Main results of the PAMELA space experiment after 5 years in orbit

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Abstract. After five years of data taking in space, the experiment PAMELA is showing very interesting features in cosmic rays, namely in the fluxes of protons, heliums, electrons, that could have significant implications on the production, acceleration and propagation of cosmic rays in the galaxy. In addition, PAMELA measurements of cosmic antiproton and positron fluxes are setting strong constraints to the nature of Dark Matter. PAMELA is also measuring the radiation environment around the Earth, and has recently discovered an antiproton radiation belt. The study of particles related to the Solar activity is part of the scientific program of PAMELA too, providing important improvements in the comprehension of the solar modulation mechanisms. In this paper PAMELA main results are reviewed.

1. Introduction

PAMELA (a Payload for Antimatter-Matter Exploration and Light nuclei Astrophysics), is a space experiment performed by an international collaboration formed by Italy, Russia, Germany and Sweden. The instrument is housed in a pressurized container attached to the Russian Resurs-DK1 Earth-observation satellite. It was launched into space on June 15th, 2006 by a Soyuz-U rocket from the Baikonur cosmodrome in Kazakhstan, and placed in a nearly-polar (inclination 70°) low-Earth elliptical orbit at an altitude in the range 350 - 610 km. Conceived mainly for searching primordial antimatter, signals from dark matter annihilation, exotic matter as strangelets, PAMELA performs also other important tasks as the study of the mechanisms of acceleration and propagation of cosmic rays in the Galaxy and of the cosmic ray solar modulation and the detection of solar flares. Studies of the interaction of particles with the terrestrial magnetosphere complete the PAMELA research program. Here the most recent and major results obtained by PAMELA are presented and summarized. For a more extensive and detailed review, the reader is referred to the included bibliography.

2. The PAMELA Instrument

The central part of the PAMELA apparatus is a magnetic spectrometer, consisting of a 0.43 T permanent magnet and a tracking system to measure the sign and the rigidity (momentum over charge) of charged particles through their deflection in the magnetic field. A Time of Flight system, composed of a set of three double-layer planes of segmented scintillators provides a fast signal for triggering the data acquisition and for measuring the time-of-flight and ionization energy losses (dE/dx) of traversing particles. The separation between the leptonic and hadronic components is mainly carried out by an imaging silicon-tungsten calorimeter, 16 radiation length deep, with a rejection power of 10^5 for protons versus positrons, placed under the spectrometer. A neutron detector at the bottom of the instrument improves the rejection power, by counting the neutrons produced in the shower initiated in the calorimeter by the incident particles and more abundant for hadrons than for leptons. A large shower-tail scintillator under the calorimeter and an anticoincidence system complete the PAMELA instrument. Since July 2006 PAMELA is daily delivering about 16 Gigabytes of data to the Ground Segment in Moscow. More technical details can be found in [1].

3. PAMELA Results

3.1. Data analysis

Particle identification in PAMELA is based on the determination of the rigidity measured by the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. One source of background in the antimatter samples comes from the spillover (protons in the antiproton sample and electrons in the positron sample) that can be eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks. The spillover limits the rigidity interval in which the measurements can be performed. Another important source of background comes from the misidentification of like-charged particles (electrons in the antiproton sample and protons in the positron sample). While the electron to antiproton ratio is of the order of 10^2, the proton to positron ratio increases from about 10^3 at 1 GeV to approximately 10^4 at 100 GeV. Therefore, positron data need a very careful analysis, to be done using the most performing available instrumental and statistical tools, because of the possibility of misidentification of protons as positrons. Electron and positron identification for PAMELA was based on the matching between the momentum measured by the tracker and the total energy measured in the calorimeter, the starting point and the lateral and longitudinal profiles of the reconstructed shower and the neutron detector response. This analysis technique has been tested at the proton and electron beams at CERN, Geneva for different energies, by Monte Carlo simulations and by using flight data. An extensive discussion of the different methods used to assure and cross check a correct separation between the different components can be found in [2] and [3].

