Stefano Profumo
UC Santa Cruz
Santa Cruz Institute for Particle Physics
T.A.S.C. [Theoretical Astrophysics in Santa Cruz]

Cosmic Ray Electrons and Positrons from Fermi Gamma-Ray Pulsars

“Focus on Indirect Dark Matter Searches”
IPMU – University of Tokyo
Kashiwa, December 11, 2009
1. (as per talk title) contribution to CR e+e- from Fermi gamma-ray pulsars

(work in collaboration with UC Santa Cruz undergrad Lev Gendelev and grad Michael Dormody)

2. some thoughts about the “Fermi haze”

(work in collaboration with UC Santa Cruz grad Tim Linden)
• Rotation-powered Pulsars can seed $\text{e}^+\text{e}^-$ direct pair production

(strong rotationally induced electric fields in the magnetosphere accelerate and extract $\text{e}^-$ from stellar surface, which radiate gamma rays; gammas cascade produce $\text{e}^+\text{e}^-$ pairs, escaping the magnetosphere from the polar cap regions)

• SNR & PWN shock acceleration
Propagation of charged species: diffusion equation

\[ \frac{\partial f}{\partial t} = \frac{D(\gamma)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial (P(\gamma) f)}{\partial \gamma} + Q. \]

Distribution function

\[ f(r, t, \gamma) \]

\[ \gamma = \frac{E_{e^\pm}}{m_e} \]

\[ D(\gamma) \propto \gamma^\delta \]

\[ P(\gamma) = p_0 + p_1 \gamma + p_2 \gamma^2 \]

0: Coulomb; 1: Brems; 2: IC & Synch

(*) Atoyan, Aharonian, Volk, 1995
Approximate solution to the electron/positron distribution function\(^(*)\)

(only IC and Synch losses – burst-like injection)

\[
f(r, t, \gamma) = \frac{N_0 \gamma^{-\alpha}}{\pi^{3/2} r^3} (1 - p_2 t \gamma)^{\alpha - 2} \left( \frac{r}{r_{\text{dif}}} \right)^3 e^{-(r/r_{\text{dif}})^2}
\]

\[\gamma < \gamma_{\text{cut}} \equiv \gamma_{\text{cut}}(t) = (p_2 t)^{-1}\]

\[p_2 = 5.2 \times 10^{-20} \frac{w_0}{1 \text{ eV/cm}^3} \text{ s}^{-1}\]

\[r_{\text{dif}}(\gamma, t) \simeq 2 \sqrt{D(\gamma) t \frac{1 - (1 - \gamma/\gamma_{\text{cut}})^{1-\delta}}{(1-\delta) \gamma/\gamma_{\text{cut}}}}\]

\(^(*)\) Atoyan, Aharonian, Volk, 1995
Main feature of high-energy (10-1000 GeV) e⁺e⁻: they lose energy very efficiently

Energy losses \( \sim E^2 \), via synchrotron and inverse Compton

\[
\frac{t_{\text{Lifetime}}}{\text{yr}} \approx 5 \times 10^5 \left( \frac{1 \text{ TeV}}{E} \right) \left[ \left( \frac{B}{5 \ \mu\text{G}} \right)^2 + 1.6 \times \left( \frac{w}{1 \text{ eV/cm}^3} \right) \right]^{-1}
\]

In conjunction with conventional diffusion models, this short radiative cooling time limits the sources of high energy electron/positron both in space and time

Astrophysical sources relevant for energetic e⁺e⁻ production must be young (\( \sim 10^5 \) yr) and nearby (\(<\text{kpc}\))
Example of a **burst**-like injection at different **times**, 
\( r = 100 \text{ pc} \), injection power-law: 2.2

\[
E^3 J(E) \left( \text{GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \right)
\]

\[
\begin{array}{c}
1 - t = 2.5 \times 10^4 \text{yr} \\
2 - t = 5 \times 10^4 \text{yr} \\
3 - t = 1 \times 10^5 \text{yr} \\
4 - t = 2 \times 10^5 \text{yr} \\
5 - t = 4 \times 10^5 \text{yr}
\end{array}
\]

