Radiation from accelerated particles in shocks and reconnection regions

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PIC simulations of relativistic electron-positron (electro-ion) jets injected into a stationary medium show that particle acceleration occurs within the downstream jet. The Weibel instability is responsible for generating and amplifying highly nonuniform, small-scale magnetic fields. These magnetic fields contribute to the electron's transverse deflection behind the jet head. Recently, reconnection in jets is proposed for additional particle acceleration mechanism for AGN jets and gamma-ray bursts. Various reconnection simulations have been performed; RPIC simulations, resistive relativistic MHD, and two-fluid simulations. Besides reconnection, Kelvin-Helmholtz instability (KHI) is responsible for particle acceleration. The additional particle acceleration and electromagnetic fields generated by reconnection contribute to radiation.

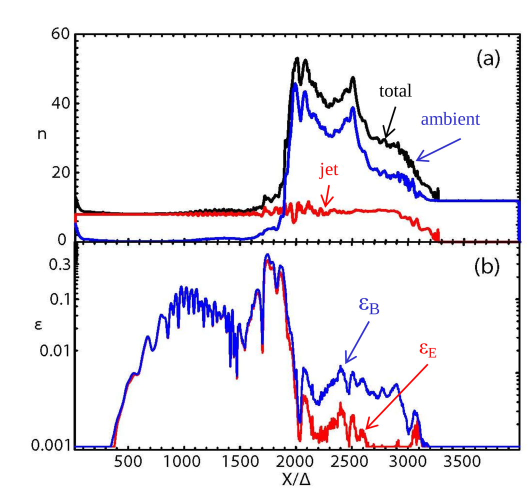
The radiation from deflected electrons has different properties than synchrotron radiation which is calculated in a uniform magnetic field. This radiation obtained self-consistently may be important to understanding the complex time evolution and/or spectral structure in gamma-ray bursts, relativistic jets, and supernova remnants. Recent new RPIC simulations with anti-parallel magnetic fields in jet and ambient show strong magnetic fields are generated at the shock. New recent calculation of spectra with various different Lorentz factors of jets and initial magnetic fields. New spectrum based on small scale simulations is presented.

Key Scientific questions

- **How do shocks in relativistic jets evolve?**
- **How magnetic fields affect shocks and reconnection?**
- **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 radiation?**

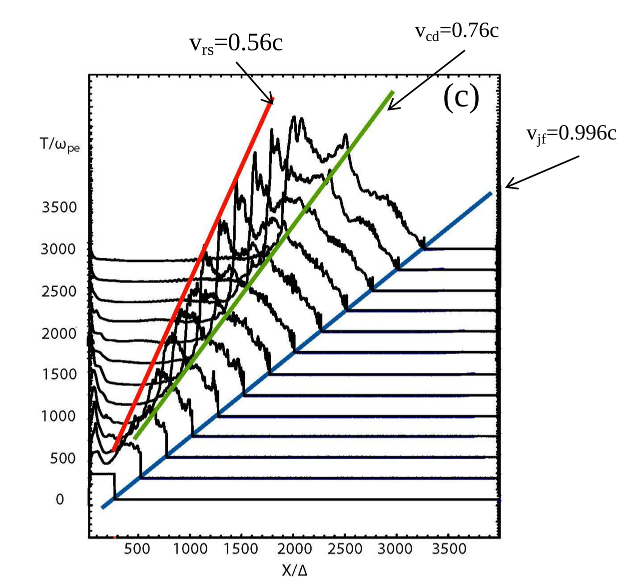
-- for some answers see Nishikawa et al. 2006, ApJ, 642, 1267 Ramirez-Ruiz, Nishikawa & Hededal, 2007, ApJ, 671, 1877 Nishikawa et al. 2009, ApJ, 698, L10 --

