Radiation processes in relativistic shocks

bonus: CRs + B-fields in a Foreshock

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Simulations:
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  Anatoly Spitkovsky (Princeton)
  Luis Silva and the Plasma Simulation Group (Portugal)
  Aake Nordlund and his group (Niels Bohr Institute, Copenhagen, Denmark)

Theory:
  Davide Lazatti and his group at U.Colorado Boulder
Motivation: ubiquitous Weibel – sub-Larmor-scale fields
Weibel shock: 2D PIC $e^{-p}, \Gamma=15$
Magnetized outflow: reconnection

Small-scale field generation (Weibel instability) at a reconnection site

...see talks at this conference

Non-relativistic electron-positron pair plasma

Relativistic electron-positron pair plasma
(Zenitani & Hesse, PoP, 2008)
Jitter radiation
Deflection parameter:

\[ \delta \equiv \frac{\alpha}{\Delta \theta} = \frac{eB\lambda}{mc^2} \]

\( \omega_s \sim \gamma^2 \omega_H \)

\( \omega_j \sim \gamma^2 c/\lambda \)

… independent of \( \gamma \)

When \( \delta \ll 1 \), one can assume that

- particle is highly relativistic \( \gamma \gg 1 \)
- particle’s trajectory is piecewise-linear
- particle velocity is nearly constant \( r(t) = r_0 + c t \)
- particle experiences random acceleration \( w_\perp(t) \)

\( v = \text{const} \)

\( w_\perp(t) = \text{random} \)

Jitter radiation. Theory

The dominant contribution to the integral comes from small angles. The dominant contribution to the integral comes from small angles.

\[ \frac{dW}{d\omega} = \frac{e^2 \omega}{2\pi c^3} \int_{\omega/2}^{\infty} \frac{|w_{\omega'}|^2}{\omega'^2} \left( \frac{\omega}{\omega' \gamma^2} + \frac{\omega'^2}{2\omega'^2 \gamma^4} \right) d\omega' \]

where \( w_{\omega'} = \int w e^{i\omega' t} dt \) is the Fourier component of the particle’s acceleration, \( \omega' = \omega (1 - n \cdot v/c) \), and \( n \) is the unit vector pointing toward the observer.

\[ \omega' \approx \omega (1 - v/c + \theta^2/2) \]
\[ \approx \omega/2 (1 - v^2/c^2 + \theta^2) \]
\[ \approx \omega/2 (\theta^2 + \gamma^{-2}) \]

Lienard-Wichert potentials

Small-angle approximation

Spectral power

Fourier image of the particle acceleration from the 3D "(vxB) acceleration field"

\[
\mathbf{w} = \frac{e}{\gamma mc} \mathbf{v} \times \mathbf{B}
\]

\[
\mathbf{w}_\alpha = \frac{e}{\gamma mc} \frac{1}{2} e_{\alpha \beta \gamma} (v_\beta \dot{B}_\gamma - v_\gamma \dot{B}_\beta).
\]

\[
|\mathbf{w}_{\Omega, \mathbf{k}}|^2 = \frac{(ev/\gamma mc)^2 (\delta_{\alpha \beta} - v^{-2} v_\alpha v_\beta) B_{\Omega, \mathbf{k}}^\alpha B_{\Omega, \mathbf{k}}^{* \beta}}{B_{\Omega, \mathbf{k}}^\alpha B_{\Omega, \mathbf{k}}^{* \beta}}
\]

\[
B_{\Omega, \mathbf{k}}^\alpha B_{\Omega, \mathbf{k}}^{* \beta} = C (\delta_{\alpha \beta} - n_\alpha n_\beta) f_z(k_{||}) f_{xy}(k_{\perp}),
\]


