Relativistic MHD Simulations of Relativistic Jets with RAISHIN *

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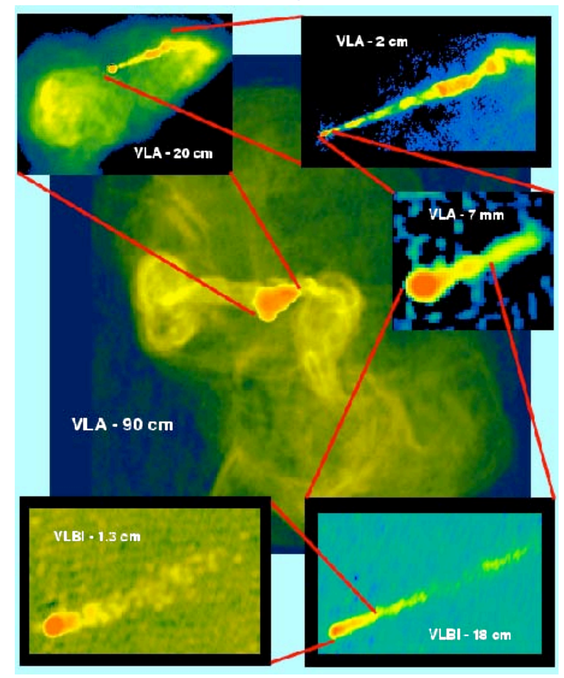
- We have developed a new three-dimensional general relativistic magnetohydrodynamic (GRMHD) code ``RAISHIN'' using a conservative, high-resolution shock-capturing scheme. The code has been tested and used in a number of different astrophysical applications.
- We have performed 2D GRMHD simulations of jet formation from a geometrically thin accretion disk near both non-rotating and rotating black holes. Similar to previous results (Koide et al. 2000, Nishikawa et al. 2005a) we find magnetically driven jets. The rotating black hole creates a second, faster, and more collimated inner jet inside an outer accretion disk jet.
- We have investigated the effect of magnetic fields on a jet hydrodynamic boost mechanism (Aloy & Rezzola 2006). The RMHD simulations find that magnetic fields can provide more acceleration than a pure-hydrodynamic case.
- We have performed 3D RMHD simulations to study the Kelvin-Helmholtz (KH) instability of magnetized spine-sheath relativistic jets. Growth of the KH instability is reduced significantly by mildly relativistic sheath flow and can be stabilized by magnetized sheath flow.

1. Astrophysical Jets

- ***Astrophysical jets: outflow of highly collimated plasma***
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocities ~c.
  - Generic systems: Compact object (White Dwarf, Neutron Star, Black Hole) + Accretion Disk
- ***Key Problems of Astrophysical Jets***
  - Acceleration mechanism
  - Collimation
  - Long term stability
- ***Modeling of Astrophysical Jets***
  - Magnetohydrodynamics + Relativity (SR+GR)

M87 jet



2.GRMHD Code "RAISHIN"

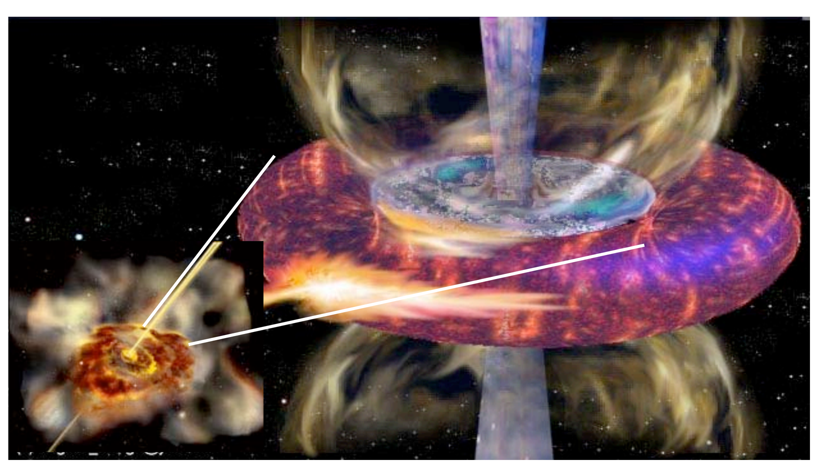
Mizuno et al. 2006a, ApJS submitted
Astro-ph/0609004

