Particle-in-cell Simulations for Relativistic Jets in Gamma-ray Bursts

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Hartmann, D. H. (University of Clemson, USA)

Using computational resources for parallel applications

- 18PF when fully deployed
- 4,200 Intel Knights Landing nodes, each with 68 cores, 96GB of DDR RAM, and 16GB of high speed MCDRAM
- 1,736 Intel Xeon Skylake nodes (to be added fall 2017)

https://www.tacc.utexas.edu/systems/stampede2

- Stampede 2, Maverick, and Ranch at University of Texas
- Comet and Gordon at San Diego Supercomputer Center
- Pleiades at NASA; For our large-scale simulations: e.g., 10,000 cores, 5.76TB memory, 7.55 hours cpu time

Outline

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Questions

- Why do we need particle-in-cell (or kinetic) plasma simulations for GRB jets?
- Particle-in-cell (PIC; microscopic level) & magnetohydrodynamics (MHD; macroscopic level), both can be used to describe relativistic jets
- MHD cannot explain the generation of magnetic field, particle acceleration, and emission of radiation in a self-consistent way
- PIC can provide insights into the processes at work in the GRBs; possible answers for shocks, magnetic reconnection, and flares
- However, we need two main ingredients:
  - a scalable numerical code for very large simulation system
  - compare the synthetic spectra with those obtained from observations

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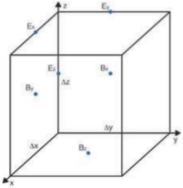
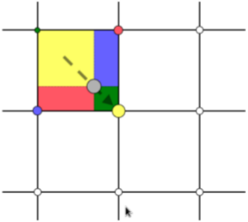
PIC code

- fields are discretized on a finite 3D mesh (the computational grid); 3D Yee mesh is used to store the magnetic and electric fields
- a tri-linear interpolation function (linear in each spatial dimension) is used to interpolate the electric and magnetic fields to the particles positions



- PIC uses computational particles (called macro-particles) composed of ions and electrons
- weight factors for each node volume



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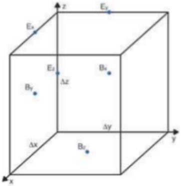


- fields are discretized on a finite 3D mesh (the computational grid); 3D Yee mesh is used to store the magnetic and electric fields
- a tri-linear interpolation function (linear in each spatial dimension) is used to interpolate the electric and magnetic fields to the particles positions
- these fields are then used to advance the velocity of the particles in time via the Lorentz force equation
- charges and currents derived from the particles velocities and positions are then used as source terms to re-calculate the electromagnetic fields

Gamma-ray bursts jets

- GRBs are the most extreme explosions in Universe
- they release $\sim 10^{55}$ erg within a few secs as γ-rays
- long (> 2 seconds) GRBs and short (< 2 seconds) GRBs
- long GRBs: deaths of massive stars
- short GRBs: merger of two compact objects (neutron stars or black holes)
- furthest GRB at redshift z=9.4 ($\sim$ 13.14 billion years ago)

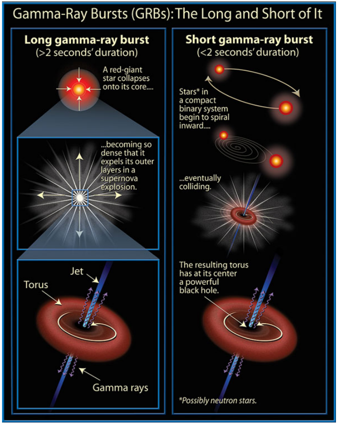
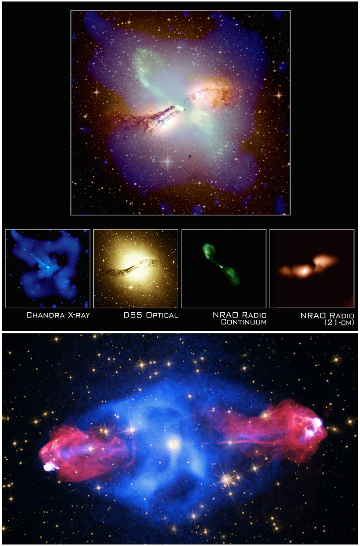
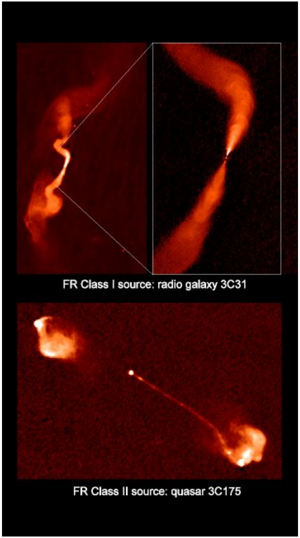


