CR from space based observatories: results of the PAMELA mission

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International Baikal Summer School on Astrophysics and Ohysics of Elementary Particles
Bolshye Koty 23-30 July 2009
19-th century:
- discovery of electricity
- acceleration of the electrons
- production of X-rays

→ Energy up to few KeV

End of 19-th century
- discovery of natural radioactivity

→ Energy up to few MeV

Beginning of 20-th century:
- access to high atmosphere
- discovery of Cosmic Rays

→ Energy up to many GeV

Second half of 20-th centuries
- accelerators reach CR energies

Particle Physics

Years 60’s of 20-th century:
- access to space

Astrophysics

Years 70’s of 20-th century:
- permanent presence in space

The Great Observatories and the Freedom Space Station
International Space Station "FREEDOM"

Hubble Space Telescope
Space Station “FREEDOM” (1983)
THE GREAT OBSERVATORIES
FOR SPACE ASTROPHYSICS

- CGRO
- AXAF (CXO+ XMM)
- HST
- SIRTF

- Heavy Nuclei Collector (HNC)
- Particle-Antiparticle Superconducting Magnet (ASTROMAG)

facilities on board of the Freedom SS

- Advanced Composition Explorer (ACE)
- Very Long Base Interferometer (VLBI)
A.C.E.

ISTP/WIND

ASTROMAG

HNC

Cut-off momentum

**Tab. 1 - Particle Astrophysics Program for 1985-1995. Schematic from the report of NASA Cosmic Ray Program Working Group, dec. '85.**

**A. Major Programs:**
- Gain of a factor $10^{-3}$ in K.E. range
- A x 12 acceptance time exposure

**Explorers outside Magnetosphere**

**Magnet Facility for Space Station**

**B. Low Cost/Frequent Flights**
- High altitude balloons
- Shuttle and Space Station attached payloads

**C. Existing and Planned Programs**
- Continuation of exp.s in still operating spacecrafts
- International Solar Terrestrial Program for WIND spacecraft (ISTP/WIND)
- Relay of Cosmic Ray Nuclei experiment
- Heavy Nuclei Collector for second LDEF flight (HNC/LDEF-2)

**D. Laboratory Investigation and Theory**
- Cross-section measurements and accelerator calibrations
- Theory
- Instrument development
- Infrastructures

**E. Studies for the Future**
- Assembly of large arrays in space 
  - High energy, $10^{15+17}$ eV
  - Ultra Heavy Nuclei $Z>50$
  - Ultra HE (Fly's Eye)
- Interstellar probe (till several 100 AU)
- Exp.s on Polar Platform ($p, \pi, \mu$ Ultra Heavy nuclei)
Fluxes of Cosmic Rays

- Direct detection: Balloons & Satellites
- Indirect detection (EAS): [arrays & florescence]

- 1 particle per m² second
- Knee: 1 particle per m² year
- Ankle: 1 particle per km² year

Energy (eV)

E⁻².⁷
E⁻³
E⁻³.³
E⁻².⁷

13 decades
31 decades
Nuclear Composition of Galactic Cosmic Rays (~2 GeV/nucleon)

Relative Flux ($Si = 10^6$)

Nuclear Charge ($Z$)

- Individual Elements
- Even-Z Elements
- Element Groups

- $10^{-2} H$
- $10^{-6} H$
- $10^{-10} H$
- $10^{-12} H$

- 1 per cm$^2$sr·hour
- 1 per cm$^2$sr·day
- 1 per m$^2$sr·hour
- 1 per m$^2$sr·day
- 1 per m$^2$sr·year
High Z
Light Elements and Isotopes
Antiparticles and Antinuclei
Elemental Composition
Extreme Energy CR

Cosmic Rays from Space

Fluxes of Cosmic Rays

Direct detection
Balloons & Satellites

Indirect detection (EAS)
[arrays & fluorescence]

Knee (1 particle per m²-year)

Anide (1 particle per km²-year)

