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Nuclear Instruments and Methods in Physics Research A 588 (2008) 243–246

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Magnetospheric and solar physics observations with the PAMELA experiment

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Abstract

PAMELA is a satellite-borne experiment designed to make long duration measurements of the cosmic radiation in Low Earth Orbit. It is devoted to the detection of the cosmic-ray spectra in the 100 MeV–300 GeV range with primary scientific goal the measurement of antiproton and positron spectra over the largest energy range ever achieved. Other tasks include the search for antinuclei with unprecedented sensitivity and the measurement of the light nuclear component of cosmic rays. In addition, PAMELA can investigate phenomena connected with solar and Earth physics. The apparatus consists of: a Time of Flight system, a magnetic spectrometer, an electromagnetic imaging calorimeter, a shower tail catcher scintillator, a neutron detector and an anticoincidence system. In this work we present some measurements of galactic, secondary and trapped particles performed in the first months of operation.

PACS: 96.50.S−; 94.20.Wq; 94.30.Hn; 94.30Cb

Keywords: Cosmic rays; Antimatter; Solar Particle Events; Satellite-borne experiment; Magnetospheres

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doi:10.1016/j.nima.2008.01.046

1. Introduction

(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics PAMELA) space-borne experiment has been launched on June 15th 2006. It is the first long duration space experiment devoted to the research of antimatter at 1 AU (Astronomical Unit) [1]. The instrument is optimized for the detection of the antiparticle component of cosmic rays. In particular, PAMELA is able to measure, during the three years of expected life time, antiproton and positron spectra in a wide energy range (from 80 MeV to 190 GeV for $\bar{p}$ and from 50 MeV to 270 GeV for e^+) achieving a high precision in this energy range. Any observed deviation from the expected secondary spectrum could provide evidence for a dark matter signature or give constraints to existing cosmological models, as for an excess of $\bar{p}$ that could be due to neutralino annihilation [2].

Beyond these, which are the main goals of the experiment, PAMELA measures electrons, in an energy range from 50 MeV to 400 GeV, protons, from 80 MeV to 700 GeV, and the heavier components of cosmic rays (nuclei from Helium up to oxygen, with a sensitivity on the ratio $\overline{\mathrm{He}}/\mathrm{He}$ of the order of 10^{-8}). This allows for a better estimation of the parameters that intervene modelling the propagation of charged particles in the interstellar space and can extend the knowledges about the origin, acceleration and propagation of galactic cosmic rays (GCRs).

The study of the heliosphere [3] and the Earth magnetosphere [4] is also possible, thanks to the detection of cosmic rays of solar origin and particles trapped in the geomagnetic field, main subject of this paper.

Several significant solar events [5] are expected during the lifetime of the experiment, three years from the solar minimum. It will be possible to observe solar modulation, and, thanks to the detection of antiparticles, charge dependent effects.

Moreover, since the instrument follows an high inclination (70°), elliptical orbit (350 × 610 km), it is well suited for studying the geomagnetic cutoff and its variations [6] and monitoring trapped radiation while passing through the Van Allen Belts.

2. The PAMELA instrument

The instrument is able to provide information about mass, charge and velocity of the particles that it can detect with an acceptance of $21.6\,\mathrm{cm}^2\,\mathrm{sr}$. The core of the apparatus is a magnetic spectrometer, constituted by a permanent magnet and a $300\,\mu\mathrm{m}$ thick silicon microstrip tracker [7] that can reconstruct the track of the incident particle and measure the rigidity (momentum per unit of charge) with a Maximum Detectable Rigidity (MDR), measured on beam test, of about 1 TV.

A scintillator system (the Time of Flight system—ToF: three layers, each composed of two planes orthogonally segmented in bars) provides a fast trigger signal, that starts the acquisition of the whole system, and allows to measure the ToF with high precision and the absolute value of the charge of the incident particles by means of energy loss measurements [8]. The distance between the upper and lower ToF plane is 77.3 cm, sufficient to allow the detector to separate down-going particles from the up-going ones and perform velocity measurement below $\simeq 1\,\mathrm{GeV}$. The absolute value of the charge is measured also by energy loss in the tracker. This instrument also performs charge sign (to separate particles from antiparticles) and rigidity measurement measuring particle bending in the 0.43 T magnetic field. A silicon–tungsten calorimeter (16.3 radiation lengths, 0.6 interaction lengths) measures the energy released by the incident particle and performs the hadron–lepton separation providing topological and energetic information about the shower development in the calorimeter [9]. The shower tail catcher and the neutron detector [10] are also used to increase the rejection power of the apparatus. An anticoincidence system is employed to reject spurious events in the off-line phase [11].

