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Cosmic ray electrons and positrons over decade with the PAMELA experiment

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Abstract. The PAMELA experiment has measured cosmic ray particles and antiparticles fluxes at Earth orbit from June 2006 till January 2016 onboard the Resurs-DK1 satellite. Measurements were carried out during the solar minimum of 23 solar cycle with negative polarity $A < 0$ of heliospheric magnetic field till the beginning of 24 cycle with positive polarity $A > 0$. In this paper, the results of observations of electron and positron fluxes are presented in wide energy range from several hundreds MeVs till several TeVs These measurements provide important information to study cosmic ray sources and propagation in Galaxy and heliosphere.

1. Introduction

The magnetic spectrometer PAMELA was launched onboard the Resurs-DK1 satellite on the 15th of June 2006 and it was continuously taking data during almost 3200 days till January 2016. The satellite had a quasi-polar (70° inclination) elliptical orbit at an altitudes between 350 and 600 km. The main goal of the experiment is to study the energy spectra of particles and antiparticles of cosmic radiation in a wide energy range from tens of MeV to several TeV. Measurements of the ratio of the fluxes of positrons to the total flux of electrons and positrons in the PAMELA experiment [1], confirmed by subsequent data from FERMI-LAT and AMS-02 [2, 3] showed that it increases with energy, starting from 5 GeV in contradiction to the "standard" diffusion model of the generation and propagation of cosmic rays. This growth may mean the existence of sources of primary positrons, including those associated with hypothetical dark matter. Results of the PAMELA observation of electron and positron fluxes near the Earth, which were made in first years of the flight, were reported in papers [4]. These results show features of spectra at high and low energies. At low energies $E < 5$ GeV, the PAMELA experiment obtained the ratio of the flux of positrons to the total flux of electrons and positrons $I_{e^+}/I_{(e^+ + e^-)}$ is noticeably lower than in previous stratospheric measurements carried out in the period of the positive polarity of the interplanetary magnetic field $A > 0$ in the 80-90 years [5]. The solar wind and heliospheric magnetic field affect the propagation of cosmic rays modifying their spectrum at low energies. The modulation effect depends primarily on the level of solar activity and the parameters of the heliospheric field. Since the direction of the drift heliospheric magnetic field defined by particle charge this lead to a dependence of the modulation on the sign of the charge. In particular, electrons and positrons will be modulated differently during periods of positive and negative polarity of the heliospheric field [6]. Indeed, during in the in PAMELA experiment measurements in 2006-2015, a change in the ratio of positrons and electrons fluxes was observed in 2013-2014. After the polarity reversal (in 2013 [7]), there was a rapid increase in the ratio of the fluxes of positrons and electrons, and by the end of 2015 it almost reached the level of the 90's [5].

This paper presents new data obtained by processing the entire set of data accumulated in the PAMELA experiment over 10 years of work on the Earth orbit from June 2006 to January 2016.

2. PAMELA spectrometer

The instrument consists of a Time-of-Flight system (ToF), an anticoincidence system, a magnetic spectrometer, an electromagnetic calorimeter, a shower tail catching scintillator and a neutron detector. The ToF system provides the main trigger for particle acquisition, measures the absolute value of the particle charge and its flight time while crossing the apparatus (the accuracy is better than 350 ps). A rigidity is determined by the magnetic spectrometer, composed by a permanent magnet with a magnetic field intensity 0.4 T and a set of six micro-strip silicon planes. The spatial resolution of the tracker system of the spectrometer was observed to be about $\sim$4 μm, corresponding to a maximum detectable rigidity exceeding $\sim$1 TV. The high energy electron and positron identification is provided by the electromagnetic imaging calorimeter. The calorimeter consists of 22 double strip silicon layers interleaved by tungsten planes. Total thickness of tungsten is 16.3 radiation and 0.6 nuclear interaction lengths. Particles not cleanly entering the PAMELA acceptance are rejected by the anticoincidence system. Neutron detector and shower scintillator improve particle identification. Using of the ToF system, the magnetic spectrometer and the calorimeter information allows electrons and positrons identification and measuring their energy from $\sim$50 MeV up to $1-2$ TeV.

The acceptance is about 21.6 cm^{2}sr [4].

