3D RMHD Simulations of Magnetized Spine-Sheath Relativistic Jets

Yosuke Mizuno (NSSTC/UAH), Philip Hardee (UA),
Ken-Ichi Nishikawa (NSSTC/UAH)

Mizuno, Hardee & Nishikawa, 2007, ApJ, 662, 835
Hardee, 2007, ApJ, 664, 26
Hardee, Mizuno & Nishikawa, 2007, ApSS, 311, 281

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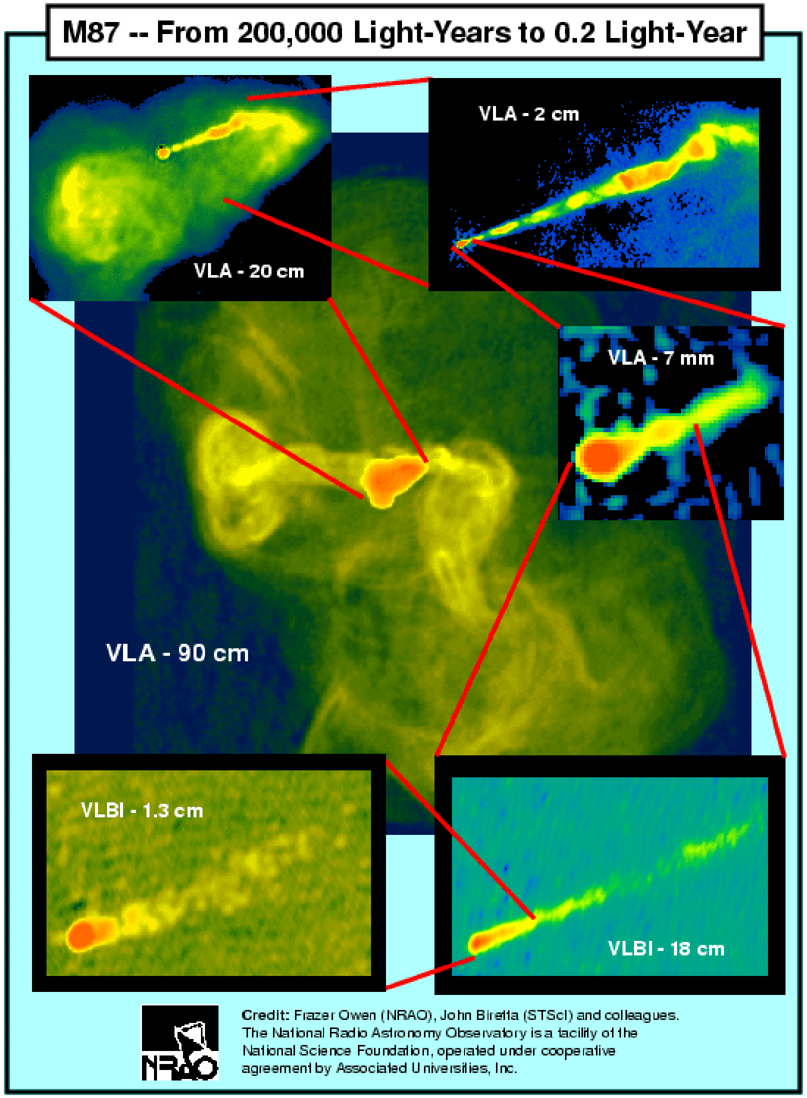
Astrophysical Jets

M87

- *Astrophysical jets: outflow of highly collimated plasma*
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ~ c, Relativistic Jets.
  - Generic systems: Compact object (Whit Dwarf, Neutron Star, Black Hole) + Accretion Disk

- *Key Problems of Astrophysical Jets*
  - Acceleration mechanism and radiation processes
  - Collimation
  - Long term stability (research topics)