3. Particles in Earth's magnetosphere

In addition to galactic and solar cosmic rays, PAMELA is able to detect reentrant albedo particles, produced by the interaction of galactic particles with the atmosphere, and particles trapped in the Earth radiation belts. Along its orbit PAMELA crosses both the inner radiation belt in the region of the South Atlantic Anomaly (SAA), over Brazil, and the outer radiation belt near the north and the south poles.

Furthermore, due to gravitational perturbations of the keplerian orbit, a consequence of nonsphericity of the Earth, the perigee and the apogee precede on the orbital plane more than 1° per day, which constantly change the altitude of the satellite for each latitude [12, p. 140]. Thanks to these characteristics of the orbit and to the long duration of the mission, PAMELA is able to perform detailed measurements of the energy spectra of these particles in each point of the Earth magnetosphere spanning latitudes from −70° to +70° and altitudes from 350 km to 610 km.

3.1. Low energy particles

PAMELA energy range can be extended to measure the proton and electron population in the radiation belts using the four scintillator planes. In this case the scintillator counters are used to measure integral fluxes of particles at lower energies starting from 36 MeV for protons and 3.5 MeV for electrons using the coincidence of the two top scintillators. In Fig. 1 it is shown the counting rate of one of the photomultipliers connected to the top scintillator. It is possible to see how the detector is sensitive to trapped particles in both the inner and the outer radiation belts.

This allows to test the models for particles flux in the radiation belts, like NASA AP-8/AE-8, AFRL CRRES and SAMPEX/PET PSB97, and to extend them to the

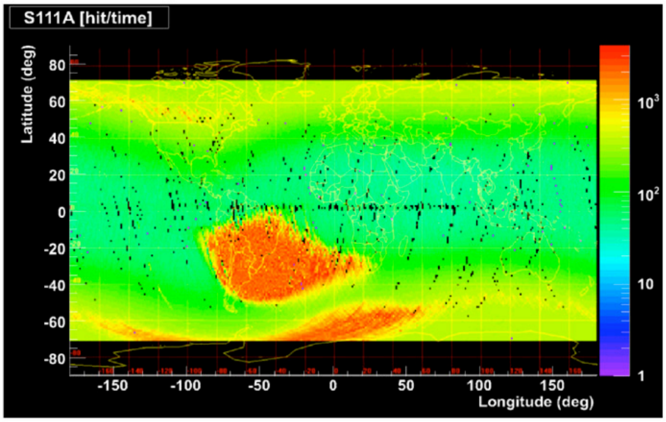

Fig. 1. Counting rate of the top scintillators of the apparatus. It is sensitive to protons from 20 MeV and electrons from 2 MeV, therefore it detects trapped particles in the inner radiation belt (the big area over Brazil) and in the outer radiation belt (the bands near the south and north poles).

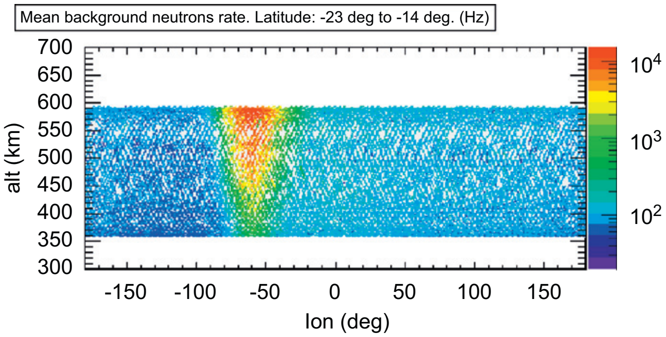

Fig. 2. Counting rate of neutrons as function of altitude and longitude (latitudes from 23°S to 14°S).

highest energies of the trapped particles (see e.g. Ref. [13]). In the three years of mission PAMELA is also expected to monitor temporal variations in the radiation belts and it has already observed the effects of the magnetic storms during the high activity of the Sun in December 2006. The existence, intensity and stability of secondary antiproton belts [14,15], produced by the interaction of cosmic rays with the atmosphere is also being investigated.

PAMELA neutron counter can also be used to measure background neutrons. They can be produced in the interaction of cosmic rays in the atmosphere or with the satellite. In Fig. 2 it is shown the secondary neutron counting rate at different values of longitude and altitude for latitudes between 23°S and 14°S. Measurement of background neutrons can be used to assess the fluence at Space Station altitudes ($\simeq 350\,\mathrm{km}$) where they contribute to about 20% to the crew dose.

