Understanding the Pulsar High-Energy Emission: Macroscopic and Kinetic Models

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Outline

• The Fermi Era (Success Requirements)
• Macroscopic Global Models
• Kinetic PIC Global Models
• Summary → Future
$N_p \rightarrow \times 30 \quad N_p > 205 \ (117 \text{ in } 2\text{PC}; \text{Abdo et al. 2013})$

**Discovery Astronomy** established a number of trends and correlations
Fermi provides not only *phase-averaged* spectra but also *phase-resolved* for a dozen of pulsars.

\[ N_p \rightarrow \times 30 \quad N_p > 205 \quad (117 \text{ in 2PC}; \text{Abdo et al. 2013}) \]
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Fermi $\epsilon_{cut}$ values under simple assumptions provide a unique insight through the determination of the $E_{acc}$.

1) CR, Radiation Reaction Limit Regime

2) At the ECS near the LC

\[
0 = \frac{d\gamma_L}{dt} = \frac{q_e c E_{acc}}{m_e c^2} - \frac{2q_e^2 \gamma_L^4}{3 R_C^2 m_e c}
\]

\[
E_{cut} = \frac{3}{2} c \hbar \gamma_L^3 \frac{1}{R_C}
\]

Kalapotharakos et al. (2017a)
Fermi $\epsilon_{cut}$ values under simple assumptions provide a unique insight through the determination of the $E_{acc}$. 

**Assumptions**

1) CR, Radiation Reaction Limit Regime

2) At the ECS near the LC

$$0 = \frac{d\gamma_L}{dt} = \frac{q_e c E_{acc}}{m_e c^2} - \frac{2q_e^2 \gamma_L^4}{3R_C^2 m_e c}$$

$$E_{cut} = \frac{3}{2} \frac{c \hbar \gamma_L^3}{R_C}$$

**Simplicity**

Kalapotharakos et al. (2017a)
FFE models

Contopoulos, Kazanas, & Fendt (1999)
Spitkovsky (2006)

Kalapotharakos er al. (2012)

Bogovalov (1999)
Macroscopic Dissipative Models

\[ J = \frac{c \rho B}{B^2} + \frac{c B \cdot \nabla \times B - E \cdot \nabla \times B}{B^2} \]  
FFE

\[ J = \frac{c \rho E \times B}{E_0^2 + B^2} + \sigma E || \]  
Kalapotharakos et al. (2012, 2014, 2017a)

\[ J = \frac{c \rho E \times B + (c^2 \rho^2 + \gamma^2 \sigma^2 E_0^2)^{1/2} (B_0 B + E_0 E)}{B^2 + E_0^2} \]  
Gruzinov (2007, 2008)

\[ J = \frac{c \rho E \times B + \gamma \sigma (B_0 B + E_0 E)}{B^2 + E_0^2} \]  
Li et al. (2012)

\( \sigma : 0 \rightarrow \infty \)

VRD \xrightarrow{\text{FFE}}
FIDO Models

Kalapotharakos et al. (2014, 2017a)
FIDO Models

Radio-lag ($\delta$) vs peak-separation ($\Delta$)

test particles
Curvature Radiation

Kalapotharakos et al. (2014)
FIDO Models

FFE Inside Dissipative Outside (FIDO) model

\[ \zeta = 15^\circ, \quad \zeta = 30^\circ, \quad \zeta = 45^\circ, \quad \zeta = 60^\circ, \quad \zeta = 75^\circ, \quad \zeta = 90^\circ \]

\[ \sigma \rightarrow \infty \text{ inside the LC} \]
\[ \sigma = 30\Omega \text{ outside the LC} \]
The FIDO model allows the calculation of the phase-averaged, phase-resolved spectra and the calculation of the total $\gamma$-ray luminosity.

FIDO Models

Kalapotharakos et al. (2017a)
The FIDO model allows the calculation of the phase-averaged, phase-resolved spectra and the calculation of the total \(\gamma\)-ray luminosity.

