Particle-in-cell Simulations of Global Relativistic Jets with Helical Magnetic Fields

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work with:
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Hartmann, D. H. (University of Clemson, USA)

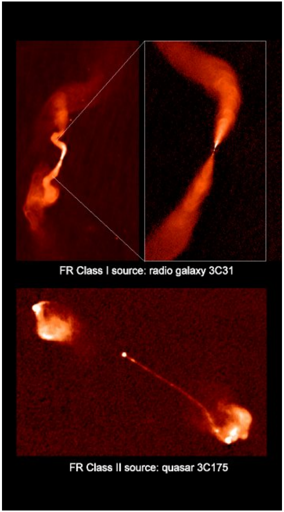
Self-consistent relativistic PIC code (version of TRISTAN code):

- collisionless shocks (Weibel instability) and kinetic Kelvin-Helmholtz instability (kKHI) at relativistic jet-sheath shear boundaries
- previously, full-scale shock simulations without velocity shear interactions at the jet boundary with the ambient plasma (interstellar medium)
- and then global shock simulations including velocity shear interactions used only very small simulation boxes
- we performed "global" jet simulations by injecting a cylindrical unmagnetized jet into an ambient plasma to study shock and velocity shear instabilities (kKHI and MI (Mushroom instability)) simultaneously
- we included jets with helical magnetic field

Using computational resources for parallel applications:

- **Stampede**, **Maverick**, and **Ranch** at University of Texas, Austin
- **Comet** and **Gordon** at San Diego Supercomputer Center
- **Pleiades** at NASA

Relativistic jets in AGN



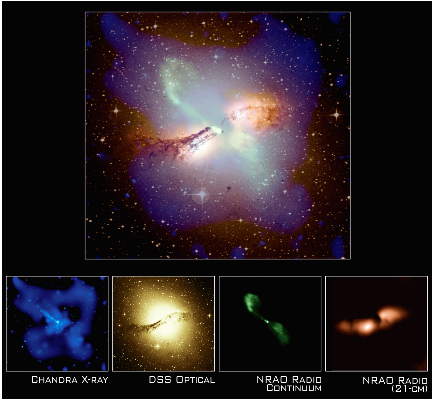


Figure: Image credit: cv.nrao.org and chandra.harvard.edu

Gamma-ray burst jets

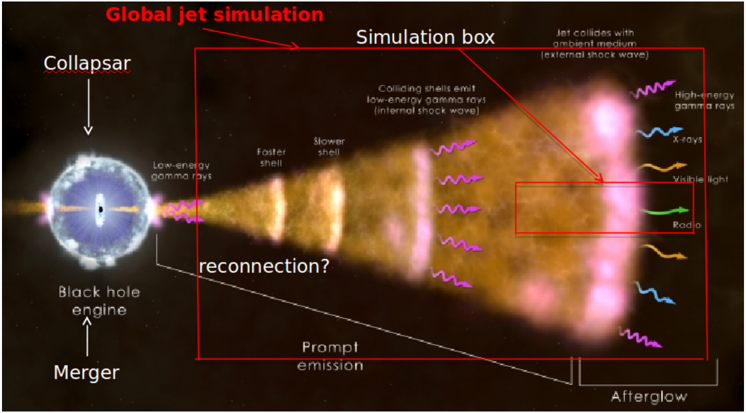


Figure: Image credit: www.nasa.gov

Key scientific questions

- How do velocity shears generate magnetic fields and accelerate particles?
- How do global jets evolve with different species?
- How the Weibel instability and kKHI affect the evolution of shock with global jets?
- How do helical magnetic fields affect shocks and reconnection?
- What are the dominant radiation processes?
- How do shocks in relativistic jets evolve in various ambient plasma- and magnetic field configurations?
- How is magnetic field energy released in jets?