- RAISHIN utilizes conservative, high-resolution shock capturing schemes to solve the 3D GRMHD equations

* *Reconstruction:* Piecewise linear method (Minmod and MC slope-limiter function; second-order), convex ENO (third-order), Piecewise parabolic method (fourth-order)
* *Riemann solver:* HLL and HLLC approximate Riemann solver
* *Constrained Transport:* Flux interpolated constrained transport scheme
* *Time advance:* Multi-step TVD Runge-Kutta method (second and third -order)
* *Recovery step:* Koide 2 variable method and Noble 2D method

3. 2D GRMHD Simulations of Jet Formation

Mizuno et al. 2006b, Astro-ph/0609344



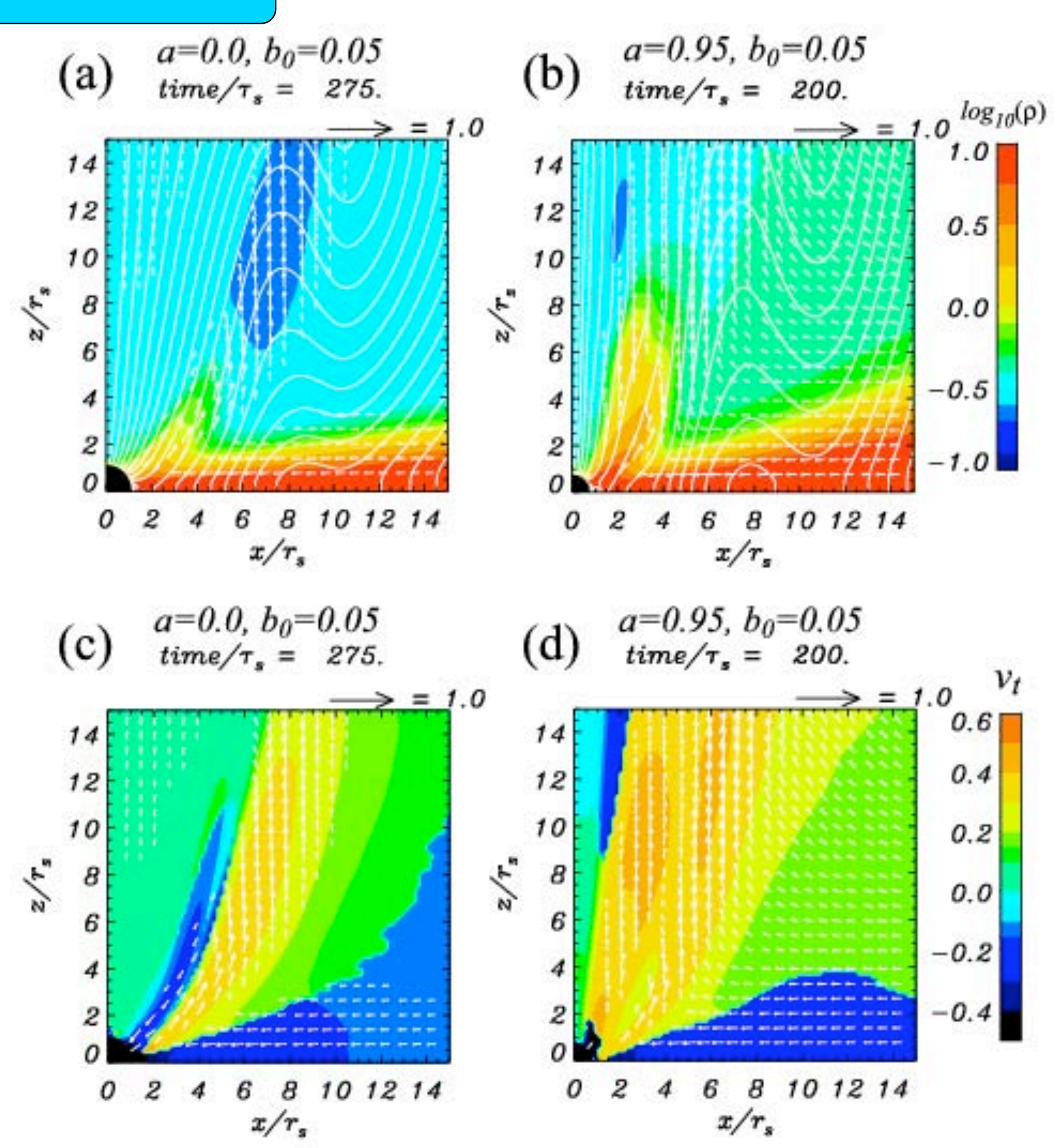
Schematic picture of the jet formation near a black hole