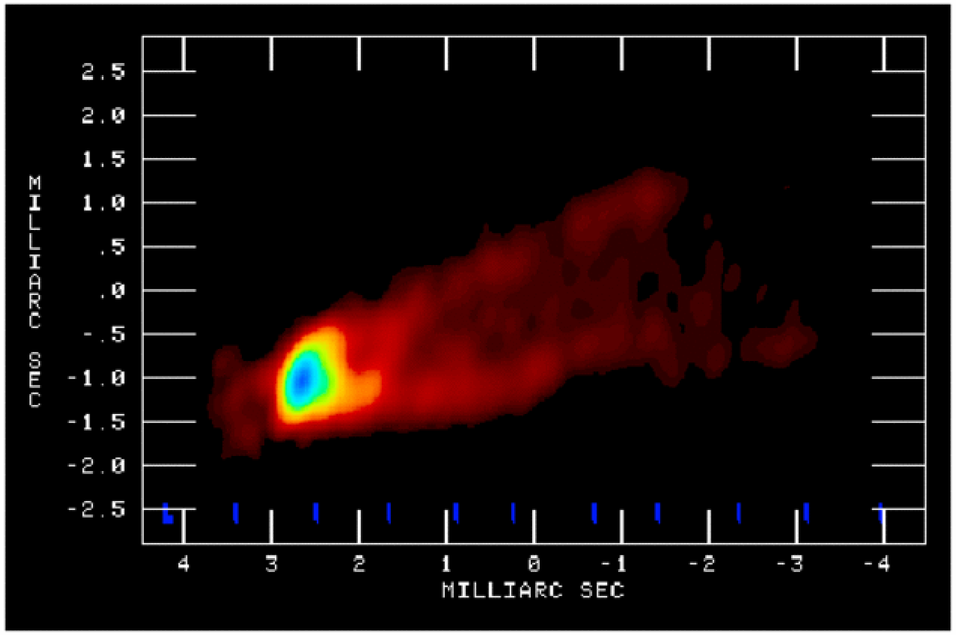
- *Model for Astrophysical Jets*
  - Magnetohydrodynamics (MHD) + relativity
    - Jet velocity ~ Keplerian velocity of accretion disk
    - Can keep collimated structure by magnetic hoop-stress
    - Direct extraction of energy from a rotating black hole (BZ process)



Instability of Relativistic Jets

- When jets propagate outward, there are possibility to grow of two major instabilities
  - Kelvin-Helmholtz (KH) instability
    - Important at the shearing boundary flowing jet and external medium
  - Current-Driven (CD) instability
    - Important in twisted magnetic field

- Interaction of jets with external medium caused by such instabilities leads to the formation of shocks, turbulence, acceleration of charged particles etc.
- Used to interpret many jet phenomena
  – quasi-periodic wiggles and knots, filaments, limb brightening, jet disruption etc

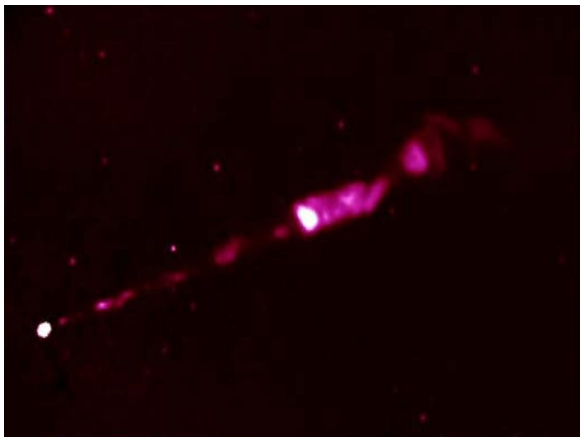


Limb brightening of M87 jets (observation)

Spine-Sheath Relativistic Jets (observations)

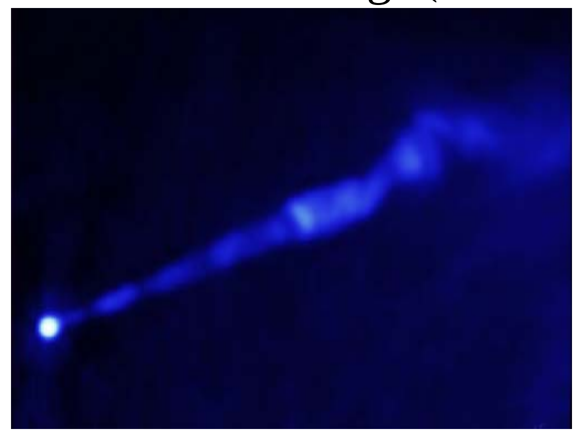
M87 Jet: Spine-Sheath (two-component) Configuration?