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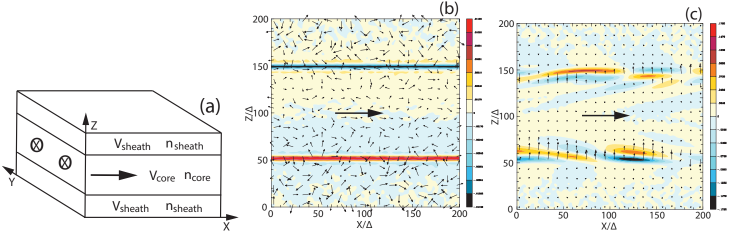
Generation of magnetic field in core-sheath jets via kKHI (Nishikawa et al. 2014, ApJ)

- $(L_x, L_y, L_z) = (1005\Delta, 205\Delta, 205\Delta)$, $\lambda_s = c/\omega_{pe} = 12.2\Delta$
- (a) slab model, $v_{sheath} = 0$, $v_{core} = 0.9978$ ($\gamma_{core} = 15$), $v_{am,th,e} = 0.030$, $v_{jt,th,e} = 0.014$
- (b) $e^- - p^+$ plasma jet, $m_p/m_e = 1836$
- (c) $e^\pm$ plasma jet



- color bar: y-component of generated magnetic field (red: positive, blue: negative)

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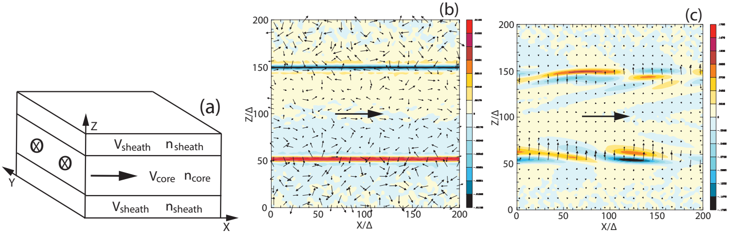

- static electric field grows due to the charge separation by the negative and positive current filaments

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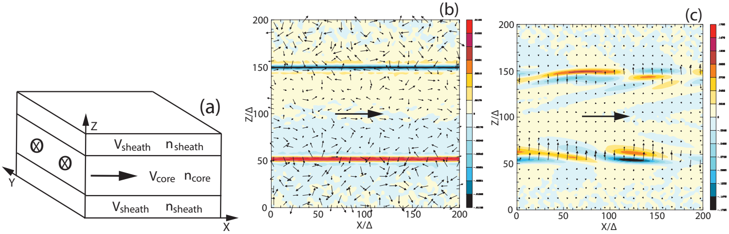

- current filaments at velocity shear generate magnetic field transverse to the jet along the velocity shear

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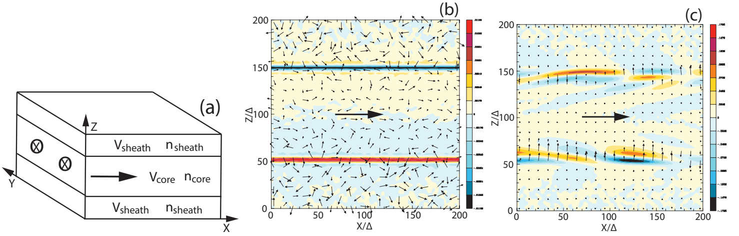

- non-relativistic jet generate kKHI quickly and magnetic field grows faster than the jet with higher Lorentz factor

Outline

- Global jet simulations with shock and kKHI (Nishikawa et al. 2016, ApJ)
- Global jet simulations with helical magnetic field - reconnection (Nishikawa et al. 2016, galaxies)
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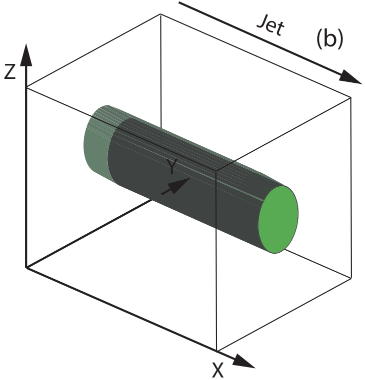
Global jet simulations with shock and kKHI with large simulation system