(1 particle per m²-second)
THE GREAT OBSERVATORIES FOR SPACE ASTROPHYSICS

1991
CGRO

AXAF (CXO+ XMM)

1999

Heavy Nuclei Collector (HNC)
and
Particle-Antiparticle Superconducting Magnet (ASTROMAG)
facilities
on board of the Freedom SS

1990
HST

1999
CANCELLED

1999
Advanced Composition Explorer (ACE)

2002
SIRTF

+ Very Long Base Interferometer (VLBI)
(A) MAJOR PROGRAMS: gain of a factor 10^{-3} in the KE range

EXPLORER outside magnetosphere

MAGNET FACILITY for Space Station

Cut-off momentum

0.1 1 10 100 1000

K.E. (GeV)

(B) LOW COST/FREQUENT FLIGHTS
- High altitude balloons
- Shuttle and Space Station attached payloads

(C) EXISTING AND PLANNED PROGRAMS
- Continuation of exp.s in still operating spacecrafts
- International Solar Terrestrial Program for WIND spacecraft (ISTP/WIND)
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- Heavy Nuclei Collector for second LDEF flight (HNC/LDEF-2)

(D) LABORATORY INVESTIGATION AND THEORY
- Cross-section measurements and accelerator calibrations
- Theory
- Instrument development
- Infrastructures

(E) STUDIES FOR THE FUTURE
- Assembly of large arrays in space
- High energy, 10^{15+17} eV
- Ultra Heavy Nuclei Z > 30
- Interstellar probe (ill. several 100 AU)
- Exps on Polar Platform (p, e, Ultra Heavy nuclei)

ASTROMAG

BESS, PAMELA, AMS

AGILE, Fermi-GLAST

HNC

ENTICE, ECCO

(JEM-S-) EUSO, TUS, KLYPVE, OWL
CR from space based observatories:  
*What happened in the last 20 years?*

- Loss of Challenger Shuttle (1986)
- Freedom Space Station cancelled (beginning of 1991)
- Consequently: HNC and ASTROMAG facilities cancelled

**for HNC:**
- precursors on LDEF and MIR, but ENTICE + ECCO not funded

**for ASTROMAG:**
- *LISA* collaboration (USA) for isotopes studies continued by ballooning, but it was stopped by the ISOMAX accident.
- *MAGIC-SCINATT* collaboration (USA+Japan) continued by ballooning, but with limited results, ACCESS on ISS never funded.
- *WIZARD* collab. (It,USA,S,D) continued by ballooning, constructed with Russia the Russian-Italian Mission (RIM) program, flew *PAMELA* [and other missions: SilEye-1-2-3, NINA, NINA-2, ALTEINO, ALTEA]
- Japanese-USA built up the *BESS* ballooning program
- a new Elementary Particle physicist collaboration (*AMS*) joined in studying the same thematic

**Antimatter**
- *ASTROGAM* collab. disbanded, AGILE and Fermi-GLAST launched in 2008

**UHECR**
- Linsley and Scarsi created the EUSO program, now continuing in different scenarios (*JEM-EUSO, S-EUSO*)
- Russians are testing new methods with the Lunar Orbiter Radio Detector (**LORD**) on board of the Luna-Glob Moon satellite

**High Z**
- precursors on LDEF and MIR, but ENTICE + ECCO not funded

**Isotopes**
- *LISA* collaboration (USA) for isotopes studies continued by ballooning, but it was stopped by the ISOMAX accident.
- *MAGIC-SCINATT* collaboration (USA+Japan) continued by ballooning, but with limited results, ACCESS on ISS never funded.
- *WIZARD* collab. (It,USA,S,D) continued by ballooning, constructed with Russia the Russian-Italian Mission (RIM) program, flew *PAMELA* [and other missions: SilEye-1-2-3, NINA, NINA-2, ALTEINO, ALTEA]
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**CR @ Knee**
- *MAGIC-SCINATT* collaboration (USA+Japan) continued by ballooning, but with limited results, ACCESS on ISS never funded.
- *WIZARD* collab. (It,USA,S,D) continued by ballooning, constructed with Russia the Russian-Italian Mission (RIM) program, flew *PAMELA* [and other missions: SilEye-1-2-3, NINA, NINA-2, ALTEINO, ALTEA]
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**[HE γ’s]**
- *ASTROGAM* collab. disbanded, AGILE and Fermi-GLAST launched in 2008
Antimatter on a Cosmological scale?