Shock formation, forward shock, reverse shock



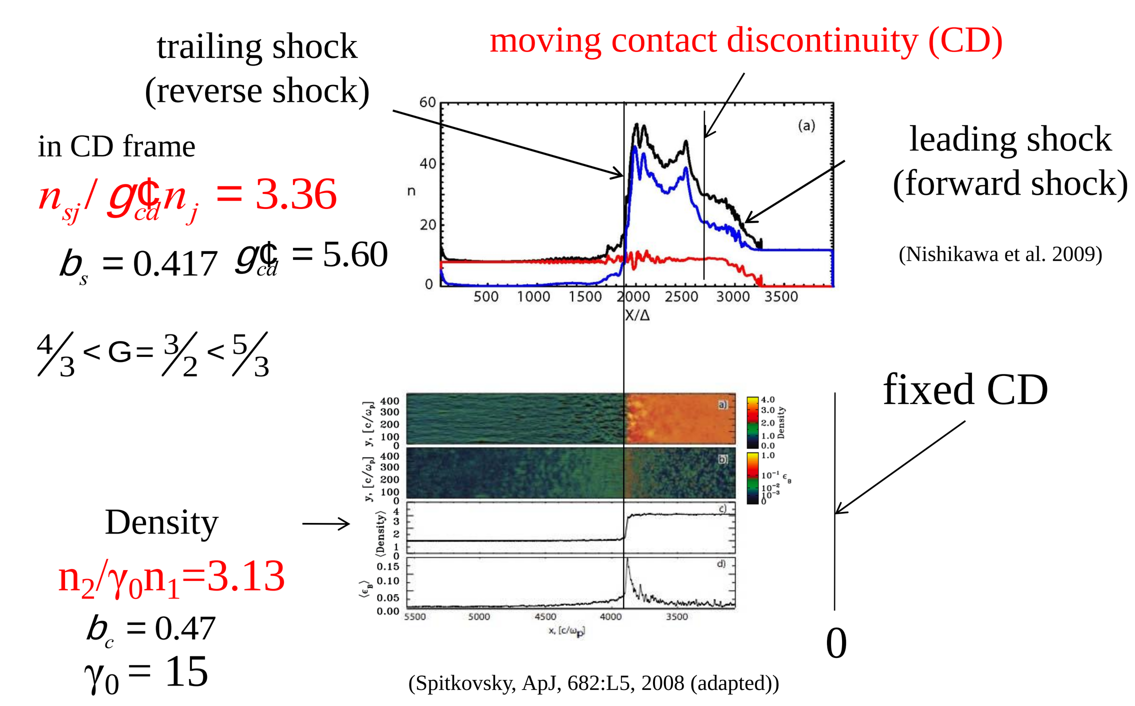
(a) electron density and (b) electromagnetic field energy (ε_B, ε_E) divided by the total kinetic energy at $t = 3250\omega_{pe}^{-1}$

(Nishikawa et al. ApJ, 698, L10, 2009)



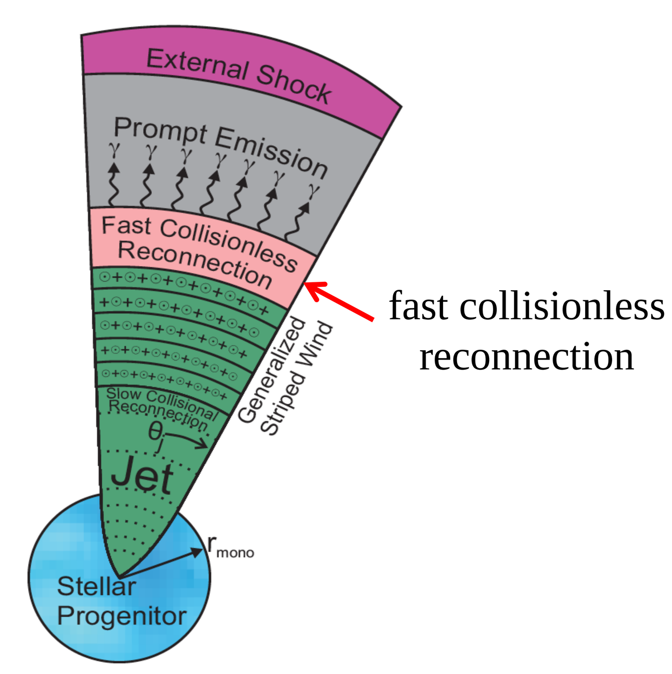
Time evolution of the total electron density. The velocity of jet front is nearly c, the predicted contact discontinuity speed is 0.76c, and the velocity of trailing shock is 0.56c.

