Trapped positrons observed by PAMELA experiment

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Abstract. Measurements of electron and positron spatial distributions in energy range from 80 MeV to several GeV below the geomagnetic cutoff rigidity were carried out using the PAMELA magnetic spectrometer. The instrument is installed on board the Resurs-DK satellite which was launched June 15th 2006 on an elliptical orbit with the inclination 70 degrees and the altitude 350-600 km. The procedure of trajectories calculations in the geomagnetic filed gives a way to separate stably trapped and short lived albedo components produced in interactions of cosmic ray protons with the residual atmosphere. The work presents spatial distributions of trapped, quasitrapped and short-lived albedo electrons and positrons in the near Earth space. Electron to positron ratio points out on different production mechanism of trapped and quasitrapped particles.
1. Introduction

High energy galactic cosmic rays interact in the Earth atmosphere resulting producing secondary particles. The flux of secondary particles is composed mainly by electrons, protons, neutrons and gamma-rays. An appreciable fraction of charged secondaries can travel backward in space along the Earth's magnetic field lines and can reach the satellite altitudes forming a high energy radiation halo in the Earth vicinity. Flux of secondary electrons was first calculated in paper [1]. Namely in this work it was considered process of decay of charged pions produced in cosmic ray proton interactions. Pions decay throw \( \pi^{\pm} \to \mu^{\pm} \to e^{\pm} \) chain to electrons and positrons. Because production rate is proportional to cosmic ray intensity \( I_{cr} \), residual atmosphere density \( \rho(h) \) and particle’s time of live \( T \) is \( \propto 1/\rho(h) \) then resulting intensity of secondary particles \( J(h) \propto I_{cr} \times \rho \times T \) will be constant with altitude in wide altitude range forming a halo around the Earth. Nuclear interactions of trapped protons of energies >300 MeV with upper atmosphere constituents could be considered for the production of positrons and over electrons in the innermost magnetosphere. Calculations performed in paper [2] predict the existence of a positron belt in a narrow region around \( L \)-shell = 1.2. The flux ratio of positrons to electrons \( e^+ / e^- \) is estimated to be \( \sim 4 \) for energies of 40-1500 MeV. This mechanism exhibits sharply decreasing spectrum. At 200-300 MeV energies, positron fluxes from the trapped proton source are still comparable with the cosmic ray born positrons, but at greater energies production by trapped protons is negligible.

The magnetic spectrometer PAMELA was launched onboard the Resurs-DK1 satellite on the 15th of June 2006 and it is continuously taking data till present time. The satellite has a quasi-polar (70° inclination) elliptical orbit at an altitudes between 350 and 600 km. Preliminary results of PAMELA observation of secondary electron and positron fluxes near the Earth, which were made in first year of the flight, were reported in paper [3]. At present time about 50TB data were downlinked for analysis during 8 year of the work. Additional accumulated statistics allows to study secondary electrons and positrons generation and propagation in magnetosphere with more details than in previous experiments. Moreover, the backtracking procedure which determines the movement of particles before their detection was applied for data analysis. This procedure offers new opportunities to compare data with models and allows to determine individual particles origin [4, 5]. This work presents PAMELA spectrometer measurements of spatial distributions of secondaries electrons and positrons made using data obtained from 2006 to 2014.

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 gives 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 psec). 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 electron and positron identification is provided by the calorimeter, a series of ministrip silicon layers interleaved by tungsten planes (16.3 radiation and 0.6 nuclear interaction lengths deep). Particles not cleanly entering the PAMELA acceptance are rejected by the anticoincidence system. Using of the TOF system, the magnetic spectrometer and additional analysis of the calorimeter information allows extracting leptons and measuring their energy (from 50 MeV to several hundred GeV) effectively. The acceptance is about 21.6 cm²°sr [6].

The main axis of PAMELA points to a local zenith. Orbit characteristics allow measuring particles with pitch angles (the angle between the particle velocity and the magnetic field vector) of about 80-90° in the equatorial region. The angle between the main axis of PAMELA and magnetic field decreases with latitude, so for middle and high latitudes it is possible observe
smaller values of pitch angles.

3. Data analysis
For each registered event the following parameters were measured or calculated: the number of tracks and energy losses in the magnetic spectrometer planes; the rigidity and the track length (by fitting the track in the magnetic field); the time of flight. A particle velocity was calculated using the time of flight and the track length. Moreover a set of variables dealing with point of interaction, transversal and longitudinal profiles was calculated using the calorimeter [6].

Electrons and positrons were identified using information about $dE/dx$ energy losses in the spectrometer planes to determine charge $Z=1$, shower properties in the electromagnetic calorimeter, particle velocity and a rigidity. The misidentification of protons and pions is the largest source of background. Particle identification based on the calorimeter data can be tuned to rejection power $10^4 - 10^5$ for protons and pions, while selecting $> 80$-90% of the electrons or positrons over all energy range.