3.2. Antiprotons

The antiproton energy spectrum and the antiproton-to-proton flux ratio measured by PAMELA [4] in the energy interval between 60 MeV and 180 GeV are shown respectively in Fig.1 and Fig.2, along with other recent experimental data and theoretical calculations done assuming pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The curves were calculated for solar minimum, which is appropriate for the PAMELA data taking period, using the force field approximation [5]. The PAMELA results are in agreement with the previous measurements. They reproduce the expected peak around 2 GeV in the antiproton flux (due to the kinematic constraints on the antiproton production) and are in overall agreement with a pure secondary production. The experimental uncertainties are smaller than the spread in the different theoretical curves and, therefore, the data provide important constraints on parameters relevant for secondary production calculations. However, a possible contribution from non thermally produced dark matter annihilation is suggested by some authors [6].

3.3. Positrons

The positron to all electron (i.e. electron + positron) ratio measured by the PAMELA experiment [7] is given in Fig.3, compared with other recent experimental results.

The calculation, shown in the same figure, for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without re-acceleration processes provides evidence

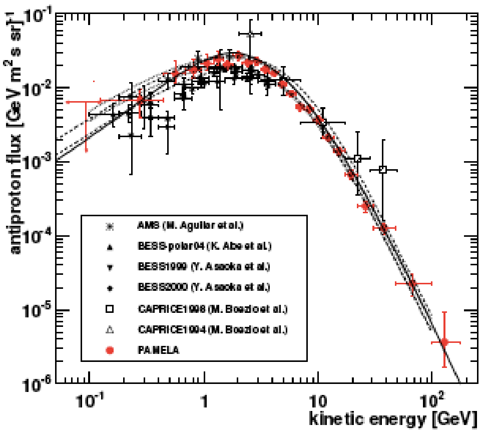

Figure 1. The PAMELA antiproton energy spectrum compared with recent measurements (see references in [4]).

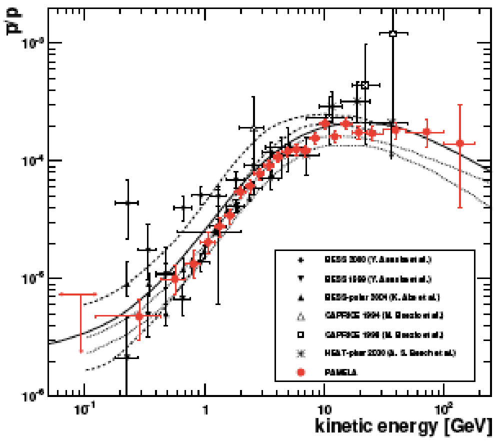

Figure 2. The PAMELA antiproton-to-proton flux ratio compared with recent measurements (see references in [4]).

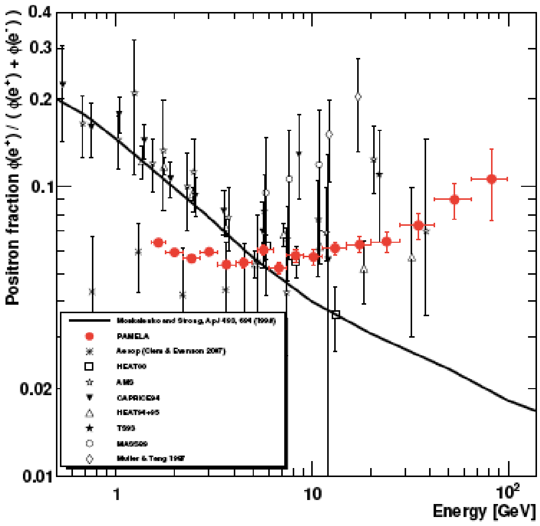

Figure 3. The PAMELA positron fraction compared with other recent experiments (see references in [7]).

that the positron fraction is expected to fall as a smooth function of increasing energy if secondary production dominates. The data, covering the energy range 1.5 - 100 GeV, show two clear features. At low energies, below 5 GeV, the PAMELA results are systematically lower than data collected during the 1990s; this can be convincingly explained by effects of charge-dependent solar modulation. At high energies, above 10 GeV, data show a positron fraction significantly increasing with energy. The background propagation model considered in Fig.3 is clearly not able to fully account for the experimental data. In particular, the rising at E > 10 GeV seems a very difficult feature to be reproduced by a pure secondary component without using an unrealistic soft electron spectrum [8], suggesting the existence of other primary sources [9].