Figure: www.nasa.gov

Relativistic jets in AGN



Centaurus A (up) & Cygnus A (down)



Gamma-ray bursts jets

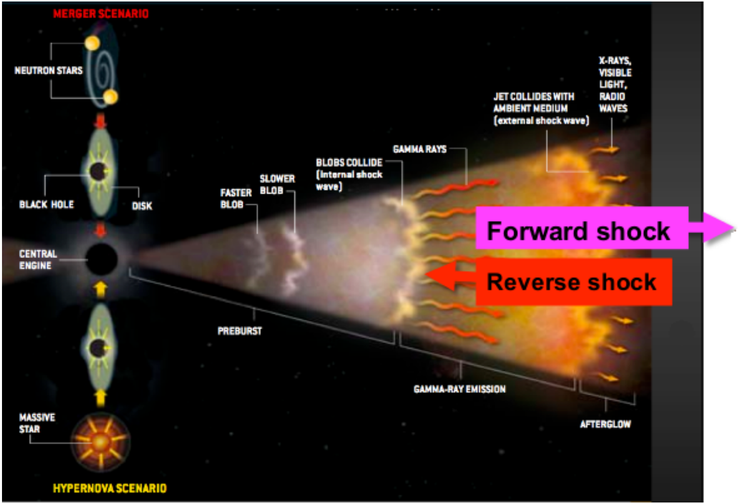
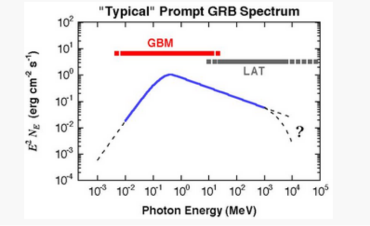
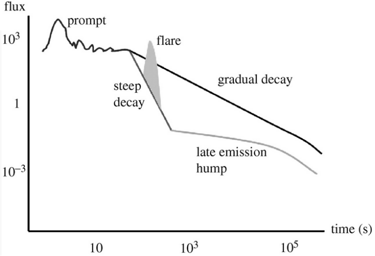


Figure: Image credit: www.nasa.gov

Spectra of gamma-ray bursts

- Present: Fermi (GLAST Burst Monitor, GBM, & Large Array Telescope, LAT) & Swift (Gamma-ray burst monitor, X-ray, UV/optical instruments)





- prompt spiky emission, primary observed in the keV-MeV with no preferred pattern in the lightcurves
- emission is fallowed by a smooth afterglow, observed in X-ray, optical, radio with non-thermal spectra

Formation of jets from black holes with GRMHD

- General Relativistic Magnetohydrodynamic simulation of jet formation from black holes (Duțan, Mizuno, & Nishikawa, PhD 2011)

Propagation of jets from black holes with RMHD

- Relativistic Magnetohydrodynamic simulation of jet propagation containing helical magnetic fields (Mizuno et al. 2012)

Propagation of jets from black holes

- Development of kink instability in MHD simulation of jet propagation with helical magnetic fields (Mizuno et al. 2012)

Astrophysical jet plasma in the kinetic limit

- collisionless plasma: diffuse, high temperature plasma
  - large free path of particles, larger than, e.g., the gyroradius
- instabilities arise from the interaction between particles and the waves that they produce, and not from collisions between particles
- examples of kinetic (or micro)instabilities driven by anisotropy of the particle velocity distribution function:
  - electromagnetic instabilities: Weibel instability
    - develops inside the jet
    - shows current filaments
  - velocity shear layer instabilities: Kelvin-Helmholtz & Mushroom instabilities
    - develop at the jet interface with the ambient medium
    - show vortex- and "mushroom"-like structures

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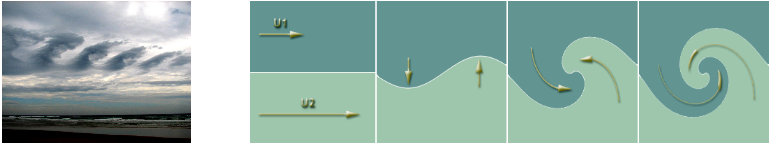
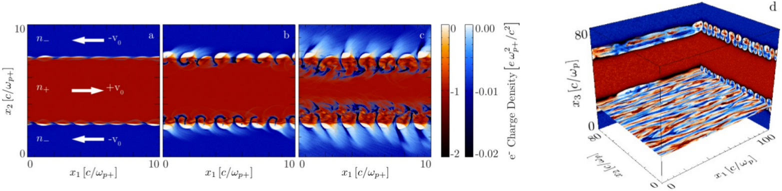
Weibel instability