Shock velocity and structure based on 1-D HD analysis



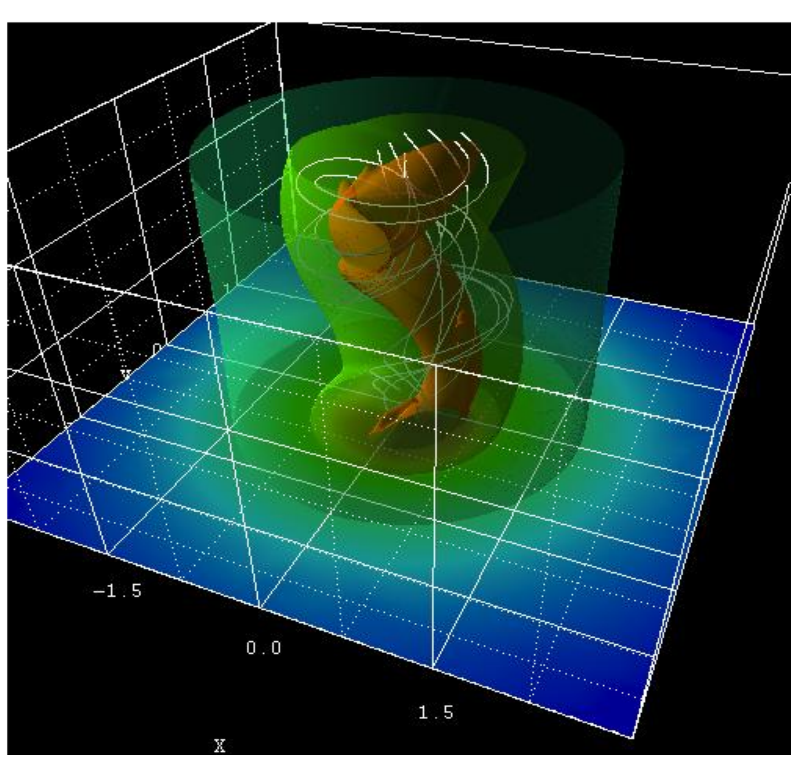
(Spitkovsky, ApJ, 682:L5, 2008 (adapted))

Reconnection in jet



Reconnection switch concept: Collapsar model or some other system produces a jet (with opening half-angle θ_j) corresponding to a generalized stripped wind containing many field reversals that develop into dissipative current sheets. (McKinney & Uzdensky, MNRAS, doi:10.1111/j.1365-2966.2011.19721.x2011)

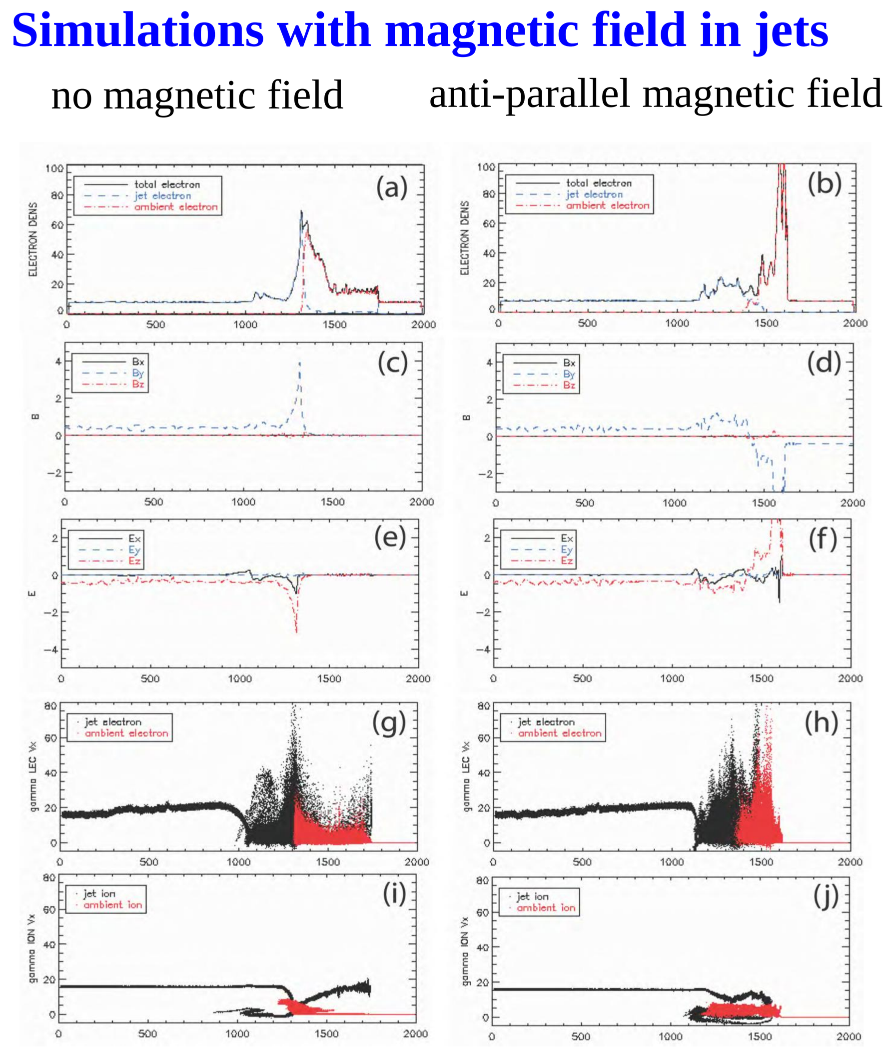
3-D kink instability with helical magnetic field



