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Astrophysical Interpretation of the PAMELA and ATIC results

New Paradigms for Dark Matter
UC Davis, December 5-6, 2008
1. Brief Data Overview

2. The Standard Story: secondar Cosmic-Ray $e^+e^-$, primary $e^-$

3. Astrophysical sources of primary $e^+e^-$

4. Putting all together
FIG. 4: PAMELA positron fraction with theoretical models. The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.
• Amazing improvement over old data
• Small payload, tricky positron/antiproton discrimination
• Any interpretation of positron data must be consistent with this!

\[ r_g/m = 3.3 \times \frac{p_\perp/(\text{GeV}/c)}{|Z|(B/T)} \]

FIG. 1: Schematic overview of the PAMELA apparatus that is approximately 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W. The magnetic field lines inside the spectrometer cavity are oriented along the y direction. The average value of the magnetic field is 0.43 T.
HEAT (With Solar Modulation)

AMS

Emulsion Chambers

\( E_e^3 \frac{dN}{dE_e} \) (m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) GeV\(^2\))

Energy (GeV)
- EGRB plus CR electrons
- power-law, 3.9
- all data: power law (3.05) plus exp cutoff at 2.1 TeV
From Atoyan, Aharonian and Volk, PRD 52 (1995) 6:

“The measured content of positrons in the total electron flux [data from 1990] is regarded as a possible “enigma” awaiting an explanation […] it is obvious that some source of positrons is needed.”
Not only do we have better data, we also have Fermi!

- We have shown that LAT can efficiently detect cosmic ray electrons from 20 GeV to \(~1\) TeV with \(~3\)% residual contamination of hadrons (with respect to the number of detected electrons).
- The **effective geometric factor** after applying our electron selections is \(~1\) m\(^2\)sr and energy resolution (\(\sigma\)) is 5-20\% depending on the energy (compare with \(~0.06\) m\(^2\)sr for Pamela “calorimeter only” mode).

[slide from Alex Moiseev]
LAT will be able to **precisely reconstruct the electron spectrum** in 20 GeV – 1 TeV energy range. We are working on extending this range in both directions.

• LAT should detect $> 10^7$ electrons above 20 GeV ($> 2,500$ above 500 GeV) per year of operation. **Excellent statistics, never achieved before. Systematic errors are under careful investigation**

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*All currently available experimental results. Not much can be said about spectral features*

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*Promising feature detected by ATIC and PPB-BETS*

[slide from Alex Moiseev]
Secondary $e^+e^-$ from primary CR protons colliding with nuclei in the interstellar medium

Diffusion is self-consistently treated (e.g. studying the secondary-to-primary ratio $\mathrm{B/C}$, the H and He abundance diffuse gamma-ray and X-ray data)

An old industry: from early codes (Orth and Buffington, 1976) to complex numerical suites (e.g. Galprop)

Primary electrons: injection spectral index of 2.1 below 10 GeV, 2.4 above 10 GeV, consistently with direct measures, gamma-ray data and synchrotron radiation studies
The cosmic rays (CR) are particles traveling through space. They are a product of various processes, including interactions in the interstellar medium (ISM), reacceleration, and convection. CR species include protons, helium, and carbon, nitrogen, oxygen (CNO). The energy losses and modulation depend on the helio-modulation, which is observed by satellites like Chandra and GLAST.

HESS Preliminary data shows the location of CR sources with high significance. The flux of CRs is measured in units of 20 GeV/n. Only one location shows modulation, as indicated in the preliminary data from PAMELA and BESS.

The CR species are mapped to various locations in the ISM and are influenced by the magnetic field (B), synchrotron radiation, and bremsstrahlung (bremss).