**Assumptions**

1) CR, RRLR

2) At the ECS near the LC

\[
B_{\text{LC}} \propto B_\ast R_{\text{LC}}^{-3} \quad R_C \propto R_{\text{LC}} \propto P
\]

\[
E_{\text{acc}} \propto B_\ast P^{-3}
\]

\[
\gamma_L \propto E_{\text{acc}}^{1/4} P^{1/2}
\]

\[
\epsilon_{\text{cut}} \propto \gamma_L^3 P^{-1}
\]

\[
\epsilon_{\text{cut}} \propto B_\ast^{-1/8}
\]

\[
\epsilon_{\text{cut}} \propto B_{\text{MP}}^{-1/4} B_\ast YP
\]

\[
\epsilon_{\text{cut}_{\text{MP}}} \approx 3 \epsilon_{\text{cut}_{\text{YP}}}
\]

Kalapotharakos et al. (2017a)
The evolution of the model light-curves with energy is similar to the observed one.

Brambilla et al. 2015
Macroscopic Models guided by observations become successful providing unique insight.

The fields and the particles are still treated separately. Not Self-Consistent!

Huge EM Fields

Rotating Magnet

charge acceleration
	pair creation triggering

Particle distribution

tends to kill the \( E_{\text{acc}} \)

What we observe is the result of this sensitive balance.
Macroscopic Models guided by observations become successful providing unique insight.

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3D Particle-In-Cell code
- Kalapotharakos et al. (2017b)
- Brambilla et al. (2017)

Cartesian
Conservative
Vay’s algorithm
Current Smoothing
Radiation Reaction Forces
Load Balancing

Kinetic simulations
- Philippov & Spitkovsky 2014, 2017
- Chen & Beloborodov 2014
- Cerutti et al. 2015, 2016
- Philippov et al. 2015, 2016
- Belyaev 2015a,b, 2016

Pleiades & Discover Supercomputers, NASA
~4000 cpus
~ $10^7 - 10^9$ particles
Towards self-consistency:
1) Arbitrary particle injection
→ consistent field structure & particle distribution

\[ \alpha = 45^\circ \quad \mu - \Omega \]
1) Arbitrary particle injection

$\alpha = 45^\circ$

Density of injected particles

3D Kinetic Models (PIC)

Log scale

$e^-$

$e^+$

Density of injected particles
3D Kinetic Models (PIC)

However, PIC particle energies are much smaller than in real pulsar magnetospheres.

- We scale-up the particle energies assuming realistic B and P values.
- Moreover, we assume that the corresponding pitch angles are rapidly reduced and so the SR is not the main component of the observed $\gamma$-ray emission.

Interpretation of the corresponding high-energy emission

Kalapotharakos et al. (2017b)
3D Kinetic Models (PIC)

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3D Kinetic Models (PIC)

Kalapotharakos et al. (2017b)

$L_\gamma \propto \dot{\mathcal{E}}$ for low $\dot{\mathcal{E}}$

$L_\gamma \propto \sqrt{\dot{\mathcal{E}}}$ for high $\dot{\mathcal{E}}$
3D Kinetic Models (PIC)

- 95% of the total emission
- Near the equatorial current sheet
- For low $\alpha$-values closer to the Y-point (LC)
- For high $\alpha$-values closer to the rotational equator compared to the theoretical extent of the ECS
The number of particles that eventually enter the ECS region regulate
• the local plasma conductivity $\sigma$,
• the corresponding $E_{acc}$, and therefore
• the observed $\gamma$-ray emission.
Summary - Future steps

• Fermi data show the way...

Macroscopic FIDO Models:

• Simple variable $\sigma$ model reproduces the FERMI phenomenology (light-curves, spectral properties).

Kinetic Models:

• 1st step toward self-consistency. Particle distribution and field structure are consistent with each other.
Summary - Future steps
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- Fermi data show the way…

**Macroscopic FIDO Models:**
- Simple variable $\sigma$ model reproduces the FERMI phenomenology (light-curves, spectral properties).

**Kinetic PIC Models:**
- 1st step toward self-consistency. Particle distribution and field structure are consistent with each other.
- The convergent results and the apparent $(\sigma - F - \dot{E})$ relation connects fundamental macroscopic quantities providing a unique insight into the understanding of the physical mechanisms behind the high-energy emission in pulsar magnetospheres.

- The next step is to model the particle injection self-consistently. It is expected that this study will reveal how the pair creation processes evolve with the spin-down power ($\dot{E}$).
Thank you!