Total accumulated statistic for electrons and positron is about $4 \times 10^6$ in whole energy range.

Gathering power of the instrument was estimated with Monte-Carlo simulation with official PAMELA Collaboration software [6]. An efficiency of the instrument may change with time and must be taken into account carefully in a data proceeding. It was verified from experimental data itself by using different combination of information from imaging calorimeter, magnetic spectrometer and time of flight system.

![Graph2D](image1)

Figure 1. An example of a particle trajectory with energy 1.06 GeV trapped in equatorial region.

![Graph2D](image2)

Figure 2. An example of a quasitrapped particle trajectory with energy 1.06 GeV.

For electrons and positrons differential spectra, a longitudinal analysis was performed for set of latitudes intervals from equator to pole region [3, 7]. These results show features of spectra for different geomagnetic regions due to their origin. Primary particles are observed mainly in polar region and above cut-off rigidity near equator. Secondary "short lived" component prevails near equator below geomagnetic cut-off at low rigidities and trapped particles can be measured in South Atlantic Anomaly with pitch-angles about 90 degree.

Using a geographical coordinates and an orientation of PAMELA as a function of time, the McIlvain geomagnetic coordinates L-shell and B were calculated for every event. For the calculation, the IGRF model (http://nssdcftp.gsfc.nasa.gov/models/geomagnetic/igrf) of the Earth magnetic field was used. Then backtracking procedure was applied for every identified events to obtain trajectory of events up to 35 second before detection and it was stopped if particles touched the Earth atmosphere on 40 km altitude or escaped magnetosphere. Boundary
escaping was chosen to be 20000 km. Trajectory helps to determine particle origin for every individual event. See in figure 1 an example of trajectory of trapped electron with energy about 1 GeV. Primary electrons and positrons were excluded from analysis together with particles in transition region near geomagnetic cut-off, applying condition $R < 10/L^3$ [GV].

Calculations of particle trajectories in geomagnetic field provides additional information about spatial distribution of secondary fluxes. This procedure gives possibility to explore fluxes in enlarged regions outside the satellite orbits. Tracking of positrons and electrons with rigidity below cut-off clearly separate measured data set in three different categories: 1) particles with very short time of live (less than 1 s) which absorbed in opposite hemisphere after first bounce; 2) particles with time of live about 1 s, points of origin for this sample lies far from the satellite position on the other longitudes. This is so-called quasi-trapped particles; 3) long lived particles with time more then tens seconds. In this case impossible to determine the point of particle origin because they makes many revolution around the Earth and may stay trapped for hours, days and ,perhaps, years.
4. Results

The track knowledge give possibility to separate particles of different origin measured in the same region. In figure 2 time of flight in magnetosphere versus of rigidity in magnetosphere is shown for equatorial region (L < 2). Typically albedo particles reach the orbit of the satellite for time about 0.1 second. For relativistic electrons and positrons this flight time do not dependent from particle’s rigidity. But if electron or positron has appropriate pitch-angle to be mirrored by magnetic field, flight time is increasing dramatically due to drift around the Earth (see figure 1b). Drift speed is increasing with particle increasing of rigidity and so flight time of quasitrapped particles is decreasing with rigidity as it is seen from figure. Such behavior of secondary albedo and quasitrapped electrons and positrons correspond to that was observed in AMS-01 experiment [5] where they were called as short-lived and long-lived second leptons.

There is also a significant part of track with very large livetime which can not be determined by tracing procedure. Figure 3 shows calculated spatial position of such trapped electrons and positrons they had 10 second before detection. In figure 4 points of measuring of trapped

Figure 5. Regions where trapped positrons were observed by PAMELA.

Figure 6. Regions where trapped electrons were observed by PAMELA.

Figure 7. $e^+/e^-$ ratio vs energy for quasitrapped and trapped components
electrons and positrons are shown. Maximum of count is observed at L-shell about 1.18 and it is increasing with local magnetic field $B$ decreasing below 0.215 G. Inside this region positron to electron ratio is maximal near West part of the South Atlantic Anomaly. In agreement with our previous analysis [7] positron fraction of very long lived trapped particles is much smaller the simple reentrant albedo one (see figure 7).

5. Summary
Secondary electron and positron fluxes have complex spatial structure caused by geomagnetic field, production cross-section and atmospheric absorption of produced secondaries. Using backtracing procedure over $\sim 10^6$ events three components of secondary positrons were clearly separated: albedo, quasitrapped and stably trapped. Measured positron to electron ratio in the PAMELA experiment points out on different production mechanism of trapped and quasitrapped particles.

Acknowledgments
We acknowledge support from, Russian Federal Space Agency (Roscosmos), the Italian Space Agency (ASI), Deutsches Zentrum fur Luft- und Raumfahrt (DLR), the Swedish National Space Board, the Swedish Research Council. Russian colleagues also acknowledge partial support from Russian Scientific Foundation (grant 14-12-00373).

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