[slide from Igor Moskalenko]
Main feature of high-energy $e^+e^-$: they lose energy very efficiently

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

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

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

Astrophysical sources must be young ($\sim 10^5$ yr) and nearby (<kpc)
Approximate solution to the electron/positron distribution function\(^(*)\)

*(only IC and Synch losses)*

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

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

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

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

\(^(*)\) Atoyan, Aharonian, Volk, 1995
Example of a burst-like injection at different times, \( r=100 \) pc, injection power-law:2.2

\( (*) \) 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

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

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-
(existing) nearby sources of CRE’s: SNR/Pulsars

- **SNR shock acceleration**
  
  *(MHD turbulence, with maximal energy limited by SNR age, free escape or synchro losses, at 10-100 TeV)*

- **Pulsar Direct (e+e-) direct pair acceleration**
  
  *(rotationally induced electric field in the magnetosphere sufficient to drive pair cascades, which then escape the magnetosphere from the polar cap regions)*
Which objects are out there? A partial list:

<table>
<thead>
<tr>
<th>SNR</th>
<th>Distance (kpc)</th>
<th>Age (yr)</th>
<th>$E_{\text{max}}$ (TeV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 185</td>
<td>0.95</td>
<td>$1.8 \times 10^3$</td>
<td>$1.7 \times 10^2$</td>
<td>1</td>
</tr>
<tr>
<td>S147</td>
<td>0.80</td>
<td>$4.6 \times 10^3$</td>
<td>63</td>
<td>2</td>
</tr>
<tr>
<td>HB 21</td>
<td>0.80</td>
<td>$1.9 \times 10^4$</td>
<td>14</td>
<td>3, 4</td>
</tr>
<tr>
<td>G65.3+5.7</td>
<td>0.80</td>
<td>$2.0 \times 10^4$</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Cygnus Loop</td>
<td>0.44</td>
<td>$2.0 \times 10^4$</td>
<td>13</td>
<td>6, 7</td>
</tr>
<tr>
<td>Vela</td>
<td>0.30</td>
<td>$1.1 \times 10^4$</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>Monogem</td>
<td>0.30</td>
<td>$8.6 \times 10^4$</td>
<td>2.8</td>
<td>9</td>
</tr>
<tr>
<td>Loop1</td>
<td>0.17</td>
<td>$2.0 \times 10^5$</td>
<td>1.2</td>
<td>10</td>
</tr>
<tr>
<td>Geminga</td>
<td>0.4</td>
<td>$3.4 \times 10^5$</td>
<td>0.67</td>
<td>11</td>
</tr>
</tbody>
</table>

Which objects are out there?

Contours of constant $e^+e^-$ flux at 3 TeV, with different cut-offs

Example of predicted $e^+e^-$ spectra
(probably not consistent with the HESS data!)

$E_c = \infty$, $\tau = 0$ yr

$D_0 = 2 \times 10^{29} (\text{cm}^2 \text{s}^{-1})$

Distant component excluding $T \leq 1 \times 10^5$ yr and $r \leq 1 \text{kpc}$

Same type of analysis applied to Pamela data

**Graphs:**

1. **All SN in the galaxy**
   - **Legend:** $N_{100} = 10, 3.3, 1$
   - **Axes:** $E_\gamma$ (GeV) vs. $dN_\gamma/dE_\gamma$ (GeV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$)

2. **Neglecting/doubling contribution from <0.5 kpc**
   - **Legend:** $N_{100} = 10, 3.3, 1$
   - **Axes:** $E_\gamma$ (GeV) vs. $\phi_{e^+}/(\phi_{e^+} + \phi_{e^-})$

**Authors:** Hooper, Blasi, Serpico, 0810.1527
Hooper, Blasi, Serpico, 0810.1527

"Geminga"

\[
\frac{dN_e^+}{dE_e^+} = \frac{E_e^+}{2} \times \left( \frac{E_e^+}{100 \text{ GeV}} \right)^{\alpha-1} \exp\left(-\frac{E_e^+}{T}\right)
\]

- \( T = 370,000 \) years
- \( E_e^+ = 3 \times 10^{47} \) erg
- \( D = 157 \) pc

"B0656+14" (Monogem)

\[
\frac{dN_e^+}{dE_e^+} = \frac{E_e^+}{2} \times \left( \frac{E_e^+}{100 \text{ GeV}} \right)^{\alpha-1} \exp\left(-\frac{E_e^+}{T}\right)
\]

- \( T = 110,000 \) years
- \( E_e^+ = 3 \times 10^{47} \) erg
- \( D = 290 \) pc
Pulsars throughout the MW and a few nearby mature pulsars (such as Geminga and B0656+14) could each plausibly generate the observed flux of positrons.

