High Energy Emission in Pulsar Magnetospheres: Modeling in the FERMI Era

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Outline

• FERMI (Success Requirements)

• Modeling $\gamma$-ray emission (CR)

• Comparison with FERMI observations
  Light curves and Spectral properties

• Successful Models - Understanding

• Summary
FERMI

Fermi has a catalytic role on the current modeling of the high energy emission in pulsar magnetospheres.

\[ N_p \rightarrow \times 25 \quad N_p > 160 \ (117 \ in \ 2PC; \ Abdo \ et \ al. \ 2013) \]

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Fermi provides not only **phase-averaged** spectra but also **phase-resolved** for a dozen of pulsars.

A successful high energy emission model should be able to reproduce the observed pulsar light curve and spectral properties.

Eventually, a physical justification consistent with the microphysics is required.
(FFE) solutions

(Aligned Rotator)

\[ J = \rho_e \frac{E \times B}{B^2} + \frac{1}{4\pi} \left( \frac{B \cdot \nabla \times B - E \cdot \nabla \times E}{B^2} \right) \]

Gruzinov (1999)

\[ E \cdot B = 0 \quad \text{Ideal condition} \]

Kalapotharakos & Contopoulos (2009)
Contopoulos & Kalapotharakos (2010)
Kalapotharakos, Contopoulos & Kazanas (2012)
(FFE) solutions

(Aligned Rotator)  Bogovalov (1999)

\[ \theta = 0. \]
Something is missing

Force-Free solutions may be a good indicator of the magnetic field structure

But...

you say nothing about the necessary accelerating electric fields

\[ E_{\text{accel}} = 0 \]
Dissipative Solutions

\[ J = c\rho \frac{E \times B}{B^2} + \frac{c}{4\pi} \frac{B \cdot \nabla \times B - E \cdot \nabla \times E}{B^2} \]

FFE

\[ J = c\rho \frac{E \times B}{E_0^2 + B^2} + \sigma E_{||} \]

Kalapotharakos et al. (2012, 2014)

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

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)

\[ \sigma: \quad 0 \quad \rightarrow \quad \infty \]

VRD \rightarrow FFE
Dissipative Solutions

Very high $\sigma$ near FFE

Figure showing a dissipative solution with parallel and antiparallel orientations.
We consider trajectories

\[ \mathbf{v} = \frac{\mathbf{E} \times \mathbf{B} \pm (B_0 B + E_0 E)}{B^2 + E_0^2} \]

\[ \frac{d\gamma}{dt} = \frac{q_e c E_{||}}{m_e c^2} - \frac{2}{3} \frac{q_e^2 \gamma^4}{R_{cr}^2 m_e c} \]

\[ \mathbf{v} = c \quad \text{motion outwards} \]

Aristotelian Electrodynamics
Gruzinov (2013)

Curvature Radiation

Uniform conductivity (\(\sigma\))

\(\sigma:\) Low \quad \rightarrow \quad High

Inner Magnetosphere \quad \rightarrow \quad Outer Magnetosphere

Current Sheet
Models vs Fermi light curves

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

Kalapotharakos et al. (2014)

FIDO Models (FFE Inside the Light-Cylinder, Dissipative Outside the Light Cylinder)
Models vs Fermi light curves

The black points are the standard pulsars observed by Fermi

Kalapotharakos et al. (2014)
Models vs Fermi light curves

Kalapotharakos et al. (2014)
Models vs Fermi light curves

FFE Inside Dissipative Outside (FIDO) model

$\sigma \to \infty$ inside the LC
$\sigma = 30\Omega$ outside the LC

$\zeta = 15^\circ$, $\zeta = 30^\circ$, $\zeta = 45^\circ$, $\zeta = 60^\circ$, $\zeta = 75^\circ$, $\zeta = 90^\circ$

$\alpha = 15^\circ$, $\alpha = 30^\circ$, $\alpha = 45^\circ$, $\alpha = 60^\circ$, $\alpha = 75^\circ$, $\alpha = 90^\circ$

phase

phase
FIDO model - Spectral properties

The FIDO model allows the calculation of the phase-averaged, phase-resolved spectra and the calculation of the total γ-ray luminosity.

