GRMHD Simulations of Jet Formation with Newly-Developed GRMHD Code

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Reference: Mizuno et al. 2006, in preparation

Introduction

- Astrophysical jet is a outflow of highly collimated plasma gas
  - In Microquasar 、 Active Galactic Nuclei 、 Gamma-Ray Bursts, Jet velocity is nearly light velocity （～ c ） .
  - Compact object （ White Dwarf 、 Neutron Star 、 Black Hole ） +Accretion Disk system
- Problem of Astrophysical Jet
  - Acceleration mechanism
  - Collimation
  - Long term stationality
- Model of Astrophysical Jet
  - Most confidential model is magnetohydrodynamic model

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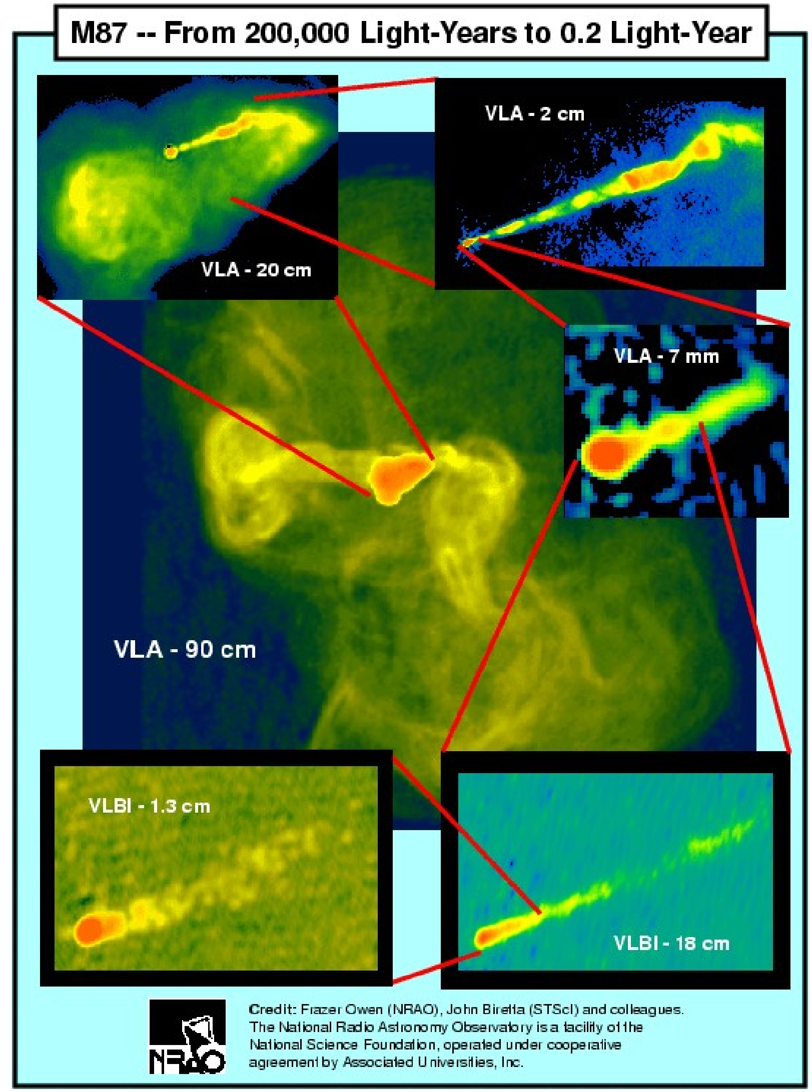


Propose to make a new GRMHD code

- The Koide's GRMHD Code (Koide 2003) has been applied to many high-energy astrophysical phenomena and showed pioneering results.
- However, the code can not perform calculation in highly relativistic (γ>5) or highly magnetized regimes.
- The critical problem of the Koide's GRMHD code is the schemes can not guarantee to maintain divergence free magnetic field.
- In order to improve these numerical difficulties, we have developed a new 3D GRMHD code RAISHIN (RelAtIviStic magnetoHydrodynamc sImulatioN, RAISHIN is the Japanese ancient god of lightening).