HST Optical Image (Biretta, Sparks, & Macchetto 1999)



Typical Proper Motions > c
Optical ~ inside radio emission
Jet Spine ?

VLA Radio Image (Biretta, Zhou, & Owen 1995)



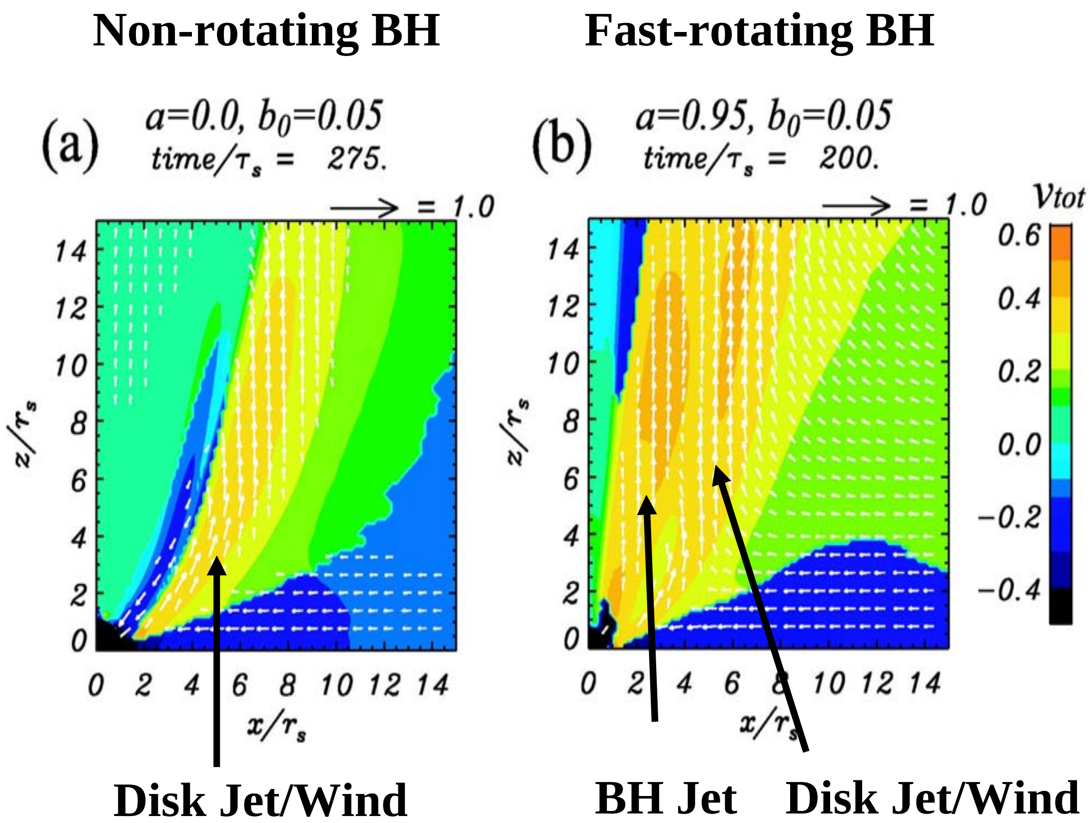
Typical Proper Motions < c
Radio ~ outside optical emission
Sheath wind ?

- Observations of QSOs show the evidence of high speed wind （~0.1-0.4c）(Pounds et al. 2003):
    - Related to Sheath wind
- Spine-sheath configuration proposed to explain
    - TeV Blazars (Ghisellini et al. 2005, Ghisellini & Tavecchio 2008)
    - TeV emission in M87 (Taveccio & Ghisellini 2008)
    - limb brightening in M87, Mrk501jets（Perlman et al. 2001; Giroletti et al. 2004）
    - broadband emission in PKS 1127-145 jet (Siemiginowska et al. 2007)

Spine-Sheath Relativistic Jets (GRMHD Simulations)

• In many GRMHD simulation of jet formation (e.g., Hawley & Krolik 2006, McKinney 2006, Hardee et al. 2007), suggest that

- a jet spine driven by the magnetic fields threading the ergosphere
- may be surrounded by a broad sheath wind driven by the magnetic fields anchored in the accretion disk.



