Lines, Features, Continua, and Polarization in MeV-GeV Science

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Future Space-based Gamma-ray Observatories
NASA Goddard Space Flight Center, 5-6 February 2015
“...Science Drivers for a new space-based gamma-ray experiment…”

Sources; Technology; Mission caps; Timing; Multiwavelength/multi-messenger

Roadmap for the MeV Domain (von Ballmoos et al.; Jan 2013)

- Galactic center
- 511 keV
- SN Ia
- Core collapse SN
- \(^{44}\)Ti
- Classical novae
- Continuum emission from Novae
- High-energy ISM
- Nuclear \(\gamma\)-ray lines from cosmic rays
- Gamma-ray binaries
- Gamma-ray lines from X-ray binaries
- Black Holes and accreting objects

- Gamma-Ray Bursts
- Active Galactic Nuclei
- Magnetars and isolated pulsars
- Pulsar wind nebulae
- Supernova remnants/superbubbles
- Starburst galaxies
- Sun at high energy
- Terrestrial \(\gamma\)-ray flashes
- Long lived radioactive isotopes
- Dark matter annihilation or decay
- Limits of modern physics
- MeV background
- MeV polarization
- TDEs
- Crab flares

medium-energy \(\gamma\) rays
0.1 – 100 MeV regime (MeV domain)
Discovery Matrix and Prime Science

- Early Universe/Cosmology
- Black Holes/Neutron Stars
- Dark Matter
- Exoplanets


- Cosmic Rays (particle acceleration)

Based on past results, where and how to go forward?
- **Electron-positron annihilation radiation**
  - $e^+ - e^- \rightarrow 2\gamma (0.511\text{ MeV}), 3\gamma$
- **Nucleosynthesis**
  - Giants, CCSNe ($^{26}\text{Al}$)
  - Supernovae ($^{56}\text{Ni}$, $^{57}\text{Ni}$, $^{44}\text{Ti}$)
  - ISM ($^{26}\text{Al}$, $^{60}\text{Fe}$)
- **Cosmic-ray induced lines**
  - Sun (2.2 MeV neutron capture; 0.511 MeV; $^{12}\text{C}^*4.4$, $^{16}\text{O}^*6.1$)
  - ISM ($^{12}\text{C}^*4.4$, $^{16}\text{O}^*6.1$, 0.511 MeV)
  - Broad vs. narrow lines
- **Dark matter lines**
  - Annihilation
  - Decay

Measurements of composition

Weniger (2012)

$^{56}\text{Ni}$: 158 keV, 812 keV (6 d)
$^{56}\text{Co}$: 847 keV, 1238 keV (77 d)
$^{57}\text{Co}$: 122 keV (270 d)
$^{44}\text{Ti}$: 1.157 MeV (78 yr)
$^{26}\text{Al}$: 1.809 MeV (0.7 Myr)
$^{60}\text{Fe}$: 1.173, 1.332 MeV (2.6 Myr)
Features

- **Proton-antiproton annihilation radiation**
  - $p + \bar{p} \rightarrow \pi$

- **$p+A \rightarrow \pi^0$ decay feature**
  - Solution to Galactic cosmic-ray origin
  - Found in IC 443, W44, W51C

- **Ps continuum feature**
  - $3\gamma/2\gamma$ ratio $\Rightarrow$ annihilation medium
  - Galaxy mapping

- **Dark matter signatures**

Ackermann et al. (2013) Science

OSSE data (Kinzer et al. 1999)
Continua

- Thermal vs. Nonthermal
  - \(\sim 20\) MeV maximum lepton temperature
  - \(\sim\) few hundred MeV maximum ion temperature

- Spectral characterization
  - Power law (1\textsuperscript{st} order Fermi acceleration)
  - PLEX (outer gap vs. polar cap)
  - Log-parabola (2\textsuperscript{nd} order Fermi acceleration)
  - Band Function (synchrotron vs. photosphere)

- Peak and frequency of \(\nu F_\gamma\) SED
  - Bulk of power output
  - Correlation analysis

Abdo et al. (2010) SEDs of Bright Fermi Blazars
Dermer et al. (2014) equipartition blazars
Polarization

- **Synchrotron emission in an ordered magnetic field**
  - Detection would undermine simple source models
  - Discriminate between synchrotron and photospheric emission

- **Compton scattering**

- **New Physics**

Laurent et al. (2013)

Antonucci (1993)
Point-source sensitivity of X-ray and $\gamma$-ray observatories

- Lack of sensitivity due to 1) non-focusing; 2) transition from Compton scattering (low-energy) to pair production (high-energy); 3) minimum interaction cross section of photons at $\sim 1$MeV; 4) strong instrumental and particle background

- MeV-regime science = Fermi science + MeV-line science
Fermi LAT Emissivity Measurements: A Cautionary Tale


- 4 Aug 2008 – 31 Jan 2009 (6 mos)
- LAT observations in third quadrant (200° < ℓ < 260°, 22° < |b| < 60°)
- No known molecular clouds, point sources subtracted; low ionized H column density N(HII)~1-2×10^{20} cm^{-2}