Detail of Schemes

- Use conservative schemes to solve the 3D GRMHD equations in each spatial direction

* *Reconstruction*
  - Piecewise linear method (Minmod and MC slope-limiter function; second-order), convex ENO (third-order), Piecewise parabolic method (fourth-order)

* *Riemann solver*
  - HLL approximate Riemann solver

* *Constrained Transport*
  - Flux interpolated constrained transport scheme

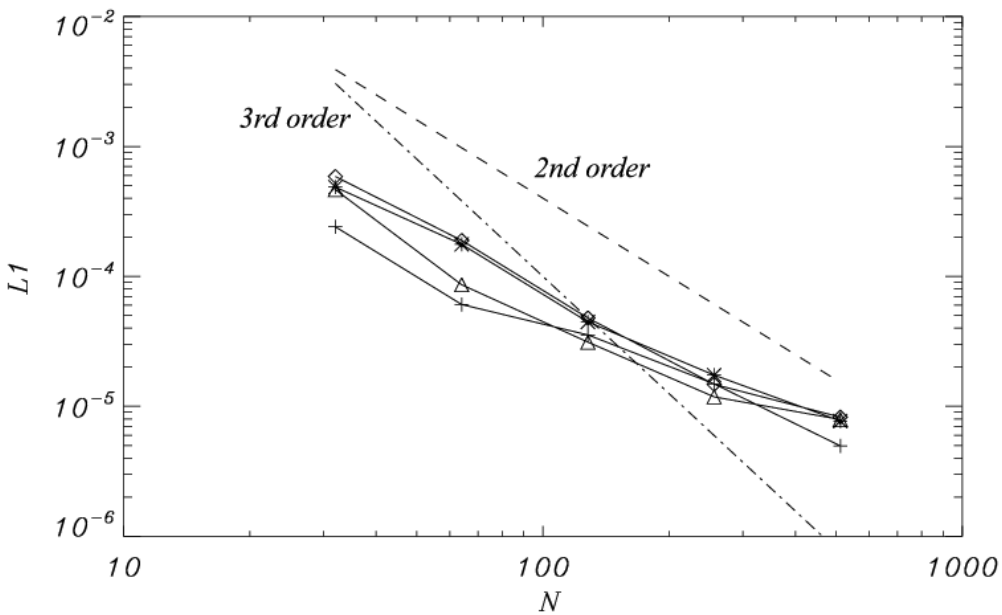
* *Time advance*
  - Multi-step TVD Runge-Kutta method (second and third -order)

* *Recovery step*
  - Koide 2 variable method and Noble 2D method

Flexibility of a New GRMHD code

- Multi-dimension (1D, 2D, 3D)
- Special and General relativity
- Different boundary conditions
- Different coordinates (RMHD: Cartesian, Cylindrical, Spherical and GRMHD: Boyer-Lindquist of non-rotating or rotating BH)
- Different spatial reconstruction algorithms
- Different time advance algorithms
- Different recovery schemes