3. Data analysis

Using the PAMELA 10^{th} data reduction for each registered event were obtained the number of tracks and energy losses in the magnetic spectrometer planes, rigidity, the time of flight, energy deposit in calorimeter strips and some others parameters. Using this data a set of variables dealing with point of interaction, transversal and longitudinal profiles was calculated for particle identification. In this work to increase statistical accuracy of results "soft" criteria were used to select tracks in magnetic spectrometer. The number of points used to determine the track curvature was equal three in the deflecting projection X and two in the projection Y. Taking into account small number of points additional quality control of selected tracks was performed according to the calorimeter and time-of-flight system data. Electrons and positrons were identified using information about dE/dx energy losses in the spectrometer planes and ToF detectors (to select charge Z=1), shower properties in the imaging calorimeter, particle velocity β and a rigidity R. In addition, for better suppression of the background of pions produced in inelastic interactions in the instrument itself, only relativistic particles with a velocity $\beta > 0.9$ were selected. No signals in the anti-coincidence system, the shower counter and the neutron detector were allowed at low eneries. On the contrary, at high energies, the check up of signals in the anti-coincidence system was not carried out to reduce event losses due to background from secondary particles produced inside the device itself. Above $\sim$100 GeV, the energy of electrons and positrons was determined according to the calorimeter data by profile fitting procedure. Estimated on base of Monte-Carlo simulation the proton rejection power is about 10^4 - 10^5, electron efficiency 50 - 70% over all energy range.

Total accumulated statistic for electrons and positron is about 5×10^6 in whole energy range both for primary cosmic ray and secondary components below geomagnetic cut-off. The main axis of the PAMELA instrument was pointed mainly to a local zenith during the flight. Primary particles are observed mainly in polar region and above vertical cut-off rigidity near equator.

Gathering power of the instrument was estimated with Monte-Carlo simulation with PAMELA Collaboration software [4]. An efficiency of detectors may change with time and must be taken into account in a data proceeding. In this work this efficiency was estimated from experimental data itself by using different combination of information from imaging calorimeter, magnetic spectrometer and time of flight system.

4. Results

The differential energy spectrum of the total flux of electrons and positrons of galactic cosmic rays is shown in figure 1. For comparison, data from recent experiments AMS-02 [8], Fermi-LAT[9], DAMPE [10], CALET [11] are presented. A feature of the spectrum is its cut-off at high energies, which clearly visible at energies above $\sim$1 TeV. Despite the fact that the results of the experiments are close to each other, the high statistical accuracy of the data brings to the conclusion that the some systematic errors exists associated with the precise determination of instruments characteristics It can be seen from the figure that in the energy range from 100 GeV to $\sim$1 TeV differences in flux measurements are observed, which, of course, makes it difficult to search for features in the spectra and to interpret the results.

The PAMELA magnetic spectrometer has a lower gettering power than many modern instruments and, despite the longer operation, the accumulated statistics are much smaller. On the other hand, it is possible to compare magnetic spectrometer data with track in the imaging calorimeter and ToF that increases the reliability of particle identification and the accuracy of energy determination. The figure shows that the PAMELA experiment results are in better agreement with the measurements of the AMS-02 spectrometer based on magnetic analysis, the transition radiation detector and calorimetric data and CALET data which is equipped with more deep ionization calorimeter. The data of the Fermi-LAT and DAMPE instruments are systematically higher.