We need to express the temporal Fourier component of the acceleration \( \mathbf{w} \equiv F_L/\gamma m \) taken along the particle trajectory in terms of the Fourier component of the field in the spatial and temporal domains. Taking the Fourier transform of \( \mathbf{w}(r_0 + vt, t) \), we have

\[
\mathbf{w}_{\omega'} = (2\pi)^{-4} \int e^{i\omega' t} dt \left( e^{-i(\Omega t - k \cdot r_0 - k \cdot v t)} \mathbf{w}_{\Omega, \mathbf{k}} d\Omega dk \right)
\]

\[
= (2\pi)^{-3} \int \mathbf{w}_{\Omega, \mathbf{k}} \delta(\omega' - \Omega + k \cdot v) e^{i k \cdot r_0} d\Omega dk,
\]

where we used that \( \int e^{i\omega t} dt = 2\pi \delta(\omega) \). In a statisti-
Radiation vs $\Theta$

B-field is anisotropic: $B_\perp=(B_x, B_y)$ is random, $B_z=0$

(Medvedev, Silva, Kamionkowski 2006; Medvedev 2006)
Face-on view

(credit: Hededal, Haugbolle, 2005)
Oblique view

(credit: Hededal, Haugbolle, 2005)
Spectra vs. viewing angle

\[ \log F_v \sim \nu^0 \]

\[ \nu_1 \]

\[ \langle B_k^2 \rangle \sim k^{-\eta} \]

\[ \nu^{-\eta-1} \]

\[ \nu^{-\eta} \]

Log \( F_v \)

Log \( \nu \)

(Medvedev 2006; S. Reynolds, S. Pothapragada, Medvedev, in prep.)
Jitter spectra from 3D PIC

Bulk Lorentz factor = 15
PDF: Thermal + non-thermal (p=2.7)

(Hededal, PhD thesis 2005)
Synchrotron “Line of Death”

Statistics is large:
About 30% of over 2700 GRBs violate synchrotron limit at low energies

\[ P(\omega) \sim \omega^{\alpha+1} \]

(Medvedev, 2000)

Non-synchrotron GRB spectra

Some GRBs cannot be synchrotron

GRB 970111
soft photon index violates
synchrotron limit for the entire burst

Multi-peak prompt GRB

Multi-peak prompt GRB

Multi-peak prompt GRB

Multi-peak prompt GRB

Multi-peak prompt GRB

Multi-peak prompt GRB

Jet viewing angle effect

Jet opening angle

Jet axis

Surfaces of equal times

$\Theta_{\text{jet}}$

$\Theta_{\text{obs}}$

To observer
“Tracking” GRBs

Also, “hardness – intensity” correlation;
Also, “tracking behavior”

$t_1$, bright, high $E_{\text{peak}}$, $\alpha \sim 0$

$t_2$, intermediate $\alpha \sim -2/3$

$t_3$, faint, low $E_{\text{peak}}$, $\alpha \sim -1$
Single pulse: F & alpha “lightcurves”

\[ F \nu \sim \nu^\alpha \]

Flux @ Epeak

No synch allowed

\[ F_v \sim \nu^\alpha \]

\[ t = \frac{R}{2\nu c} \]

Approx. 0.03 secs
Prompt spectral variability

\[ F_v \sim \nu^\alpha \]

\[ \alpha = 1/3 \]

Polarization may be expected, if jet is misaligned

(Medvedev, 2006)
(Pothapragada, Reynolds, Medvedev, in prep)
Model lightcurves

Thin shells

Thick shells
Flux @ Epeak vs alpha - correlation

Burst with Thick subpulses
Burst with Sharp subpulses

Normalized Flux at E_{peak}

Low Energy Spectral Index α
Are shock simulations relevant for GRBs?
Cooling & Weibel time-scales

Inside the ejecta:

\[
n = \frac{L}{4\pi R^2 \Gamma^2 m_p c^3} \simeq (1.8 \times 10^{15} \text{ cm}^{-3}) L_{52} R_{12}^{-2} \Gamma_2^{-2},
\]

Downstream an internal shock:

\[
\begin{align*}
B' &= (8\pi \Gamma_i m_p c^2 n' \epsilon_B)^{1/2} \simeq (1.6 \times 10^7 \text{ G}) L_{52}^{1/2} \Gamma_2^{-1} R_{12}^{-1} \epsilon_B^{1/2} \\
\gamma_e &= (m_p/m_e) \Gamma_i \epsilon_e \simeq 1.8 \times 10^3 \Gamma_i \epsilon_e.
\end{align*}
\]

from simulations

Synchrotron cooling time

\[
\tau_{cool} = \frac{6\pi m_e c}{\sigma_T \gamma_e B^2}
\]

