Microscopic Processes in Global Relativistic Jets Containing Helical Magnetic Fields

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Outline of talk

1. Introduction of relativistic jets and Weibel instability
   (Nisikawa et al 2009)

2. Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability

3. Global jet simulations with shock and KKHI with large simulation system
   \[ r_{jt} = 100\Delta \]

4. Global jet simulations with helical B fields (reconnection)
   (Nishikawa et al. Galaxies, 4, 38, 2016b)
   \[ r_{jt} = 20\Delta \]

5. New results with larger jet radius with short system
   \[ r_{jt} = 40\Delta, 80\Delta, 120\Delta \]
   (Nishikawa et al. Galaxies, 5, 58, 2017)

6. Synthetic Spectra and Polarity Images

7. Summary

8. Future plans
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 are particles accelerated?
• How do helical magnetic fields affect the Weibel instability and kKHI depending on the jet radius?
• 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 in jets released?
• Jets in Jets really happen due to reconnection?
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
Why we need to perform huge RPIC simulations of relativistic jets

- Kinetic processes are important for particle acceleration and global jet evolution
- Relativistic jets are generated from black hole with twisted strong magnetic field, which contributes for accelerate particles to very high energy via reconnection, therefore RPIC simulations of relativistic jets with helical magnetic fields can give an answer to this issue
- Kinetic instability such as kinetic Kelvin-Helmholtz instability (kKHI), Mushroom instability (MI), and the Weibel instability are ubiquitous and responsive to global evolution of jets, how they grow with helical helical magnetic fields
- AGN jets are considered for generation of high energy cosmic ray, but it requires global kinetic simulations to take into account of particle acceleration due to reconnection, which has been proposed one of possible mechanism
- At the present time no self-consistent generation of jets except GRMHD simulations (no particle acceleration is not included in GRMHD simulations)
- Investigate the cross-scale coupling for two of the most ubiquitous plasma processes that are essential to the dynamics of the relativistic jets: magnetic reconnection and plasma turbulence
- Huge supercomputer such as Pleiades and Blue Waters will make it possible for us to do a study by being able to push our simulations to the largest size possible on any supercomputer today in order to implement macroscopic processes as in fluid models
- The ability to simulation the microphysical processes responsible for reconnection, turbulence and for high energy particle acceleration is increasingly important as new cosmic-ray and neutrino observation such as Cherenkov Telescope Array (CTA), IceCube and present missions advance their observations
- This RPIC global jet simulations are new and innovative and will provide complex evolution of relativistic jets with kinetic processes which cannot be done by RMHD simulation
3D global jet simulation

NASA Pleiades

Jet injection orifice with helical magnetic fields

Jet length: 10µpc
≈1700c

Jet head (Top hat density shape)

Jet head (Top hat density shape)

system size: 2000Δ×1000Δ×1000Δ
jet radius: 100Δ

Total particles: 48.8 billions

Haswell 7.1GB/processor
10,000 processors
5.76TB memory
7:55 hours

Ambient plasma
The y component of magnetic field ($B_y$) in x-z plane at the center of jet ($E_{x,z}$)

- No helical magnetic fields
- $e^- - p^+$
- $e^\pm$
- Polarity switched clockwise
- Polarity switched counterclockwise
- Present short simulations

(Nishikawa et al. 2016a)
Reconnection in astrophysical system


(Alves’s poster, Giannios’s talk, Siyao Xu’s talk, Petropoulou’s talk)
**Global simulations with helical magnetic field**

Helical magnetic field

\[ B_0 = 0.1c \quad \sigma = B^2/n_e m_e \gamma_{\text{jet}} c^2 = 2.8 \times 10^{-3} \]

\[ B \approx 1 \text{mG (if } n_e \approx 30/\text{cm}^3) \]

\[ r_{\text{jt}} = 20\Delta \]

\[ X = 101\Delta \]

(Nishikawa et al. Galaxy, 2016b)
$e^- - p^+$ jet with $\gamma = 15$ \hspace{1cm} (120\Delta < x < 620\Delta, \hspace{0.5cm} 16\Delta < y, z < 116\Delta) \hspace{1cm} r_{jt}=20\Delta$

$B_0 = 0$ \hspace{1cm} White lines: magnetic field lines

Clipped at $x = 320\Delta, y = 66\Delta$
Particle Acceleration in Helically Magnetized RPIC Jets

$r_{jt} = 20\Delta$

$B_0 = 0.1$

$B_0 = 0$

$\gamma = 15$

$t = 500\omega_{pe}^{-1}$

$e^- - p^+$ jet

(a)

$e^\pm$ jet

(b)

(c)