Relativistic jet with helical magnetic field leads kink instability and reconnection may take place using resistive relativistic MHD simulations (this simulation was performed with RMHD code).

(Mizuno et al. ApJ, 734:19 (18pp), 2011)

Simulations with magnetic field in jets



Choi, Min, KN, 2012 (in progress)

Snapshots for unmagnetized ambient plasma (left column) and anti-parallel magnetic field in the ambient plasma (right column) at $t = 1250\ \omega_{pe}^{-1}$ (Choi, Min, & Nishikawa, 2012). The averaged values of electron density (a) and (b), magnetic field (c) and (d), electric field (e) and (f), phase space of electrons (g) and (h), and phase space of ions (i) and (j). It should be noted that reconnection occurs for the case with the collision with anti-parallel magnetic fields which is shown by the positive Ey component in (f).

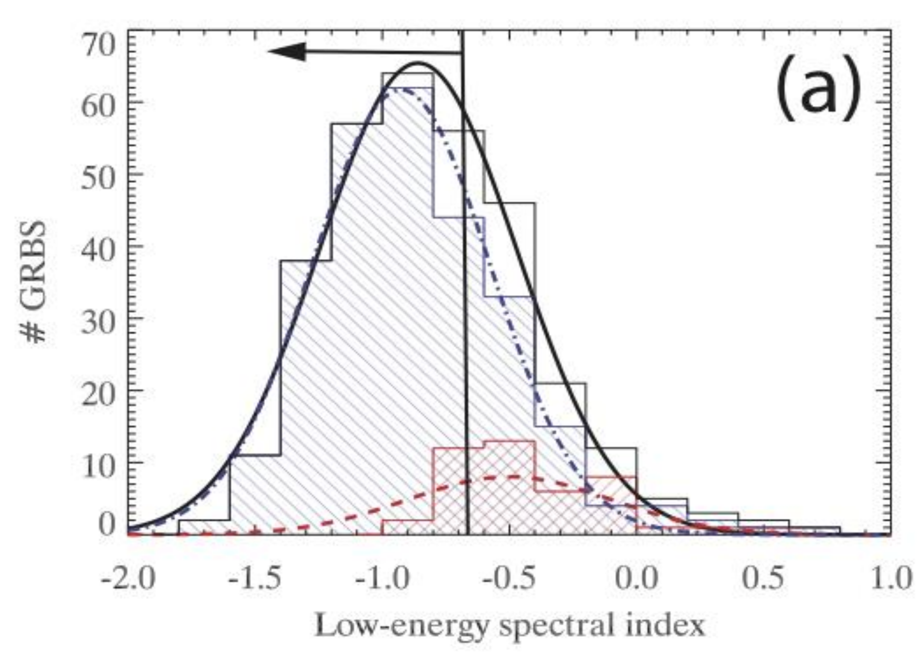
Present theory of Synchrotron radiation

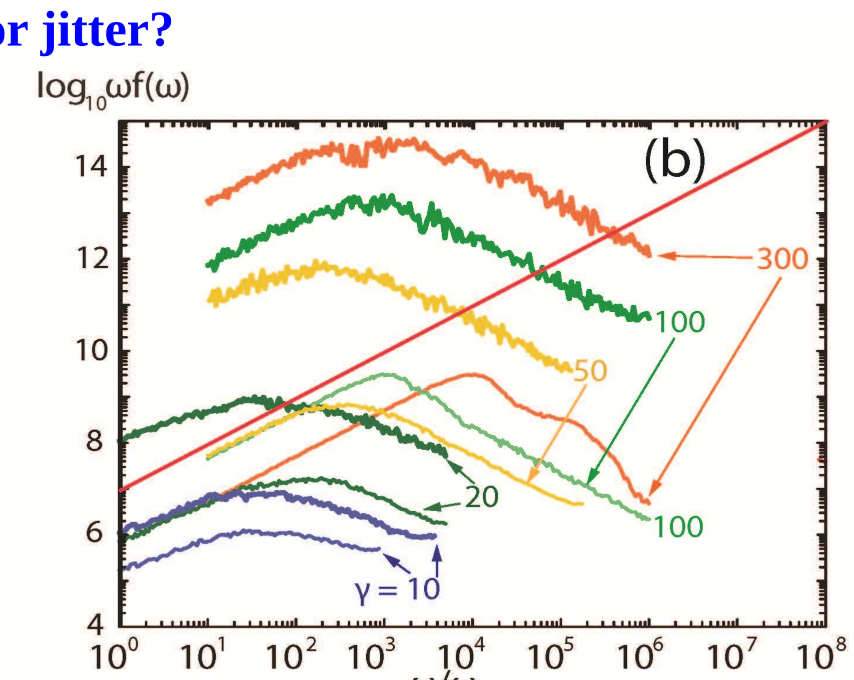
- Fermi acceleration (Monte Carlo simulations are not self-consistent; particles are crossing at the shock surface many times and accelerated, the strength of turbulent magnetic fields are assumed), New simulations show Fermi acceleration (Spitkovsky 2008)
- The strength of magnetic fields is assumed based on the equipartition (magnetic field is similar to the thermal energy) (ε_B)
- The density of accelerated electrons are assumed by the power law ($F(\gamma) = \gamma^{-p}$; $p = 2.2$?) (ε_e)
- Synchrotron emission is calculated based on p and ε_B
- There are many assumptions in this calculation

Self-consistent calculation of radiation