Linear Alfven wave Propagation Tests

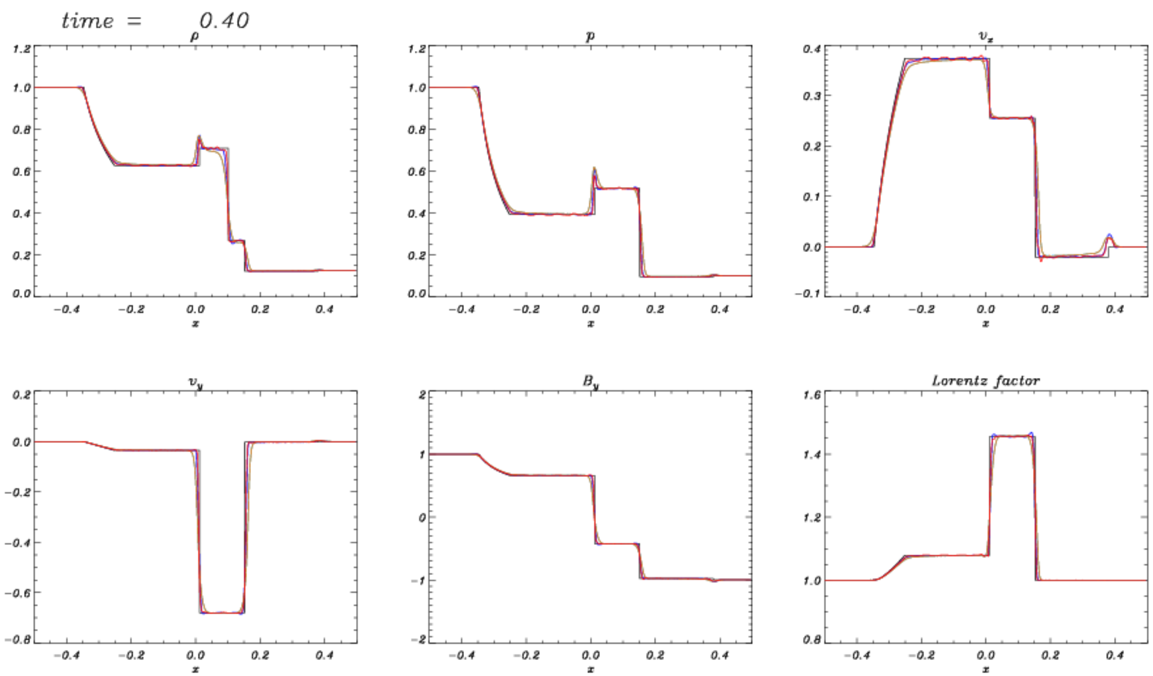


L1 norm of the error in density

- Calculate the L1 norm of the difference between the final state and the initial state
- All reconstruction schemes show the second-order of convergence

Relativistic MHD Shock-Tube Tests

Balsara Test1 (Relativistic version of Brio & Wu)

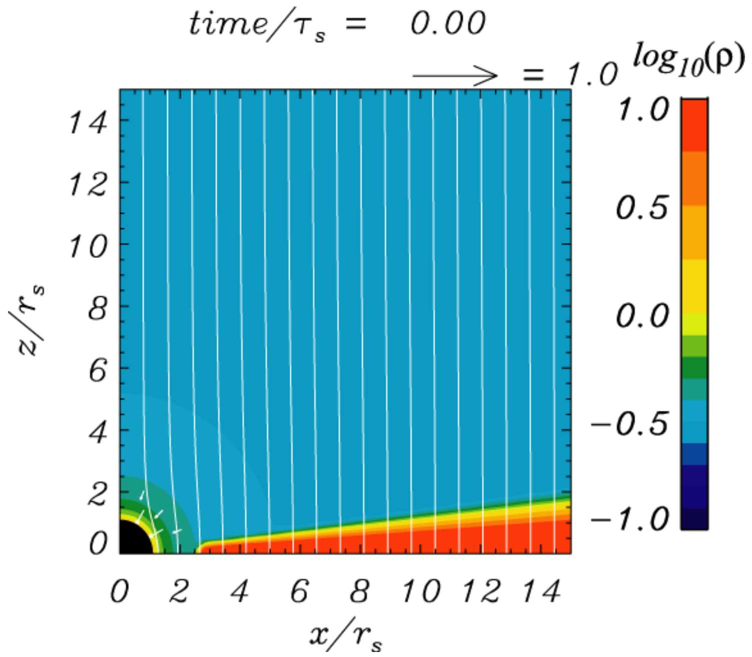


Black: exact solution, Blue: MC-limiter, Light blue: minmod-limiter, Orange: CENO, red: PPM