- Fundamental question (on 30’s to 60’s):
  how can the Universe contain equal amounts of M and antiM ??

Problem of separating M and antiM on large scale

Big Bang models based on statist. fluct.

\[ M_{\text{objects}} < 10^{-30} \, M_{\text{Sun}} \]
\[ \#\text{Baryon} / \#\text{Photon} \approx 10^{-18} \]

\[ \#\text{Baryon} / \#\text{Photon} \approx 1 \quad @ \, t \leq 10^{-35} \, \text{s} \]
\[ \#\text{Baryon} / \#\text{Photon} \approx 10^{-9} \quad \text{now} \]
1964: CP violation in nature

1967: Sakharov’s conditions to achieve baryon asymmetry in the Early Universe:

(1) Baryon decay allowed
(2) CP violation allowed
(3) A period out of equilibrium
The three Sakharov’s conditions:

- allow the possibility of an “all Matter” Universe
  \[\mathcal{CP}\text{ built in the Lagrangian}\]

but also:

- offer a solution to the Matter-antiMatter separation problem in a Baryon Symmetric Universe
  \[\mathcal{CP}\text{ is spontaneous}\]
  \[\text{there are DOMAINS with either Matter or antiMatter}\]
  \[\text{inflation can increase these DOMAINS to astronomical scale}\]
We can only investigate to understand by direct or indirect observation, if our Universe is or is not symmetric.

indirect

• by studying the spectrum of γ-ray radiation

direct

• by searching for Antinuclei
• by studying the $\bar{\nu}$ (and $e^+$) spectrum
\[ \gamma\text{-ray evidence??} \]

- 100 MeV bump
  \[ \bar{p}p \rightarrow \pi^0 + \ldots \]
  \[ \rightarrow \gamma(20\text{ MeV}) \]

- Limits on the fraction of \( \bar{p} \) on \( p \)

- If \( p \) and \( \bar{p} \) are "well mixed"

- "MeV" bump

- Redshifted annihilation from \( z \approx 100 \)
Flux (MeV/cm² - sec - sr MeV)

High-Energy diffuse cosmic background

Calculated annihilation flux

Extrapolated X-Ray flux

Photon energy (MeV)

COMPTEL experiment (ICRC 1995)
Antimatter in the Cosmic Radiation

$e^+$ • Large background from many secondary sources

$\bar{p}$ • Relatively abundant
  • Large background (from $p$+ISM) up to $\sim 10$ GeV
  • Sensible probe at very high energies ($\geq 100$ GeV)

$\bar{\nu}$ • No idea of their abundance
  • No background
  • However
    • 'diffusive' long travel
    • Galactic modulation

(direct observation)

high energy ($\Rightarrow 100$ GeV/n)
--- Experimental summary (<2009):
  • The “MeV bump” disappeared (in 1995)
  • The $p^-$ measured fluxes can be justified by production on ISM
  • The search for $N^-$ gave only upper limits

--- AT PRESENT (<2009):
  NO EXPERIMENTAL INDICATIONS FOR COSMOLOGICAL ANTIMATTER

--- NEEDED:
  HIGHER ENERGIES (for $p^-$, $e^+$, $N^-$)
  CLEANER ENVIRONMENT ($p^-$, $e^+$ in space)