Total velocity distribution of 2D GRMHD Simulation of jet formation (Hardee, Mizuno & Nishikawa 2007)

Key Questions of Jet Stability

- When jets propagate outward, there are possibility to grow of two instabilities
  - Kelvin-Helmholtz (KH) instability
  - Current-Driven (CD) instability

- How do jets remain sufficiently stable?
- What are the Effects & Structure of KH / CD Instability in particular jet configuration (such as spine-sheath configuration)?

- We investigate these topics by using 3D relativistic MHD simulations

Stabilities of magnetized spine-sheath jets against KH modes

- Hardee & Rosen (2002): stabilizing influence of a surrounding magnetized sheath wind of the helically magnetized 3D trans-Alfvenic jets
  - Jets could be stabilized to the nonaxisymmetric KH surface modes if velocity shear V_j-V_e < surface Alfven speed V_{As}

- Relativistic MHD jets are not fully addressed in both linear analysis and MHD simulation

-> present work

New 3D GRMHD Code "RAISHIN"

Mizuno et al. (2006)

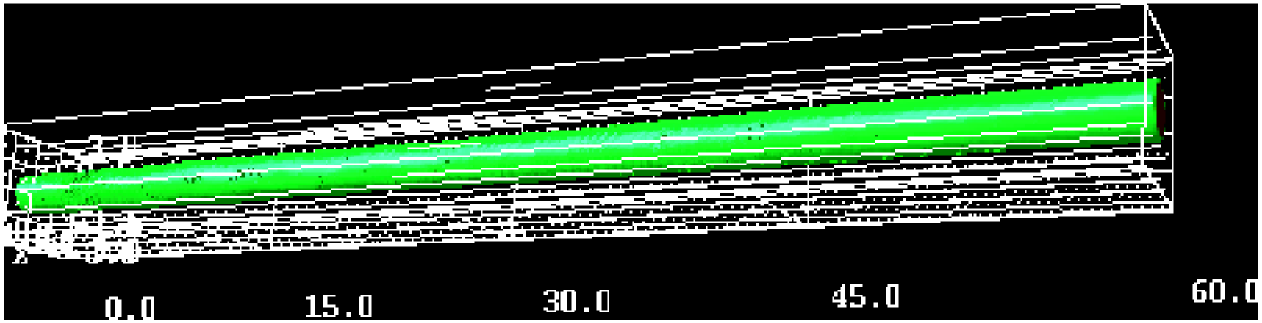
- RAISHIN utilizes conservative, high-resolution shock capturing schemes (Godunov-type scheme) to solve the 3D general relativistic MHD equations *(metric is static)*

- Ability of RAISHIN code
  - Multi-dimension (1D, 2D, 3D)
  - Special (Minkowski spcetime) and General relativity (static metric; Schwarzschild or Kerr spacetime)
  - Different coordinates (RMHD: Cartesian, Cylindrical, Spherical and GRMHD: Boyer-Lindquist of non-rotating or rotating BH)
  - Use several numerical methods to solving each problem
  - Maintain divergence-free magnetic field by numerically
  - Use constant Gamma-law or variable equation of states

