Relativistic reconnection at the origin of the Crab gamma-ray flares

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Variable Galactic Gamma-ray Sources, April 16-18, 2013, Barcelona.
Agile and Fermi discovered gamma-ray flares in the Crab Nebula

The ultra-short time variability put strong constraints on the acceleration region

[Buehler et al., 2012]

April 11, 9 days

Flux $\propto 30$

- Flare few days $\Rightarrow$ emitting region size $c t_{\text{flare}} \sim 10^{16}$ cm $\ll$ Nebula ($\sim 0.1$ pc)
  
  (Shortest variability timescale $\sim$ hours)

- If $t_{\text{acc}} = t_{\text{sync}}$ $\Rightarrow$ B $\sim$ few mG $\gg$ 200 $\mu$G, and PeV pairs!
Spectral variability at high energies

- Synchrotron photons $> 100$ MeV
- No obvious counter-parts (radio, IR, opt., X, TeV)
- April 2011 spectrum very hard, inconsistent with shock-acceleration

[Weisskopf et al. 2013]
The production of synchrotron emission $>160\text{ MeV}$ challenges classical models of acceleration.

Under ideal MHD conditions: $E<B$ (ideal MHD) $\Rightarrow \varepsilon_{\text{max}} < 160\text{ MeV}$

Synchrotron photon energy:
$$\varepsilon_{\text{max}} = \frac{3}{2} \gamma_{\text{rad}}^2 \hbar \omega_c = 160 \times (E/B)\text{ MeV}$$

Particle’s trajectory:
- Radiation reaction force:
  $$F_{\text{rad}} = 2/3 r_e^2 \gamma^2 B^2$$
- Accelerating force:
  $$F_{\text{acc}} = eE$$
- Radiation reaction limit:
  $$F_{\text{acc}} = F_{\text{rad}} \Rightarrow \gamma_{\text{rad}}$$

A way out?
1. Doppler beaming: $\varepsilon_{\text{max}} = D \times 160\text{ MeV}, D \approx 3-4$. Unlikely in the Crab ($v < 0.5 \text{ c}$)
2. By-product decay ultra-energetic particles, Unlikely.
3. Non-ideal MHD process $\Rightarrow$ Reconnection! Inside the layer $E > B$!

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Particle acceleration above the radiation reaction limit could occur at reconnection sites. The reconnecting magnetic field vanishes inside the current layer:

$+B_0 - B_0$

$2\delta$

Current layer

$E_0$

Observer

Synchrotron Photons

Ultra-relativistic, collisionless pair plasma reconnection

The reconnecting magnetic field vanishes inside the current layer:

$E_0 > B_0$

Non ideal MHD!
Zeltron: A new radiative PIC code

General properties:

- **3D, parallel (OpenMPI), relativistic, electromagnetic PIC code.**
- Developed **from scratch** by B. Cerutti
- **Includes the radiation reaction force**

Zeltron solves the **Abraham-Lorentz-Dirac equation**: [e.g. Jackson, 1975]

\[
 m_e c \frac{du^{\mu}}{ds} = -\frac{e}{c} F^{\mu\nu} u_\nu + g^{\mu} 
\]

- **\( u^{\mu} \): 4-velocity**
- **\( F^{\mu\nu} \): External electromagnetic field-strength tensor**
- **\( ds = c dt / \gamma_e \): Relativistic interval**

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Numerical setup: Harris equilibrium

Ultrarelativistic reconnection, with radiation reaction force!

\[ t \omega_1 = 0 \]

Layer thickness: 2\( \delta \)

+\( B_0 = 5 \text{mG} \)

Numerical parameters:
- 100 particles per cell
- 1440^2 grid cells
- 9000 time steps
- 8 cells per \( \delta \)
- Periodic boundary cond.

Physical parameters:
- \( B_0 = 5 \text{mG} \Rightarrow \gamma_{\text{rad}} \approx 10^9 \)
- Thermal drifting particles, \( kT = 4 \times 10^7 \text{ mc}^2 \)
- Non-thermal background particles:
  \[ \frac{dN}{d\gamma} = K\gamma^{-2}, \quad 4 \times 10^7 < \gamma < 4 \times 10^8 \]

System size: \( L = 7 \times 10^{15} \text{ cm or 2.7 light-days} \)

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Particles are accelerated at X-points along the ±z-direction, and deflected along the ±x-directions by the magnetic tension.
Time evolution of the particle energy distribution

$\gamma = 0$

$\gamma_{rad}$


Time evolution of the particle energy distribution

\[ t\omega_1 = 0 \quad t\omega_1 = 220 \quad \gamma_{\text{rad}} \]

