Particle Acceleration and Emission in Relativistic Jets

Ken Nishikawa (*NSSTC/MSFC*) (homepage: http://gammaray.nsstc.nasa.gov/~nishikawa)

P. Hardee (*Univ. of Alabama, Tuscaloosa*), R. Preece (*NSSTC/MSFC*), G. Richardson (*NSSTC/MSFC*), G.J. Fishman (*NSSTC/MSFC*)

Abstract

Shock accelerations are ubiquitous phenomena in astrophysical plasmas. Plasma waves (e.g., Buneman instability, two-streaming, Weibel instabilities) created in the shock are responsible for particle (electron, positron, and ion) acceleration. Using a 3-D relativistic electromagnetic particle (REMP) code, we have investigated particle acceleration in relativistic jets[1]. Simulations show that the Weibel instability created at the shock front accelerates particles perpendicular and parallel to the jet propagation direction. This instability is also responsible in generating magnetic fields in the relativistic jets. The simulation results show that the growth rate of the Weibel instability depends on the size of the jet, composition of the jet, and the orientation and strength of ambient magnetic fields. 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 by deflected electrons is different from synchrotron radiation, which is called jitter radiation.

Motivations

- **Study particle acceleration at external and internal shocks in relativistic jets complimentary to RMHD and other test particle simulations using relativistic particle-in-cell simulations**
- **Examine the shock surfing acceleration in a 3-D system proposed in one-dimensional simulations including the dynamics of shock transition region**
- **Study structures and dynamics of shocks caused by instabilities at the shock front and transition region in relativistic jets**
- **Estimate synchrotron emission from accelerated particles**
- **Examine possibilities for afterglows in gamma-ray bursts with appropriate ambient plasmas**

[1] Nishikawa et al. 2003, ApJ, Sept. 20, Particle acceleration in relativistic jets due to Weibel instability

Scientific objects

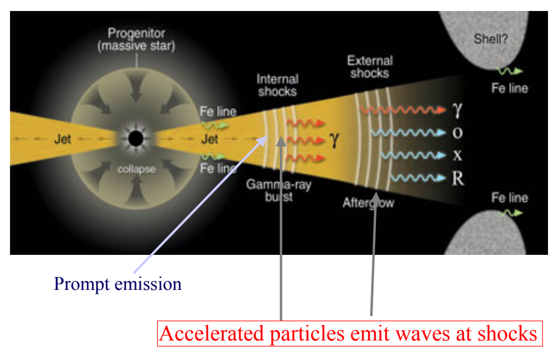
- **How do shocks in relativistic jets evolve in accelerating particles and emission?**
- **Do reverse shocks create internal shocks ?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock front and transition region?**
- **What is the main acceleration mechanism in relativistic jets, shock surfing, wakefield, Fermi models or stochastic processes?**
- **How do shocks in relativistic jets evolve in the different ambient plasma and magnetic field conditions in various astrophysical phenomena?**

Necessity of particle simulation for particle acceleration

- **MHD simulations provide global dynamics of relativistic jets including hot spots**
- **MHD simulations include heating due to shocks, however do not create high energy particles**
- **In order to take account of acceleration the kinetic effects need to be included**
- **Test particle (Monte Carlo) simulations can include kinetic effects, but not self-consistently**
- **Particle simulations provide particle acceleration and emission self-consistently, however due to the computational limitations, the size of jet is small comparing with MHD simulations**

Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)

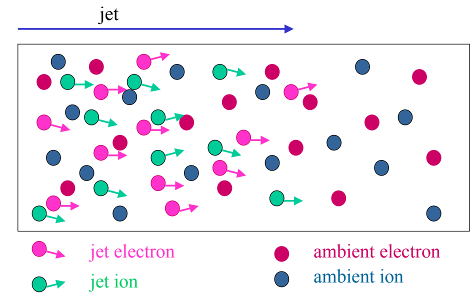


Collisionless shock

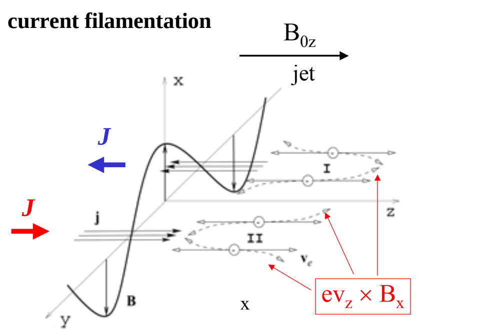
Electric and magnetic fields created self-consistently by particle dynamics randomize particles

(Buneman 1993)

$\partial B/\partial t = -\nabla\times E$
$\partial E/\partial t = \nabla\times B - J$
$dm_0\gamma v/dt = q(E + v\times B)$
$\partial\rho/\partial t + \nabla\bullet J = 0$



Weibel instability

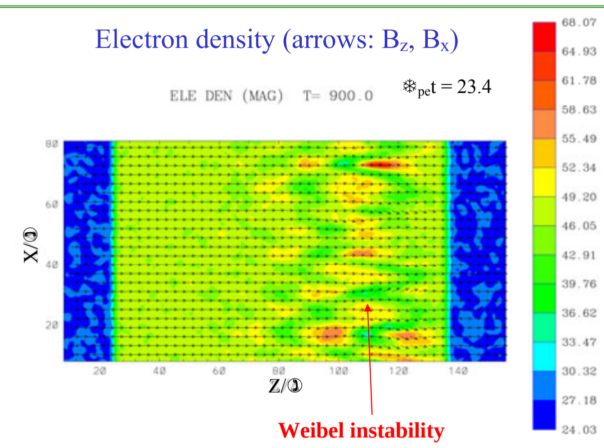


(Medvedev & Loeb, 1999, ApJ)