- 4 Aug 2008 – 1 Aug 2011 (3 years)
- 0° < ℓ < 360°, 10° < |b| < 70°
- Template mapping, after subtracting point and extended sources and isotropic emission; low-energy dispersion correction
- J.-M. Casandjian (4 yr data sets), to be submitted

Invert γ-ray spectrum to get cosmic-ray spectrum
Is there a break (hardening) in the spectrum of cosmic rays at ~ few GeV?
Measured vs. ISM Cosmic-Ray Spectrum

Naïve Theoretical Expectations:

1st order Fermi shock spectrum
- Test particle limit
- Strong shock

\[
\frac{d\dot{N}}{dp} \propto p^{-s_{inj}}, s_{inj} = 2.1 - 2.2
\]

Steepening due to escape

\[
t_{esc} \propto p^\delta, \quad \delta \approx 0.6
\]

\[
\frac{dN}{dp} \propto \frac{d\dot{N}}{dp} t_{esc} \propto p^{-s}, \quad s = s_{inj} + \delta
\]

\[
\therefore j(T_p) \propto \beta \frac{dN}{dT_p} \propto \frac{dN}{dp} \propto p(T_p)^{-s}
\]

Power-law momentum spectrum makes break in kinetic energy representation (index \( \propto -s/2 \) at \( T_p \ll m_p c^2 \), index \( \propto -s \) at \( T_p \ll m_p c^2 \))

Search for deviations from cosmic ray flux from power-law in momentum

Break in CR Spectrum
Neronov, Semikoz, & Taylor (2012)

Definite conclusions require better knowledge of nuclear production cross sections (Dermer 2012)
Power-law injection for protons and electrons

Power in ions: $3.0 \times 10^{40}$ erg/s  
power law index: 2.3 (in momentum)  
minimum injection momentum; $\beta \gamma = 10^{-4}$

Power in electrons: $2.0 \times 10^{38}$ erg/s  
power law index: 1.6 below the break; 2.5 above the break  
(same as Strong, Orlando, & Jaffe 2011)  
break at 4 GeV (momentum $\beta \gamma = 7840$)  
minimum injection momentum (electrons) $\beta \gamma = 0.05$

Nuclear enhancement factors = 2 for both $\pi^0$ production and bremsstrahlung

$$t_{esc}(p) = 20 \text{Myr} \left[ \frac{p}{p(T_p = 1 \text{GeV})} \right]^{-0.5}$$

Calcs: J. Finke; work with Andy Strong et al.

Quality of data exceeds quality of cross sections used to interpret data
Need new laboratory astrophysics measurements of $p+p$, $p+A$, $A+A' \to \pi$
Low-energy $\gamma$-ray spectra of SNRs and Cosmic-Ray Galaxies

Interpretation of low-energy spectra of SNRs sensitive to primary electrons, magnetic field, secondaries, and metallicity,

(work with J. Becerra and J. Finke)
MeV Regime Connections

The ratio of pion-decay emission to nuclear deexcitation-line emission depends very strongly on the steepness of the accelerated-ion kinetic-energy spectrum.

This ratio can be used to determine the accelerated-ion spectral index.
“Positrons in Astrophysics”

Mürren, Switzerland

20-23 March 2012

Session 1 - Direct Detection of Cosmic-Ray Positrons
Session 2 - Positron and Positronium Scattering
Session 3 - Astrophysical Sources of Galactic Positrons
Session 4 - Other Aspects of Positron-matter Interactions
Session 5 - Low-Energy Positron-Matter Interactions
Session 6 - Antimatter in Cosmic Rays
Session 7 - Antihydrogen
Session 8 - Annihilation Detection
Session 9 - Galactic e-e+ Annihilation
Session 10 - Antimatter from Dark or Domestic Matter
Session 11 - Positron and Positronium Interactions with Solids
Session 12 - Terrestrial and Extraterrestrial Positrons
Session 13 - Baryon Asymmetry
Session 14 - Future instruments for Observing e-e+ Radiation
Positron annihilation radiation from the Galactic center region

First (and brightest) γ-ray line detected from outside the solar system (Johnson et al. 1972, Rice U. Na detector; Leventhal et al. 1978 Bell-Sandia Ge detector)

Flux ($\sim 10^{-3}$ cm$^{-2}$ s$^{-1}$) + Distance (8 kpc ~ 27000 l.y.) $\Rightarrow$ Luminosity $\sim 10^{37}$ erg/s (a few $10^3$ L$_{\odot}$)

Positron annihilation rate : $\sim 2 \times 10^{43}$ s$^{-1}$

If activity maintained for $10^{10}$ years : $3 M_\odot$ of positrons annihilated
Laboratory Positron Physics

Michael Charlton, Swansea University

1949: - Discovery of Ps
1949-50: - Discovery of “ACAR”
1955: - Discovery of antiproton
1950's: - First attempts to make positron beams
1963: - Anomalous annihilation rates on some molecules
1968: - Ps formation in powders
1971-2: - First lab-based beam
1978-88: - Understanding of beam production
1981: - Discovery of Ps
1986: - Solid neon moderator
1988: - First positron plasma in lab. (accumulation device)
1995-6: - Discovery of antiproton
2000's: - Development of ...........................................
2002: - First cold antihydrogen
2007: - Discovery of Ps
2010: - Trapped antihydrogen
2011-12: First measurement