Broad range of σ values.

Low σ values everywhere applied outside the LC destroy the FF field structure.

We have explored models with low σ only near the open field boundary, extending outside the LC along the current sheet.
FIDO model - Spectral properties

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The FIDO model allows the calculation of the phase-averaged, phase-resolved spectra and the calculation of the total $\gamma$-ray luminosity.

We ran series of models with different combinations for $P$, $B$, and $\sigma$ values that correspond to the entire range of the observed spin-down rates ($\dot{E}$) for the MSP and SP.

Goldreich-Julian flux

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FIDO model - Spectral properties

Vela

Phase-resolved spectra

$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-\frac{E}{E_{\text{cut}}}}$$

Spectral Index

Cut-off energies

Fitting parameters for Vela

$$\alpha = 60^\circ$$
$$\zeta = 50^\circ$$
$$\sigma = 10\Omega$$

Brambilla et al. 2015

observations (Decesar 2013)

model
The evolution of the model light-curves with energy is similar to the observed one.
The results show a significant dependence of $L_\gamma$ on $\alpha$.

Is this dependence together with the $f_\Omega$ variability with $\zeta$ able to explain the observed $L_\gamma$ scattering?
FIDO model - Spectral properties

$L_\gamma$ is an important property

Is $L_\gamma$ the most reliable quantity?

$L_\gamma$ depends on

**Observations**
- $f_\Omega$ beaming factor
- $\alpha, \zeta$
- distance

**Models**
- assumed flux of emitting particles (multiplicity)

Large scattering Efficiency 100%
FIDO model - Spectral properties

\( E_{\text{cut}} \) values are robust and more reliable quantities.

They require no further assumptions for their determination.

**Fermi**

![Graph showing data points for log(\(E_{\text{cut}}\)) vs. log(\(\dot{E}\)) for 1-5 GeV]
Fermi $E_{\text{cut}}$ values provide a unique insight for the determination of the $E_0 (\sigma)$.

**Radiation Reaction Limit Regime**

\[ 0 = \frac{d\gamma_L}{dt} = \frac{q_e (E_\parallel E)}{m_e c^2} - \frac{2q_e^2 \gamma_L^4}{3R_c^2 m_e c} \]

\[ E_{\text{cut}} = \frac{3}{2} c \hbar \frac{\gamma_L^3}{R_c} \]

\[ f B_{LC} \]
FIDO model - Spectral properties

![Graph showing spectral properties of Fermi, MSP, and SP models with energy range 1-5 GeV.](image)
FIDO model - Spectral properties

![Graph showing spectral properties](image)
FIDO model - Spectral properties

Fermi

1-5GeV

log($E_{\text{cut}}$ (GeV))

log($\dot{E}$ (erg/s))

SP
FIDO model - Spectral properties

$\sigma$ vs $\dot{E}$ for SP
FIDO model - Spectral properties

\[ \sigma \text{ vs } \dot{E} \text{ for MS} \]
The observed $E_{\text{cut}}$ of MS pulsars are slightly higher than those of the SP (for the same $\dot{E}$).

Models show similar behavior.
Summary - Future steps

• The $\gamma$-ray emission comes from regions near the equatorial current sheet. Simple variable $\sigma$ model (FFE In –Dissipative Out) reproduces the FERMI phenomenology (light-curves, spectral properties).

Eventually, any successful $\sigma$ distribution should be supported by microphysics.

Observations
Models – Processes
Success

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

3D PIC code development

Poster
Brambilla et al.
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Observations Models – Processes Success

3D PIC code development

Kinetic simulations

macro

micro

observations
FIDO model - Spectral properties

Multiplicity of the emitting particles

Low $\dot{E}$  
wider gaps  

High $\dot{E}$  
higher multiplicity

$f_\Omega \approx 0.5$
Models vs Fermi light curves

rotational axis

rotational equator

$a = 75^\circ$

phase
Models vs Fermi light curves

Radio Lag ($\delta$)

Fermi
Models

Fraction

Peak Separation ($\Delta$)

FFE Inside Dissipative Outside (FIDO) model

$g_\delta = 0.17$

$g_\Delta = 0.06$