3D Simulations of Spine-Sheath Jet Stability

Initial condition

Mizuno, Hardee & Nishikawa, 2007

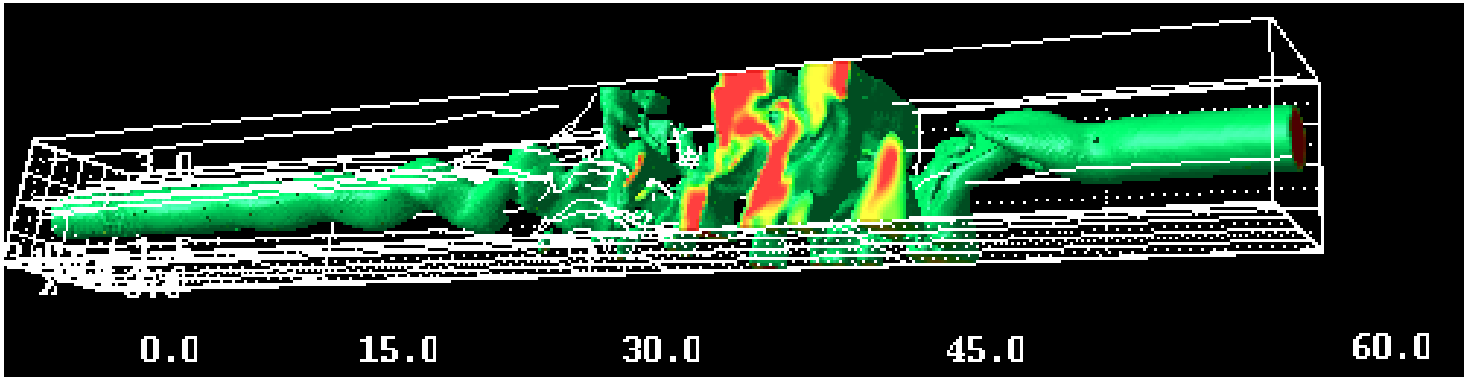


• Cylindrical super-Alfvenic jet established across the computational domain with a parallel magnetic field (stable against CD instabilities)

- Solving 3D RMHD equations in Cartesian coordinates (using Minkowski spacetime)
- Jet (spine): $u_{jet} = 0.916\ c\ (\gamma_j=2.5)$, $\rho_{jet} = 2\ \rho_{ext}$ (dense, cold jet)
- External medium (sheath): $u_{ext} = 0$ *(static), 0.5c (sheath wind)*
- Jet spine precessed to break the symmetry (frequency, ω=0.93)
- RHD: *weakly magnetized (sound velocity > Alfven velocity)*
- RMHD: *strongly magnetized (sound velocity < Alfven velocity)*
- Numerical box and computational zones
  - $-3\ r_j < x,y < 3r_j$, $0\ r_j < z < 60\ r_j$ (Cartesian coordinates) with 60*60*600 zones, $(1r_j=10$ zones)

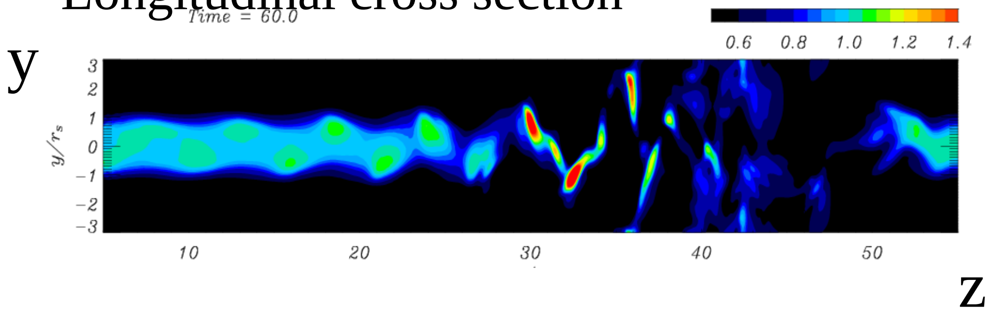
Previous works: jet propagation simulation of Spine-Sheath jet model (e.g., Sol et al. 1989; Hardee & Rosen 2002)

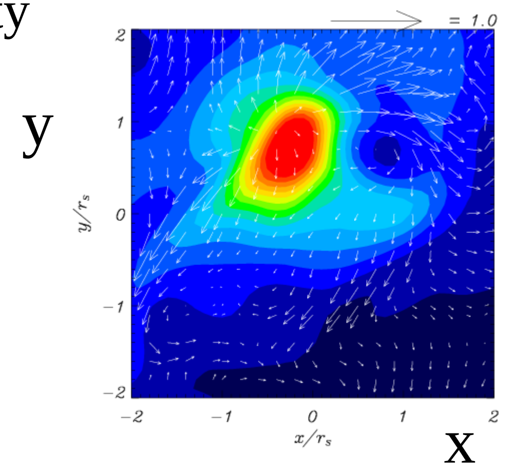
Simulation results: global structure
(nowind, weakly magnetized case)



