Trapped protons in SAA measured by the PAMELA experiment


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Abstract: An accurate measurement of under cutoff proton fluxes in the energy range 60 MeV ÷ 3 GeV has been performed by the PAMELA satellite-borne experiment. Thanks to the high identification performances and to the semipolar and elliptic satellite orbit, PAMELA is able to provide information about spectra and composition of particles in different regions of the magnetosphere. Here we present the measurement of the geomagnetically trapped protons from the inner radiation belt (SAA). The fluxes as a function of equatorial pitch angle and McIlwain L-shell are reported.

Keywords: cosmic rays, magnetosphere, radiation belt, SAA, trapped protons.

1 Introduction

PAMELA is a space-based experiment designed for a precise measurement of the cosmic radiation in the kinetic energy range from some tens of MeV up to some hundreds of GeV [1]. Thanks to the semi-polar (70° inclination) and elliptical (350±610 km altitude) satellite orbit, PAMELA is able to perform energy spectra and particle composition measurements in different regions of the terrestrial magnetosphere. Here we present the trapped proton flux measured by PAMELA in the South Atlantic Anomaly (SAA) region, in the kinetic energy interval from 60 MeV to 3 GeV. Results are compared with predictions from standard trapped particle radiation models.
2 The instrument

The PAMELA apparatus was launched from the cosmodrome of Baykonur, on June 15th 2006, onboard satellite “Resurs-DK1”. The instrument was designed to accurately measure the spectra of charged particles (including light nuclei) in the cosmic radiation, in a wide energy interval ranging from some tens of MeV to several hundreds GeV. In particular, PAMELA is optimized to identify the small component of CR antiparticles. The lifetime of the experiment has exceeded the minimum design duration for the mission (three years), allowing PAMELA to measure cosmic ray particles with an unprecedented precision [2, 3, 4, 5, 6, 7, 8].

3 Particle identification

A clean sample of protons was identified using information combined from several PAMELA subdetectors. Single track events were selected by the tracking system, with strict conditions on the number of position measurements and on the $\chi^2$ associated to the tracking fit procedure. The ToF resolution ($\sim$300 ps) provides the particle velocity ($\beta$) measurement and allows the rejection of albedo particles ($\beta < 0$) with a significance of about 30 standard deviations. Events interacting inside the apparatus were rejected by requiring no spurious signals in both the ToF and the tracking system, and no activity in the anticoincidence scintillators; further constraints were applied on the ionization loss in both the tracker silicon planes and in the ToF scintillators.

The SAA region was defined by McIlwain’s coordinates in the range $L < 1.3$ and $B < 0.216$ G, as shown in Fig.1. The spacecraft orientation is calculated by an onboard processor with accuracy better then 1° which, together with the good angular resolution ($< 2°$) of the tracking system, allows PAMELA to measure particles direction with high precision, which is fundamental for the study of anisotropic fluxes.

4 Flux anisotropy

Particle fluxes in the SAA region are highly anisotropic due to the interaction with the Earth’s atmosphere. As a consequence, the gyro-motion along magnetic field lines and bouncing between two conjugate mirror points result in a defined pitch angle distribution. Particles whose mirror points are located at an altitude where the atmosphere is dense enough, are likely to be lost in collisions with atmospheric nuclei. This defines a range of pitch angles for which magnetic trapping does not occur, that is known as the loss cone. The loss cone angle can be expressed as:

$$\alpha_{eq}^{LC} = \arcsin \sqrt{\frac{B_{eq}}{B_{atm}}}$$  (1)

where $B_{eq}$ is the magnetic field intensity at equator, and $B_{atm}$ corresponds to the field line intersection with the absorbing atmosphere (typically $\sim$ 100 km). Since $B_{atm}$ on a given field line can be different at the two hemispheres, due to the north-south asymmetry in the geomagnetic field, the lower value of $B_{atm}$ was used. The equatorial pitch angle distribution as a function of $L$-shell is shown in Fig.2; the region between superimposed lines corresponds to the pitch angle range outside the calculated loss cone.

Another source of anisotropy is related to the East-West effect: the flux of positively (negatively) charged particles arriving from East (West) is significantly lower than the one of particles from Western (Eastern) direction, since particles in the former case have their guiding centers at lower altitudes and thus their flux is significantly reduced by the atmospheric absorption. The resulting asymmetry

![Figure 1: Under-cutoff proton candidates distribution as a function of $L$-shell and geomagnetic field intensity $B$ [G]. The black line defines the SAA: $B < 0.216$ and $L < 1.3$.](image1)

![Figure 2: Under-cutoff proton candidates distribution as a function of equatorial pitch angle and $L$-shell. The region between superimposed lines corresponds to the pitch angle range outside the calculated loss cone.](image2)
A measurement of SAA trapped protons between 60 MeV ÷ 3 GeV have been presented. Data were recorded by

\[ \frac{\sin^2 \alpha}{B} = \frac{\sin^2 \alpha_{eq}}{B_{eq}} \]  