- Electrons are accelerated by the electromagnetic field generated by the Weibel instability (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated by the particle trajectory in the self-consistent magnetic field
- This calculation include Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
- Some synchrotron radiation from electron is reported (Nishikawa et al. Adv. Sci. Rev, 47, 1434, 2011)

Synchrotron or jitter?





Panel a shows the distribution of the low-energy photon index for the 318 GRBs fitted with either the Band or CPL model and with determined E_{peak}^{obs}. The solid (black) line shows the fit with a Gaussian. Also shown (hatched blue and red histograms) are the distributions for 274 long and 44 short GRBs, respectively, and their Gaussian fits (dot-dashed and dashed line for long and short events, respectively) (Adapted from Fig. 4 in Nava et al. MNRAS 415, 3153–3162 (2011)). Panel b shows the spectra for the cases of γ = 10, 20, 50, 100, and 300 with cold (thin lines) and warm (thick lines) electron jets. The low frequency slope is approximately 1 (which corresponds to $\alpha = 0$).

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.**
- **Spectra from two electrons are calculated for different condtions.**
- **The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).**
- **New numerical approach of calculating radiation from electrons based on simulations self-consistently provides more realistic spectra including jitter radiation.**

Future plans

*** Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including reconnection.**

*** Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability.**

*** Investigate radiation processes from the accelerated electrons and compare with observations (GRBs, SNRs, AGNs, etc).**

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