3D isovolume of density with B-field lines show the jet is disrupted by the growing KH instability

Longitudinal cross section

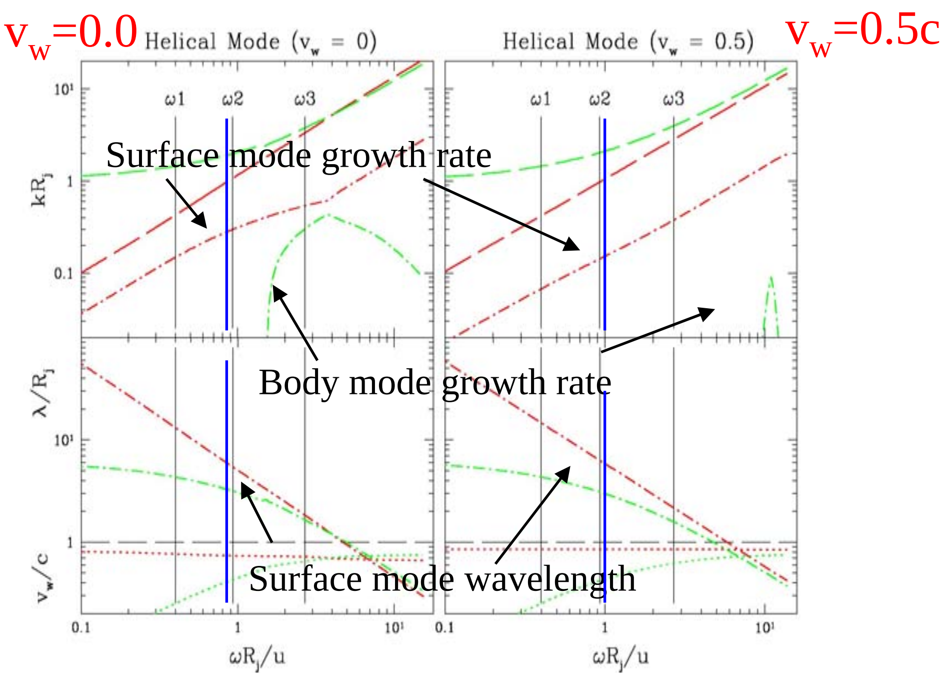




Transverse cross section show the strong interaction between jet and external medium

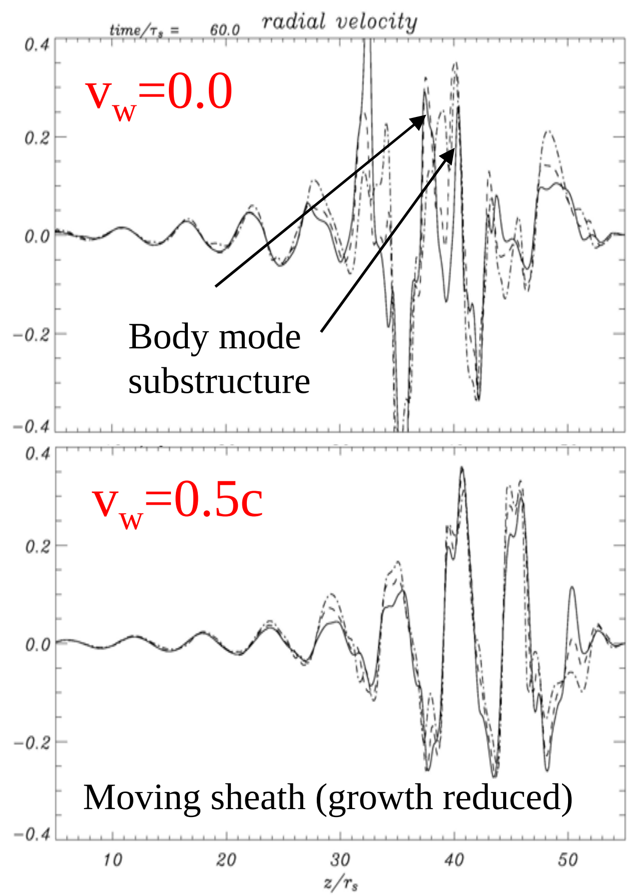
3D RHD Jet Simulations & Linear Analysis

