PROCEEDINGS OF SCIENCE

Measurements of the trapped proton and helium fluxes in the PAMELA experiment

V.V. Malakhov,[a,*] **A.A. Leonov,**[b] **A.G. Mayorov**[c] **and V.V. Mikhailov**[d]

[a] *https://orcid.org/0000-0002-4146-419X*
[b] *https://orcid.org/0000-0002-4925-7566*
[c] *https://orcid.org/0000-0001-6283-0817*
[d] *https://orcid.org/0000-0003-3851-2901*
E-mail: vvmalakhov@mephi.ru, aaleonov@mephi.ru, agmayorov@mephi.ru, vvmikhailov@mephi.ru

A new processing of the data obtained with the PAMELA spectrometer in the under-cutoff area and particularly at the lower edge of the Earth's Inner Radiation Belt (IRB) is presented. For the reconstruction of anisotropic fluxes, a new method has been developed. The method is based on the division of the instrument's field of view (FOV) into segments within which the flux could be treated as isotropic. For such an approach one single simulation data set is required. Using this method, distributions of proton fluxes measured with the PAMELA spectrometer over equatorial pitch angle, L-shell, and energy were reconstructed in a new way. Additionally, high energy (E>50 MeV/n) trapped ^{3}He nuclei were found and analyzed.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)117

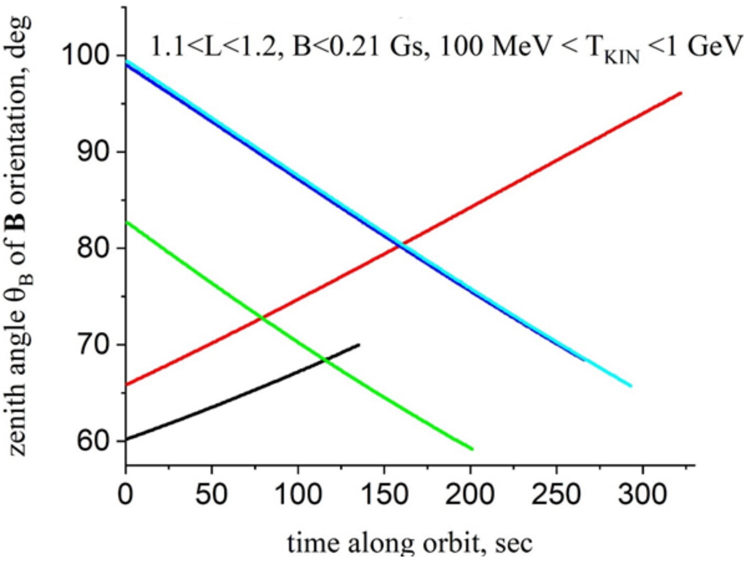

Figure 1: The orientation of the Earth's magnetic field vector B expressed in its zenith angle θ_B in the instrumental reference frame (IRF) changing with time as the instrument crosses the South Atlantic Anomaly region. The data have been taken for 01 August 2006. Lines of different colours correspond to several passages

1. Introduction

The fluxes of the trapped charged particles in the IRB are known for their high anisotropy: to the first approximation, the fluxes depend on equatorial pitch-angle α_{eq}. The form of this dependence is described analytically as $J(\alpha_{eq}) = Jsin^n\alpha_{eq}$ [1] where n depends on the average distance of the particle's trajectory from the Earth's surface expressed in Mc'Ilwain parameter L [2]. The main difficulty in the reconstruction of anisotropic flux is that for the obtainment of the instrument's response function to it, one needs to calculate the gathering power Γ which itself depends on the flux's characteristics [3]. For tracking instruments that are able to reconstruct the incident particle directions and operating in an event-by-event mode, a specific method had been developed and applied to the SAMPEX/MAST data [4]. The method is based on the calculation of the so-called effective area which serves as the instrument's response function. The main advantage of this approach is that the effective area does not depend on the flux's characteristics anymore. This method had also been used to obtain the results of the PAMELA [5–7] and CSES instruments [8] in the IRB.

The method [4] though has its limitations. The main of which is that it requires Monte-Carlo simulation of the particles' passage through the instrument for all of its possible orientations relative to the Earth's magnetic field. Because the instrument on board a satellite moves across magnetic lines it means a necessity of a huge amount of MC simulation. Figure 1 shows the values of the zenithal angle θ_B of the local magnetic field vector B in IRB changing with time as the PAMELA spectrometer crosses the South Atlantic Anomaly (SAA) region; different lines correspond to different crossings. It is seen that even for one passage the conditions vary significantly and the passages themselves differ from each other.