Direct Annihilation:
\[ e^+ + A \rightarrow 2\gamma + A^+ \]

Cross section at low energies = \( \pi \alpha^2 c Z_{eff} / v \)

Positronium Formation:
\[ e^+ + A \rightarrow Ps + A^+ \]

Excitation:
\[ e^+(E) + A \rightarrow e^+(E - E_{ex}) + A^* \]

Ionization:
\[ e^+(E) + A \rightarrow e^+(E - \Delta E) + A^+ \]
Direct Detection of Cosmic-Ray Positrons

Accardo et al. 2014: AMS-02 e+ fraction

“A Challenging Puzzle for Cosmic Ray Physics”
Spectrum in the > MeV region: constrains the energy of released e+ (or the mass of their parent dark matter particles) because they may annihilate in-flight.

**IF Dark Matter**: particle mass much smaller than “canonical” (GeV) values.
The origin of the brightest, longest known, celestial gamma-ray line is unknown.
Models for Galactic Annihilation Radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>Process</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Massive stars: $^{26}\text{Al}$</td>
<td>$\beta^+$-decay</td>
<td>$N, B/D$: Observationally inferred</td>
</tr>
<tr>
<td>Supernovae: $^{24}\text{Ti}$</td>
<td>$\beta^+$-decay</td>
<td>$\dot{N}$: Robust estimate</td>
</tr>
<tr>
<td>SNIa: $^{56}\text{Ni}$</td>
<td>$\beta^+$-decay</td>
<td>Assuming $f_{e^+,\text{esc}}=0.04$</td>
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<tr>
<td>Novae</td>
<td>$\beta^+$-decay</td>
<td>Insufficient $e^+$ production</td>
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<td>Hypernovae/GRB: $^{56}\text{Ni}$</td>
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<td>Improbable in inner MW</td>
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<td>Cosmic rays</td>
<td>p-p</td>
<td>Too high $e^+$ energy</td>
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<td>LMXRBs</td>
<td>$\gamma - \gamma$</td>
<td>Assuming $L_{e^+} \sim 0.01 L_{\text{obs,x}}$</td>
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<tr>
<td>Microquasars ($\mu\text{Qs}$)</td>
<td>$\gamma - \gamma$</td>
<td>$e^+$ load of jets uncertain</td>
</tr>
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<td>Pulsars</td>
<td>$\gamma - \gamma / \gamma - \gamma_B$</td>
<td>Too high $e^+$ energy</td>
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<td>ms pulsars</td>
<td>$\gamma - \gamma / \gamma - \gamma_B$</td>
<td>Too high $e^+$ energy</td>
</tr>
<tr>
<td>Magnetars</td>
<td>$\gamma - \gamma / \gamma - \gamma_B$</td>
<td>Too high $e^+$ energy</td>
</tr>
<tr>
<td>Central black hole</td>
<td>p-p</td>
<td>Too high $e^+$ energy, unless $B &gt; 0.4$ mG</td>
</tr>
<tr>
<td></td>
<td>$\gamma - \gamma$</td>
<td>Requires $e^+$ diffusion to $\sim 1$ kpc</td>
</tr>
<tr>
<td>Dark matter</td>
<td>Annihilation</td>
<td>Requires light scalar particle, cuspy DM profile</td>
</tr>
<tr>
<td></td>
<td>Deexcitation</td>
<td>Only cuspy DM profiles allowed</td>
</tr>
<tr>
<td></td>
<td>Decay</td>
<td>Ruled out for all DM profiles</td>
</tr>
</tbody>
</table>

Prantzos et al. (2011)
Annihilation Line Shapes

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**100% ionized**
- $n_e = 10^{13} \, \text{cm}^{-3}$
- $T = 1 \times 10^4 \, \text{K}$
- FWHM = 1.1 keV

**100% neutral**
- $n_H = 10^9 \, \text{cm}^{-3}$
- $T = 5000 \, \text{K}$
- FWHM = 2.2 keV

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**Graphs**
- Photon energy (keV)
- Photons keV$^{-1}$

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**Legend**
- total
- rc
- daf
- $3\gamma$ continuum

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**Graphs**
- Photon energy (keV)
- Photons keV$^{-1}$

---

**Legend**
- total
- dab (H)
- thermal ce
- $2g$-ice
- ilce
- dab (He)
Summary

- **Need better near-threshold cross section measurements**
  - Strong interaction; metallicity effects
  - Absence of accurate cross section information makes interpretation difficult

- **Need to grow the community**
  - Lab astro; cosmic rays; dark matter; black holes
  - $\gamma$-ray observations demonstrate level of absolute Solar modulation on interstellar cosmic-ray spectrum

- **Lack of comparable sensitivity in MeV regime hinders progress in other wavebands**