--- WHAT FOR THE NEXT FUTURE?? :
  BESS by LDB flights ($p$-exotic, $N^-$) going on
  PAMELA on satellite ($p^-$, $e^+$, $N^-$) flown middle 2006
  AMS-02 on ISS ($N^-$, $p^-$, $e^+$) to be flown in 2010
AntiM. ‘ideal scheme’
Open balloons

Class A balloons
2.8 Mm\(^3\) @ 5 g/cm\(^2\)

Lifting power \(\sim 11\) t

Balloon 5 t
services 3 t
payload 3 t @ 38÷40km
(5g/cm\(^2\) residual atm.)
Atmospheric temperature versus Altitude

Km

40

-100 0 C°

4-5 g/cm² residual atmosphere
‘open’ balloons:

Volume @ 5g/cm² > 1 Mm³
Very thin material (20μm),
  does not support pressure differences

Maximum load ≈ 3 t
Line of sight (LOS) ≈ 800 km
Tipical duration of the flight 20 hours
Maximum altitude ≈ 40 km (4÷5g/cm²)
It is necessary a:

New Generation of Antimatter Researches in Cosmic Rays

[BESS + PAMELA + AMS-2]
BESS – Long Duration Ballooning in Antarctica

Antiproton at low energy (dark matter etc...)
Antinuclei at low energy

PAMELA – Satellite borne permanent magnet spectrometer

Antiproton and positrons up to highest energies
Antinuclei up to highest energies
Dark matter searches
Solar Physics

AMS-2 – ISS borne superconducting magnet spectrometer

Antiproton and positrons up to highest energies
Antinuclei up to highest energies
Dark matter searches
from WIZARD to PAMELA
Experiments approved for the first phase of the ASTROMAG facility

**Main Physics Objectives:**
1) Antimatter component in CR
2) Isotopic spectra
3) Compositeness up to $10^{16}$ eV
WiZard: ➔ Russian Italian Missions (RIM)

MASS-89, 91, TS-93, CAPRICE 94-97-98

NINA-1

NINA-2

PAMELA

• M 89
• M 91
• TS 93
• C 94
• C 97
• C 98

PAMELA

Antimatter search

Life Science

Solar physics

SILEYE-1

NINA-1

NINA-2

SILEYE-2

Alteino-SILEYE-3

LAZIO-SIRAD

ALTEA-SILEYE-4

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Neutron Detector

- 5 magnets, 4.8 kG @ center
- IMAGING (2.4mm granularity)
  - 16 Xo deep
  - 44 Si layers + W
  - 4.4 kchannels
- Si μ-strip, double side, double metallization
  - 6 planes x 6 sensors
  - 37 kchannels
- 36 He3 counters
- 2 layers
- 2 layers
- 9 counters
- 2 layers
- 1 layer
- Readout pitch 50μ
- Resolution <3μ
- Granularity 2 x 2 x 4 mm³

MASS = 480 kg
POWER = 345 W
GF = 20.5 cm²sr
MDR = 740 GV/c
PAMELA

- Positrons: 50 MeV - 270 GeV
- Antiprotons: 80 MeV - 190 GeV
- Limit on antinuclei: ~7 $10^{-8}$ (He /He)
- Electrons: 50 MeV - 2 TeV
- Protons: 80 MeV - 700 GeV
- Nuclei: < 300 GeV/n (Z ≤ 8)

study of the solar modulation after the 23rd solar cycle maximum.

<table>
<thead>
<tr>
<th>GF</th>
<th>20.5 cm² sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>480 Kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>120 x 40x45 cm³</td>
</tr>
<tr>
<td>Power Budget</td>
<td>345W</td>
</tr>
</tbody>
</table>
PAMELA milestones

- Launch from Baikonur: June 15\textsuperscript{th} 2006, 0800 UTC.
- Power On: June 21\textsuperscript{st} 2006, 0300 UTC.
- Detectors operated as expected after launch

- PAMELA in continuous data-taking mode since commissioning phase ended on July 11\textsuperscript{th} 2006

- As of ~ now:
  - ~1200 days of data taking (~73% live-time)
  - ~15 TByte of raw data downlinked
  - >10\textsuperscript{9} triggers recorded and under analysis
32.3 GV positron
36 GeV/c interacting proton
Pamela
senza trucchi
Data Analysis

• The Analysis has been done using only flight data

• Beam tests and MC simulations only for cross-checks
Antiprotons
Search of structures in antiproton spectrum

Secondary production (upper and lower limits) 
Simon et al.