The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio) data, difficult to explain in the framework in which the neutralino is the dominant dark matter component. A suitable explanation requires a very high mass (M >10 TeV) neutralino [10], which is unlikely in the context of allowable energy supersymmetry breaking models. Better descriptions are obtained in terms of leptonic annihilation channels for a wide range of the WIMP masses [10]. Furthermore, all explanations in terms of dark matter annihilation require a boost factor for the annihilation standard rate ranging between 10^2 to 10^3. Among the models proposed to explain the PAMELA data, it is worth to cite also the Kaluza-Klein (KK) dark matter [11], in the Universal Extra Dimension framework. Besides particle physics interpretations, a variety of astrophysical models have been put forward to explain the positron excess. One plausible explanation relates to a contribution from nearby and young pulsars, objects well known as particle accelerators. Only a few months before the publication of PAMELA positron data, the ATIC collaboration reported an excess in the galactic all electron (sum of electrons plus positrons) energy spectrum at energies of $\sim 500 - 800$ GeV [12], which led to the speculation over the existence of a nearby source of energetic electrons, either of astrophysical or exotic nature. Later in 2009, the Fermi collaboration released results about the all electron spectrum up to 1 TeV [13]. Fermi high precision data show that this spectrum falls with energy as $E^{-3.0}$ - harder than the conventional diffusive model - but does not exhibit the same prominent spectral features of ATIC. The significant flattening of the Fermi data may suggest the presence of one or more local sources of high energy CR electrons, but also dark matter scenarios cannot be excluded. Many different articles appeared, which took into account in the same theoretical frame the data from PAMELA, ATIC and Fermi.

3.4. Proton and Helium spectra

PAMELA has measured the absolute cosmic ray proton and helium spectra [14] in the rigidity interval between 1 GV and 1.2 TV (Fig.4). The results are consistent with those of other experiments within the statistical and systematic uncertainties. The differences at low energies ($<$ 30 GeV) are caused by solar modulation effects. PAMELA results overlap with ATIC-2 data [15] between $\sim$ 200 and $\sim$ 1200 GV, but differ both in shape and absolute normalization at lower energies. The extrapolation to higher energy of the PAMELA fluxes suggest a broad agreement with those published by CREAM [16] and JACEE [17] but are higher than the RUNJOB [18] helium data. To gain a better understanding of the spectra, the results have been re-analyzed in terms of rigidity instead of kinetic energy per nucleon (Fig.5). Two important conclusions can be drawn from the PAMELA data.

Firstly, the proton and helium spectra have different spectral shapes. If a single power law is fit to the data between 30 GV and 1.2 TV, the resulting spectral indices show a significant difference. Secondly, the PAMELA data show clear deviations from a single power law model. The spectrum of protons gradually softens in the rigidity range 30 - 230 GV. At 230 - 240 GV the proton and Helium data exhibit an abrupt spectral hardening. This hardening could be interpreted as an indication of different populations of cosmic ray sources. Analysis of further data is in progress and more details of these results and of the analysis procedure can be found in [14].

3.5. Geomagnetically trapped cosmic-ray antiprotons around Earth

The most recent major result obtained by PAMELA is the observation - for the first time - of antiprotons trapped in Earth's inner radiation belt [19]. The antiparticle population originates from CR interactions in the upper atmosphere and subsequent trapping in the magnetosphere.