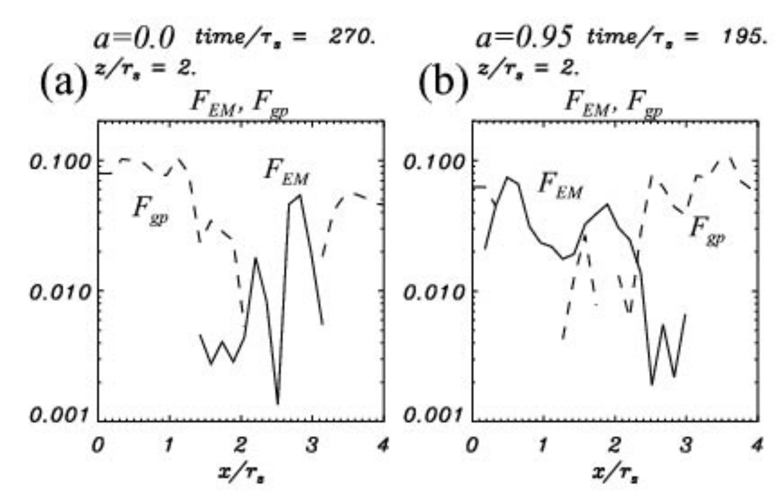
Initial Condition

- Geometrically thin accretion disk ($\rho_d/\rho_c=100$) rotates around a black hole ($a=0.0, 0.95$)
- The back ground corona is free-falling to a black hole (Bondi solution)
- The global vertical magnetic field (Wald solution; $B_0=0.05(\rho_0 c^2)^{1/2}$)

Numerical region and grid points

$1.1(0.75)\ r_S < r < 20\ r_S$, $0.03 < \theta < \pi/2$, with $128*128$ computational zones





The z-component of Lorentz force and the gas pressure gradient on the $z/r_S=2$ surface

- The matter in the disk loses its angular momentum by magnetic field and falls to a black hole.
- A centrifugal barrier decelerates the falling matter and make a shock around $r=2r_S$.
- The matter near the shock region is accelerated by the J×B force and the gas pressure and forms jets.
- These results are the same as previous work (Koide et al. 2000, Nishikawa et al. 2005).
- In the rotating black hole cases, jets form much closer to the black hole's ergosphere and the magnetic field is strongly twisted due the frame-dragging effect.