Sharp cutoff, set by \( t \)

**Distance** sets normalization, and affects spectrum, 
\( s = r/r_{\text{dif}} \), and more distant, more peaked)

(*) Atoyan, Aharonian, Volk, 1995
The effects of a **non-burst-like** injection

in Fig. 4 represent the fluxes of electrons from the source at the same distance $r = 100$ pc and of age $t = 10^5$ yr continuously injecting relativistic electrons with the power-law index $\alpha = 2.2$ into ISM, but with the total luminosity varying in time during $0 \leq \tau \leq t$ as

$$L_e(\tau) = \frac{L_0}{(1 + \tau/\tau_*)^k}$$

for three different values of the characteristic “decay” time $\tau_*$: $\tau_*/t = 0.1$ (curve 1), $\tau_*/t = 0.01$ (curve 2), $\tau_*/t = 0.001$ (curve 3). This kind of time-dependent in-

(*) Atoyan, Aharonian, Volk, 1995
Electromagnetic processes and emission in a pulsar environment

Multi-Wavelength observations help:

(i) set the scale of the total power in relativistic e+e-

(ii) understand the e+e- spectrum

examples:

• HESS J1825-137
• Vela X (HESS)
• Geminga (Milagro)

(*) Aharonian and Bogovalov, 2002
An **asset** of the pulsar scenario: pulsars **exist**, detailed **catalogues**, very **accurate** data.
Region relevant for Pamela and Fermi ~ 1-2 kpc from Sun
Not all pulsars are **gamma-ray** (and e+e-) pulsars.

E.g., in the outer gap model, **pair** production sets in if

\[ E_x E_\gamma > m_e^2 \]

This condition depends on **magnetic field** intensity and period

\[ g = 5.5 \ P^{26/21} \ B_{12}^{-4/7} < 1. \]

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**Profumo, 0812.4457**
Role of **Fermi** to assess the *origin* of high-energy CRE:

1. Accurate CRE **Spectral Information** (probably not conclusive by itself)

2. **Local CRE source**? → Compare the **Inverse Compton** and **Bremss.** emis. predicted from the measured CRE spectrum with diffuse **gamma-ray data**

3. **Anisotropy**: search for excess CRE from bright nearby **pulsars**
   (problem: pulsar proper motion !!
   also ongoing: East-West asymmetry search !!)

4. Discovery and improved understanding of **gamma-ray pulsars**, guaranteed sources of e+e-
The Fermi First Pulsar Catalogue

- Includes high-confidence (> ) pulsed sources in the first 6-months of data

- **16 gamma-ray selected**
  (majority from blind-search campaign)

- **24 radio-selected**
  (via ephemerides, and of which 8 millisecond)

- **6 pre-Fermi GR pulsars**
Galactic Center
Gamma-Ray sel
Millissecond P
Other radio-loud

Fig. 3.— Galactic plane pulsar distribution (polar view). The star represents the Galactic center. The two circles centered at the Earth’s position have radii of 3 kpc and 5 kpc. For pulsars with different possible distances, the nearer values from Table 5 are used. Note that the millisecond pulsars (MSPs), while having a significantly lower $E$ than the other pulsars (see Figure 8), are detectable due to their close proximity. The one exception (PSR J0218+4232) also exhibits a significantly higher $E$ than the other MSPs. Blue squares: gamma-ray-selected pulsars. Red triangles: millisecond gamma-ray pulsars. Green circles: all other radio loud gamma-ray pulsars. Black dots: Pulsars for which gamma-ray pulsation searches were conducted using rotational ephemerides. Gray dots: Known pulsars which were not searched for pulsations.
The Issue of **naming** new Pulsars