Primary production from $\chi\chi$ annihilation 
($m(\chi) = \sim 1$ TeV) 
(astro-ph 9904086)

Secondary production (CAPRICE94-based) 
Bergström et al.
Antiproton-to-proton ratio

*preliminary*
(Petter Hofverberg’s PhD Thesis)

astro-ph 0810.4994
⇒ PRL 102 (2009)
Antiproton-to-proton ratio
Secondary Production Models

CR + ISM $\rightarrow$ p-bar $+$ ...

(Ptuskin et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: drift model (A<0, $\alpha=15^\circ$)

(Donato et al. 2001)
- **Diffusion model with convection and reacceleration**
- Solar modulation: spherical model (f=500MV)
  $\rightarrow$ Uncertainty band related to propagation parameters (~10% @10GeV)
  $\rightarrow$ Additional uncertainty of ~25% due to production cs should be considered!!

(Moskalenko et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: spherical model (f=550MV)
No evidence for any antiproton excess
Antiproton to proton ratio

preliminary
Positrons
Proton / positron selection

- Time-of-flight: trigger, albedo rejection, mass determination (up to 1 GeV)
- Bending in spectrometer: sign of charge
- Ionisation energy loss ($dE/dx$): magnitude of charge
- Interaction pattern in calorimeter: electron-like or proton-like, electron energy

**Proton**

**Positron**
Pamela e+ results

\[ \frac{\phi(e^+)}{\phi(e^+)} \]

Positron fraction vs Energy (GeV)

- Muller & Tang 1987
- MASS 1989
- TS93
- HEAT94+95
- CAPRICE94
- AMS98
- HEAT00
- Clem & Eveson 2007
- PAMELA


Accepted on Nature
Positron fraction
Secondary Production Models

CR + ISM $\rightarrow \pi^\pm + \ldots \rightarrow \mu^\pm + \ldots \rightarrow e^\pm + \ldots$
CR + ISM $\rightarrow \pi^0 + \ldots \rightarrow \gamma\gamma \rightarrow e^\pm$

(Moskalenko & Strong 1998)
GALPROP code
• Plain diffusion model
• Interstellar spectra
Dark Matter

• $e^+$ yield depend on the dominant decay channel
  → **LSPs** seem disfavored due to suppression of $e^+e^-$ final states
    → low yield (relative to p-bar)
    → soft spectrum from cascade decays
  → **LKP**s seem favored because can annihilate directly in $e^+e^-$
    → high yield (relative to p-bar)
    → hard spectrum with pronounced cutoff @ $M_{LKP} (>300$ GeV)

LKP -- $M = 300$ GeV
(Hooper & Profumo 2007)
Primary positron sources

Astrophysical processes

• Local **pulsars** are well-known sites of e⁺e⁻ pair production:
  → they can individually and/or coherently contribute to the e⁺e⁻ galactic flux and explain the PAMELA e⁺ excess (both spectral feature and intensity)
    → No fine tuning required
  → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution
    → possibility to discriminate between pulsar and DM origin of e⁺ excess

All pulsars (rate = 3.3 / 100 years)
(Hooper, Blasi, Serpico 2008)
PAMELA Positron Fraction

- Pulsar Component
  - Atoyan et al. 95
  - Zhang & Cheng 01
  - Yüksel et al. 08
- Secondary production
  - Moskalenko & Strong 98
- KKDM (mass 300 GeV)
  - Hooper & Profumo 07
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.
Example: pulsars

