Astrophysical Interpretation of AMS-02 Leptonic Data

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Report on:

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Cosmic-rays leptons

- Excellent data on cosmic-rays leptons are available from space-borne detectors, from about up 0.5 GeV to few hundreds of GeV

\[
- e^- \text{ Flux} \\
- e^+ \text{ Flux} \\
- (e^- + e^+) \text{ Flux} \\
- e^+/(e^- + e^+) \\
\]

AMS-02 Collab, PRL 110 (2013) 141102
AMS-02 Collab, 33rd ICRC Conference (2013)
AMS-02 Collab, 33rd ICRC Conference (2013)
Sources of cosmic-rays leptons

- **Primates**
  - Supernova remnants (SNR): electrons
  - Pulsar Wind Nebulae (PWN): electrons, positrons
  - Exotic sources, like e.g. Dark Matter (electrons, positrons)

- **Secondaries**
  - From cosmic-rays (mostly p and He) interactions in the Galaxy: (electrons, positrons)
In this talk: astrophysical interpretation

- **Primaries**
  - Supernova remnants (SNR): electrons
  - Pulsar Wind Nebulae (PWN): electrons, positrons

- **Secondaries**
  - From cosmic-rays (mostly p and He) interactions in the Galaxy: (electrons, positrons)
Primary electrons from SNR

- Particles accelerated through first-type Fermi mechanism
- Electron source spectrum:
  \[ Q(E) = Q_0 \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left( -\frac{E}{E_c} \right) \]
  \( E_c = 2 \text{ TeV} \)

- Normalization estimated from radio data:
  \[ Q_0 = 1.2 \cdot 10^{47} \text{ GeV}^{-1} (0.79)^{\gamma} \left[ \frac{d}{\text{kpc}} \right]^2 \left[ \frac{\nu}{\text{GHz}} \right]^{(\gamma-1)/2} \left[ \frac{B}{100\mu \text{G}} \right]^{-(\gamma+1)/2} \left[ \frac{B^\nu}{\text{Jy}} \right] \]

- Green catalog: 274 SNR with information on distance, age, radio flux and radio spectral index
Primary electrons from SNR

- We subdivide SNR into:
  - Near component:
    - closer than 3 kpc
    - 35 SNR in catalog, treated as single, independent sources
    - $\gamma$ and $Q_0$ derived from radio data
  - Far component:
    - treated as an single average population with:
      $$\rho(r, z) = \rho_0 r^a \exp\left(-r/r_0\right) \exp\left(-|z|/z_0\right)$$
    - $(a, r_0, z_0) = (2.35, 1.5 \text{ kpc}, 0.1 \text{ kpc})$  
    - $\gamma$ and $Q_0$ as free parameters in the fit

Primary electrons and positrons from PWN

- Pulsars can be treated as sources of highly-boosted pair-produced electrons and positrons

- Electron/positrons source spectrum:

\[ Q(E) = Q_0 \left( \frac{E}{E_0} \right)^{-\gamma_{\text{PWN}}} \exp\left(-\frac{E}{E_c}\right) \quad E_c = 2 \text{ TeV} \]

- Normalization derived from the spin-down energy \( W_0 \)

\[ \int_{E_{\text{min}}}^{\infty} dE \ E \ Q(E) = \eta \ W_0 \quad W_0 \approx \tau_0 \dot{E} \left(1 + \frac{t_{\text{age}}}{\tau_0}\right)^2 \]

\( \tau_0 \sim 10 \text{ kyr} \) PSR decay time

- ATNF catalog: PWN with information on distance, age and total emitted power

- Free parameters: \( \gamma_{\text{PWN}}, \ \eta \)
Secondary electrons and positrons

\[(p, \text{He})_{\text{prim}} + \text{ISM} \rightarrow e^\pm\]

Dedicated fit on AMS-02 data (*)

(*) Haino (ASM-02 Collab), 33rd ICRC Conference (2013)
(*) Choutko (ASM-02 Collab), 33rd ICRC Conference (2013)
Transport equation

\[ \partial_t N - \vec{\nabla} \cdot \left[ K(E) \vec{\nabla} N \right] + \partial_E \left[ b^{\text{loss}}(E) N \right] = Q(E, \vec{x}, t) \]

- diffusion
- energy losses
- source term

Geometry: cylindrical diffusive halo \((R, L)\) + thin disk \((h = 100 \text{ pc})\)

Diffusion: uniform in the whole (disk + diffusive halo) volume \(K(E) = K_0 \beta (R/1 \text{ GV})^\delta\)

Energy losses: synchrotron on magnetic fields, inverse Compton on ISRF

<table>
<thead>
<tr>
<th>Model</th>
<th>(L) (kpc)</th>
<th>(\delta)</th>
<th>(K_0) (kpc(^2) Myr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED</td>
<td>4</td>
<td>0.70</td>
<td>0.0112</td>
</tr>
</tbody>
</table>

Transport in the Heliosphere: Force field \(\phi\)
**Fit to AMS-02 data**

- **Electrons**
  - Graph showing the distribution of electron fluxes in different energy ranges.
  - Data points and error bars indicate measurements.
  - Various models are overlaid for comparison.