To normalize the overall flux, on the order of a few percent of the pulsars’ spin down power is required to be transferred into the production of electron-positron pairs.

Possible handle over a DM scenario: anisotropy
Similar conclusions for Geminga

Three lines employ different spectra, energy output and age

Consistent with IC emission detected by MILAGRO

Yuksel, Kistler, Stanev, 0810.2784
Non-burst-like injection model employed here
data probably compatible with ATIC, HESS

Yuksel, Kistler, Stanev, 0810.2784
Can we invoke Occam’s razor to “dissect” PAMELA and ATIC data?

Any SNR/pulsar is characterized by:

- Emitted **power** $W/10^{48}$ ergs above 1 GeV
- **Distance**
- **Age** [assuming burst-like injection]
- Electron/Positron **spectral index** $\alpha$

Normalize $W$ to get the best fit to either the $e^+e^-$ or the Pamela data, use $\delta=0.55$ and $D=1.8\times10^{27}$ cm$^2$/s (fav.by Pamela CR data)

See if we can fit data with **existing** pulsars

Profumo, in preparation
Normalization to Best Fit of $e^+e^-$ data, $\alpha=2.2$

- Fit to ATIC, HESS and Em.Ch. [$\chi^2$/d.o.f=4,6,8]
- Fit to Pamela, [$\chi^2$/d.o.f=1,10,20]
- Nearby SNR/Pulsars

Profumo, in preparation
Profumo, in preparation
Normalization to Best Fit of $e^+e^-$ data, Distance=300 pc

- Fit to ATIC, HESS and Em.Ch. [$\chi^2$/d.o.f=4,6,8]
- Fit to Pamela [$\chi^2$/d.o.f=0.5,2,10]
Normalization to Best Fit of Pamela data, Distance=300 pc

- Fit to ATIC, HESS and Em.Ch. [$\chi^2$/d.o.f=4,6,8]
- Fit to Pamela [$\chi^2$/d.o.f=0.5,2,10]

Profumo, in preparation
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Profumo, in preparation
SNR-X: \(\sim 0.7\) kpc,
\(5 \times 10^5\) yr
\(\sim 10^{48}\) erg

...might be yet to be discovered!

Profumo, in preparation
Profumo, in preparation
Are there SNR-X candidates in actual Pulsar catalogue?
A candidate for SNR-X:

B0355+54
Examples of multi-wavelength predictions for leptonic SNR

\[ \tau(E_c) = 10(E/20 \text{ TeV})^{-\delta} \text{ yr.} \]

\[ B_x = 2 \times 10^{-5} \text{ G and } B_y = 3 \times 10^{-6} \text{ G} \]

\[ \alpha_c = 2, E_c = m_e c^2, \delta = 0; \]

\[ \alpha_c = 2.5, E_c = 100 \text{ GeV}, \delta = 0.5 \]

\[ E_c = 10 \text{ TeV and } \delta = 0.5 \]

Aharonian et al, 1997
• SN are widely believed to be the primary source of galactic CR
• SN are known to exist, and to produce $e^+e^-$
• Perfect fits to PAMELA, ATIC and HESS data with SNR/Pulsars
• Existing things are enough: a case for Occam’s razor?

*Entia non sunt multiplicanda praseter necessitatem*

• Fermi-LAT is discovering new pulsars almost every day
• The $e^+e^-$ produced in SNR have several observable signatures
  (gamma rays, X-ray, Radio…)
• $e^+e^-$ data from Fermi-LAT will also tell us where the positrons come from
Examples of multi-wavelength predictions for leptonic SNR

Aharonian et al, 1997