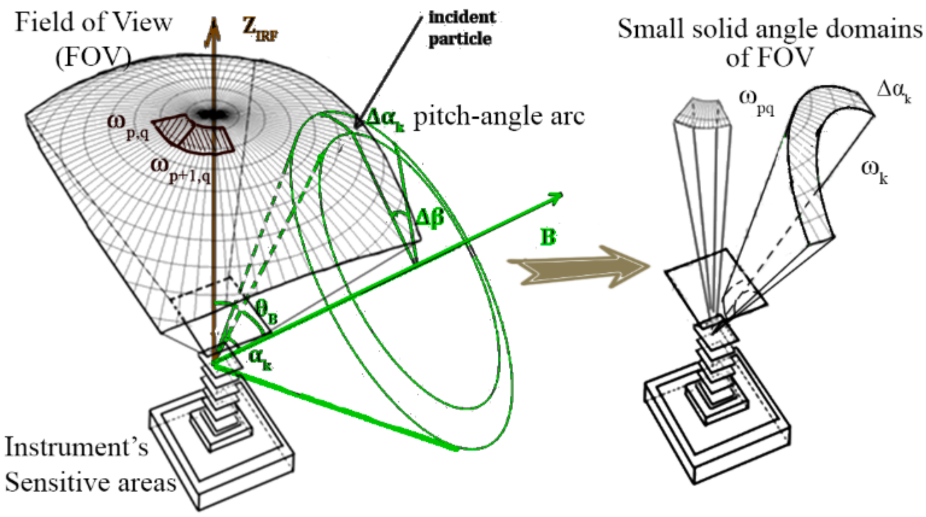

Figure 2: The PAMELA spectrometer's FOV and solid angle domain segments ω_{pq} and arcs ω_k formed by the overlapping of a pitch-angle band $\Delta\alpha$ with FOV

2. Proposed method

In this paper, for the new processing of the PAMELA spectrometer data in the IRB, we propose a new method of calculation of the anisotropic fluxes. It consists in the division of the spectrometer's FOV into segments within which one can treat the flux as isotropic and thus use simple geometrical factor G as the response function. A segment can be of any form within which the isotropy of the flux is expected. Thus, for any instrument's orientation in space respective to the magnetic field, a single sample of isotropic flux simulation can be used for each energy. The first draft of the method was published in [9].

In figure 2 an accurate representation of the sensitive areas of the PAMELA detectors is shown along with its FOV. ω_{pq} is a small solid angle domain where indices p and q are over the azimuthal and the zenithal angles in the IRF correspondingly. Let us call the geometrical factor of the instrument relative to the registration of the particles within ω_{pq} Partial Geometrical Factor (PGF) G_{pq}. It can be calculated in the usual way [3]:

$$G_{pq} = \frac{N_{pq}}{N_0}\pi S \tag{1}$$

where N_{pq} is the number of selected events within ω_{pq}, N_0 is the total number of the simulated events, and πS is the geometric factor of the opening aperture.

In figure 2, B is the vector of the Earth's magnetic field at the point of registration and $\Delta\alpha_k$ is a k^{th} local pitch angle band from α_k to α_{k+1}. The overlapping of this band with FOV forms domain ω_k in the shape of an arc. The PGF of this domain G_k can also be calculated using (1) where one needs to use the number of events incident within ω_k as N_{pq}. Alternatively, using the property of additivity of PGF, G_k can be calculated as the sum of ω_{pq} domains lying within ω_k:

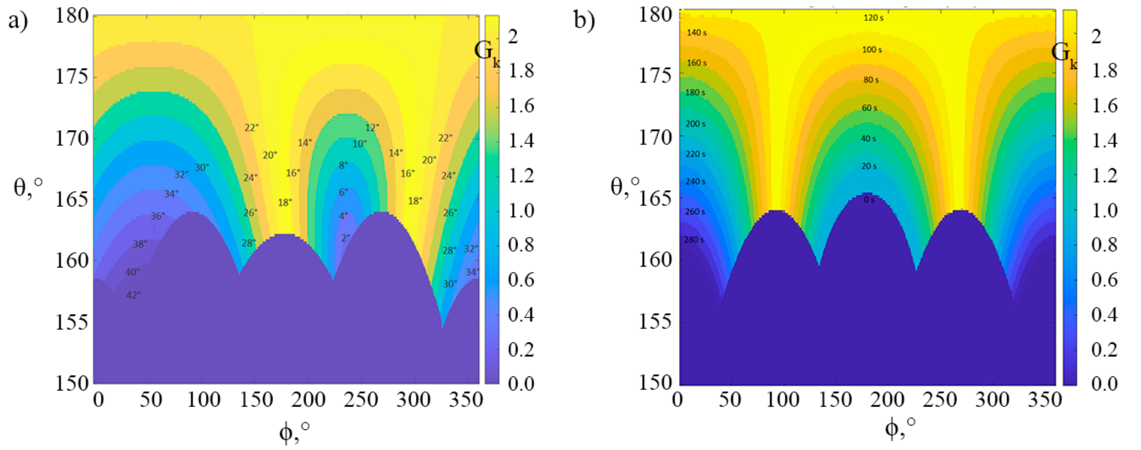

Figure 3: a) Representation of the pitch-angle arcs with 2° step over the local pitch-angle on the plot of azimuthal vs. zenithal angles in the IRF for the orientation of vector B in IRF characterized by $\theta_B = 20°$ and $\phi_B = 237°$; b) changes in shape and position of the arc corresponding to $89° - 91°$ local pitch-angle band as the instrument crosses SAA area. The colour codes PGF G_k in both cases.

$$G_k = \sum_{\omega_{pq} \in \omega_k} G_{pq} \tag{2}$$

Figure 3a shows the IRF zenithal vs azimuthal angles plot representation of domains ω_k for an arbitrarily chosen fixed direction of B. The colour codes the PGF G_k of each arc. To calculate G_k from an MC simulation data sample one needs to convert the track directions of all selected events from the IRF to the local magnetic field reference frame (MRF). The transition matrix can be written in the following way:

$$\mathbb{M} = \begin{bmatrix} \frac{-B_x B_z}{\sqrt{1-B_z^2}} & \frac{B_y}{\sqrt{1-B_z^2}} & B_x \\ \frac{-B_y B_z}{\sqrt{1-B_z^2}} & \frac{-B_x}{\sqrt{1-B_z^2}} & B_y \\ \sqrt{1-B_z^2} & 0 & B_z \end{bmatrix} \tag{3}$$

where B_x, B_y, B_z are the components of the vector B in IRF. The matrix of the selected incident particles' directions X_M is then calculated as

$$X_M = \mathbb{M}^T \times X \tag{4}$$

where T denotes transposition, X describes the selected incident particle directions vector, and three rows correspond to x, y, and z coordinates of the tracks. The zenithal angle of the track in the MRF is the pitch angle, over bands of which it is necessary to distribute selected events.

The boundaries of the arcs in the IRF can be analytically derived and are described with the following expressions:

$$\tan\theta_k = \frac{\sqrt{B_z^2(\sin^2\alpha_k\cos^2\beta - \cos^2\alpha_k) - 2B_z\sqrt{1-B_z^2}\sin\alpha_k\cos\alpha_k\cos\beta - \sin^2\alpha_k\cos^2\beta + 1}}{\sqrt{1-B_z^2}\sin\alpha_k\cos\beta + B_z\cos\alpha_k} \tag{5}$$

$$\tan\phi_k = \frac{B_y\sqrt{1-B_z^2}\cos\alpha_k - B_yB_z\sin\alpha_k\cos\beta - B_x\sin\alpha_k\sin\beta}{B_x\sqrt{1-B_z^2}\cos\alpha_k - B_xB_z\sin\alpha_k\cos\beta + B_y\sin\alpha_k\sin\beta} \tag{6}$$

where α_k is the local pitch angle and β is the gyrophase angle.

Since the instrument constantly and rapidly changes its orientation in the Earth's magnetic field (see figure 1), the described way of the PGF calculation allows deriving it only at a fixed moment. Thus it is actually an instant PGF. To calculate it for a prolonged period of time, one needs to take into account its variations. In figure 3b changes in the shape and PGF of ω_k domain corresponding to the $89° - 91°$ local pitch-angle band are shown as the satellite crosses the SAA region. The PGF (colour-coded) and the shape of the arc are calculated every 10 seconds. To calculate the flux for each time interval one needs an effective PGF composed of the instant PGFs for each moment within the interval. It can be defined in the following way:

$$G_k = G(\Delta\alpha_k) = \sum_{j=1}^{R_m} G_j(\Delta\alpha_k)\frac{\Delta t_j}{\Delta t_m} \tag{7}$$

where Δt_j is the duration of j^{th} short time interval, G_j is an instant PGF relative to $\Delta\alpha_k$ pitch-angle band, Δt_m is the total time of observation, R_m is the number of short time intervals composing Δt_m.