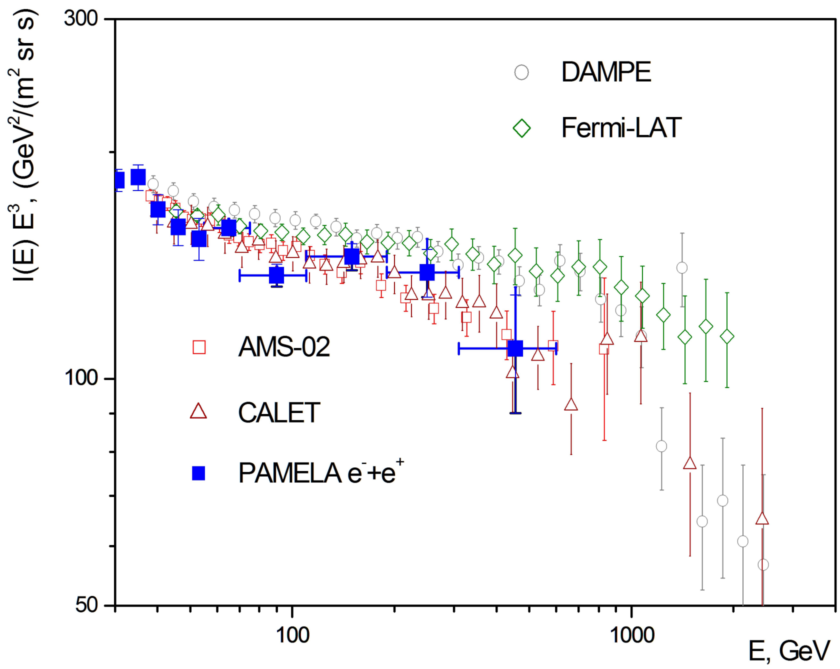

Figure 1. Differential energy spectra of electrons and positrons flux.

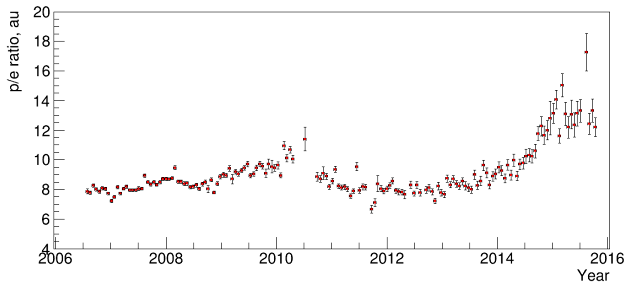

Figure 2. Proton to electron fluxes ratio vs time. $R = 0.5$ - 2.2 GV

At low energies figure 2 shows the obtained ratio of the fluxes of protons and electrons as a function of time in the rigidity range $R = 0.5$ - 2.5 GV. The entire observation period was divided into equal intervals of 20 days each. The maximum of the ratio was observed at the end of 2009 and it coincided with a minimum of solar activity when extreme maximum of proton fluxes was reached. Starting from 2010, the ratio of fluxes of protons and electrons begins to decrease, and from 2011 to 2013, during the phase of growth of solar activity, it remains almost constant. The change of polarity occurred in 2013-2014 [7]. Since then, there has been a rapid increase in the ratio. Shown in figure 2 the dependence repeats the behavior of the relationship between the fluxes of positrons and electrons from time [5], but due to the greater statistical accuracy of data it shows features associated with faster processes in the heliosphere. Figures 3 and 4 shows count rate of electrons and positrons in the same rigidity interval. The uniqueness of simultaneous measurements of the variations of electrons, positrons and protons lies in the fact that they make it possible to determine the contribution of drift processes to the effect of cosmic ray modulation which is extremely important for the development of theoretical models [6].

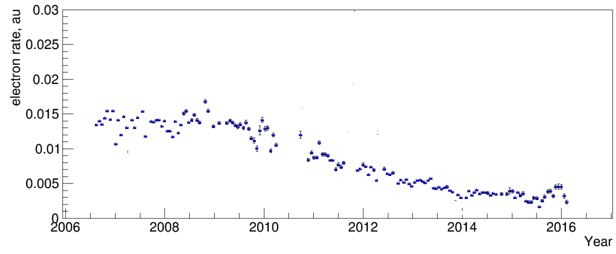

Figure 3. Electron count rate vs time. $R = 0.5$ - 2.5 GV

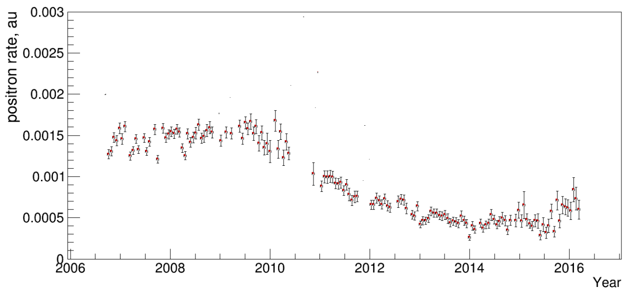

Figure 4. Positron count rate vs time. $R = 0.5$ - 2.5 GV

5. Summary
New particle selection was applied to PAMELA data to obtain clean sample of electrons and positrons from several hundreds MeVs till several hundreds GeVs. The increase in static accuracy allows to reveal new features in the spectra and temporal dependencies of fluxes.

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