- **Positrons**
  - Graph showing the distribution of positron fluxes.
  - Similar to the electron graph, with data points, error bars, and model overlays.

- **Sum**
  - Combined electron and positron fluxes.
  - Shows the total flux across different energy bands.

- **Positron fraction**
  - Fraction of positrons relative to the sum of positrons and electrons.
  - Graph illustrates the fraction at various energy levels.
  - Models are present to analyze the fraction distribution.
Fit to AMS-02 data

- Reconstructed parameters (for MED)

  - Far SNR:  \( Q_0 = (2.748 \pm 0.027) \times 10^{50} \text{ GeV}^{-1} \)
    \( \gamma = 2.382 \pm 0.004 \)

  - PWN:  \( \eta = 0.0320 \pm 0.0016 \)
    \( \gamma_{\text{PWN}} = 1.90 \pm 0.03 \)

  - Normalization of secondaries:
    \( \tilde{q}_{\text{sec}} = 1.080 \pm 0.026 \)

    \( \phi = (830 \pm 22) \text{ MV} \)
The case for pulsars energy cut-off
The high-energy sector is dominated by local discrete sources:

- The electron and (electron+positron) fluxes are well compatible with a local SNR remnant contribution
- The positron flux (and the positron fraction) require local positron sources, and PWN from the ATNF catalog can provide a fairly viable solution

We therefore attempt two additional analyses to study the high-energy positron window (relevant also for DM):

- “Single-source” analysis
- “Powerful-sources” analysis
“Single-source” analysis

- We explore the PWN parameter space by injecting positrons from a single PWN-like emitter.

- Free parameters:
  - spectral index \( \gamma_{\text{PWN}} \)
  - distance \( d \)
  - age \( T \)
  - emitted power in the e\(^+\)/e\(^-\) channel \( \eta W_0 \)

- Once we find the required properties (if any) of a PWN-like emitter to reproduce the AMS-02 data, we look back into the ATNF catalog.
"Single-source" analysis

\[ \gamma = 1.5 \]

\[ \eta W_0 = [10^{46}, 10^{47}] \text{ erg} \]
\[ \eta W_0 = [10^{47}, 10^{48}] \text{ erg} \]
\[ \eta W_0 = [10^{48}, 10^{49}] \text{ erg} \]
\[ \eta W_0 = [10^{49}, 10^{50}] \text{ erg} \]
\[ \eta W_0 = [10^{50}, 10^{51}] \text{ erg} \]

PWN ATNF catalogue
PWN near and young
“Single-source” analysis

\[ \gamma = 1.8 \]

\[ \gamma = 2.0 \]

\[ \gamma = 2.2 \]
“Single-source” analysis: best-fit PWN

<table>
<thead>
<tr>
<th>Name</th>
<th>$\gamma_{fit}$</th>
<th>$d_{fit}$ (kpc)</th>
<th>$T_{fit}$ (kyr)</th>
<th>$\eta W_{0,fit}$ ($10^{49}$ erg)</th>
<th>$\chi^2$/dof</th>
<th>$d_{cat}$ (kpc)</th>
<th>$T_{cat}$ (kyr)</th>
<th>$W_{0,cat}$ ($10^{49}$ erg)</th>
<th>$\eta_{fit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geminga</td>
<td>1.74</td>
<td>0.24</td>
<td>344.6</td>
<td>0.341</td>
<td>0.68</td>
<td>0.25</td>
<td>342</td>
<td>1.25</td>
<td>0.27</td>
</tr>
<tr>
<td>J1741-2054</td>
<td>1.68</td>
<td>0.25</td>
<td>378.0</td>
<td>0.413</td>
<td>0.62</td>
<td>0.25</td>
<td>386</td>
<td>0.47</td>
<td>0.88</td>
</tr>
<tr>
<td>B1742-30</td>
<td>1.52</td>
<td>0.19</td>
<td>539.1</td>
<td>0.770</td>
<td>0.54</td>
<td>0.2</td>
<td>546</td>
<td>0.83</td>
<td>0.92</td>
</tr>
<tr>
<td>J1918+1541</td>
<td>1.65</td>
<td>0.64</td>
<td>2355</td>
<td>6.48</td>
<td>0.92</td>
<td>0.68</td>
<td>2310</td>
<td>3.4</td>
<td>1.90</td>
</tr>
</tbody>
</table>
“Single-source” analysis: fluxes

electrons

\[ E^3 \Phi \text{[GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ E \text{[GeV]} \]

e\^+ + e^-

\[ e^+/(e^+ + e^-) \]

