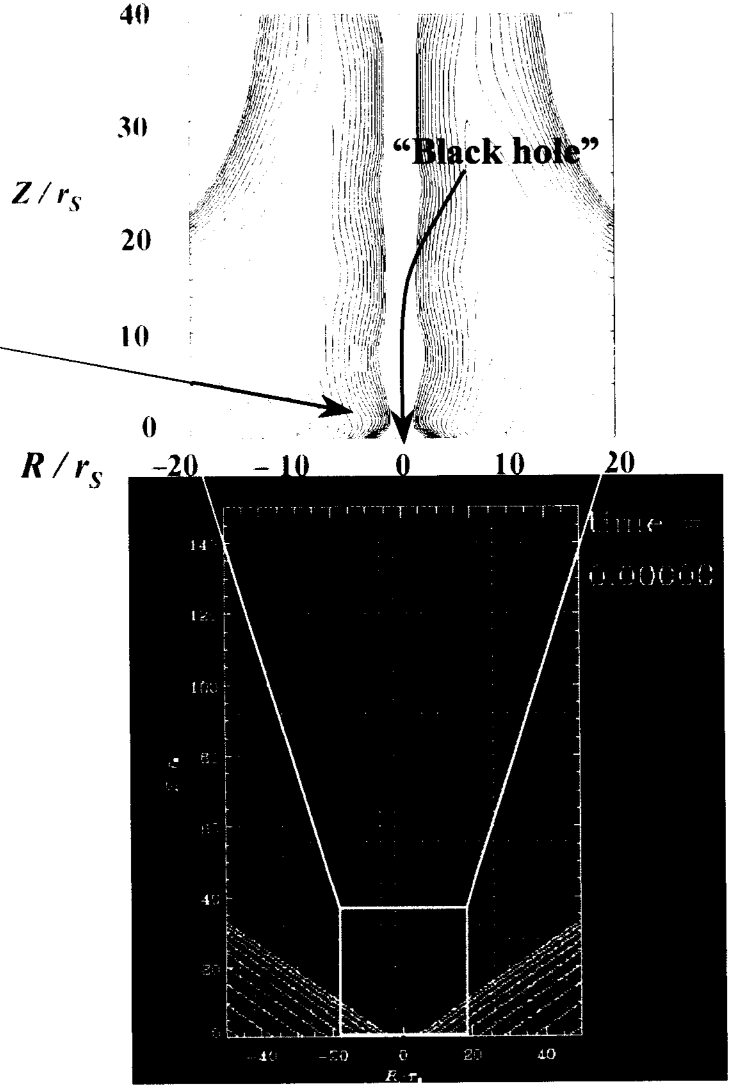
  Γ

- in these pseudo-relativistic simulations (Lind, Meier, & Payne 1994; Meier *et al.* 1997; Meier *et al.* 2000):
  - Similar to previous "disk as boundary" simulations, but
  - Infinitely-thin at $R = 6GM/c^2$
  - B_R, B_φ, and V_R are all on the boundary (as would be the case in an actual accretion disk)



Pseudo-Relativistic Simulations of Black Hole Accretion Disks (continued)

- (Meier et al. 1997; 2000):
  - This and create a <u>new magnetic field structure</u>:
    - Gravitational and magnetic forces cause injected , above the disk
    - This , creating a substantial B_R
    - Differential rotation winds B_R up into B_φ, which expels and collimates a narrow jet
  - This inner jet in the accreting corona case is <u>similar to that in the accreting torus case</u> shown by Shibata-san
  - A <u>slowly-collimated disk wind</u> (like the Blandford-Payne solutions) <u>also occurs</u> occasionally, but usually only when the inner jet is weak

