Radiation from accelerated particles in relativistic jets with shocks, shear-flow and reconnections

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Outline

1. Standard radiation mode
2. Self-consistent radiation method using PIC simulations
3. Synthetic spectra in shocks generated by the Weibel instability
4. Importance of reconnection in relativistic jet
5. Strong magnetic field amplification with magnetic fields
6. Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability
7. Summary
8. Future plans
**Present theory of Synchrotron radiation**

- **Fermi** acceleration (Monte Carlo simulations are not self-consistent; particles are crossing the shock surface many times and remain accelerated, the strengths of turbulent magnetic fields are assumed), Some simulations exhibit Fermi acceleration (Spitkovsky 2008)
- The strength of magnetic fields is estimated based on **equipartition** - magnetic field energy is comparable to the thermal energy): $\varepsilon_B \sim u(T)$
- The distribution of accelerated electrons is approximated by the power law ($F(\gamma) = \gamma^{-p}; p = 2.2$?) ($\varepsilon_e$)
- **Synchrotron** emission is calculated based on $p$ and $\varepsilon_B$
- There are many assumptions in this calculation!
Synchrotron Emission: radiation from accelerated electrons

Theoretical Spectra
(Sari, Piran & Narayan 1998)

- $N(\gamma_e) \propto \gamma_e^{-p}$
- $+B$
- Cooling

BM, PL, BB by talk by S. Guiriec

 Talks by G. Vianello and D. Guetta
Self-consistent calculation of radiation

• Electrons are accelerated by the electromagnetic field generated by the Weibel instability and KKHI (without the assumption used in test-particle simulations for Fermi acceleration)
• Radiation is calculated using the particle trajectory in the self-consistent turbulent magnetic field
• This calculation includes Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
Radiation from particles in collisionless shock

To obtain a spectrum, “just” integrate:

\[
\frac{d^2 W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3} \left| \int_{-\infty}^{\infty} \frac{n \times [(n - \beta) \times \dot{\beta}]}{(1 - \beta \cdot n)^2} e^{i\omega(t' - n \cdot r_0(t')/c)} dt' \right|^2
\]

where \( r_0 \) is the position, \( \beta \) the velocity and \( \dot{\beta} \) the acceleration.

**New approach**: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Frederiksen et al. 2010, ApJL
Shock formation, forward shock, reverse shock

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

Time evolution of the total electron density. The velocity of the jet front is $\sim c$, the predicted contact discontinuity speed is $0.76c$, and the velocity of the reverse shock is $0.56c$.

Synthetic spectra with different Lorentz factors with cold and warm thermal temperatures

Figure a shows the spectra for the cases of $\gamma = 10, 20, 50, 100, \text{ and } 300$ with cold (thin lines) and warm (thick lines) electron jets. Fig. b shows modeled Fermi spectra in $vF$ units at early (a) to late (e) times (Abdo et al. 2009). The red lines indicate slope in $vF \sim 1$. 
Radiation in a larger system

System size: $8000 \times 240 \times 240$  
Electron-positron: $\gamma = 15$

(a) $150 \omega_{pe}^{-1} \leq t \leq 225 \omega_{pe}^{-1}$

(b) $200 \omega_{pe}^{-1} \leq t \leq 275 \omega_{pe}^{-1}$
Reconnection switch concept: Collapsar model or some other system produces a jet (with opening half-angle $\theta_j$) corresponding to a generalized stripped wind containing many field reversals that develop into dissipative current sheets (McKinney and Uzdensky, 2012, MNRAS, 419, 573). This reconnection needs to be investigated by resistive RMHD, which is in progress within our research effort.
Relativistic jet with helical magnetic field, which leads to the kink instability and subsequent reconnection, can be simulated using resistive relativistic MHD (this simulation was performed with ideal RMHD code).

Simulations with magnetic field in jets

no magnetic field          anti-parallel magnetic field

Snapshots for unmagnetized ambient plasma (left column) and anti-parallel magnetic field in the ambient plasma (right column) at $t = 1450 \omega_{pe}^{-1}$ (Choi, Min, and 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). Reconnection occurs for the case of anti-parallel magnetic fields and is indicated by the positive $E_y$ component in (f).