- Weibel instability can generate magnetic fields from scratch and produce collisionless shocks, where particles are accelerated and radiation is emitted (Nishikawa 2012)

Kelvin-Helmholtz and Mushroom instabilities (KHI, MI)



Development of KHI at velocity shears

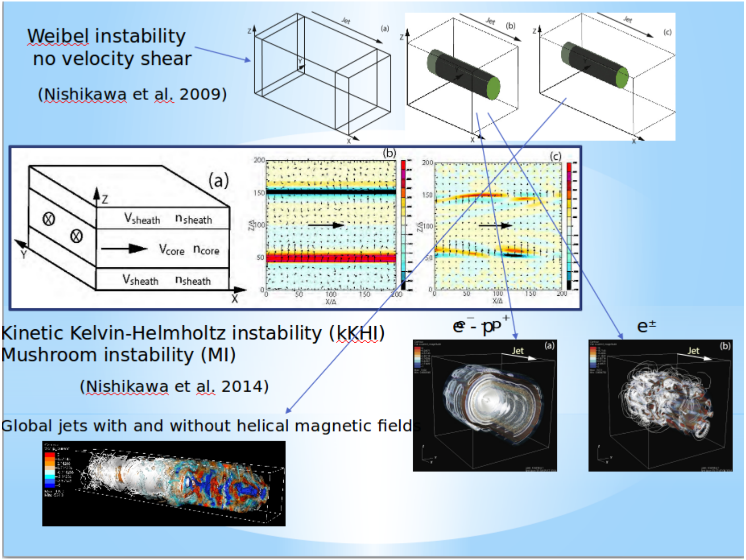


PIC simulation of counter-stream flows (Alves 2012)

Left: KHI & Right: MI

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) simultaneously
- we included jets with helical magnetic field



Weibel instability
no velocity shear

(Nishikawa et al. 2009)

Kinetic Kelvin-Helmholtz instability (kKHI)
Mushroom instability (MI)

(Nishikawa et al. 2014)

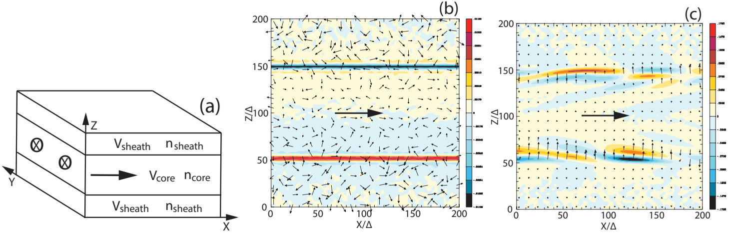
Global jets with and without helical magnetic fields

$e^- - p^+$

$e^\pm$

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

- $(L_\mathrm{x}, L_\mathrm{y}, L_\mathrm{z}) = (1005\Delta, 205\Delta, 205\Delta)$, $\lambda_\mathrm{s} = c/\omega_\mathrm{pe} = 12.2\Delta$
- (a) slab model, $v_\mathrm{sheath} = 0$, $v_\mathrm{core} = 0.9978$ ($\gamma_\mathrm{core} = 15$), $v_\mathrm{am,th,e} = 0.030$, $v_\mathrm{jt,th,e} = 0.014$
- (b) $e^- - p^+$ plasma jet, $m_\mathrm{p}/m_\mathrm{e} = 1836$
- (c) $e^\pm$ plasma jet



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

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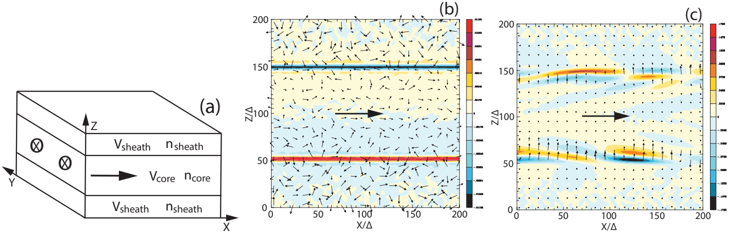

- static electric field grows due to the charge separation by the negative and positive current filaments