Fermi-LAT Pulsar **Blind search** at UC Santa Cruz
(including the “**slug**” pulsar)
1. **Distance** estimates from gamma-ray data

2. Simple + universal PSR emission model

3. Estimate of **contribution** to local e+e- flux

**Main results:**

- gamma-ray pulsar contribution can be **substantial** from 10 of the brightest Fermi pulsars
- 6/10 are blind-search **gamma-ray selected** pulsars
- outline of regions where **radio-pulsars** might contribute without a gamma-ray signal
\[ L_\gamma \approx w \dot{E} \approx C \times \left( \frac{\dot{E}}{10^{33} \text{ ergs}^{-1}} \right)^{1/2} \times 10^{33} \text{ ergs}^{-1} \]

\( w \) : Gamma-Ray conversion efficiency

\( C \) : constant of \( O(1) \) – fitted with PSR subset with solid distance determinations

\[ L_\gamma = 4\pi f_\Omega D^2 F_\gamma, \]

\( f_\Omega \) : flux correction factor – from Watters et al “Atlas”

\[
 f_\Omega = f_\Omega(\alpha, \zeta_E) = \frac{\int \int F_\gamma(\alpha, \zeta, \phi) \sin(\zeta) d\zeta d\phi}{2 \int F_\gamma(\alpha, \zeta_E, \phi) d\phi}.
\]

plus: standard error propagation
Distance Determinations: Results

The graph shows the relationship between distance (in kpc) and E_{dot} (in erg/s) for various pulsars. The red squares indicate EGRET + Ephemerides PSRs, and the black circles represent Blind Search PSRs. The pulsar J0633+1746 is highlighted, along with Geminga.
Contribution to the local e+e- Flux

\[ Q(E, t, \vec{r}) = Q_0 \left( \frac{E}{1 \text{ GeV}} \right)^{-\Gamma} \exp\left[-E/E_{\text{cut}}\right] \delta(t - t_0) \delta(\vec{r}) \]

\[ E_{\text{cut}} = 1 \text{ TeV}, \quad \Gamma = 1.7. \]

\[ \int_{m_e}^{\infty} Q(E) \, dE = E_{\text{out}} = \eta \frac{\dot{E} r_{\text{ch}}^2}{\tau}, \quad \text{with } \tau \simeq 10^4 \text{ yr and } \eta = 0.4. \]

\[ \frac{\partial N_e(E, t, \vec{r})}{\partial t} - D(E) \nabla^2 N_e - \frac{\partial}{\partial E} \left( b(E) N_e \right) = Q(E, t, \vec{r}), \]

\[ D(E) = D_0 (E/1 \text{ GeV})^\delta \quad \text{and} \quad D_0 = 3.6 \times 10^{28} \text{ cm}^2/\text{s and } \delta = 0.33 \]
Contribution to the local e+e- Flux
Contribution to the local e+e- Flux – a closer look (1)

- Rather narrow **age** and **spin-down luminosity** ranges
- **Flat contribution** over those ranges
Contribution to the local $e^+e^-$ Flux – a closer look (2)

- Steeply declining contribution with distance
- Largest contributions between 100 and 1000 GeV
Do we expect known **radio pulsar** (~1,500) to be still more important than ~50 **gamma-ray pulsars**?
Do we expect known **radio pulsar** (~1,500) to be still more important than ~50 **gamma-ray pulsars**?

There is parameter space where gamma-ray quiet pulsars could significantly contribute!

\[ \frac{E}{E_{\text{max}}} \simeq 1. \]

\[ R_{\text{diff}} \simeq 2.7 \text{ kpc} \left( \frac{D_0}{3.6 \times 10^{28} \text{ cm}^2/\text{s}} \frac{1.4 \times 10^{-16} \text{ s}}{b_0} \right)^{1/2} \left( \frac{100 \text{ GeV}}{E} \right)^{1-\delta}. \]

\[ N_e \propto \exp\left[-\left(\frac{r}{R_{\text{diff}}}\right)^2\right] \]
Some thoughts about the “Fermi haze”