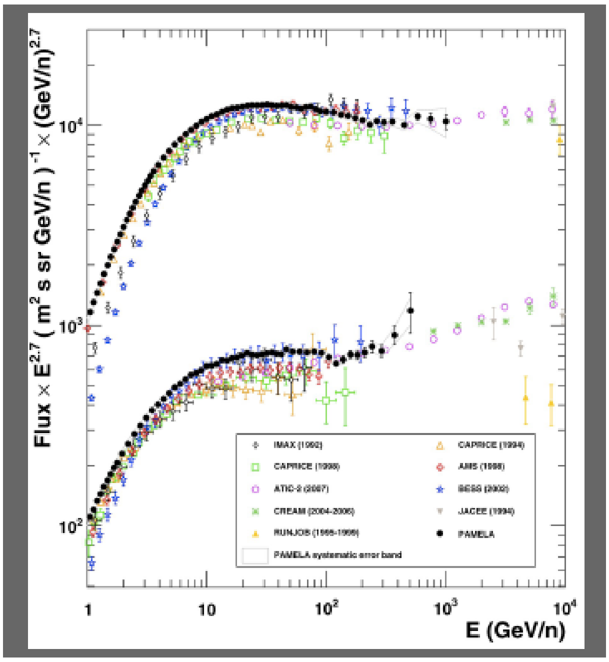

Figure 4. Proton (top points) and Helium (bottom points) absolute fluxes measured by PAMELA above 1 GeV/n compared with previous experiments (see details and references in [14]).

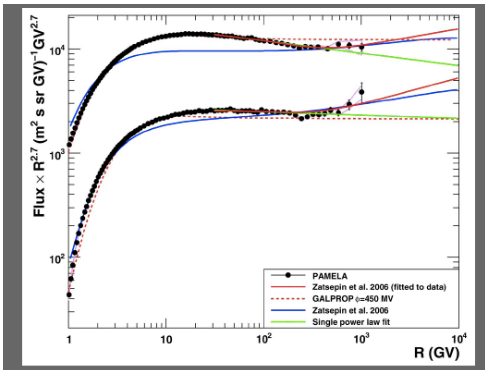

Figure 5. Proton (top points) and Helium (bottom points) data measured by PAMELA in the rigidity range 1 GV - 1.2 TV. The shaded area represents the estimated systematic uncertainty (see details and references in [14]).

PAMELA data confirm the existence of a significant antiproton flux in the South Atlantic Anomaly (SAA) region below ~ 1 GeV in kinetic energy, as shown in Fig.6.

The flux exceeds the galactic CR antiproton flux by three orders of magnitude at the current solar minimum, thereby constituting the most abundant antiproton source near the Earth. A measurement of the sub-cutoff antiproton spectrum outside the SAA region is also reported. PAMELA results allow CR transport models to be tested in the terrestrial atmosphere and significantly constrain predictions from trapped antiproton models, reducing uncertainties concerning the antiproton production spectrum in Earth's magnetosphere.

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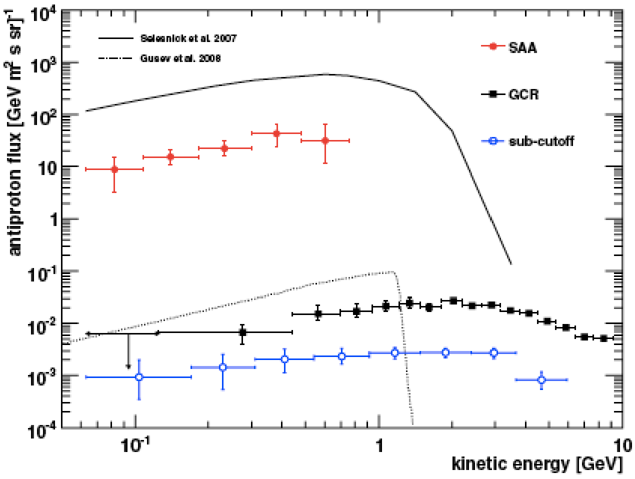

Figure 6. Geomagnetically trapped antiproton spectrum measured by PAMELA in the SAA region (red full circles). The error bars indicate statistical uncertainties. Trapped antiproton predictions by [20] for the PAMELA satellite orbit (solid line), and by [21] at L-shell = 1.2 (dotted line), are also reported. For comparison, the mean atmospheric under-cutoff antiproton spectrum outside the SAA region (blue open circles) and the galactic CR antiproton spectrum (black squares) measured by PAMELA ([4]) are also shown.

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