SNR local
SNR d > 3 kpc
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE

positrons

\[ E^3 \Phi \text{[GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ E \text{[GeV]} \]

e\^+

\[ e^+/(e^+ + e^-) \]

SNR local
SNR d > 3 kpc
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE

sum

\[ E^3 \Phi \text{[GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ E \text{[GeV]} \]

e\^+ + e^-

\[ e^+/e^+ \]

SNR local
SNR d > 3 kpc
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE

positron fraction

\[ E^3 \Phi \text{[GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ E \text{[GeV]} \]

e^+

\[ e^+/e^+ \]

SNR local
SNR d > 3 kpc
TOT
AMS-02
PAMELA
FERMI
HEAT
CAPRICE
“Powerful-source” analysis

- We identify in the ATNF catalog a limited number of PWN potentially able to sizeably contribute to the local high-energy positron flux
  - For definiteness: 5 “most-powerful” sources
  - Selected by a ranking algorithm, according to their contribution to the local positron flux

- For each of them, we allow $\gamma_{\text{PWN}}$ and $\eta$ to vary, and we fit the AMS-02 data
“Powerful-sources” analysis (5)

<table>
<thead>
<tr>
<th>ATNF</th>
<th>Association</th>
<th>$d$ [kpc]</th>
<th>$T$ [kyr]</th>
<th>$W_0$ [$10^{49}$ erg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0633+1746</td>
<td>Geminga</td>
<td>0.25</td>
<td>343</td>
<td>1.26</td>
</tr>
<tr>
<td>J2043+2740</td>
<td></td>
<td>1.13</td>
<td>1204</td>
<td>26.0</td>
</tr>
<tr>
<td>B0355+54</td>
<td></td>
<td>1</td>
<td>567</td>
<td>4.73</td>
</tr>
<tr>
<td>B0656+14</td>
<td>Monogem</td>
<td>0.28</td>
<td>112</td>
<td>0.178</td>
</tr>
<tr>
<td>J0538+2817</td>
<td></td>
<td>1.3</td>
<td>622</td>
<td>6.18</td>
</tr>
</tbody>
</table>

Graphs showing the efficiency and spectral index for various sources.

- Geminga
- J2043+2740
- B0355+54
- Monogem
- J0538+2817
“Powerful-source” analysis (5 + 1)

5 “most-powerful” pulsars + “PWN background”
“Powerful-source” analysis (5+1)

- **Electrons**
  - **SNR local**
  - **SNR d > 3 kpc**
  - **Geminga**
  - **J2043+2740**
  - **B0355+54**
  - **Monogem**
  - **J0538+2817**
  - **AMS-02**
  - **PAMELA**
  - **FERMI**

- **Positrons**
  - **PWN Tot**
  - Geminga
  - J2043+2740
  - B0355+54
  - Monogem
  - J0538+2817
  - TOT
  - AMS-02
  - PAMELA
  - FERMI

- **Sum**

- **Positron fraction**

- **Electrons**
  - **SNR local**
  - **SNR d > 3 kpc**
  - **Geminga**
  - **J2043+2740**
  - **B0355+54**
  - **Monogem**
  - **J0538+2817**
  - **AMS-02**
  - **PAMELA**
  - **FERMI**

- **Positrons**
  - **PWN Tot**
  - Geminga
  - J2043+2740
  - B0355+54
  - Monogem
  - J0538+2817
  - TOT
  - AMS-02
  - PAMELA
  - FERMI

- **Sum**

- **Positron fraction**

- **Electrons**
  - **SNR local**
  - **SNR d > 3 kpc**
  - **Geminga**
  - **J2043+2740**
  - **B0355+54**
  - **Monogem**
  - **J0538+2817**
  - **AMS-02**
  - **PAMELA**
  - **FERMI**

- **Positrons**
  - **PWN Tot**
  - Geminga
  - J2043+2740
  - B0355+54
  - Monogem
  - J0538+2817
  - TOT
  - AMS-02
  - PAMELA
  - FERMI

- **Sum**

- **Positron fraction**
Summary and Conclusions

- The whole AMS-02 leptonic data have been analysed in a self-consistent theoretical framework
  - Primary electrons: distant sources ave flux + local SNR in Green catalog
  - Secondary leptons: from cosmic-rays interactions with the ISM
  - Primary high-\(E\) positrons: PWN from ATNF catalog

- Remarkable agreement with the data for all types of analyses
  - average contribution from all ATNF catalog PWN
  - single dominant PWN in ATNF
  - a few most-powerful PWN in ATNF

- The analysis provides hints on the required properties of emitters, which will require further cross-checks in other channels (like radio or gamma-rays) and theoretical models
Backup slides
bounds from gamma-rays on “positive” interpretation of positron fraction

Cirelli, Kadastik, Raidal, Strumia, NPB813 (2009) 1
as updated in arXiv:0809.2409v5