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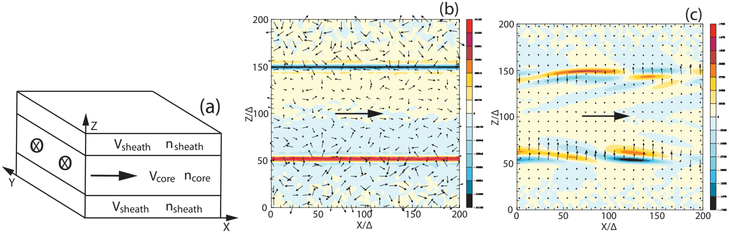
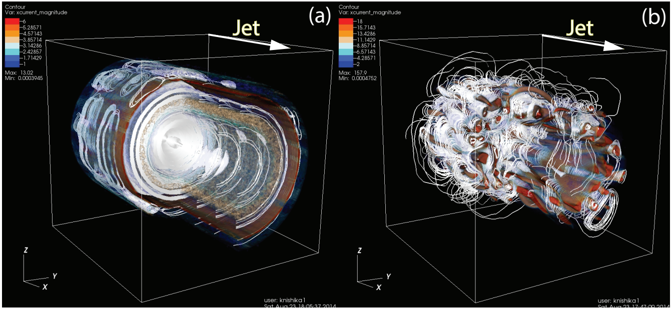


- current filaments at velocity shear generate magnetic field transverse to the jet along the velocity shear

Cylindrical kKHI simulations

(Nishikawa et al. 2014, 2016)

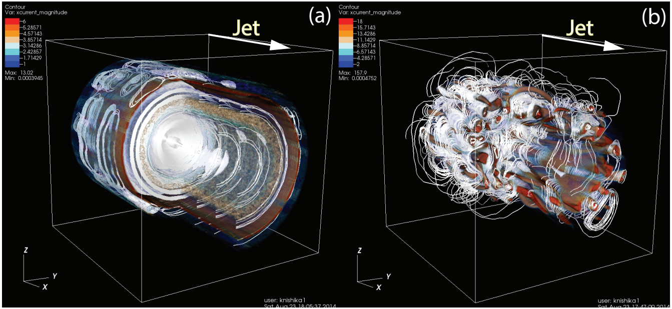
- (a) e^--p^+ jet; (b) $e^\pm$ jet
- (a) currents are generated in sheet-like layers and magnetic fields are wrapped around jet; toroidal magnetic fields outside of the jet show signatures of kKHI and MI



Cylindrical kKHI simulations

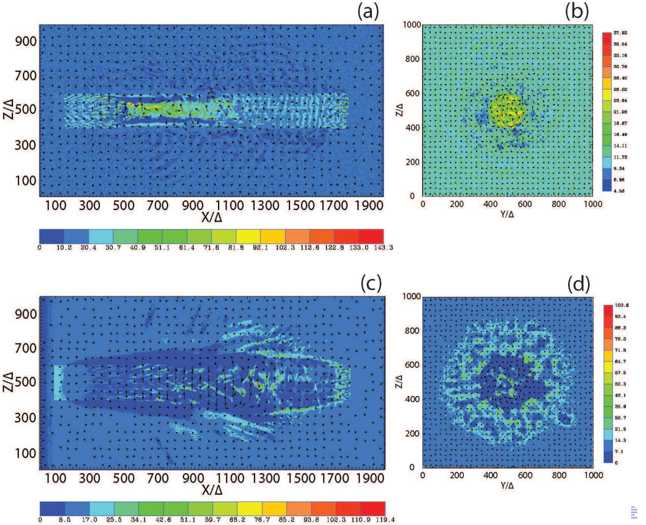
(Nishikawa et al. 2014, 2016)

- (a) e^{-}-p^{+} jet; (b) $e^{\pm}$ jet
- (b) many distinct current filaments are generated near the velocity shear; individual current filaments are wrapped by the magnetic field – indication of MI