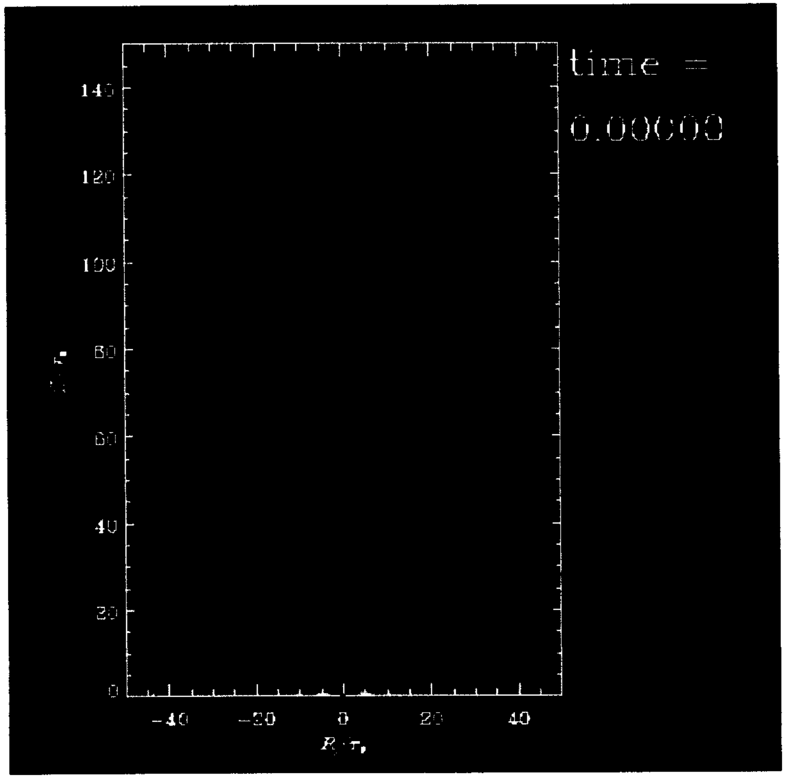


Pseudo-Relativistic Simulations of Black Hole Accretion Disks (continued)

- (Meier *et al.* 1997; Meier 1999):
  - There appears to be a critical MHD luminosity (analogous to the Eddington limit)

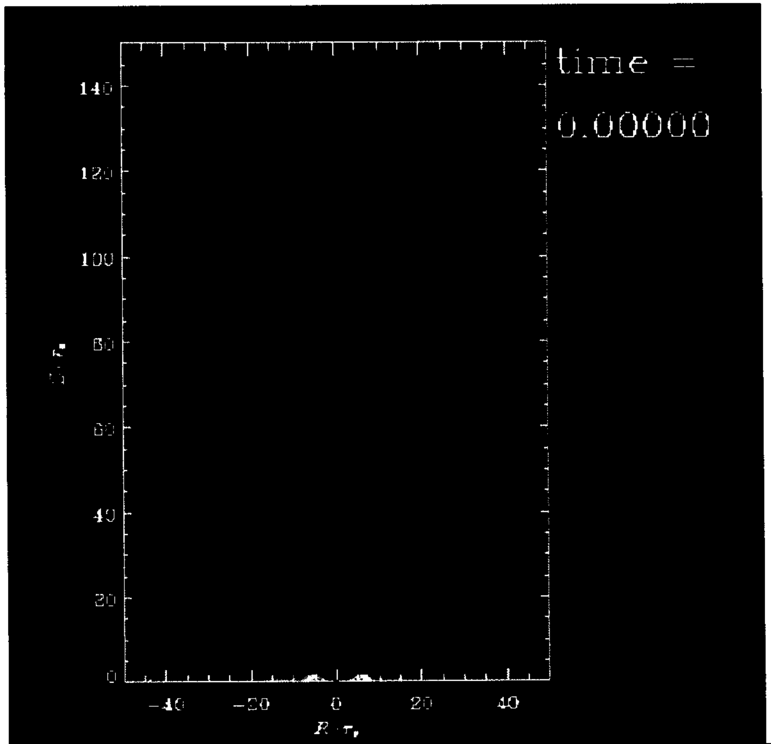
$L_{crit} \equiv E_{escape}/\tau_{free-fall} =$