4. MHD boost for relativistic jets

Mizuno et al. 2007, in preparation

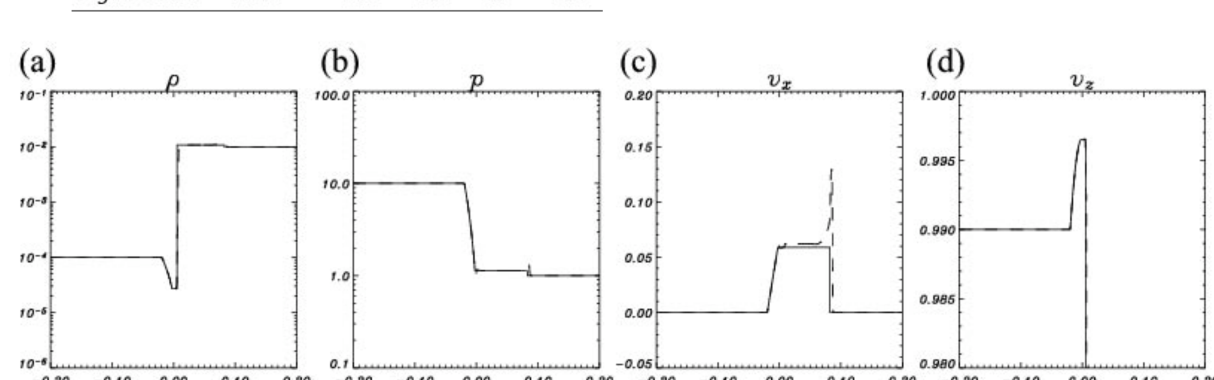
Introduction

- The acceleration mechanism boosting relativistic jets to highly-relativistic speed is not fully known.
- Recently Aloy & Rezzolla (2006) have proposed a powerful hydrodynamical acceleration mechanism of relativistic jets by the motion of two fluid between jets and external medium
- We have investigated the effect of magnetic field to the hydrodynamic boost mechanism by using RMHD simulations

Initial condition

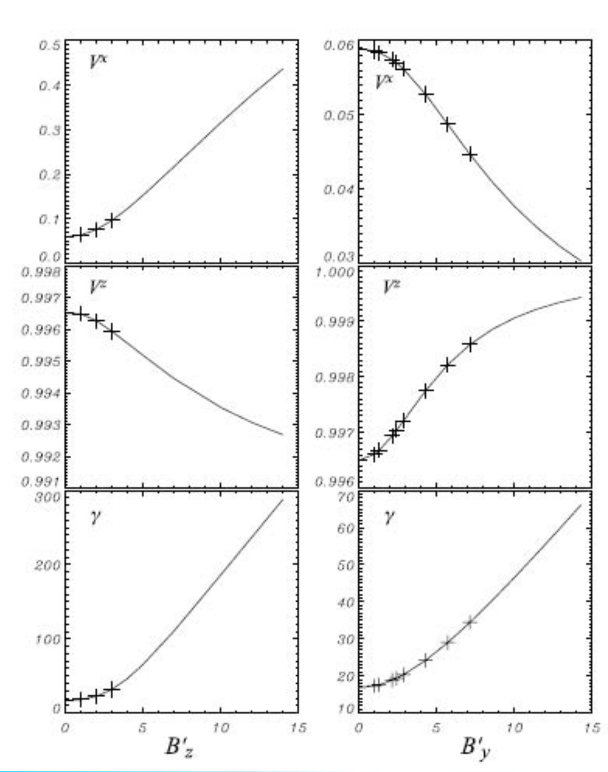
- Consider a Riemann problem consisting of two uniform initial states (left: jet with $v_z=0.99c$, right: external medium)

	ρ	p	v^x	v^y	v^z
left state	10.0^{-4}	10.0	0.0	0.0	0.99
right state	10.0^{-2}	1.0	0.0	0.0	0.0



Hydro simulation result show the acceleration of jets by hydrodynamic boost mechanism

To investigate the effect of magnetic fields, put the poloidal (Bz) or toroidal (By) components of magnetic field in the jet region



- The presence of the magnetic field more efficiently accelerates the jet than pure-hydrodynamic case
- The magnetic field can in principle play an important role in this relativistic jet boost mechanism

5. Long-Term Stability of Magnetized Spine-Sheath Jets

Mizuno, Hardee & Nishikawa 2006, Submitted to ApJ

Introduction

- GRMHD simulation results suggest that a jet spine driven by the magnetic fields threading the ergosphere may be surrounded by a broad jet sheath driven by the magnetic fields anchored in the accretion disk
- Recent observations of QSOs also indicate that a highly relativistic jet could reside in a high speed wind or sheath (e.g., Pounds et al. 2003).
- We have performed 3D RMHD simulations to investigate the long-term stability of magnetized sheath-spine relativistic jets by disruptive Kelvin-Helmholtz instabilities.