3.2. Galactic and reentrant albedo particles

In the first approximation, because of the geomagnetic field, particles of galactic and solar origin can reach PAMELA only if they have a rigidity greater than a minimum value called cutoff while, at lower rigidities, they are deflected away by the Lorentz force. Because of its high inclination orbit, PAMELA is measuring the primary particle flux in regions of the magnetosphere with different cutoff values, ranging from the maximum rigidities ($\simeq 15\,\mathrm{GV}$) at the magnetic equator to rigidities below the minimum trigger energy at the magnetic poles. Regions with the same cutoff values can be characterized, in a dipole approximation of the Earth magnetic field, by the McIlwain L parameter [16]. In Fig. 3, the proton differential energy spectra for different intervals of L values are shown (the plot refers to particles outside the SAA). In vertical Stormer approximation the cutoff G is given by $G = 14.9\,\mathrm{GV}/\mathrm{L}^2$. The highest L line shows the spectrum measured near the magnetic poles, corresponding to the primary GCR flux. For all the regions the two components, above and below cutoff, are visible. The values of rigidity where the other spectra drop off from this primary flux are the upper cutoff values for the selected regions. Galactic particles can reach PAMELA if their rigidity is above this upper cutoff. Particles below the lower cutoff are usually called "reentrant albedo", and are produced in the interaction of cosmic rays with the atmosphere. Part of the secondary products of this interaction are sent back into space and are deflected back toward the Earth by the magnetic field where they are detected by PAMELA.

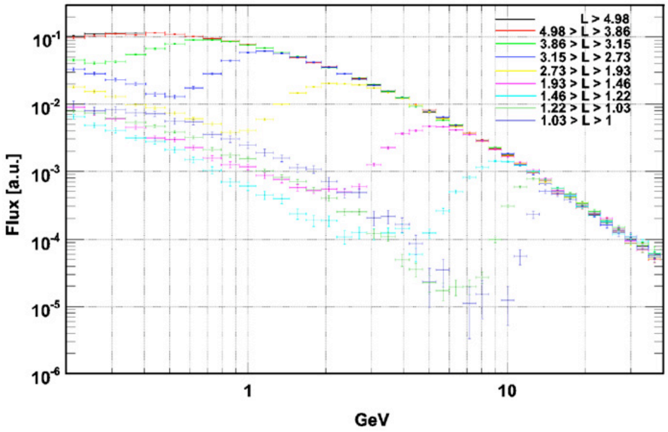

Fig. 3. Plot of the differential energy spectrum of PAMELA at different cutoff regions. It is possible to see the primary spectrum at high rigidities and the reentrant albedo (secondary) flux at low rigidities.

Thanks to its continuous data taking, PAMELA may also detect cutoff variations during geomagnetic storms and solar energetic particles (SEP) events: this is necessary to study their energy spectra (see Section 3.3).

3.3. Particles in the solar environment

PAMELA measures the effect of the influence of the Sun on charged particles that reach the Earth: the Sun activity changes the intensity of GCRs, resulting in the GCR modulation effect, and produces particles itself, that constitute the dominant component of cosmic rays at low energies.

The launch of PAMELA occurred in the recovery phase of solar minimum toward the solar maximum of cycle 24. Long time measurements will observe the increasing solar modulation and the magnetic spectrometer will allow the observation of a modulation charge sign dependence.

The measurement of charged particles helps in addressing several aspects of solar and heliospheric physics as solar particles acceleration mechanisms, and in improving actual studies on the radiation exposure expected on the International Space Station [6].

The study of the solar particle acceleration mechanism is an important subject, especially at high energies where, up to now, only few data exist demonstrating acceleration of protons or ions. Different mechanisms of particle acceleration and subsequent propagation result in different energy spectra that can be measured [17]. PAMELA is able to detect the solar component of cosmic rays in a very wide energy range (see Section 2), covering also spectral regions where few data are available from the current spacecrafts or ground Neutron Monitors.

The fast time response and the precise determination of the particles arrival time allow to measure the temporal profile [18] of the solar particle events. This is object of study because the detection of protons and heavier ions, if combined with observation of various photon emissions and neutron monitors, can give information about the site and nature of the SEP acceleration mechanism [19]. The capability to separate isotopes of H and He can also contribute to investigate selective acceleration processes and to study the nuclear and isotopic composition of gradual and impulsive events [20].

At the time of writing the most significant events occurred between December 6th and 17th, as revealed by the GOES satellites (that classified them as flare of X9.0 and X3.4 class), and by the images of the SOHO spacecraft. In particular the LASCO instrument on board of SOHO detected a powerful coronal mass ejection (CME) generated by the storm associated to the second solar flare. Data analysis is currently in progress to provide energy spectra for this events.

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