$L_{MHD} \sim 0.8\ L_{crit}$



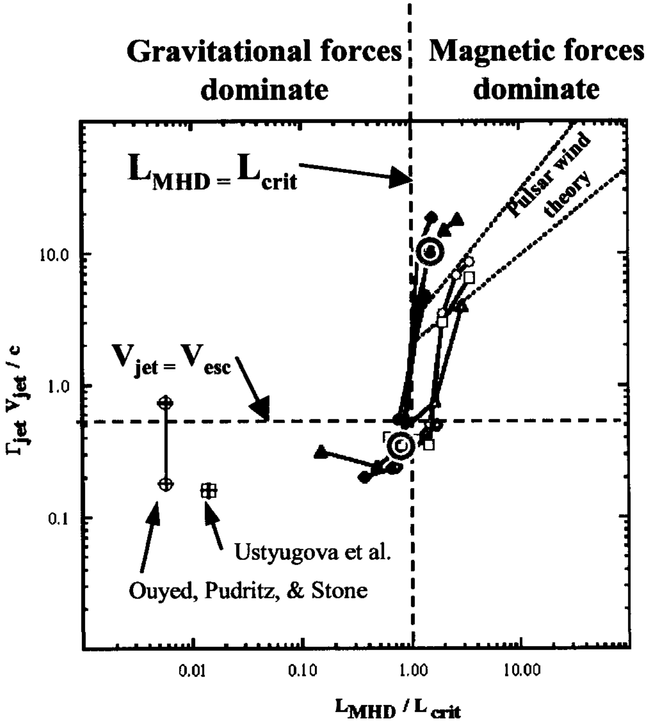
When $L_{MHD} < L_{crit}$, $V_{jet} \sim V_{esc}$ resulting in a relatively

$L_{MHD} \sim 1.5\ L_{crit}$



When $L_{MHD} > L_{crit}$, V_{jet} is determined by $L_{MHD} \sim \Gamma_{jet} \dot{M} c^2$, resulting in a relatively

Pseudo-Relativistic Simulations of Black Hole Accretion Disks (continued)



Jets with high MHD power and low mass flux ("Poynting flux dominated") have the potential for reaching high Lorentz factors ($\Gamma >> 10$)

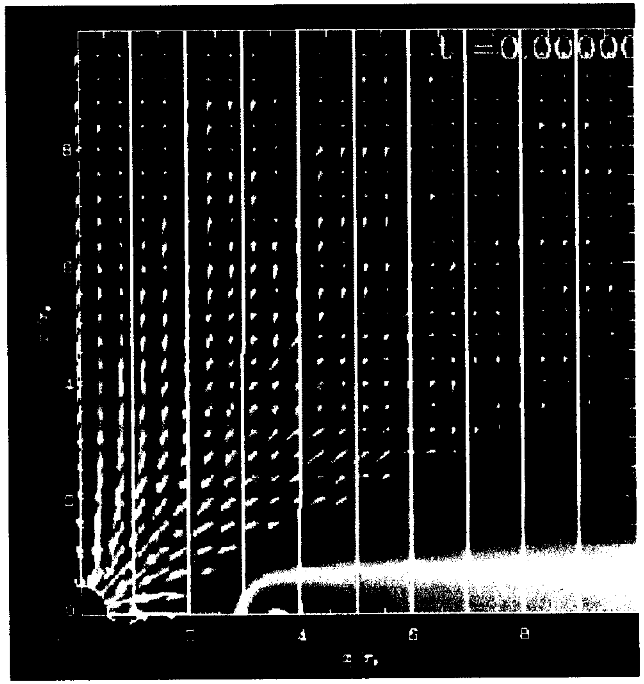
However $L_{MHD} > L_{crit}$ can happen where the magnetic field can be strong and the density low

In the accretion disk itself $L_{MHD} < L_{crit}$, or the magnetic forces will dynamically destroy the disk

Jets with low MHD power or high mass flux are initially bound and can only reach the disk escape velocity