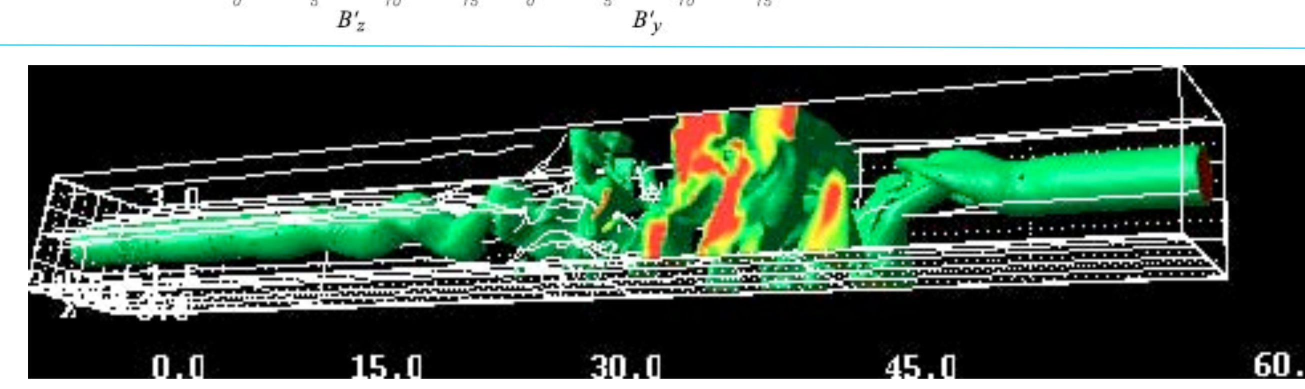
Initial Condition

- Cylindrical Jet established across the computational domain
  $u_j = 0.916\ c\ (\gamma_j=2.5)$, $\rho_j = 2\ \rho_e$
- External steady medium or flow outside the jet,
  $u_e = 0$ (no wind), $0.5c$ (wind)
- Jet precessed to break the symmetry (w=0.93)

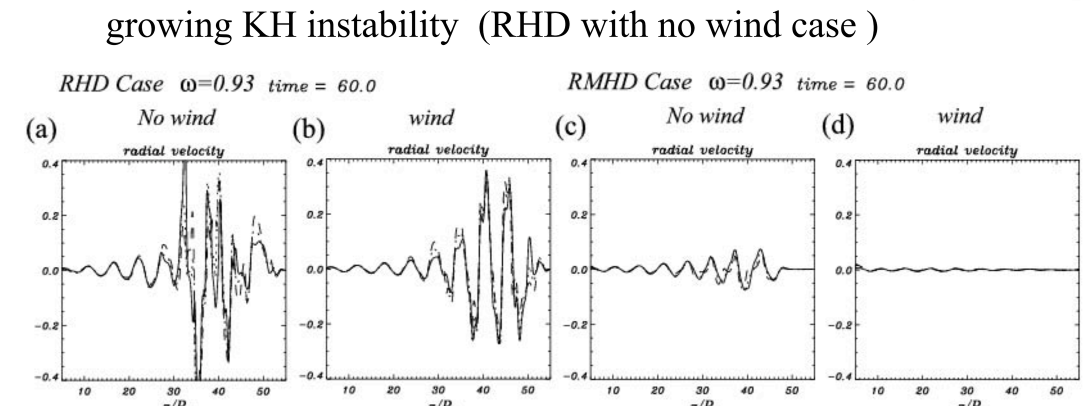
RHD: *weakly magnetized* ($a_{j,e} >> v_{Aj,e}$)
  $a_j = 0.511\ c$, $a_e = 0.574\ c$, $v_{A(j,e)} < 0.07\ c$
RMHD: *strongly magnetized* ($a_{j,e} < V_{Aj,e}$)
  $v_{Aj} = 0.45\ c$, $v_{Ae} = 0.56\ c$, $a_j = 0.23\ c$, $a_e = 0.30\ c$

Numerical region and grid points

$6R_j*6R_j*60R_j$ in Cartesian coordinates with $60*60*600$ computational zones



3D isovolume of density with B-field lines show the jet is disrupted by the growing KH instability (RHD with no wind case)



1D cut of radial velocity along jet

- Growth of the KH instability driven by jet spine-sheath interaction is reduced significantly by mildly relativistic sheath flow and can be stabilized by magnetized sheath flow

*1st GLAST Symposium, Stanford Univ., February 5-8, 2007