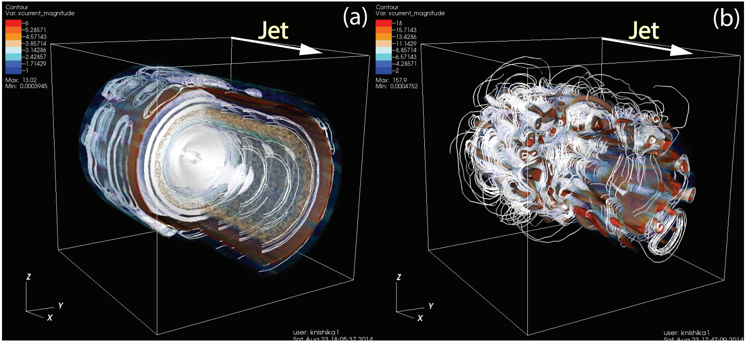
- cylindrical kKHI simulations (Nishikawa et al. 2014, 2016)
- system size $(2005\Delta, 1005\Delta, 1005\Delta)$, jet radius 100Δ, total particles 48.8 billions
- jet length 1700c $\sim$ 10 μpc

NASA Pleiades:
10,000 processors
5.76TB memory
7.55 hours



Cylindrical kKHI simulations

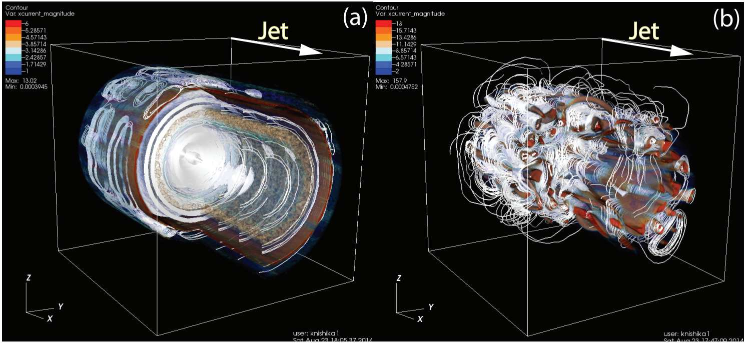
(Nishikawa et al. 2014, 2016)



- (a) e^{-}-p^{+} plasma jet, (b) $e^{\pm}$ plasma jet
- J_{x} current magnitude with magnetic field lines (white lines) at simulation time $t = 300\,\omega_{\mathrm{pe}}^{-1}$

Cylindrical kKHI simulations

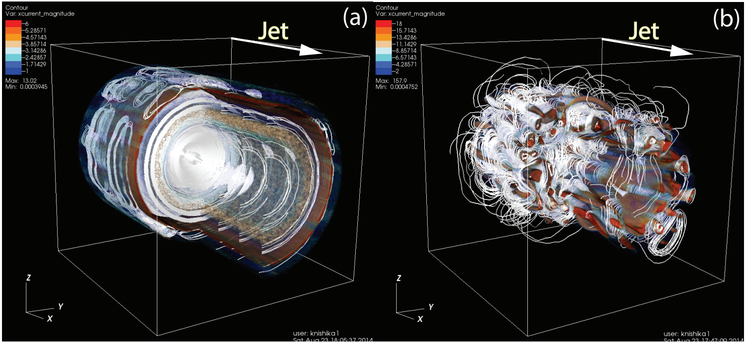
(Nishikawa et al. 2014, 2016)



- (a) currents are generated in sheet-like layers and magnetic fields are wrapped around jet; toroidal magnetic fields outside of the jet show signatures of kKHI and MI