General Relativistic Simulations of Black Hole Accretion Disks

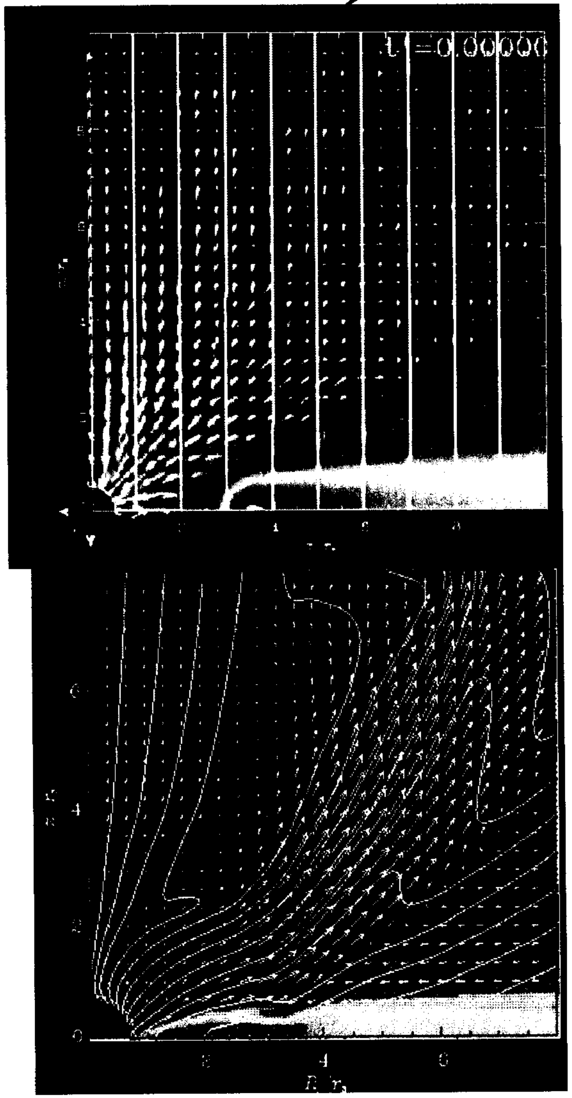
- : Koide, Shibata, & Kudoh (1998); Koide, Meier, Shibata, & Kudoh (1999a,b)
-
  - Thick accretion disk with inner edge at R = 4.5 GM/c^2
  - Initial vertical magnetic field ($V_{\text{Alfvén}}$ = 0.01c)
  - Fixed and flow
-
  - (Schwarzschild) , (ADAF-like)
  -
  - (Kerr) (a/M=0.95) (ADAF-like)
  -
    - Co-rotating with the black hole rotation
    - Counter-rotating against the black hole rotation



General Relativistic Simulations of Black Hole Accretion Disks (continued)

- [illegible]
  - Disk plunges rapidly toward black hole (counter-rotating orbits are unstable!)
  - Dragging of inertial frames by rotating black hole reverses spin of disk
  - A jet is generated from the inner disk edge in a manner similar to non-relativistic simulations
  - A very low density region forms inside the jet --- potentially the beginning of a magnetically-switched, high Lorentz factor flow

- [illegible]
  - Disk free-falls rapidly into ergosphere
  - Rotation of black hole contributes significantly to acceleration of jet
  - Highest jet velocities achieved so far are of order the ergospheric escape velocity:



General Relativistic Simulations of Black Hole Accretion Disks (continued)

-
  - Disk toward black hole (co-rotating orbits are stable!)
  - Some outflow is produced, but it is rather slow so far ($V_{jet} \sim 0.4$ c)
  - Further evolution is unclear (simulation had to be stopped for numerical reasons)

-
  - Jet is produced
  - Jet speed is limited to $V_{jet} \sim V_{esc}$ ($R=6GM/c^2$) = 0.6 c

- The fastest and most powerful jets are produced when
  - The central black hole rotates rapidly
  - The accreting material falls rapidly into the ergosphere
  - The material accelerated in the jet is of very low density (*i.e.*, $L_{MHD} > L_{crit}$ or, for Keplerian rotation, $V_{Alfvén} > V_{esc}$)

Summary of All Simulations Performed

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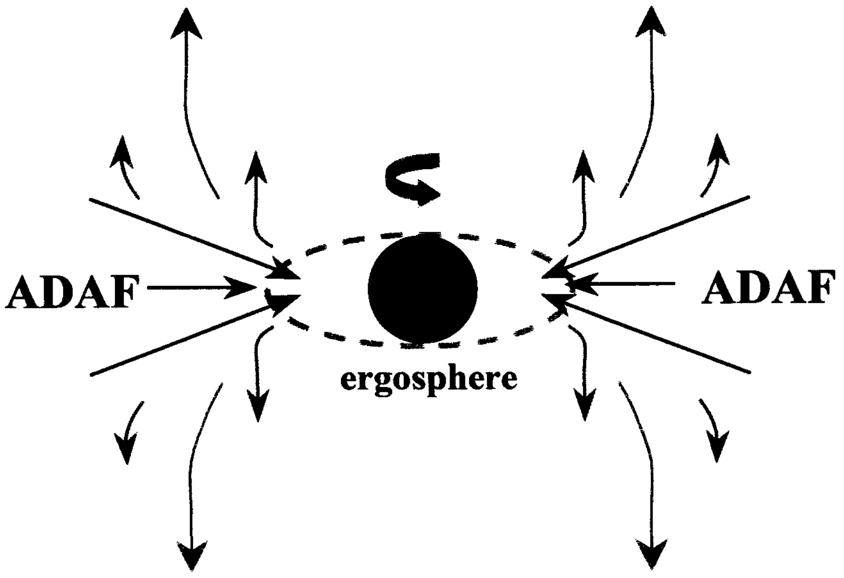
  - The central black hole rotates rapidly
  - The accreting material falls rapidly into the ergosphere
  - The material accelerated in the jet is of very low density (*i.e.*, $L_{MHD} > L_{crit}$ or, for Keplerian rotation, $V_{Alfvén} > V_{esc}$)