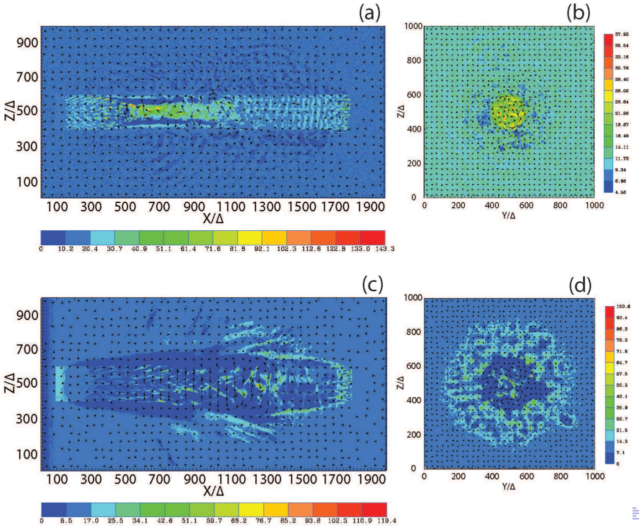
Electron density

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



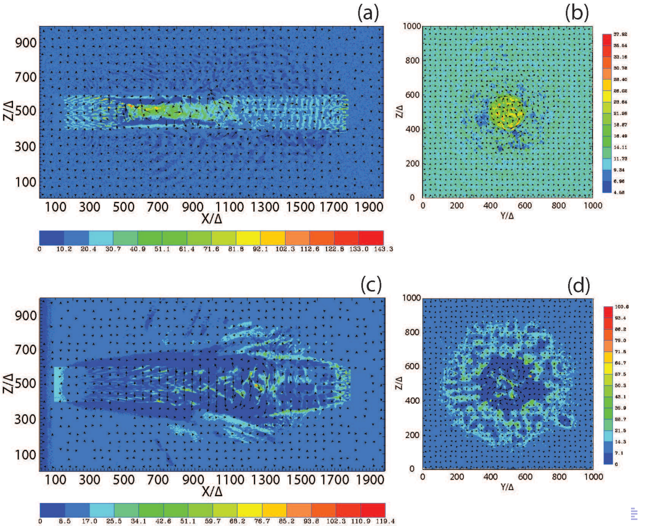
Electron density

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



Electron density

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



Global jet simulations with helical magnetic field

(Nishikawa et al. 2016, Galaxies, Duțan et al. 2017, IAU)

- $(L_x, L_y, L_z) = (645\Delta, 131\Delta, 131\Delta)$
- 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 $x = 100\Delta$
- $\lambda_{\rm s} = c/\omega_{\rm pe} = 10.\Delta$
- $\lambda_{\rm D} = 0.5\Delta$
- $v_{\rm jt,th,e} = 0.014c$, $v_{\rm am,th,e} = 0.030c$
- $m_{\rm p}/m_{\rm e} = 1836$

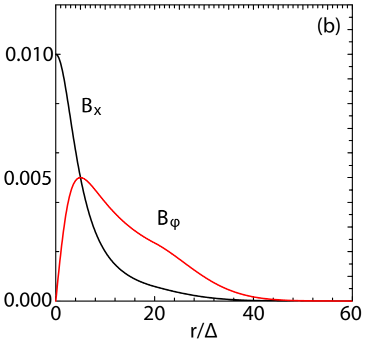
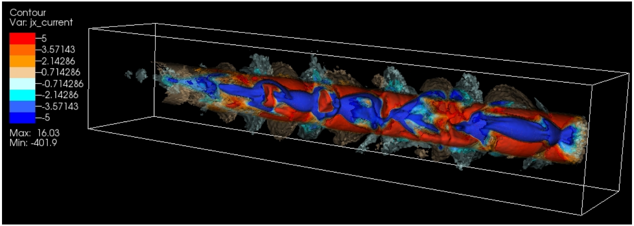


Figure: Magnetic field component profiles across the jet. Field structure taken with damping applied outside of the jet with length-scale b = 200. Jet boundary is located at $r_{\rm jet} = 20\Delta$.

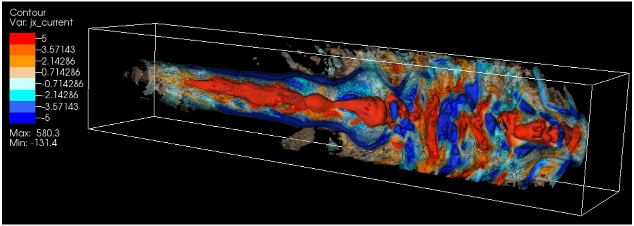
Global jet simulations with helical magnetic field

- 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

(a)



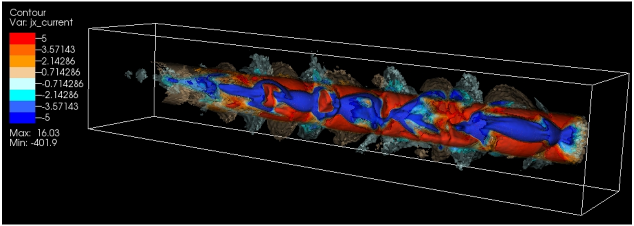
(b)



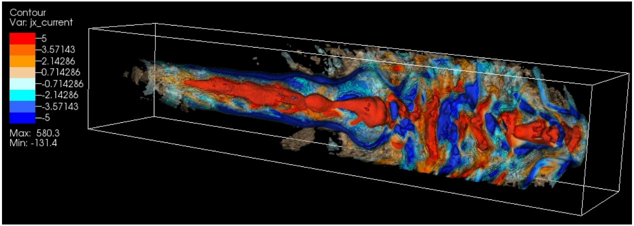
Global jet simulations with helical magnetic field

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

(a)

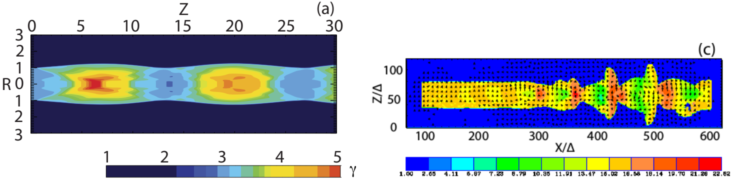


(b)