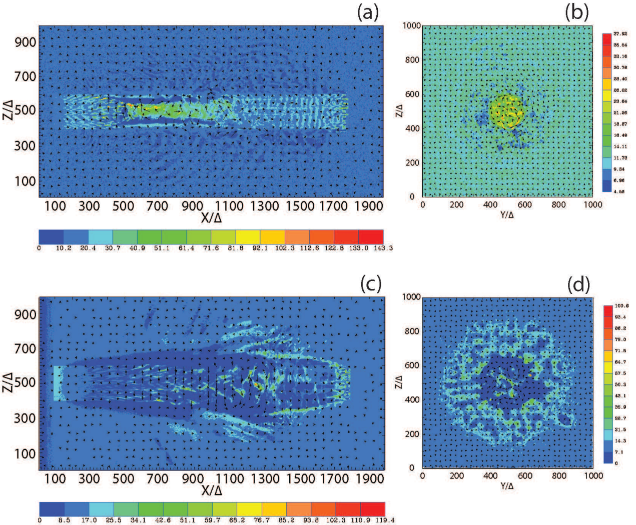
Cylindrical kKHI simulations

(Nishikawa et al. 2014, 2016)



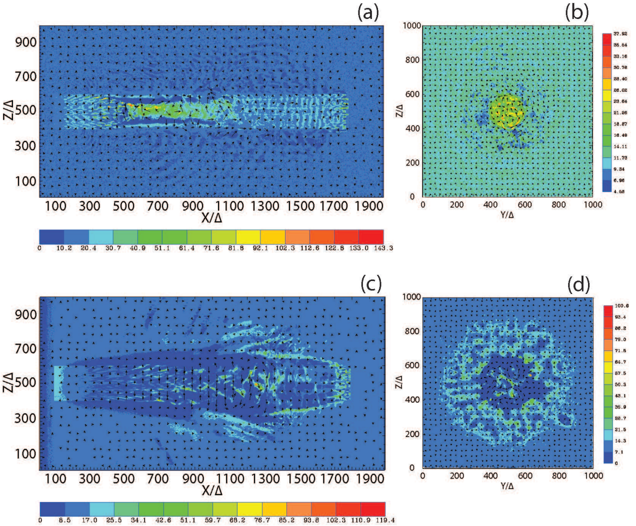
- (b) many distinct current filaments are generated near the velocity shear; individual current filaments are wrapped by the magnetic field – indication of MI

Electron density



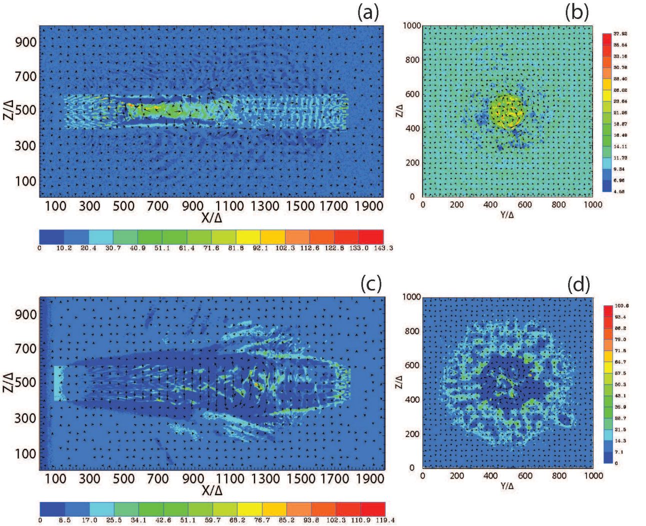
- colors: electron density; arrows: magnetic field
- (a-b) e^--p^+ jet; (c-d) $e^{\pm}$ jet
- (b) at $500X/\Delta$; (d) at $1200X/\Delta$

Electron density



- (a) jet collimation $500 - 700X/\Delta$ due to toroidal magnetic field generated by kKHI and MI; no collimation after $1000X/\Delta$

Electron densitv

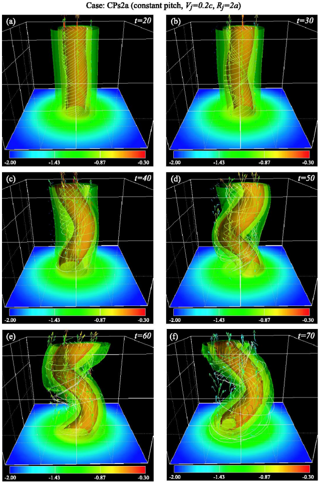


- (c) mixed jet & ambient particles at velocity shear; Weibel instability excited at $1250X/\Delta$; particles move away from jet at the velocity shear due to kKHI

