Indirect Searches for Dark Matter in Space
Status, Results and Perspectives
from Recent and Future Experiments

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Outline

- Rare cosmic messengers as markers of exotic physics (dark matter)
- Antimatter: Positrons, Antiprotons, Electromagnetic: All-electrons, Gamma Rays
  - Origins, secondary vs. primary vs. exotic
  - An experimental perspective:
    - The early years (1965-1995) – 30 years
    - The recent past (1995-2005) – 10 years
    - The present (2005-now) – 4 years … accelerated development!
- Future Prospects
p, pbar, e± in Cosmic Rays

- Primary p, nuclei, e−, γ produced at CR acceleration sites (e.g., supernova shocks, PWNs);
- Secondary e± produced in equal numbers in the ISM: CR nuclei + ISM ⇒ π± → μ± → e±;
- Secondary pbars, rare nuclei also produced in the ISM;
- e± lose energy rapidly (dE/dt ∝ E^2):
  - IC scattering on interstellar photons;
  - synchrotron radiation (interstellar B field ~ few μG);
  - explains softer spectrum for electrons;
  → Very high energy electrons (and positrons) are “local” (~kpc)
- e±/(e± + e−) fraction is small (~10%);
  → substantial primary e− component.
Positrons in a Proton Stack

CR $e^+$ measurements are challenging:

- Flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of approximately $5 \times 10^3$;
- Proton rejection of $\sim 10^{-5}$ is required for a positron sample with less than 5% proton contamination;
- This gets worse with energy:
  - proton rejection of $5 \times 10^{-6}$ @ 50 GeV
  - $2 \times 10^{-6}$ @ 100 GeV

Remember: The single largest challenge in measuring CR positrons is the discrimination against the enormous proton background! (pbar measurements are a little more forgiving)
Energy Spectra

CR $e^-$ (and $e^+$) spectrum $E^{-3.3}$ much softer than proton spectrum $E^{-2.6}$.

- Proper particle ID becomes more important at higher energies to reject hadronic background;
- Spillover from tails in lower energy bins can become problematic;
- Separating electrons from positrons at high energy requires a magnetic spectrometer with sufficient maximum detectable rigidity.
Early $e^+$ measurements: 1965-1995

What caused the dramatic rise at high energies?
Interesting physics or ... ?

25-30% $e^+$ ??

Light Halo WIMPs

Leaky Box
HEAT-e± was first to employ powerful particle ID: (rigidity vs. TRD) + (rigidity vs. EM shower shape) + (Energy-momentum matching) resulting in improved hadron rejection (∼10^{-6}).
HEAT-\(e^{\pm}\) Instrument

**TRD:**
- dE/dx losses in MWPC
- TR only for \(e^{\pm} (\gamma > 4 \times 10^3)\)
- rejection \(\sim 3 \times 10^{-3}\)

**Calorimeter:**
- EM showers for \(e^{\pm}\)
- Hadronic or no showers for \(p\)
- rejection \(\sim 3 \times 10^{-3}\)

**Energy - Momentum match for \(e^{\pm}\)**
- rejection \(\sim 10^{-1}\)
HEAT-e± Instrument

Caution required!
Hadronic showers can occasionally mimic EM showers (early $\pi^0 \rightarrow 2\gamma \rightarrow$ EM shower)
Important: Dual techniques of particle ID allow measurement on accelerator calibration or simulation. HEAT-e± achieved a measured proton rejection of 10^-6.

Note: atmospheric corrections for local secondaries necessary at balloon altitudes...
HEAT e\(^+\) Feature

3 flights, 2 instruments, 2 geomagnetic cutoffs, 2 solar epochs; Trend consistent with secondary production at low energy but all show small excess positrons at high energy.

Structure in e\(^+\) fraction as first observed by HEAT; could be DM signature (or nearby pulsars)...