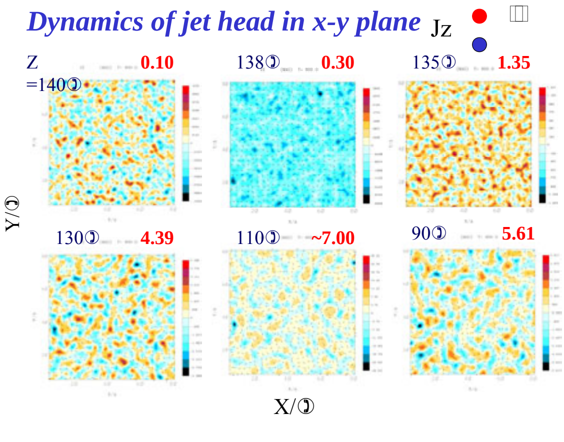
Parameters for *flat* jet injected parallel to B

Electron-ion jet, $m_i/m_e = 20$
$\beta = v_j/c = 0.9798$, $v_{et}/c = 0.1$
$n_j/n_a \approx 0.85$
$\gamma = (1-(v/c)^2)^{-1/2} = 5$
$v_{je} = 0.1v_{et}$, $v_{ji} = 0.1v_{it}$, $v_{it} = 0.0111$
$\omega_{pe}/\Omega_e = 2.89$, $V_A/c = 0.0775$, $M_A = 12.65$
β_e $(=8\pi n_eT_e/B^2) = 1.66$
$\omega_{pe}\Delta t = 0.026$, $r_j = 40\,\Delta x \approx 10\, c/\omega_{ce}$ (infinite)
$\lambda_e = 1.389\Delta$, $\lambda_i = 6.211\Delta$

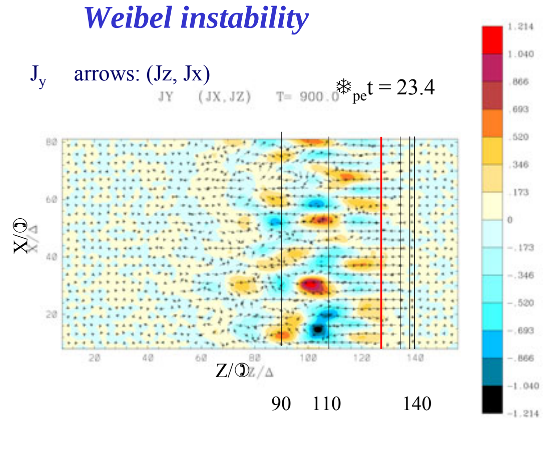
Electron density (arrows: B_z, B_x)



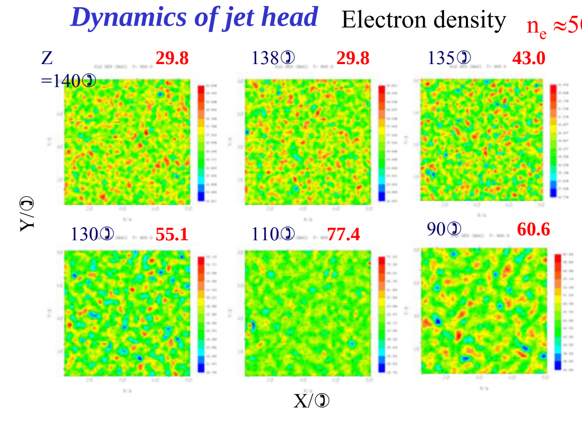
Dynamics of jet head in x-y plane



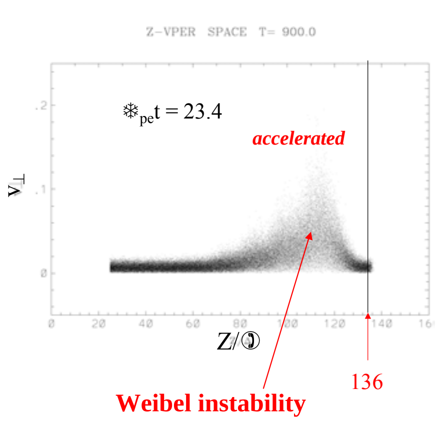
Weibel instability



Dynamics of jet head



Perpendicular acceleration of jet electron



Summary

- **Simulation results show Weibel instability which creates filamented currents and density along the propagation of jets.**
- **The growth rate of Weibel instability depends on the size of jets, compositions, strength and direction of ambient magnetic fields.**
- **In a one-dimensional system Buneman instability is responsive to the surfing acceleration, Weibel instability is excited in the 3-D system.**
- **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 Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for Jitter radiation (Medvedev, 2000, ApJ).**
- **Weibel instability may play a major role in particle acceleration in relativistic jets**
- **The dynamics of jet head is complicated and further investigation is necessary**

Future plans for particle acceleration in relativistic jets

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **In order to improve the performance of the code, HPF or MPI will be used**
- **Implement better boundary conditions at the free boundaries**
- **Investigate synchrotron (jitter) emission from the accelerated electrons and compare with observations (Blazars and gamma-ray burst emissions)**
- **Develop a new code implementing synchrotron loss and/or inverse Compton scattering**
- **Compare simulation results with relativistic electron-positron experiments at SLAC to understand particle acceleration in astrophysical relativistic jets**

GAMMA RAY 4 Years of Chandra Observations, September 16 - 18, 2003