Three main contributions to the diffuse gamma-ray emission:

- **Galactic** emission
  - Neutral Pions – inelastic hadronic cosmic-ray processes
  - e+e- Radiative Losses: Inverse Compton & Bremsstrahlung

- **Isotopic** emission (extra-galactic + cosmic ray mis-ID)

(*) J-M Casandjian, Fermi Symposium 2009
The standard full-glory approach

- **SNR RX J1713-3946**
  - 42 sigma (2003+2004 data)
  - HESS Preliminary

- **X,γ**
- **e⁺,e⁻**
- **π⁺,π⁻**

- **ISM**
- **ISRF**
- **Energy losses**
- **Reacceleration**
- **Convection**
- **etc.**

- **B**
- **Chandra**
- **GLAST**

- **Diffusion**

- **PSF**

- **Flux**
  - 20 GeV/n

- **CR species:**
  - Only 1 location
  - Modulation

- **Helio-modulation**

[slide from Igor Moskalenko]
Is there an **excess** gamma-ray diffuse **emission**?
Relevant for: e+e- responsible for the haze, DM annihilation

Dobler et al: simple diagnostic:
fit **spatial templates** to Fermi gamma-ray sky

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**Dust** (far IR 100 µ emission)
=> ISM Gas => $\pi^0$ (no CR sources!)

**Synchrotron** emission map
=> IC emission (same e+e-, but…)

(*) Dobler et al, 0910.4583
Large residuals in a region morphologically comparable to the microwave WMAP haze excess

(*) Dobler et al, 0910.4583
The resulting “Fermi haze” has an intriguing **morphology**

Try to fit with a **bi-variate gaussian** additional diffuse component (expected from e.g. e+e- producing WMAP haze, or DM secondaries)

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(*) Dobler et al, 0910.4583
Residuals are now at a “noise” level – satisfactory fit!

Proceed to use the relative normalization to calculate spectra

(*) Dobler et al, 0910.4583
Are **spatial templates** accurate enough to claim a Fermi haze?

**Test quantitatively** by employing the predictions of the full-glory approach

**First template - First assumption**: gas (dust) traces $\pi^0$'s

Map (norm. to 1) of ratio of $\pi^0$'s to ISM col. dens.

**Issue**: **cosmic rays sources** live in the haze region!
Second Template - Second Assumption: Synchrotron traces IC

Issue: while both are sourced by e+e-, the emissions follow the magnetic field and inter-stellar radiation field energy densities with potentially very different morphologies!
Second Template - Second Assumption: Synchrotron traces IC

Try a constant magnetic field model
(retaining a detailed ISRF model)
again, produce an artificial haze
Assuming a “sharper” galactic magnetic field model (smaller z scale) one produces again an (energy-dependent) artificial haze.
**Systematic effects** in the spatial templates **artificially** produce a **haze** and affect the low-energy determination of an excess

At large energies: very **low statistics** + very large **cosmic ray** contamination

A **full-glory** galactic cosmic ray simulation is necessary

but is it **sufficient**?!
Fermi gamma-ray sky (source subtracted) and Galprop predictions

(from Casandjian, poster @ Fermi Symposium, 2009)
The **residuals** trace the polarized synchrotron emission presumably from the nearby **Loop I** (North Polar Spur) supernova shell (~100 deg!!)

**Local** cosmic ray **structure** maybe key to understand the diffuse emission beyond galactic cosmic ray simulations and models

(*) J-M Casandjian, Fermi Symposium 2009
Unfortunately charged cosmic rays don’t travel **straight lines** and they are sometimes not produced by our **favorite sources**….
Unfortunately charged cosmic rays don’t travel *straight lines* and they are sometimes not produced by our *favorite sources*...

Yet, the field is in the midst of a *unique and exciting spur of data*
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A solid prediction: **boredom not in sight for theorists!**