(d)
Average Lorentz factor of jet electrons

$e^- \cdot p^+ \text{ jet}$

$r_{jt}=40\Delta$

$e^\pm \text{ jet}$

$r_{jt}=20\Delta$

$\gamma = 15 \quad B_0 = 0.1$

$t = 500\omega^{-1}_{pe}$

Electrons

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Average Lorentz factor of jet electrons

\[ \gamma = 15 \quad B_0 = 0.1 \quad t = 500 \omega_{pe}^{-1} \]

e\^− - p\^+ jet

\[ r_{jt} = 120\Delta \]

\[ 1.00 \quad 18.89 \]

\[ r_{jt} = 80\Delta \]

\[ 1.00 \quad 20.15 \]

\[ 1.00 \quad 23.38 \]

\[ 1.00 \quad 25.64 \]
Particle Acceleration in Helically Magnetized RPIC Jets

- **$r_{jt} = 40\Delta$**
  - red: $\gamma v_x$
  - blue: $\gamma v_y$

- **$r_{jt} = 20\Delta$**

- **$B_0 = 0.1$**
- **$\gamma = 15$**
- **$t = 500\omega_{pe}^{-1}$**

- **$e^-$ - $p^+$ jet**
- **$e^\pm$ jet**
Particle Acceleration in Helically Magnetized RPIC Jets

\[ t = 500 \omega^{-1}_{pe} \]

\[ B_0 = 0.1 \]

\[ \gamma = 15 \]

\[ r_{jt} = 80\Delta \]

\[ r_{jt} = 120\Delta \]

\[ e^- - p^+ \text{ jet} \]

\[ e^\pm \text{ jet} \]

red: \( \gamma v_x \)
blue: \( \gamma v_y \)
Current density $J_x$ in $e^- - p^+ jet$  

$r_{jt} = 120 \Delta$

$Reconnection?$

$x = 580 \Delta$

$x = 280 \Delta$

$x = 380 \Delta$

$x = 480 \Delta$
\[ B_0 = 0.1 \]

Current density \( J_x \) in jets with MF streaming lines

\[ t = 500 \]
\[ \omega = \frac{1}{\gamma} = 15 \]
\[ r_{jt} = 120 \]
\[ \Delta r_{jt} = 40 \]

Mushroom instability, Weibel and kink-like instabilities
Current density $J_x$ in jets and MF streaming lines

$e^- - p^+ \text{ jet}$

$r_{jt} = 80\Delta$

$e^\pm \text{ jet}$

$\gamma = 15 \quad B_0 = 0.1$

$t = 500\omega^{-1}_{pe}$

$J_x$

Adiabatic Stochastic Acceleration?

$B$ vec tors
Synthetic Spectra

\[ r_{jt} = 80 \Delta \]

- head-on radiation
- \( 5^\circ \) off-axis angle

\[ B_0 = 0.1c, \; \gamma_{jet} = 15 \]
\[ \gamma_{jet} = 100, \; \text{pair jet} \]
**Image maps of polarity**

\[ r_{\text{jet}} = 40\Delta \text{ at time } t = 500 \omega_{\text{pe}}^{-1} \]

\[ \gamma_{\text{jet}} = 15 \]

\[ \nu_{\text{obs}} = 43 \text{ GHz} \]

Panels show a rendering of the total intensity in the total intensity I in the co-moving frame highlighting the structure of magnetic fields at the jet front \((420\Delta < x < 620\Delta, 29\Delta < y, z < 229\Delta)\) for the \(e^\pm\) jet with \(r_{\text{jet}} = 40\Delta \text{ at time } t = 500 \omega_{\text{pe}}^{-1} \). Total intensity (I) map at an observing frequency of 43 GHz (a). Panel (b) - Q map. Panel (c) - U map. Panel (d) - V map. In the observing frequency of \(\nu_{\text{obs}} = 43 \text{ GHz} \).
**Electron densities and** $B_y$

$e^- - p^+ \text{ jet}$

$B_y = 120\Delta$  \hspace{1cm} $\gamma = 15$

$B_0 = 0.1$  \hspace{1cm} $t = 500\omega_{pe}^{-1}$

electron density

$e^\pm \text{ jet}$

$3.597$  \hspace{1cm} $-3.597$

$282.6$  \hspace{1cm} $-1.775$

$157.5$  \hspace{1cm} $1.775$
Summary for global jet simulations with helical magnetic fields

• The evolution of jets depends on the size of jet radius
• For the small jet radius ($r_{jt} = 20\Delta$) (Nishikawa et al 2016b)
  The electron-proton jet shows recollimation shocks due to the kinetic instabilities (MI)
  The electron-positron jet shows the growth of kink-like instability which generate the turbulent current filaments expanding outside the jet
• For the larger jet radius ($r_{jt} = 80\Delta$ and $120\Delta$)
  The more complicated structures are generated by the mixed instabilities (Weibel, kKHI, MI and kink-like instability).
• Further simulations with a even larger system (larger jet radius) need to be investigated with varying the strength and structure of helical magnetic fields
Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand jet evolution with helical magnetic fields.
- Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability using larger systems.
- Investigate radiation processes from the accelerated electrons in turbulent magnetic fields and compare with observations using global simulation of shock, KKHI and reconnection with helical magnetic field in jet (GRBs, SNRs, AGNs, etc).
- Magnetic field topology analysis for understanding reconnection evolution and associated flares.
- Particle acceleration and radiation and flares in shocks and reconnection with helical magnetic field.
- Synthetic imaging with polarity.