H. Yüksak et al., arXiv:0810.2784v2
Contributions of e− & e+ from Geminga assuming different distance, age and energetic of the pulsar

diffuse mature & nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527
Pulsars: Most significant contribution to high-energy CRE: Nearby \((d < 1 \text{ kpc})\) and Mature \((10^4-10^6 \text{ Tyear})\) Pulsars

S. Profumo

- Example of fit to both Fermi and Pamela data with known (ATNF catalogue) nearby, mature pulsars and with a single, nominal choice for the \(e+/e-\) injection parameters
Preliminary

PAMELA Electron Flux

Flux (m$^2$ sr s GeV$^{-1}$)

Energy (GeV)

PAMELA
Cosmic-ray antimatter search

(95% C.L.)

- Aizu et al. 61
- Evenson 72
- Smoot et al. 75
- LEAP 87
- Bodhwar et al. 78
- Buffington et al. 81
- BESS 95
- BESS 93+94+95
- AMS 98
- BESS 93-00
- BESS combined (new)
- PAMELA (2006–2009) expected

Antihelium-to-Helium Ratio

Rigidity (GeV^10)
Galactic cosmic-ray origin & propagation
Cosmic Rays Propagation in the Galaxy

\[ \frac{\partial N_i(E, z, t)}{\partial t} = D(E) \cdot \frac{\partial^2}{\partial z^2} N_i(E, z, t) - N_i(E, z, t) \left\{ \frac{1}{\tau_i^{\text{int}}(E, z)} + \frac{1}{\gamma(E)\tau_i^{\text{dec}}} \right\} \]

**diffusion**

**interaction and decay**

\[ + \sum_{k>i} \frac{N_k(E, z, t)}{\tau_{k \rightarrow i}^{\text{int}}(E, z)} + Q_i(E, z) \]

**secondary production**

**primary sources**

\[ - \frac{\partial}{\partial E} \left\{ \left\langle \frac{\partial E}{\partial t} \right\rangle \cdot N_i(E, z, t) \right\} + \frac{1}{2} \frac{\partial^2}{\partial E^2} \left\{ \left\langle \frac{\Delta E^2}{\Delta t} \right\rangle \cdot N_i(E, z, t) \right\} \]

**energy changing processes**

(ionisation, reacceleration)
PAMELA: Galactic H and He spectra

- Very high statistics on a very wide energy range
- Precise measurement of spectral shape
- Possibility to study time variations and transient phenomena

Very high statistics on a very wide energy range

\( \gamma \approx 2.73 \)

\( Z=1 \)

\( Z=2 \)
Proton flux

- Local spectrum:
  - injection spectrum ⊗ galactic propagation

- Local primary spectral shape:
  ⇒ study of particle acceleration mechanism

\[ N_p \propto Q_p \lambda_{esc} \]

\[ \gamma \approx 2.76 \]

Power-law fit: \( \sim E^\gamma \)

still large discrepancies among different primary flux measurements

(Statistical errors only)
Solar modulation

(statistical errors only)

Interstellar spectrum

Increasing GCR flux

Decreasing solar activity

July 2006
August 2007
February 2008
Nuclei identification

- Important input to secondary production + propagation models
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - $^3\text{He} / ^4\text{He}$
    - d / He
B/C

Preliminary

- ATIC, Panov et al., ICRC07
- CREAM, Ahn et al., Astro-ph 0808.1718
- HEAO3, Engelmann et al., A&A 223 (1990) 96E
- PAMELA (2009)

Kinetic energy, GeV/n

B/C ratio
PAMELA preliminary results

Li/C

Be/C

Primary and secondary spectra: Magnetic equator

P/(cm$^2$ sr GeV s)

- Penumbra
- Secondary particles (reentrant albedo)

RED: JULY 2006
BLUE: AUGUST 2007
Primary and secondary spectra: Intermediate latitudes

P/(cm^2 sr GeV s)