Electron/proton dynamical time

\[
\omega_{ps,\text{rel}} = \left( \frac{4\pi e^2 n}{\Gamma_{int} m_s} \right)^{1/2}
\]

\[
\epsilon_B = \frac{B^2}{4\pi m_p c^2 n \Gamma'},
\]

\[
\epsilon_e = \frac{U_e}{m_p c^2 n \Gamma'}.
\]

\[
n = \frac{L_{\text{kin}}}{4\pi R^2 \Gamma_{\text{blast}}^2 m_s c^2}
\]
Cooling & Weibel time-scales

(Medvedev & Spitkovsky, in prep)
Cooling & Weibel time-scales

(Medvedev & Spitkovsky, in prep)
Bonus:
Self-similar foreshosk model with CR generated B-field
The model

\[ y = x \cdot B(\gamma(x)) \]
Assume *steady state* and neglect nonlinear effects:
- effect of pre-conditioning of upstream on Weibel instability
- nonlinear feedback of B-fields on
  - CR distribution function
  - Shock structure
  - CR acceleration
- time evolution of generated fields

\[ B(x) \sim B_0 \left( \frac{x}{x_0} \right)^{-\frac{s-1}{s+1}} \]
\[ \lambda(x) \sim x(2\xi_B) \]

Valid at: \( x \leq x_{\text{max}} \):

\[ s = p - 1 \sim 1.2 \]
\[ x_0 \sim (2 \times 10^7 \text{ cm}) \frac{n_{\text{ISM}}^{-1/2}}{(2\xi_B)} \sim (10^9 \text{ cm}) \frac{n_{\text{ISM}}^{-1/2}}{\xi_B} \]
\[ B_0 \sim (0.2 \text{ gauss}) \xi_B^{1/2} n_{\text{ISM}}^{1/2} \Gamma_{\text{sh}} \sim (1 \text{ gauss}) E_{52}^{1/2} R_{17}^{-3/2} \]

\[ x_{\text{max}} = \text{Min} \left[ \frac{R}{2\Gamma_{\text{sh}}}, \frac{X}{x_0} \right] = \text{Min} \left[ \frac{R}{(2\Gamma_{\text{sh}})}, \frac{x_0 (B_0 / B_{1\text{ISM}} \Gamma_{\text{sh}})^{\frac{s+1}{s-1}}}{x_{\text{max}}} \right] \]
\[ x_{\text{max}} \sim \frac{R}{2\Gamma_{\text{sh}}} \sim 5 \times 10^8 \frac{x_0}{x_{\text{max}}} E_{52}^{1/3} n_{\text{ISM}}^{-1/3} \Gamma_{\text{sh}}^{-5/3} \]

Typical field:
\[ B(x_{\text{max}}) \sim (0.2 \text{ gauss}) E_{52}^{0.45} n_{\text{ISM}}^{0.09} R_{18}^{-1.3} \]
\[ \lambda(x_{\text{max}}) \sim x_{\text{max}}/(2\xi_B) \sim (5 \times 10^{17} \text{ cm}) E_{52}^{-1/2} n_{\text{ISM}}^{1/2} R_{18}^{5/2} \]

B-field spectrum near a shock
\[ B_\lambda \propto \lambda^{-\frac{s-1}{s+1}} \sim \lambda^{-0.091} \]

(Medvedev & Zakutnyaya, in prep)
Magnetic field with small spatial coherence length are ubiquitous. They form due to the *Weibel-type instability* via the current filament formation.

Radiation emitted by electrons in Weibel-generated magnetic fields – Jitter radiation – has spectral properties that make it more favorable over synchrotron models. *The Weibel+Jitter shock model can be tested against GRB data: e.g., spectral variability and afterglow lightcurves.*

A model of a self-similar foreshock magnetized by streaming CRs is presented, but more understanding is needed on B-field evolution and acceleration/heating. Larger and longer PIC simulations are needed.

More understanding is still needed for external shocks of afterglows (Weibel vs vorticity models, post-shock turbulence) and prompt emission (magnetized outflows).