Choi, Min, KN, 2012 (in progress)
Simulations of Kinetic Kelvin-Helmholtz instability with counter-streaming flows

The left panel shows magnetic field lines generated in the relativistic shear scenario of Alves et al. (2012). The right panel shows the electron density in orange (blue) of the plasma that flows in the positive (negative) $x_1$ direction. In this panel darker regions in the color map indicate high electron density, whereas lighter regions indicate low electron density.
Simulations of KHI with core and sheath jets

RMHD, no wind $\omega=0.93$, time=60.0

case of $V_{\text{sheath}} = 0$

Study of the relativistic velocity shear interface KKHI instability

\[
\begin{align*}
\omega - \lambda \pi n \omega^2 / \epsilon_0^3 \mu^2 &= 0 \\
\begin{cases}
\lambda(k^2 c^2 + \gamma^2 \omega^2_p - \omega^2)^{1/2} (kV_+ - \omega)^2 [ (kV_+ - \omega)^2 - \omega^2_p ] \\
+ (k^2 c^2 + \gamma^2 \omega^2_p - \omega^2)^{1/2} (kV_+ - \omega)^2 [ (kV_+ - \omega)^2 - \omega^2_p ]
\end{cases} = 0
\end{align*}
\]

Low-frequency limit \((V_- = 0)\)

\[
\omega \sim \frac{(\gamma_{jt} \omega_{p,am}/\omega_{p,jt})}{(1 + \gamma_{jt} \omega_{p,am}/\omega_{p,jt})} kV_{jt} \pm i \frac{(\gamma_{jt} \omega_{p,am}/\omega_{p,jt})^{1/2}}{(1 + \gamma_{jt} \omega_{p,am}/\omega_{p,jt})} kV_{jt}.
\]
New KKH simulations with core and sheath jets in slab geometry

Magnetic field structures generated by shearing relativistic electron-ion flows with $\gamma = 15$ with stationary sheath plasmas. The magnetic field intensity of $B_y$ is plotted in the $y-z$ plane at the center of the box (a) (jet out of the plane), in the $x-z$ plane at the center of the box (d) (jet along $+x$-direction indicated by the arrow). Fig. b shows the magnetic finds $B_y$ (red), $B_x$ (black), and $B_z$ (blue). Fig. c shows the $x$-component of the current. Positive currents are stronger than negative currents, therefore the $B_y$ components are generated as shown in Fig. b. Nishikawa et al. in preparation.
Summary of 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 presence of ions in the ambient plasma enhances the strength of the generated magnetic fields due to the excitation of the ion Weibel instability.
• This enhanced magnetic field with electron-ion ambient plasma may be the cause 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 were calculated for different conditions.
• The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006; Frederiksen et al. 2010, Medvedev et al 2011).
• Our new numerical approach of calculating radiation from electrons based on a self-consistent simulations 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 and KKHI.
• 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 (GRBs, SNRs, AGNs, etc).
Radiation in a small system

without iteration

with iteration
Shock velocity and structure based on 1-D HD analysis

reverse shock

\[ \frac{n_{sj}}{\gamma'_{cd} n_j} = 3.36 \]
\[ \beta_s = 0.417 \quad \gamma'_{cd} = 5.60 \]
\[ \frac{4}{3} \leq \Gamma = \frac{3}{2} < \frac{5}{3} \]

Density

\[ \frac{n_2}{\gamma_0 n_1} = 3.13 \]
\[ \beta_c = 0.47 \]
\[ \gamma_0 = 15 \]

forward shock

moving contact discontinuity (CD)

(Nishikawa et al. 2009)

\[ n_{sj}/\gamma'_{cd} n_j = 3.36 \]
\[ \beta_s = 0.417 \quad \gamma'_{cd} = 5.60 \]
\[ \frac{4}{3} \leq \Gamma = \frac{3}{2} < \frac{5}{3} \]

fixed CD