HEAT results:
PRL 75, 390 (1995);
Ap. J. Lett. 482, L191-L194 (1997);
Ap. J. 498, 779-789 (1998);
Astropart. Phys. 11, 429-435 (1999);
Ap. J. 559, 296-303 (2001);

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<td>Geomagnetic cutoff rigidity</td>
<td>~ 4 GV</td>
<td>~ 1 GV</td>
<td>~ 4 GV</td>
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<td>Solar cycle epoch</td>
<td>near minimum</td>
<td>near maximum</td>
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For $m_\chi > m_W$, $\chi\chi \rightarrow WW$ annihilation leads to peak at $\sim \frac{1}{2}M_W$ but $\mu, \tau$ cascades, $\pi$ decays and Galactic propagation “wash out” peak towards lower energy. $e^+/e^+e^-$ enhancement at $\sim 10$ GeV (insensitive to WIMP mass!)
2005-Now: PAMELA

Originally PAMELA planned for a TRD but it could not be flown.

No atmospheric corrections needed.

Particle ID based on calorimetry.

- $S1$, $S2$, $S3$: double layers, x-y
- Plastic scintillator (8 mm)
- ToF resolution $\sim 300$ ps ($S1$-$S3$ ToF $\geq 3$ ns)
- Lepton-hadron separation $< 1$ GeV/c
- $S1.32.03$ (low rate) / $32.33$ (high rate)

- Permanent magnet, 0.43 T
- 21.5 cm$^2$/gr
- 6 planes double-sided silicon strip detectors (300 $\mu$m)
- 5 $\mu$m resolution in bonding view + MDR
- $\sim 300$ GV (6 plane) / $500$ GV (5 plane)

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 6.6 L
- $dE/dx$ $\sim 5.5\%$ (10 - 300 GeV)
- Self trigger $\sim 300$ GeV / 600 cm$^2$/sr

- $S6$ $^3$He counters
- $^3$He($n$,p)$^3$H, $E_n = 780$ keV
- 1 cm thick poly + Cd moderator
- $\geq 300$ $\mu$s collection
PAMELA $e^\pm$ Selection with Calorimeter

After cuts on E-R match, shower starting point

Flight data
Rigidity 20-30 GV

Test beam data
Momentum 50 GeV/c

Z = -1

$e^-$

Negative rigidity

Normalized number of events

Z = +1

$e^+$

p

Positive rigidity

Fraction of energy along the track

Fraction of energy along the track

Number of events
Selecting $e^+$ with PAMELA

Critical region 10-100 GV; Increasing $p$ contribution

Neutrons detected by ND

Note: $n$ detector efficient for $E > 100$ GeV
Comparison HEAT & PAMELA


Possible charge sign dependent solar modulation.

Rise is unexpected, and could indicate a substantial primary positron component.

In the region of interest PAMELA and HEAT are completely consistent with each other.
Fitting PAMELA with Dark Matter

Grajek et al. PRD 79, 043506 (2009); 200 GeV Wino-like neutralino; difficult to accommodate pbar, \( \gamma \) bounds; liberties with e\(^+\) propagation must be taken…

![Graph showing positron fraction vs energy](image)
Nearby Pulsar (Geminga) as a Source


![Graph showing positron fraction vs energy with data points and two curves labeled Moskalenko & Strong (2004) and Yuksel et al. (2009).]
CERN calibration configuration:

5 layers of 5 cm BGO (2.5 cm in x and 2.5 cm in y)

~ 22 rad length ~ 1 interaction length

Flight config:

4 layers:

~ 18 rad length ~ .8 interact. length
• Designed to measure nuclei, not e± (e.g., unusual trigger);
• Uses 18 rad. len. EM calorimeter with a 0.75 int. len. C target;
• Use of a low Z target is good for detecting nuclei but increases probability of hadronic contamination of electron spectra;
• Leakage out the back of calorimeter can lead to pileup at lower energy. Common problem with miscalibrated calorimeters;
• No magnet, no e± separation;
• Flew in 2000, 2002; 2008 Nature paper only refereed publication so far...
Electron identification based on shower shape in *thin* calorimeter

Electron excess from KK dark matter

Lodz ICRC 2009: ATIC reanalysis could make the bump go away

CREAM: we shied away from this…
Fermi-LAT

- Precision tracker (Si strips/W sheets), CsI calorimeter, anticoincidence;
- Optimized for detecting gamma rays, electrons;
- No prominent spectral features;
- ATIC feature not seen!