Comparing our results with Mizuno et al. 2015

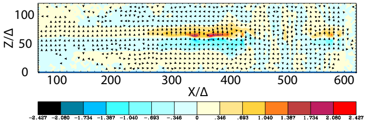
- (a) 2D plot of the Lorentz factor for HMF case with $B_0 = 0.2$ at $t = 200$ (MHD, Mizuno et al. 2015)
- (b) Lorentz factor of jet electrons for e^--p^+ ($y/\Delta = 63$) at time $t = 500\,\omega_{\rm pe}^{-1}$ (our PIC simulations)

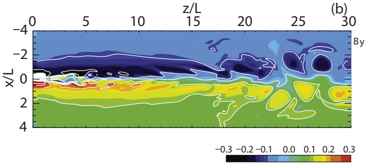


(Nishikawa et al. 2016, Galaxies)

Comparing our results with Singh et al. 2016

- (a) B_y for the $e^{\pm}$ jet case (our PIC simulations)
- (b) azimuthal magnetic field component B_y with $|B_y|$ magnitude contours for the case of decreasing density with $\Omega_0 = 4$ at $t = 70$ (MHD, Singh et al. 2016)
- disruption of helical magnetic fields can be caused by the current-driven kink instability





(Nishikawa et al. 2016, Galaxies)

Key scientific questions

- How do the kinetic instabilities lead to magnetic field generation/ amplification, particle acceleration, and emission of radiation in GRB jets?
- How the kinetic instabilities affect the evolution of shock in GRB jets?
- How do the shocks in GRB jets evolve in various ambient plasma and magnetic field configurations?
- How do the helical magnetic fields affect shocks and reconnection?
- How is the magnetic field energy released in jets? Reconnection?

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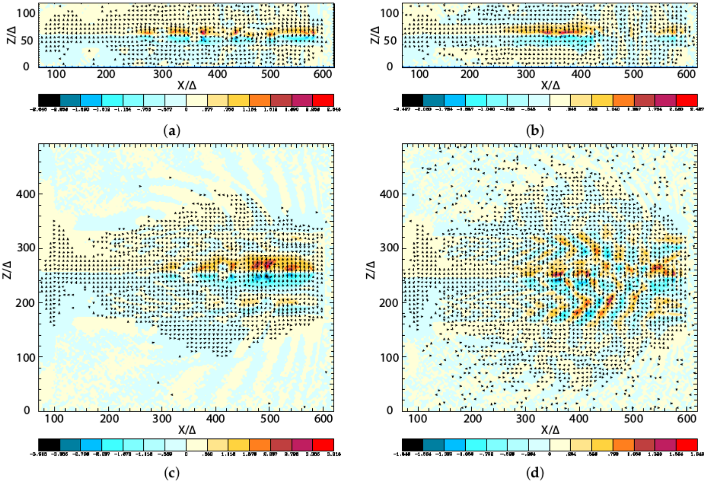
Global jet simulations with helical magnetic field

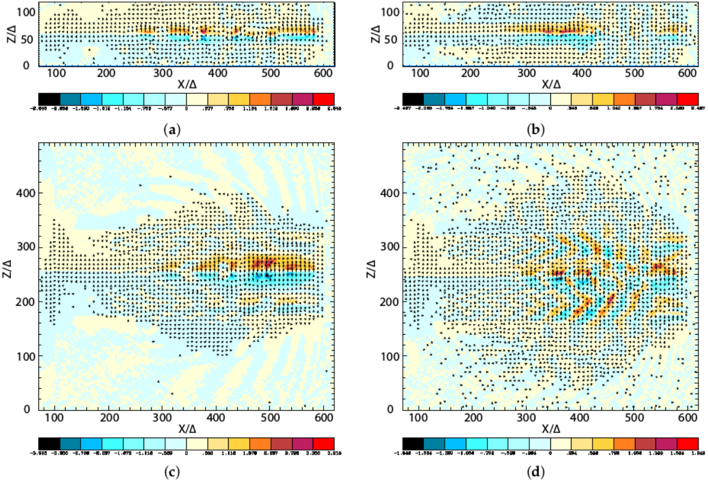
- isocontour plots of $|B_{\mathrm{y}}|$ at the center of jets, $t = 500\,\omega_{\mathrm{pe}}^{-1}$
- (a,c) e^{-}-p^{+} jet, (b,d) $e^{\pm}$ jet; $r_{\mathrm{jt}} = 20$ and 80Δ



(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- for thicker jet, disruption of helical magnetic fields is seen
- caused by instabilities and/or reconnection

