Particle-in-cell simulations of relativistic pair plasma reconnection and application to the Crab gamma-ray flares

Benoît Cerutti

Center for Integrated Plasma Studies
University of Colorado, Boulder, USA.

Collaborators: Gregory Werner (CIPS), Dmitri Uzdensky (CIPS), Mitch Begelman (JILA)

B. Cerutti
Astrophysical motivations: Flares in the Crab

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Crab Nebula 0.3-3 keV
Synchrotron radiation from ultra-relativistic $e^+/e^-$ pairs
$B \sim 100 \mu G - mG, \gamma \sim 10^6$

Shortest variability timescale $\sim$ hour

[Beuchler +, 2012]

The puzzles
- The variability: $t_{\text{flare}} <<$ Light crossing time Nebula
- The energetics of the flare: 1% nebula radiates all the flux
- Synchrotron photons energy: above 100 MeV
The production of synchrotron emission $>100$ MeV challenges classical models of acceleration

- Synchrotron photon energy: $\varepsilon_{\text{max}} = \frac{3}{2} \gamma^2 \hbar \left(\frac{eE}{m_e c}\right) > 100$ MeV
- $\gamma_e m_e c^2 > 10^{15}$ eV (B/1 mG), highest-energy particle associated with a specific astrophysical object!

- Maximum energy of electrons are limited by radiative losses:
  - Accelerating electric force: $f_{\text{acc}} = eE$
  - Radiation reaction force: $f_{\text{rad}} = 2/3 r_e^2 \gamma^2 B^2$
  - Synchrotron photon energy: $\varepsilon_{\text{max}} = \frac{3}{2} \gamma_{\text{rad}}^2 \hbar \omega_c = 160 \times (E/B)$ MeV

In classical acceleration mechanisms: $E < B$ (ideal MHD) $\Rightarrow \varepsilon_{\text{max}} < 160$ MeV

- Possible solution with relativistic Doppler boosting effect:
  [e.g. Komissarov & Lyutikov 2010, Bednarek & Idec 2011]

  $\varepsilon_{\text{max}} = D \times 160$ MeV

  But then $D \approx 3-4$, unlikely in the Crab Nebula (bulk motion $< 0.5$ c)

  [Hester+2002]
Particle acceleration above the radiation reaction limit could occur at reconnection sites

\[ E_0 \geq B_0 \]

The reconnecting magnetic field vanishes inside the current layer:

\[ B_0 - B_0 \]

Adapted from © http://mrx.pppl.gov/

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Goal

Study particle acceleration in relativistic collisionless pair plasma reconnection, and its radiative signature for an external observer.

\[ \delta + B_0 - B_0 \]

Current layer

\[ E_0 \]

Observer

Synchrotron Photons

PIC codes

**VORPAL**

Commercial software developed at the Univ. of Colorado and Tech-X Corporation. [*Nieter & Cary 2004*]

Simus. done by G. R. Werner

**ZELTRON**

Developed from scratch by B. Cerutti at Univ. of Colorado. 2D and 3D relativistic parallel PIC with open MPI.

+ Radiation reaction force!
Initial setup: Relativistic Harris equilibrium

2.5 D & No guide field

Layer thickness: $\delta$

Current: $+J_0$

Current: $-J_0$

Upstream $\beta \approx 0.025$

Double periodic boundary conditions
Time evolution of reconnection

NO radiation reaction force.

[Cerutti et al., ApJLetters, 2012b]

The layer is tearing unstable and breaks up into a chain of magnetic islands separated by secondary reconnection layers.
Particles are accelerated at X-points along the $\pm z$-direction, and deflected along the $\pm x$-directions by the reconnected field $B_y$. [Cerutti et al., ApJLetters, 2012b]
Simulation with the **radiation reaction force** and **ultra-relativistic non-thermal background pairs**

\[ L_x \times L_y = (1024 \rho_c)^2 \quad \text{with} \quad \rho_c = mc^2/eB_0 \]

\[ B_0 = 1000 \text{ Gauss} \]

\[ \gamma_{\text{rad}} (E = B_0) = 3 \times 10^6 \]

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No clear evidence of **non-thermal** particle acceleration.

ϕ May require a larger separation of scales (bigger box size?)
Evidence for relativistic Speiser orbits

Sample of 150 particle orbits

$L_x \times L_y = (500 \rho_c)^2$

Particles well magnetized $\approx$ ideal MHD!

Particles’ beam $E > B$, non-ideal MHD!

Speiser orbits!
A typical high-energy particle orbit

Speiser orbit
Orbit shrinks

E>B

Low-energy and magnetized
Particle kicked out of the layer.
Magnetized and RADIATING! (E<B)

\[ \gamma \approx \text{Linear acceleration } E>B \]
Little radiative losses

[\text{Cerutti et al., in preparation, 2012}]
Evidence for >160 MeV synchrotron photons!

Isotropic average

Total synchrotron flux background particles

Synchrotron radiation above 160 MeV limit!

[cerutti et al., in preparation, 2012]
Energy-resolved particles’ angular distribution

Using the Aitoff projection:

@ t = 376 $\omega_c^{-1}$

$1.0E+05 < \gamma < 1.1E+05$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$

$1.6E+05 < \gamma < 1.8E+05$
Energy-resolved particles’ angular distribution

@ t = 376 $\omega_c^{-1}$

$2.6E+05 < \gamma < 2.8E+05$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$

$4.1E+05 < \gamma < 4.5E+05$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$

$1.0 \times 10^6 < \gamma < 1.1 \times 10^6$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$

$1.0E+06 < \gamma < 1.1E+06$
Energy-resolved particles’ angular distribution

@ $t = 376 \omega_c^{-1}$

$2.7E+06 < \gamma < 2.9E+06$

Strong energy-dependent anisotropy!

Same effect without the radiation reaction force

[B. Cerutti et al., ApJLetters, 2012b]
The high-energy radiation flux is highly anisotropic!

Apparent high-energy flux INCREASED!

Photon energy > 100 MeV

Synchrotron radiation above 160 MeV limit!

[Cerutti et al., in preparation, 2012]
High-energy lightcurves

Reconnection naturally generates bright, ultra-rapid, symmetric sub-flares of radiation

[Cerutti et al., ApJLetters, 2012b]
High-energy particle anisotropy

High-energy particles only
\[ t \omega_c = 0 \]

The beam of high-energy particles sweeps across the line of sight intermittently: bright symmetric flares.
Summary and future directions

- **Strong beaming** of the high-energy radiation
- **Ultra-rapid time variability** of the flux (sweeping beam).
- **Particle acceleration** inside the layer where $E > B$:
  $\Rightarrow$ Synchrotron radiation $> 160$ MeV

Futures directions:

- 3D with guide field: Effect of the **kink instability on anisotropy**?
- Application to other flaring astrophysical objects:
  e.g. Active Galactic Nuclei, Gamma-ray Bursts
- **Non-thermal particle acceleration** with reconnection?