Simulations of relativistic, collisionless shocks:
The X-ray hot spots in the M87 jet

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We investigate here the effects of plasma instabilities driven by e± pair jets. The injection of e± pairs induces strong streaming motions in the ambient medium. Using three-dimensional particle-in-cell simulations, we show that plasma instabilities driven by these streaming e± pairs are responsible for the excitation of near-equipartition, turbulent magnetic fields. Our results reveal the importance of the electromagnetic filamentation instability in ensuring an effective coupling between e± pairs and ions, and may help explain the origin of X- ray radiation from hot spots in the relativistic jets such as M87. The magnetic fields generated by the Weibel instability create highly nonuniform, small-scale magnetic fields, which contribute to the electron's transverse deflection. The radiation from electrons in these environments (jitter radiation) is different from synchrotron radiation.

Key Scientific questions

- **How do shocks in relativistic jets evolve?**
- **How are particles accelerated?**
- **What are the dominant radiation processes?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock fronts and transition regions?**
- **How do shocks in relativistic jets evolve under various ambient plasma and magnetic fields?**
- **How do magnetic fields generated by the Weibel instability contribute to jitter radiation?**

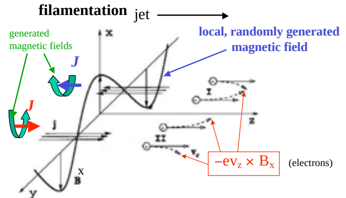
-- for some answers see Nishikawa et al. 2006, ApJ, 642, 1267 --

Ramirez-Ruiz, Nishikawa & Hededal, ApJ, Nov. 2007

Weibel instability

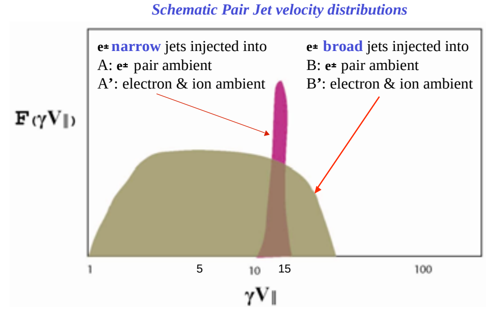
Growth time: $\tau_{growth} = \gamma_{sh}^{1/2}/\omega_{pe}$

Length: $\lambda = \gamma_{th}^{1/2} c/\omega_{pe} = (\gamma_{th}/\gamma_{sh})^{1/2}\,\tau c$

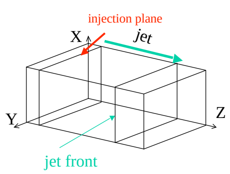


adapted from Medvedev & Loeb, 1999, ApJ 526, 697

Schematic Pair Jet velocity distributions

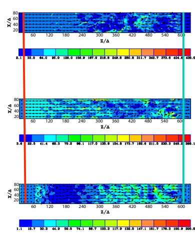


3-D RPIC simulation geometry



The system size is not scaled

Density perturbation by the Weibel instability / *Parallel current J_z (arrows: $J_{z,x}$)*

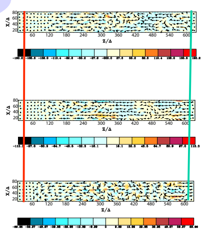


Electron-positron jet $\omega_{pe}t \sim 4\,\tau_{growth}$

A': $\gamma = 12.57$ (ele-ion ambient)

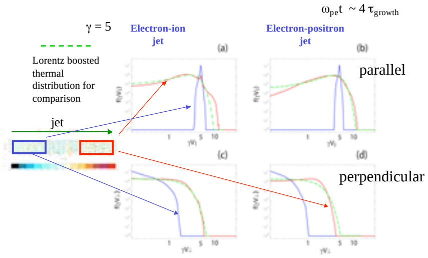
B': $2 < \gamma < 30$ (ele-ion ambient)

B: $2 < \gamma < 30$ (pair ambient)



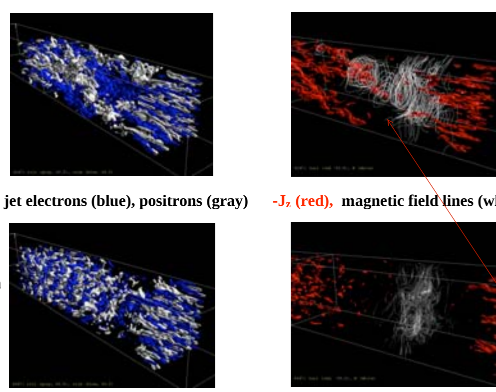
γV distribution functions (parallel, perpendicular to the jet)

$\omega_{pe}t \sim 4\,\tau_{growth}$



(Nishikawa et al. 2006)

3-D isosurfaces of density of jet particles and J_z for narrow jets ($\gamma v_{||}$=12.57)



A' **electron-ion ambient**

$t = 59.8\omega_e^{-1}$ **jet electrons (blue), positrons (gray)** **$-J_z$ (red), magnetic field lines (white)**

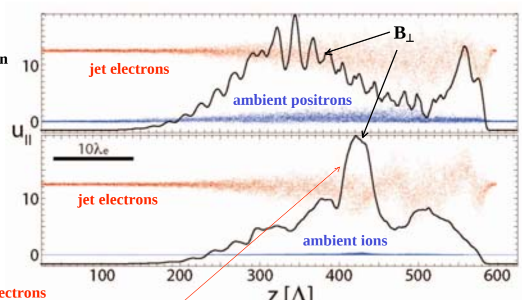
A **electron-positron ambient**

Magnetic field generation and particle acceleration with e± narrow jets ($u_{||} = \gamma v_{||} = 12.57$)

$t = 59.8\omega_e^{-1}$

electron-positron ambient $\varepsilon_{Bmax} = 0.012$

electron-ion ambient $\varepsilon_{Bmax} = 0.061$

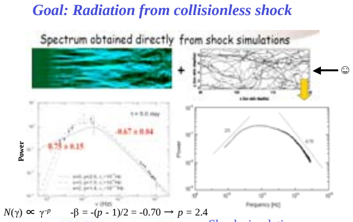


red dot: jet electrons
blue dots: ambient (positrons and ions)
$B_\perp$: arbitrary units

(Ramirez-Ruiz, Nishikawa, & Hededal, ApJ, Nov., 2007)

ambient ions generate stronger merged current filaments

Goal: Radiation from collisionless shock



$N(\gamma) \propto \gamma^{-p}$ $-\beta = -(p-1)/2 = -0.70 \rightarrow p = 2.4$

GRB 000301c (Panaitescu 2001) Shock simulations

Hededal Thesis: http://www.astro.ku.dk/~hededal (astro-ph/0506559)

ala Hededal & Nordlund 2005 (astro-ph/0511662)

Results

- **The Weibel instability creates filamented currents and density structure along the propagation axis of the jet.**
- **The growth rate of the Weibel instability depends on the Lorentz factor, composition, and strength and direction of ambient B fields.**
- **The electron-ion ambient enhances the generated magnetic fields with the excitation ion Weibel instability.**
- **This enhanced magnetic field with electron-ion ambient plasma may be an origin of large upstream magnetic fields in GRB shocks.**
- **In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.**
- **The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).**

Future plans

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics using the newly developed codes with OpenMP and MPI.**
- **Further diagnostics will be developed including calculation of jitter radiation.**
- **Implement better boundary conditions at the free boundaries**
- **Investigate radiation processes from the accelerated electrons and compare with observations (AGN, GRBs, SNRs, etc).**

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