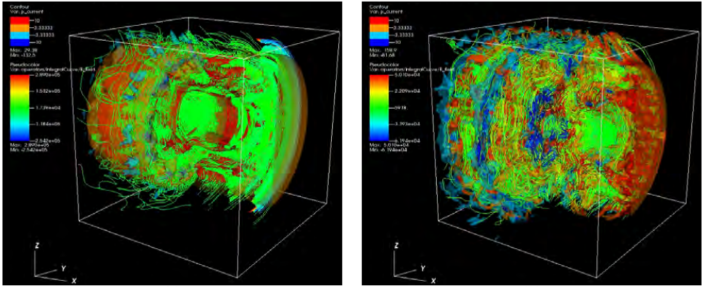


(a) (b) (c) (d)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- 3D isosurface plots of the J_x intensity at $t = 500\,\omega_{\rm pe}^{-1}$
- (a) e^--p^+ jet, (b) $e^{\pm}$ jet; $r_{\rm jt} = 80\Delta$

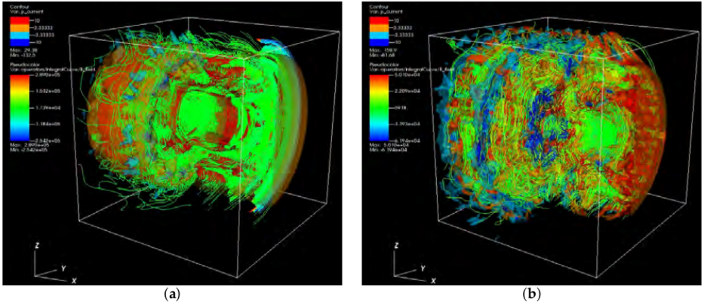


(a) (b)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

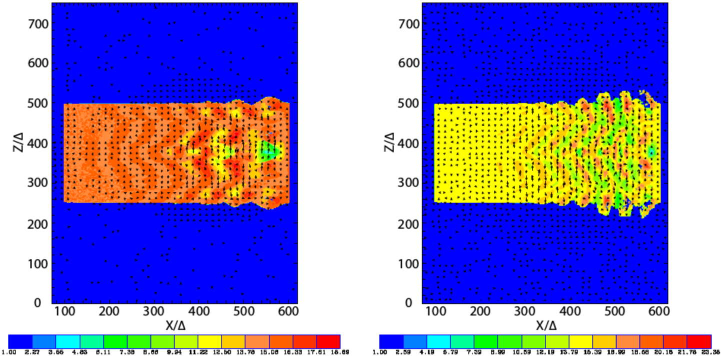
- plots show complicated patterns from instabilities
- helical magnetic field is disrupted
- different from jet without helical magnetic field



(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- for particle acceleration, 2D plots of the Lorentz factor of jet electrons
- (a) e^{-}-p^{+} jet, (b) $e^{\pm}$ jet; $r_{\rm jt} = 120\Delta$, $t = 500\,\omega_{\rm pe}^{-1}$

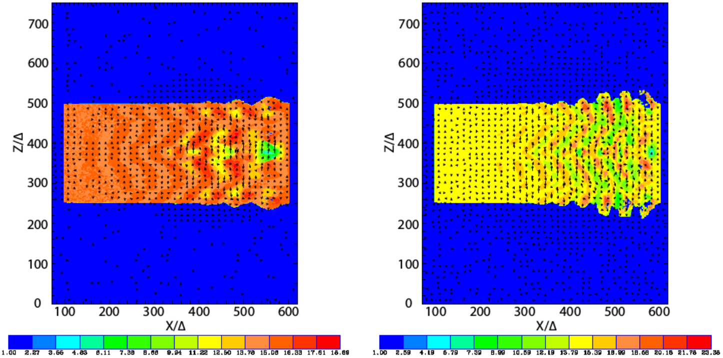


(a) (b)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- patterns of the Lorentz factor coincided with the changing directions of local magnetic fields that were generated by instabilities
- arrows (black spots) show magnetic fields in (x, z) plane

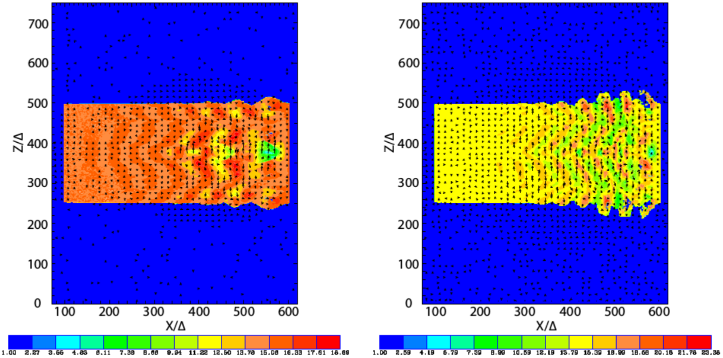


(a) (b)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- structures at the edge of jets are generated by the kKHI.
- recollimation-like shock is found more clearly in the e^--p^+ jet (corn-shaped weaker Lorentz factor with the light green)