3D kink instability with helical magnetic field

(Mizuno et al. 2011, ApJ)

- relativistic jets with helical magnetic field, which leads to the kink instability and subsequent reconnection, can be simulated using rezistive relativistic MHD
- Mizuno et al. simulations were performed with ideal RMHD code



Global jet simulations with helical magnetic field

- $(L_x, L_y, L_z) = (645\Delta, 131\Delta, 131\Delta)$
- periodic boundary conditions
- $n_{\rm jt} = 8$ and $n_{\rm am} = 12$
- jet with radius $r_{\rm jt} = 20\Delta$ is injected in the middle of the $y - z$ plane $((y_{\rm jc}, z_{\rm jc}) = (63\Delta, 63\Delta))$ at $x = 100\Delta$
- $\lambda_{\rm s} = c/\omega_{\rm pe} = 10.\Delta$
- $\lambda_{\rm D} = 0.5\Delta$
- $v_{\rm jt,th,e} = 0.014c$, $v_{\rm am,th,e} = 0.030c$
- $m_{\rm p}/m_{\rm e} = 1836$ $\gamma_{\rm jt} = 15$, $v_{\rm am} = 0$

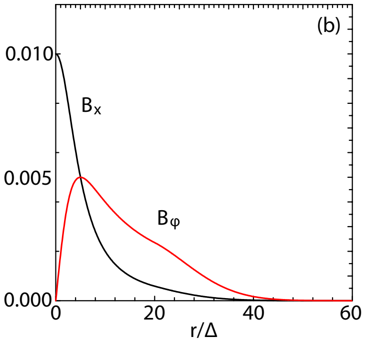
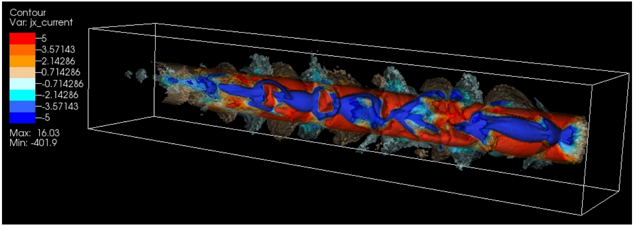


Figure: Magnetic field component profiles across the jet. Using Mizuno et al. 2015, helical magnetic field. Field structure taken with damping applied outside of the jet.

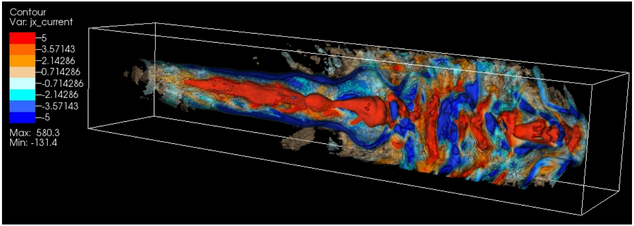
(Nishikawa et al. galaxies, 2016)

Global jet simulations with helical magnetic field

(a)



(b)

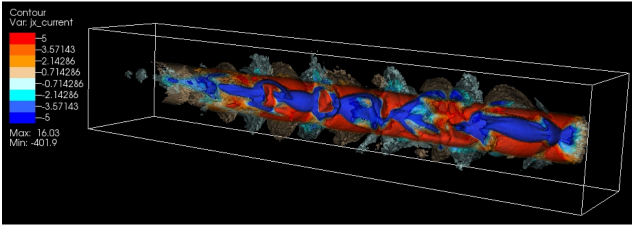


- isocontour plots of the J_x intensity at the center of the jets at $t = 500\,\omega_{\rm pe}^{-1}$
- (a) e^--p^+ jet, (b) $e^\pm$ jet