A. A. Abdo et al., PRL 102, 181101 (2009)
“Cannot exclude the possibility of a 50% contamination by γ’s”
Summary of Electron Observations

• $E^3$ plot enhances spectral features;
• Moskalenko & Strong (2009) (dot-dashed red): GALPROP w/injection spectrum modified to fit FERMI data
• No reason to believe simple diffusion model can fit data over wide energy range (solar modulation issues at low energy, local sources at high energy).

• Fermi LAT does not see ATIC excess but spectral index does not match conventional diffusion model;
• Decline at low energy (<5 GeV) due to solar modulation;
• HESS sees expected decline in all-electron spectrum above 1 TeV;
• Green dashed curve below 2 TeV: Kobayashi (2004); prediction of the local electron flux from distant sources;
• Purple dashed curve above 2 TeV: Kobayashi (2004); contribution from Vela pulsar.
Hooper, Stebbins and Zurek PRD 79, 103513 (2009) fits ATIC excess with nearby (1-2 kpc) clump of annihilating DM;

Given the disagreement with Fermi-LAT, it is instructive to see how easy it was to fit ATIC…
Fitting Fermi Data with Conventional Diffusion Model + Local Source...

• Details of Fermi, HESS data can also be reproduced using modified GALPROP + contribution from GEMINGA (same as for positron fit).
What about pbars?

O. Adriani et al., PRL 102, 051101 (2009)

- Within range of modeling and experimental uncertainties, secondary production scenarios work very well, with no hint of additional signal required…
- Any dark matter enhancement of the pbar signal would be an extreme experimental challenge!
Future: CREST, CALET

- Antarctic LDB experiment designed to extend all-electron flux measurements up to 50 TeV;
- Detects UHE Electrons through their *synchrotron radiation* in the earth’s magnetic field;
- ConUS test flight May 2009;
- Antarctic flight Dec 2010.

**Completion of electron picture... nothing to do with dark matter...**

**CALET-POLAR: 2011 balloon flight;**

**Eventually, potential CALET on Space Station ... 2013??**
AMS

Alpha Magnetic Spectrometer (AMS);
- ISS, launch on STS-134 on Sept. 16, 2010? (in Obama budget);
- Last Space Shuttle mission; program termination Sept. 30, 2010;
- Good prospect to verify PAMELA (if it flies!).
PEBS

Positron Electron Balloon Spectrometer (PEBS);
- R&D Phase 2006-2009;
- PEBS-1 with permanent magnet: 2012 Kiruna (Sweden) flight;
- PEBS-2 with superconducting magnet: 2014/15 Antarctic flight?
- Very good prospects, not dependent on vagaries of Shuttle program…
PAMELA e$^+$ enhancement is very exciting (begs for confirmation);

Compatible with earlier HEAT e$^+$ spectral feature up to $\sim$20 GeV, in region where p rejection requirement is less dire);

Continued rise to 100 GeV looks like what one could expect from proton contamination; if real, it could be a DM signature but could also be due to an astrophysical source (nearby pulsar);

Excitement over the ATIC all-electron spectral feature has abated somewhat...

Fermi-LAT sees power-law spectrum essentially devoid of spectral features; electron spectrum easily accommodated by adjusting diffusion model parameters or source model;

The ability of theory to reproduce any feature demonstrates the lack of discriminating power of cosmic-ray positron and electron data taken alone;

Unraveling the origin of the features seen in the positron fraction is possible with combined observations (direct WIMP searches, $\gamma$-rays, accelerator data...) and improved theoretical modeling;

Hard experiments can sometimes be wrong; caution is needed when interpreting positron and electron spectra...

Exciting prospects for more data in the near future!