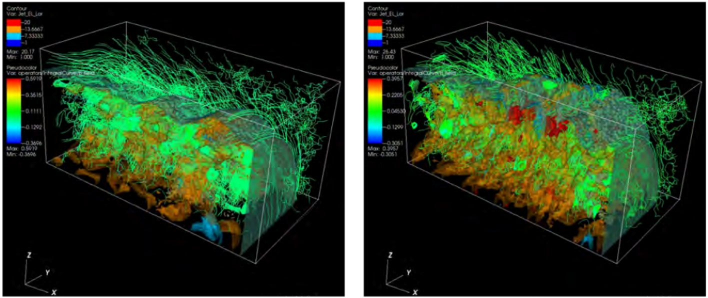


(a) (b)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- for particle acceleration, 3D isosurface plots of the Lorentz factor of jet electrons
- (a) e^{-}-p^{+} jet, (b) $e^{\pm}$ jet; $r_{\rm jt} = 120\Delta$, $t = 500\,\omega_{\rm pe}^{-1}$
- color scales for the contour (upper left) for (a,b) are red: 20.0; orange: 13.67; right blue: 7.33; blue: 1

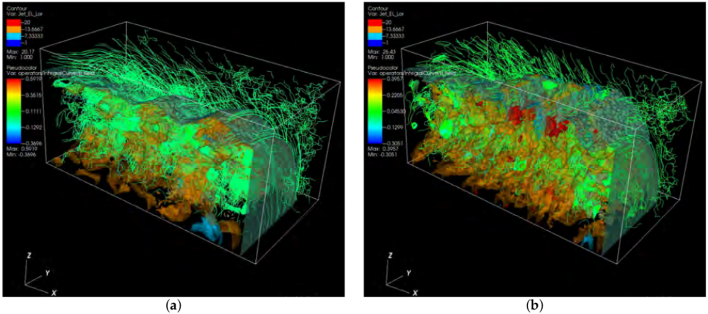


(a) (b)

(Nishikawa et al. 2017, Galaxies)

Global jet simulations with helical magnetic field

- lines show the magnetic field stream lines in the quadrant of the front part of jets
- plots of Lorentz factor in (y, z) plane show Mushroom instability in the circular edge of the jets
- red zones, possibly magnetic reconnection



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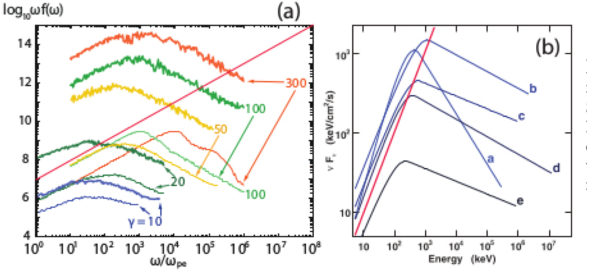
Further work: Calculation of radiation spectra directly from simulations

- we will compare synthetic spectra with those obtained from observations, and their spectral evolution
- use the method employed by Nishikawa et al. 2009



- (a) shows the spectra for Lorentz factor 10, 20, 50, 100, and 300 with cold (thin lines) and warm (thick lines) electron jets

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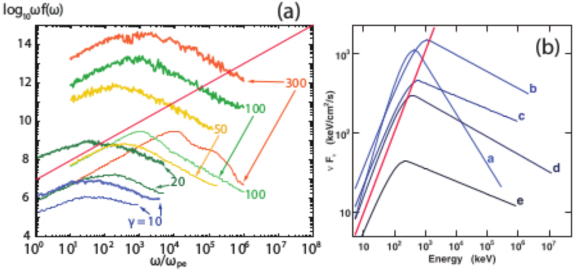

- (b) shows modeled Fermi spectra at early (a) to late (e) times of GRB080916C (Abdo et al. 2009, Science)

Summary

- simulation of jets containing helical magnetic fields show new type of growing instabilities
- presence of helical fields suppresses the growth of the kinetic instabilities, such as the Weibel instability, kKHI, and MI
- electron-proton jet shows recollimation-like shock structures in the current density, similar to recollimation shocks observed in RMHD simulations.
- electron-positron jet presents growth of a kink-like instability
- scalable global jet simulations for thicker jets: distortion of the HMF, reconnection
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