New results from PAMELA after 10 years in orbit

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**PAMELA INSTRUMENT**

**Time-Of-Flight**
- plastic scintillators + PMT
- Trigger
- Albedo rejection
- Mass identification up to 1 GeV
- Z identification from $dE/dx$

**Electromagnetic calorimeter**
- W/Si sampling (16.3 X₀, 0.6 λI)
- Discrimination $e^+ / p$, anti-p / $e^-$
- Direct E measurement for $e^-$

**Neutron detector**
- plastic scintillators + PMT
- High-energy e/h discrimination

**Spectrometer**
- microstrip silicon tracking system + permanent magnet
- Magnetic rigidity $\Rightarrow R = pc/Ze$
- Z sign
- Z value from $dE/dx$

GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W
Isotopic composition
[ACE]
Solar Modulation
[PAMELA, ULYSSES]

Antimatter
Dark Matter
[BESS, PAMELA, AMS-02]

Elemental Composition
[CREAM, ATIC, TRACER, NUCLEON, CALET, GAMMA-400?]

Extreme Energy CR
[AUGER, EUSO, TUS/KLYPVE, OWL??]
Absolute fluxes of primary GCRs
Protons, Helium nuclei, electrons etc
First high-statistics and high-precision measurement over three decades in energy

- Deviations from single power law (99.7%):
  - Spectra gradually **soften** in the range $30 \div 230$ GV
  - Spectral **hardening** @ $R \approx 235$ GV $\Delta \gamma \approx 0.2 \div 0.3$

Origin of the hardening?
(e.g. see P. Blasi, arXiv:1312.1590)
- At the sources: multi-populations, etc.?
- Propagation effects?

Adriani, O et al., Science 332 (2011) 6025
INTERPRETATIONS

- Local source of hadrons at high energies?

- Multi-source distributed across the Galaxy

- Single source with spectral breaks?

- Different type of acceleration / propagation mechanisms?

Clear evidence of different H and He slopes

\[
\gamma_{>232\text{GV},\text{H}} = 2.67 \pm 0.03 \pm 0.05 \quad \gamma_{>243\text{GV},\text{He}} = 2.477 \pm 0.06 \pm 0.03
\]
**Solar modulation**

**Ratio = 0.988**

GLOBAL PICTURE: ELECTRON SPECTRUM (PAMELA & AMS-02)

Solar modulation

Flux \( \text{[m}^2 \text{s sr GeV}^{-1}] \times E^3 \) vs Kinetic Energy [GeV]

- PAMELA Solar Modulation Analysis
- AMS02
- FERMI
Secondary cosmic rays

Antiparticles (antiprotons, positrons), secondaries from homogeneously distributed interstellar matter (light nuclei)

HYDROGEN & HELIUM ISOTOPES
- Boron & Carbon are important proxies for transport
  - B is pure secondary
  - C is its parent nucleus (primary)

- B/C linked to the diffusion coefficient
  \[ D(E) \rightarrow \text{modelisation} \]

**BORON & CARBON SPECTRA & B/C RATIO**

July 2006 – December 2009
(0.44–129 GeV/n)

In the 200-300 GeV region, only a lower limit at 90% C.L. is presented because of a possible overestimation of the proton contamination.

- **PAMELA data along with theoretical predictions (GALPROP & DM model)**

- **DM annihilation of particles (mass 1.2 TeV) via a boson (580 MeV mass) to charged lepton pairs**

- **Pulsars?**

Adriani, O et al., PRL 111 (2013) 081102
The good agreement between the experimental data and the calculations of secondary production can constrain models of galactic DM i.e. predicting heavy WIMP candidates.

Low-energy data can constrain models with light (∼10 GeV) candidates.