The intensity of the trapped particles flux in each bin over E, α_{eq}, L, t can be obtained in the usual way:

$$J_k = \frac{N_k}{\Delta E\Delta T G_k} \tag{8}$$

where ΔT is the total time of observation of the pitch-angle band $\Delta\alpha_k$. Here, values of G_k can be easily derived with the MC simulation of the isotropic flux using 7.

3. Results

For proton selection in the PAMELA spectrometer, basic criteria, as described e.g. in [10, 11], have been applied. The secondaries were roughly selected by the requirement $L < 3$. Distributions over several geomagnetic parameters (L-shell, equatorial pitch-angle α_{eq} and energy E) were reconstructed de novo for a two months interval in 2006. In figure 4 several examples of proton fluxes spectra and equatorial pitch-angle distributions are shown. In 4*a* trapped protons energy spectra for a set of L-shell at the lower boundary of the IRB are shown. These spectra have been obtained for the equatorial pitch-angle band $75 - 76°$ for the period from August to September 2006. Figure 4*b* shows the proton fluxes' distribution over equatorial pitch-angles for the same

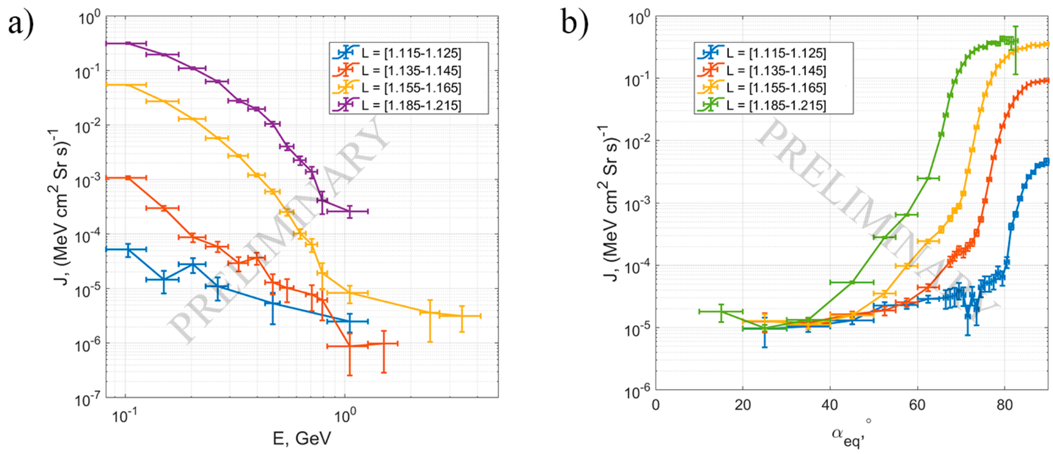

Figure 4: a) Proton energy spectra for $\alpha_{eq} \in [75; 76]^\circ$ at different L-shells; b) Proton fluxes of $E \in [80; 120]MeV$ distribution over equatorial pitch angle at different L-shells; all data are gathered for August-September, 2006;

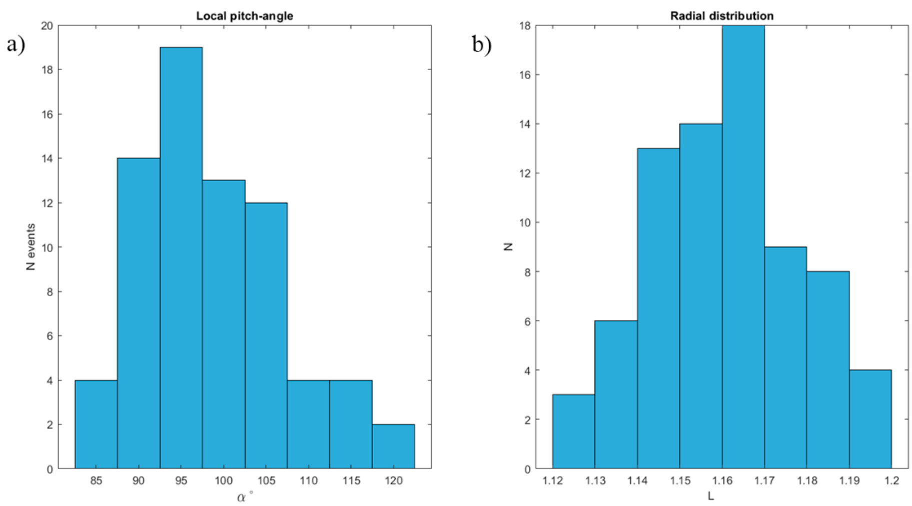

Figure 5: Distribution of ^{3}He events registered with the PAMELA spectrometer in the IRB over a) local pitch angle α b) L-shell

set of L-shells as for the spectra and for the energy range $80 - 120MeV$. These results show the statistical capability of the PAMELA spectrometer for measurements at the edge of the IRB.