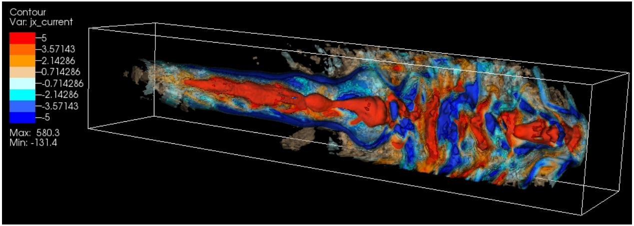
(Nishikawa et al. galaxies, 2016)

Global jet simulations with helical magnetic field

(a)



(b)



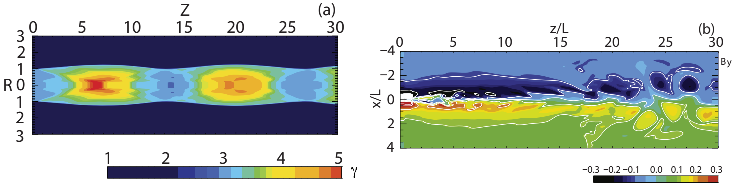
- (a) recollimation-like shocks are seen
- (b) growing instabilities and currents expanding outside the jet leading to a turbulent current density structure

(Nishikawa et al. galaxies, 2016)

Movie: Recollimation-like shocks

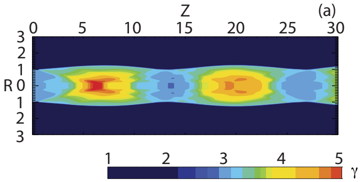
(Nishikawa et al. galaxies, 2016)

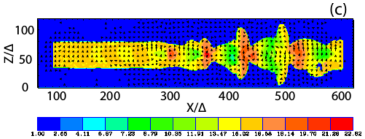
Results from MHD simulations



- (a) 2D plot of the Lorentz factor for HMF case with $B_0 = 0.2$ at $t = 200$ (Mizuno et al. 2015)
- (b) azimuthal magnetic field component B_y with $|B_y|$ magnitude contours for the case of decreasing density with $\Omega_0 = 4$ at $t = 70$. The disruption of helical magnetic fields can be caused by the current-driven kink instability (Singh et al. 2016)

Comparing our results with Mizuno et al. 2015

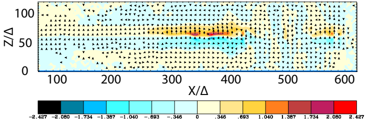


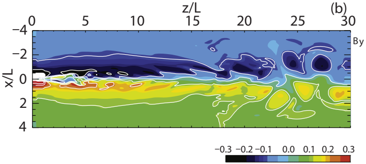


- (a) 2D plot of the Lorentz factor for HMF case with $B_0 = 0.2$ at $t = 200$ (Mizuno et al. 2015)
- (c) Lorentz factor of jet electrons for e^--p^+ $(y/\Delta = 63)$ at time $t = 500\,\omega_{\mathrm{pe}}^{-1}$

(Nishikawa et al. galaxies, 2016)

Comparing our results with Singh et al. 2016





- (a) B_y for the $e^{\pm}$ jet case
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Summary for global jet simulations without HMF

- Size of jet radius is critical for the evolution of jets
- Simulations with jet radius $r_{\rm jet} = 200\Delta$ show clear differences for electron-proton and electron-positron jets
- Electron-proton jet shows jet collimation due to the toroidal magnetic field generated by kKHI
- Electron-proton jet shows the well-defined jet boundary by the edge current by protons
- Electron-positron jet shows the growth of kKHI and the Weibel instability which generate the strong current filaments expanding outside the jet
- Electron-proton jet shows strong toroidal magnetic field in the whole jet which may contribute circularly-polarized radiation

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- These simulations show new type of growing instabilities for both electron-proton and pair plasma jets
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- New instabilities appear, associated with recollimation shocks and current-driven kink instability
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- Evidence for growth of a kink-like instability in the electron-positron jet

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