(2)

where \( B \) and \( B_{eq} \) denote respectively the local and the equatorial magnetic field magnitude. Then the flux \( J_{ijk} \) in the \( i^{th} \) energy bin from \( E_i \) to \( E_{i+1} \), the \( j^{th} \) equatorial pitch angle bin from \( \alpha_{eq}^{j-1} \) to \( \alpha_{eq}^{j+1} \) and the \( k^{th} \) \( L \)-shell bin from \( L_k \) to \( L_{k+1} \), is related to the number of detected particles \( N_{ijk} \), corrected for selection efficiencies, by:

\[ J_{ijk} = \frac{N_{ijk}}{2\pi \int_{E_i}^{E_{i+1}} dE \int_{\alpha_{eq}^{j-1}}^{\alpha_{eq}^{j+1}} d\alpha_{eq} \int dt_k \hat{H}(E, \alpha) \frac{d\alpha}{d\alpha_{eq}}} \]  

(3)

where the integral over \( t_k \) includes times where the satellite \( L \), which is a function of \( t \), is within the \( k^{th} \) \( L \)-shell bin; \( \hat{H}(E, \alpha) \) is the mean effective area (cm\(^2\)) of the apparatus, obtained by weighting the effective area \( H(E, \alpha, \Psi) \) at a given orientation \( \Psi \) by the time \( \Delta T_i \) spent by PAMELA at the same \( \Psi \) (in a given \( L \)-shell bin):

\[ \hat{H}(E, \alpha) = \frac{\sum_i H(E, \alpha, \Psi_i) \cdot \Delta T_i}{\sum_i \Delta T_i} \]  

(4)

\[ = \frac{\sum_i \left[ \frac{d\beta}{2\pi} \int d\Psi A(E, \theta_l, \phi_l) \sin \alpha \cos \theta_l \right] \cdot \Delta T_i}{\sum_i \Delta T_i} \]  

(5)

where \( \beta \) is the gyrophase angle, \( \theta_l = \theta(\alpha, \beta, \Psi_l) \) and \( \phi_l = \phi(\alpha, \beta, \Psi_l) \) are respectively the zenith and the azimuth angle describing particle direction in the PAMELA frame, and \( A(E, \theta, \phi) \) is the apparatus response function. The PAMELA effective area \( H(E, \alpha, \Psi) \) was calculated with Monte Carlo integration according to [9], under the approximation of a flat \( \beta \) distribution. The calculation was performed by varying \( \alpha, \theta_l, \phi_l \) in steps of \( 1^\circ \) over the whole range of possible values (see Fig.2-3). The dependence of the instrument response on particle rigidity was studied by estimating effective areas at 10 rigidity values in the range of interest.

6 Results

More than 3 million under-cutoff protons were identified in the kinetic energy interval 60 MeV ÷ 3 GeV. The analyzed data sample was acquired by PAMELA between July 2006 and December 2008 (~850 days of data taking), corresponding to a period of minimum solar activity (with negative polarity, \( A < 0 \)).

Data were divided into equatorial pitch angle bins of 5\(^\circ\) width, and into 20 \( L \)-shell bins, each corresponding to 0.5\(^\circ\) of invariant latitude \( \Lambda = \arccos \sqrt{1/L} \). Only events with an equatorial pitch angle value outside the loss cone (see Fig.2) were selected. Measured proton distributions were corrected by means of simulations to take into account interactions inside the apparatus (inelastic reactions, multiple scattering, ionization loses). Selection efficiencies were determined using flight data, while test beam and simulation data were used to support and cross-check the calculation. The differential trapped proton flux \((\text{GeV} \cdot \text{sr} \cdot \text{s} \cdot \text{m}^2)^{-1}\) measured by PAMELA at \( L=1.147 \) as a function of kinetic energy and equatorial pitch angle, is shown in Fig.5. In Fig.4 the trapped proton flux measured by PAMELA, at equatorial pitch angle \( \alpha_{eq}=90^\circ \) and for four different \( L \)-shell values, is compared with predictions from AP8min [10] and from SAMPEX/PET PSB97 [11] models.

7 Conclusions

A measurement of SAA trapped protons between 60 MeV ÷ 3 GeV have been presented. Data were recorded by
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Figure 4: The trapped proton spectrum measured by PAMELA, at equatorial pitch angle $\alpha_{eq}=90^\circ$, for four different $L$-shell values. The error bars indicate statistical uncertainties. Predictions from AP-8min [10] (dotted red line) and from SAMPEX/PET PSB97 [11] (solid blue line) models are also reported.

Figure 5: The trapped proton flux ($GeV \cdot sr \cdot s \cdot m^2$)$^{-1}$ measured by PAMELA at $L$-shell=1.147 as a function of kinetic energy and equatorial pitch angle.

the PAMELA satellite-borne experiment in the period from July 2006 to December 2008 (850 days). Proton fluxes have been reported as a function of equatorial pitch angle and $L$-shell. PAMELA results can be used to validate existing trapped particle radiation models, providing information on the trapping and interaction processes in Earth’s magnetosphere. The analysis will soon be improved with the data sample acquired after 2008, and with the measurement of under-cutoff fluxes outside the SAA region.

References