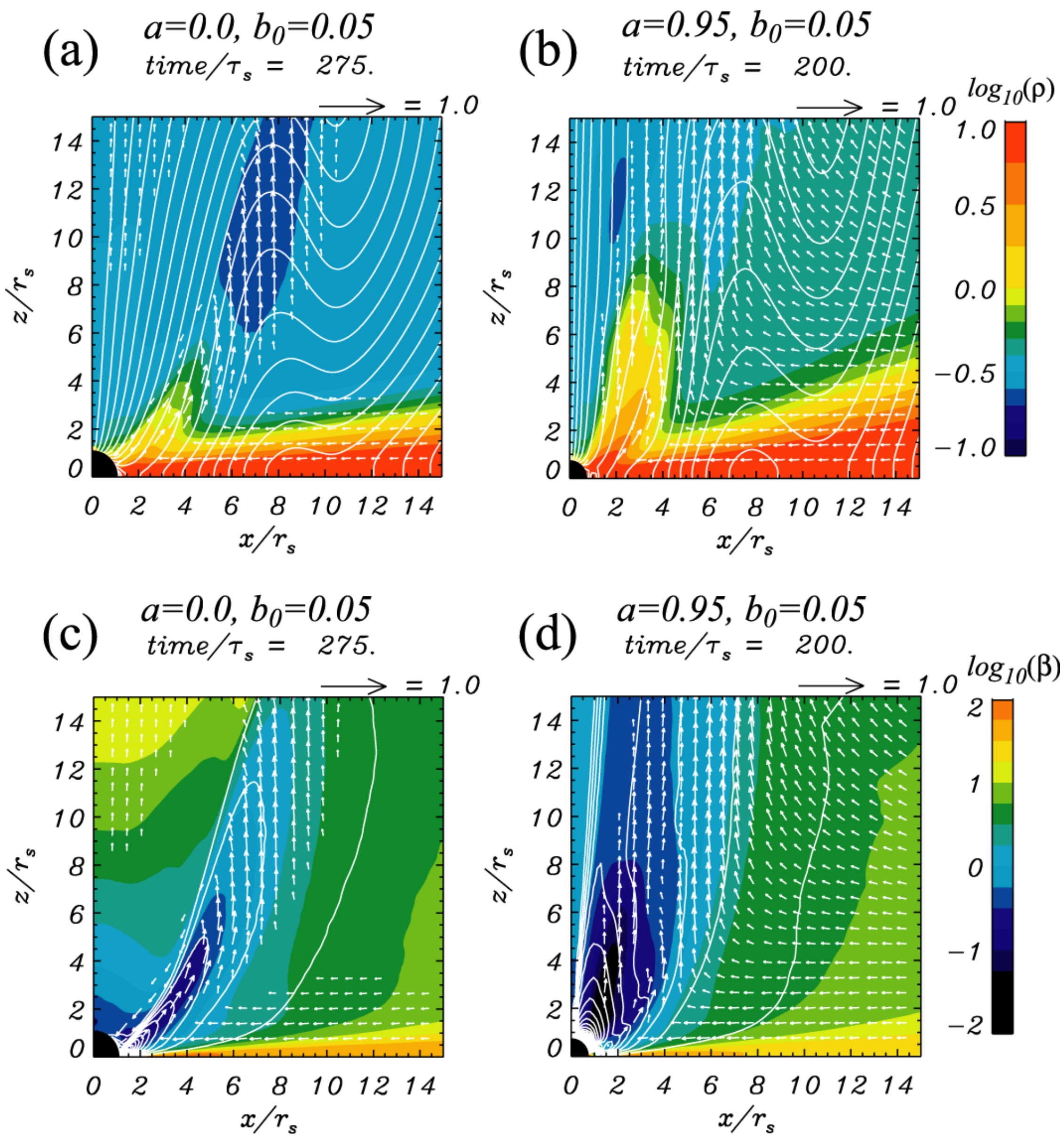
- The results show the good agreement of the exact solution calculated by Giacommazo & Rezzolla (2005).
- Minmod slope-limiter and CENO reconstructions are more diffusive than the MC slope-limiter and PPM reconstructions.
- Although MC slope limiter and PPM reconstructions can resolve the discontinuities sharply, some small oscillations are seen at the discontinuities.

2D GRMHD Simulation of Jet Formation

- Initial condition
  - Geometrically thin accretion disk (ρ_d/ρ_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=*0.1* , 0.05$(\rho_0 c^2)^{1/2}$)
- Numerical Region and Mesh points
  - $1.0\, r_S < r < 40\, r_S$, $0 < \theta < \pi/2$, with *128*128* mesh points
- Method
  - minmod slope-limiter, HLL, flux-CT, RK3, Noble 2D method



Results



Color: density (upper), plasma beta (lower)
White curves: magnetic field lines (upper), toroidal magnetic field (lower)
vector: poloidal velocity

- The simulation results show that the jet is formed in the same manner as in previous work (Koide et al. 2000) and propagates outward.
- 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.

Summary

- We have developed new 3D GRMHD code by using a conservative, shock-capturing scheme.
- The numerical fluxes are calculated HLL aproximate Riemann solver method
- Flux-interpolated CT scheme is used to maintain a divergence-free magnetic field
- We have discribed code perfomance on various 1 dimensional special relativistic test problems and they show accurate results
- We have performed the jet formations from a geometirically thin accretion disk near non-rotating and rotating black holes.
- The simulation result showed the jet formation by the same manner of previous works and propagate longer time than previous GRMHD simulations.

Future Work

- Code development
  - Parallelization by using MPI (speed up)
  - Physical EOS
  - Neutrino treatment (cooling, heating)
  - resistivity
- Connection to relativistic radiation transfer (observational expectation); see Nishikawa et al. 2005 (astro-ph/ 0509601)
- Connection to Nucleosysthesis
- Apply to many high-energy astrophysical phenomena (especially relativistic outflows from AGNs, microquasars, neutron stars, and GRBs and related physics)