RHD Jet Dispersion Relation Solutions (Linear analysis)



3D RHD Jet Simulation Results at ω2

1D cut of radial velocity along jet



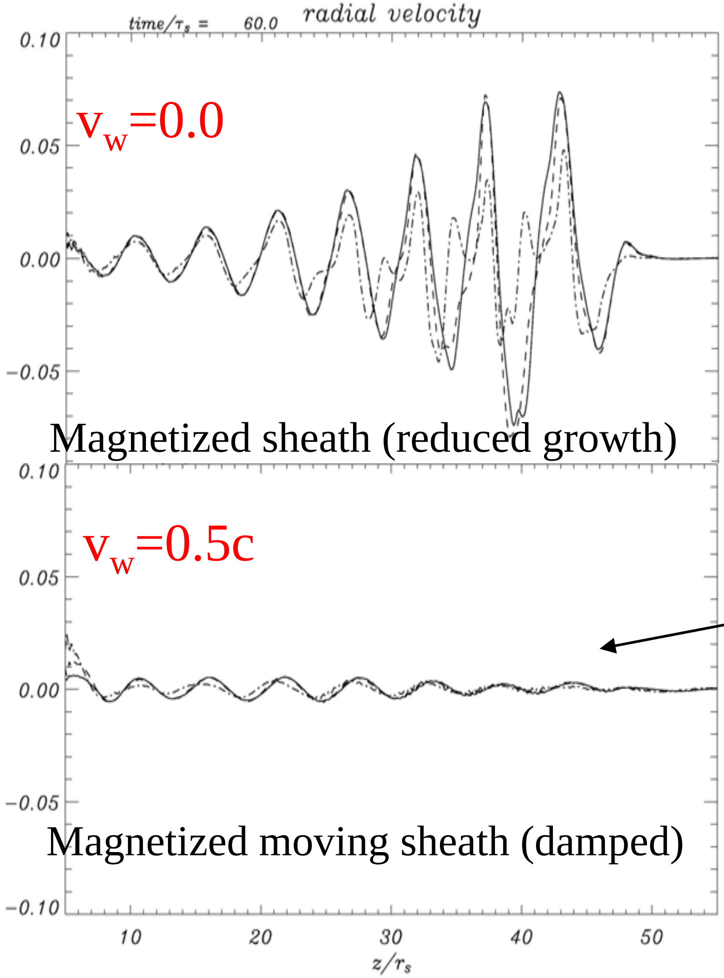
- A sheath with v_w = 0.5c significantly reduces the growth rate (red dash-dot) of the surface mode at simulation frequency ω2, and slightly increases the wavelength.
- Growth associated with the 1st helical body mode (green dash-dot) is almost eliminated by sheath flow.

- The sheath wind reduces the growth rate and slightly increases the wave speed and wavelength as predicted.
- Substructure associated with the 1st helical body mode is eliminated by sheath wind as predicted.

3D RMHD Jet Simulations & Theory

3D RMHD Jet Simulation Results at $\omega 2$

1D cut of radial velocity along jet



The magnetized sheath reduces growth rate relative to the fluid case and the magnetized sheath wind damped growth of KH modes.

Criterion for damped KH modes

Magnetized sheath flow has reduced the "velocity shear" to less than the "surface" Alfvén speed:

$$\boxed{\gamma_j^2 \gamma_e^2 \left(u_j - u_e\right)^2 < V_{As}^2}$$

Note that for comparable conditions in spine and sheath $V_{As} = 2\,\gamma_A\,(B^2/4\pi W)^{1/2}$ and $(B^2/4\pi W)^{1/2}$ can be >> c.

Summary

- We have investigated stability properties of magnetized spine-sheath relativistic jets by the theoretical work and 3D RMHD simulations.
- The most important result is that destructive KH modes can be stabilized by the presence of magnetized sheath wind even when the jet is super-Alfvenic flow.
- Even in the absence of stabilization, spatial growth rate of destructive KH modes can be reduced by the presence of sheath wind (~0.5c) around a relativistic jet spine (>0.9c)

For further information, please contact:
Yosuke.Mizuno-1@nasa.gov