Time evolution of the particle energy distribution

\[ t\omega_1 = 0 \quad t\omega_1 = 220 \quad t\omega_1 = 440 \]

\[ \gamma_{\text{rad}} \]

Time evolution of the particle energy distribution

\[ t_\omega_1 = 0 \quad t_\omega_1 = 220 \quad t_\omega_1 = 440 \quad t_\omega_1 = 660 \]

\[ \gamma_{\text{rad}} \]

Energetic particles are **bunched** into the layers and magnetic islands

\[ \gamma > 5 \times 10^8 \]

![Graph showing bunched particles](image)

\[ t = 309 \omega_1^{-1} \]

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Evidence for relativistic Speiser orbits

Sample of 150 particle orbits

Particles’ beam $E>B$, non-ideal MHD!

Particles well magnetized $\approx$ ideal MHD

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A typical high-energy particle orbit with $\gamma > \gamma_{\text{rad}}$

Phase 1. Drifting towards the layer

Phase 2. Linear acceleration, weak rad. losses, where $E>B$ (non-ideal MHD)

Phase 3. Ejection, fast cooling and emission of $>160$ MeV synchrotron

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Evidence for $>160$ MeV synchrotron photons!

Total synchrotron flux (optically thin)

[Isotropic]

$>160$ MeV!

Energy-resolved radiation’ angular distribution

$0.1 \text{ MeV} < \epsilon_1 < 0.2 \text{ MeV}$

$\Omega_{50}/4\pi = 0.43$

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Energy-resolved radiation’ angular distribution

$1.0 \text{ MeV} < \epsilon_1 < 1.2 \text{ MeV}$

$\Omega_{50}/4\pi = 0.35$

Spectral energy distribution
Energy-resolved radiation’ angular distribution

9.6 MeV < $\epsilon_1$ < 11.0 MeV

$\Omega_{90}/4\pi=0.21$

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Energy-resolved radiation’ angular distribution

$102.4\,\text{MeV} < \epsilon_1 < 117.8\,\text{MeV}$

$\Omega_{50}/4\pi=0.05$

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Energy-resolved radiation’ angular distribution

955.4 MeV < $\epsilon_1$ < 1098.5 MeV

$\Omega_{50}/4\pi = 0.02$

Strong energy-dependent anisotropy of the energetic particle.
=► beaming of the high-energy radiation!
Evidence for $>160$ MeV synchrotron photons!

Total synchrotron flux (optically thin)

$\nu F_\nu$ [Arbitrary units] vs $\epsilon_1$ [MeV]

- Anisotropic!
- Isotropic

Observer

$155.7 \text{ MeV} < \epsilon_1 < 179.0 \text{ MeV}$

$\Omega_{50}/4\pi=0.04$

$>160$ MeV!


Apparent high-energy flux INCREASED! $\Rightarrow$ « KINETIC BEAMING »

[Cerutti et al., 2012b]

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Time variation of the >100 MeV flux

The beam of high-energy radiation sweeps across the line of sight intermittently = bright symmetric flares.
Expected lightcurves, including the light propag. time

MODEL

Symmetric shape $\Delta t \ll L_x/c$

OBSERVATIONS


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Ultra-short time variability $< 6 \text{ hours}$ due to particle bunching and anisotropy

Observer

Observed ultra-short time variability $< 8 \text{ hours}$

[Buehler et al., 2012]
Expected correlation Flux/Energy

OBSERVATIONS

\[ \text{Flux} = K \varepsilon_{\text{cut}}^{+3.42\pm0.86} \]

[Buehler et al., 2012]

MODEL

\[ \text{Flux} = K \varepsilon_{\text{cut}}^{+3.8\pm0.6} \]

Where could magnetic reconnection operate in the Crab?

Pulsar wind
Current sheet (striped wind)
[Coroniti 1990]

Polar region
- High magnetic field (Z-pinch)
- Kink unstable [Begelman 1998]
  (See also Lyubarsky 2012)
Flares: Analog of Sawtooth crashes in tokamaks? [Uzdensky + 2011]

Termination shock
Dissipation of the striped wind
[Lyubarsky 2003]
The discovery of these flares has a considerable impact in high-energy astrophysics!

• Smoking gun of rapid magnetic dissipation in the Nebula
  Solution to the long-standing « σ-problem »?

• The model of the Crab Nebula is a prototype for ALL the other high-energy astrophysical sources: AGN jets, lobes, gamma-ray bursts, magnetars, …