For helium selection, we separated the corresponding domains on the dE/dx vs rigidity plots for different planes of the tracking and Time-of-flight systems, as described in [10]. The geomagnetic area where the entrapment of the helium nuclei is possible was selected with the following criteria: 1.12<L<1.20, B<0.216 Gs.

In figure 5 the number of selected events of ^{3}He of energies $E > 50MeV/n$ for the whole period of observation (from 2006 to 2016) is shown depending on local pitch-angle (a) and L-shell (b). The pitch-angle distribution is peaked at about 95° indicating the trapped origin of the particles.

What is important here is that all events are grouped within $80 - 110^{\circ}$ band over local pitch angles and correspond to L-shells at the edge of the IRB.

4. Conclusion

For the new processing of the PAMELA spectrometer experimental data gathered in the under-cutoff area and particularly on the lower edge of the Earth's inner radiation belt a new method of anisotropic flux reconstruction has been developed. The method is based on splitting the instrument's field of view into small segments within which the fluxes can be treated as isotropic. This approach significantly simplifies the calculation of the instrument's response function, which in this case can be calculated using just a single set of Monte-Carlo simulations of isotropic flux for each energy interval. Thus, a simpler and more robust reconstruction of the fluxes distributions is possible.

Using the proposed method, distributions of the proton fluxes over equatorial pitch angles, L, and energy have been reconstructed for two months in 2006.

Additionally, ^{3}He events of energies $E > 50 MeV/n$ registered in the PAMELA experiment at the lower boundary of the Earth's inner radiation belt were analyzed. Their distribution over the local pitch angle and L, similar to that of protons, indicates that they are probably trapped. However, an additional analysis is required.

Acknowledgments

This work was supported by the Russian Science Foundation, project №19-72-10161, https://rscf.ru/en/project/19-72-10161/

References

[1] H.M. Fischer, V.W. Auschrat and G. Wibberenz, *Angular distribution and energy spectra of protons of energy 5 E 50 MeV at the lower edge of the radiation belt in equatorial latitudes*, *Journal of Geophysical Research* **82** (1977) 537.

[2] C.E. McIlwain, *Magnetic coordinates*, *Space Science Reviews* **5** (1966) 585.

[3] J. Sullivan, *Geometric factor and directional response of single and multi-element particle telescopes*, *Nuclear Instruments and Methods* **95** (1971) 5.

[4] R.S. Selesnick, A.C. Cummings, J.R. Cummings, R.A. Mewaldt, E.C. Stone and T.T. von Rosenvinge, *Geomagnetically trapped anomalous cosmic rays*, *Journal of Geophysical Research* **100** (1995) 9503.

[5] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Boezio, E.A. Bogomolov et al., *Trapped proton fluxes at low Earth orbits measured by the PAMELA experiment*, *The Astrophysical Journal* **799** (2015) .

[6] A. Bruno, M. Martucci, F.S. Cafagna, R. Sparvoli, O. Adriani, G.C. Barbarino et al., *Solar-cycle Variations of South Atlantic Anomaly Proton Intensities Measured with the PAMELA Mission*, *The Astrophysical Journal Letters* **917** (2021) L21.

[7] A. Bruno, M. Martucci, F.S. Cafagna, R. Sparvoli, O. Adriani, G.C. Barbarino et al., *East–West Proton Flux Anisotropy Observed with the PAMELA Mission*, *The Astrophysical Journal* **919** (2021) 114.

[8] M. Martucci, S. Bartocci, R. Battiston, W.J. Burger, D. Campana, L. Carfora et al., *New results on protons inside the South Atlantic Anomaly, at energies between 40 and 250 MeV in the period 2018–2020, from the CSES-01 satellite mission*, *Physical Review D* **105** (2022) 062001.

[9] V.V. Malakhov and A.G. Mayorov, *Calculating a Directional Flux in Near-Earth Space*, *Bulletin of the Russian Academy of Sciences: Physics* **85** (2021) 386.

[10] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Boezio, E.A. Bogomolov et al., *PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra*, *Science* **332** (2011) 69.

[11] O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Boezio, E.A. Bogomolov et al., *Time Dependence of the Proton Flux Measured by PAMELA during the 2006 July-2009 December Solar Minimum*, *The Astrophysical Journal* **765** (2013) 91.