Penumbra

Secondary particles (reentrant albedo)
A look at Earth: the geomagnetic field
Spectrum of proton radiation belt inside the SAA

\[
\begin{align*}
& B > 0.30 \text{ G} \\
& 0.22 \text{ G} \leq B < 0.23 \text{ G} \\
& 0.21 \text{ G} \leq B < 0.22 \text{ G} \\
& 0.20 \text{ G} \leq B < 0.21 \text{ G} \\
& 0.19 \text{ G} \leq B < 0.20 \text{ G} \\
& B < 0.19 \text{ G} \\
\text{Always:} & \quad 10 \text{ GV} < \text{cutoff} < 11
\end{align*}
\]
Solar Physics

Solar CR propagation
Solar Energetic Particle events (SEPs)

**Proton detection threshold**: 80 MeV

**Electron detection threshold**: 50 MeV

- Solar modulation effects
- High energy component of Solar Proton Events (from 80 MeV to 10 GeV)
- High energy component of e- and e+ in Solar Events (from 50 MeV)
  + Nuclear composition of Gradual and Impulsive Events
  + He isotopic composition
December 13th 2006 event

Protons

Arbitrary units

10^2

10

1

10^{-1}

10^{-2}

10^{-3}

GeV

1/1/07 00:00 - 05:00

a 0:00 - 2:10
b 3:00 - 3:45
c 3:45 - 4:30
d 4:30 - 5:00
e 8:00 - 10:00

Preliminary!
December 13th 2006 SEP event

(SEPs accelerated during CMEs)

**SEP spectral shape and time evolution**

⇒ study of particle acceleration mechanisms in CME

Solar quiet spectrum
• PAMELA is measuring the Antiprotons and Positrons to the high energies (> 150GeV) with an unprecedented statistical precision
• PAMELA is setting a new lower limit for finding Antihelium
• PAMELA is looking for Dark Matter candidates
• PAMELA is providing measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium
• PAMELA is able to measure the high energy tail of solar particles.

For the future (other >2 years data):
Fluxes of e+ (≤300GeV), e- (≤500 GeV, ≤2TeV), p (≤700GeV)
Fluxes of light nuclei (up to O) and light isotopes
Monitoring of solar activity by SEP measurement
Anomalous CR (??), Jovian e- (?)
Cosmic-ray antimatter search

- Aizu et al. 61
- Evenson 72
- Smoot et al. 75
- LEAP 87
- Badhwar et al. 78
- Buffington et al. 81
- BESS 95
- BESS 93+94+95
- AMS 98
- BESS 93+94
- BESS combined (new)
- PAMELA (2006–2009) expected
- AMS-2 on ISS
Altezza: 320-390 Km
Inclinazione: 51.7°
AMS-02 on ISS
In Orbit 2009

TRD
Vacuum Case
Tracker
MAGNET
He Vessel

RICH

Map showing collaborations and participating institutes around the world.
The Completed AMS Detector on ISS

Transition Radiation Detector (TRD)

Silicon Tracker

Electromagnetic Calorimeter (ECAL)

Magnet

Ring Image Cerenkov Counter (RICH)

Time of Flight Detector (TOF)

Size: 3m x 3m x 3m
Weight: 7 tons
Pamela and AMS-02 Space Observatories at 1AU

Matter : Antimatter
PBH  Dark Matter
Galactic cosmic rays

Solar Energetic particles

Jovian electrons

Solar Modulation

Anomalous Nuclei
Nearby e⁻ Sources

R. B., SAA, Albedo, secondary particle

Magnetospheric physics

Earth’s magnetosphere

Rings
Bohm diffusion
Neutral sheet
Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm²)

Source

creation acceleration injection

(further acceleration?)

Propagation (through Galaxy)

Modulation (through Heliosphere)

Particle Astrophysics Experiments

Extended Air Shower

Underground, Under-ice, Underwater

Direct detection

Cosmic Ray

SIRFT
CGRO
AXAF(CXO)
HST

Atmosphere
40 km
23 Xo