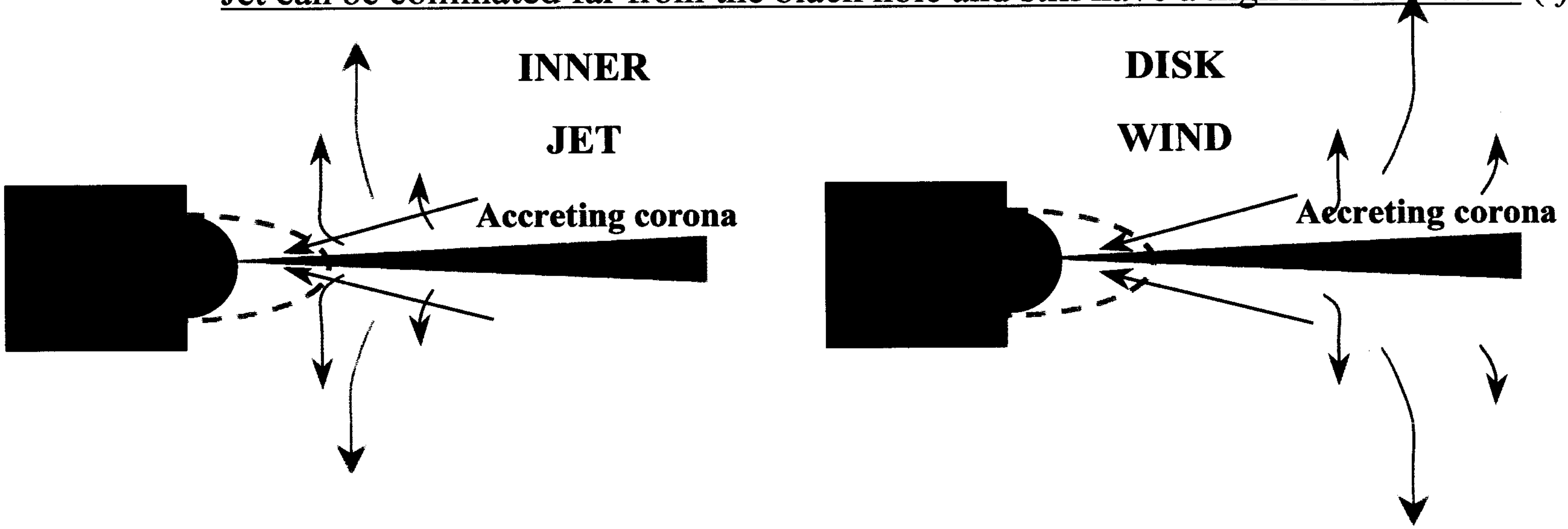
The Association of Advection-Dominated Accretion Flow (ADAFs) with Jet Production in Microquasars

-
  - Rapid infall toward black hole
  - Little rotation in the accretion flow until it plunges into the ergosphere
  - Jet is produced and collimated very near the black hole
  - Much of the outflow is at the escape velocity ($\Gamma < 3$)
  - Highest Lorentz-factor flow ($\Gamma >> 10$) can occur in low-density, Poynting-flux-dominated, "coronal holes"



The Association of Advection-Dominated Accretion Flow (ADAFs) with Jet Production in Microquasars (continued)

-
  - Magnetic field is anchored in thin Keplerian-rotating accretion disk
  - Rotating disk can accelerate or
  - Again, much of the outflow is at the escape velocity ($\Gamma < 3$)
  - But, high Lorentz-factor flow ($\Gamma >> 10$) can occur in low-density, Poynting-flux-dominated, "coronal holes"
  - Jet can be collimated far from the black hole and still have a high Lorentz factor (*cf.*)



The Future

- General relativistic MHD simulations
  - Improve GRMHD code to handle very low-density flows
  - Investigate magnetic switching in fully-relativistic, finite-thickness accretion disk situations
- Accretion disk <u>structure</u> calculations
  - Investigate the structure of a rotating black hole magnetosphere and its implications for MHD-driven outflow