Cosmic Rays in the Heliosphere
PAMELA OBSERVATIONS IN THE HELIOSPHERE

Neutron Monitor counts
http://cosmicrays.oulu.fi/

Computed HCS tilt angle
http://wso.stanford.edu/

PAMELA observations covers ~ one solar cycle

The PAMELA proton spectra over four months compared with the computed spectra


Evolution of the proton energy spectrum from July 2006 to December 2009
2010 – 2014 period

The overall flux decreases from the maximum

Solar particles subtracted from calculation

Trying to medelize the galactic spectrum even in a condition of non-quiet environment
The PAMELA electron and positron spectra over the last solar minimum

Variation of the $e^-$, $e^+$ and $p$ flux between July 2006 and December 2009

The positron to electron ratios relative to July–December 2006 for three different energy intervals

Shaded area = period with no well-defined HMF polarity

The bottom panel: Oulu neutron monitor count rate

The positron fraction derived in for three time periods

THE 2006 DECEMBER 13th EVENT

- High performance even under high rate of particles
- Particle sensitivity to discriminate solar proton from solar helium (if present)
- Fluxes evaluated in narrow time intervals to study sudden variation of solar fluxes
Preliminary

PAMELA SOLAR ENERGETIC PARTICLES SPECTRA
The PAMELA Mission: Herding a new era in precision cosmic ray physics


PAMELA OVERALL RESULTS

- Results span 4 decades in energy and 13 in fluxes

[Diagram: PAMELA data showing fluxes of various particles over energy range]
PAMELA has been in orbit studying cosmic rays for ~10 years $\rightarrow >10^{10}$ triggers registered and $>38$ TB of data has been down-linked.

Study on solar energetic particles emitted during solar events: information on acceleration mechanisms, transport processes and magnetospheric effects $\rightarrow$ 30 different events to study.

Solar Modulation:
1. Helium
2. positrons
3. light nuclei

Lithium & Beryllium absolute spectra

Isotopic ratios

MORE....
THANK YOU!
1) Different trigger configuration → optimal response to higher rates during SPE

2) Collecting solar particles down to 80 MeV and up to several GeVs (ideal for Ground Level Enhancement studies)

3) Over 30 polar passes every day → good capabilities in catching the onset of an event
Cosmic Rays in the Magnetosphere
Comparison with trapped proton empirical models


Re-entrant albedo proton spectra vs latitude $|\Lambda|$

Adriani et al., JGR A120 (2015) 3728

A. Bruno et al.: “PAMELA’s measurement of geomagnetically trapped and albedo protons”- Poster 1 CR: 30/07/2015

V. Mikhailov et al.: “Secondary positrons and electrons observed by the PAMELA spectrometer” – CR04: 31/08/2015

S. Koldobskiy et al.: “Measurement of trapped and quasitrapped deuterons in PAMELA experiment” - CR06: 31/08/2015
First measurement of p-bar trapped in the inner belt

29 p-bars discovered in SAA and traced back to mirror points

p-bar flux exceeds GRC flux by 3 orders of magnitude, as expected by models

Adriani, O et al., ApJL 737 (2011), L29
ANISOTROPIES IN THE $e^+$ DATA

**Positrons - $R > 10$ GV**

Significance map for backtraced positrons
Background: Protons
Angular scale $10^\circ$

Histogram of calculated significance

**Electrons $R > 10$ GV**

Significance map for backtraced electrons
Background: Monte Carlo simulations
Angular scale $10^\circ$

Histogram of calculated significance

Number of events as a function of the angular distance from the Sun direction
No antiHe detected in a sample of 6,330,000 events with $|Z|\geq 2$, from 0.6 to 600 GV.

Widest energy range ever reached

- No anomalous $A/Z$ particle has been found (for $Z < 8$) in the rigidity range $1 < R < 1.0 \times 10^3$ GV and mass range $4 < A < 1.2 \times 10^5$

- Upper limit as a function of Baryon Number ($A$) set

M. Ricci & M. Casolino, et al., “New upper limit on strange quark matter flux with the PAMELA space experiment” – Poster 1 CR: 30/07/2015