PROCEEDINGS OF SCIENCE

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

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A simple and robust method of reconstruction of the geomagnetically trapped fluxes detected with the PAMELA spectrometer is proposed. Instead of multiple calculations of the effective area for different pitch-angles and different orientations of the instrument relative to the geomagnetic field vector, a value of an effective geometrical factor (GF) is estimated using one simulation sample with additional information about the instrument's orientation relative to the vector of the Earth magnetic field. In this procedure, the additivity of the geometrical factor for different parts of the instrument's field of view (FOV) is used. The simulation data sample is obtained in a standard way using Monte Carlo calculations of the isotropic flux. The method was tested on the task of reconstruction of the angular distribution of the Galactic proton flux. The proton fluxes recovered in the Earth's Inner Radiation Belt (IRB) with this method were compared with the measurements of the NOAA-17 experiment and showed a good agreement. As a result, the proton and helium fluxes over different geomagnetic regions on the inner edge of the Earth's inner radiation belt is recovered,

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1. Introduction

Recently the measurements of the geomagnetically trapped proton fluxes for energies ranging from 80 MeV to the entrapment limit were carried out by the PAMELA mission at low Earth orbits [1, 2]. There, basic properties of the trapped proton fluxes, including their spatial and angular distributions, energy spectra, and temporal variations at the inner boundary of the IRB were investigated. For that analysis, considering the high anisotropy of fluxes in the region, an approach developed for SAMPEX/MAST position-sensitive instrument [3] was utilized. It required calculation of the instrumental response function for different orientations of the instrument (hereafter speaking about the instrument's orientation we mean the orientation relative to the Earth's magnetic field B at the observation point) and different pitch-angles for each orientation. For PAMELA it meant an enormous amount of simulation which is the reason why not all the data have been processed and not with the highest accuracy and particularization.

In this paper, we propose a simple and robust method of reconstruction of the geomagnetically trapped proton fluxes detected with the PAMELA spectrometer. It is based on the assumption that for an anisotropic flux, the sphere the particles come from to the observer can be split into small solid angle domains within which the flux can be treated as isotropic. More specifically, the instrument's response function calculated in the assumption of the isotropy within small domains turns out to be enough representative for the anisotropic flux calculation. Thus, in this case, it can be calculated using just one sample of simulated isotropic flux data with the assigned directions in the Instrument's reference frame (IRF) for each orientation, managing the shape of the domains. The preliminary realizations of the method were already presented in [4]. The method was tested on the task of reconstruction of the angular distribution of the Galactic Cosmic Ray proton flux which is known to be isotropic. The results derived in the IRB were also compared with the measurements of the NOAA-17 experiment [5, 6] carried out in the same geomagnetic region.

2. Pamela measurements in the Earth's inner radiation belt

The PAMELA is a space-based spectrometer conceived to study the charged cosmic radiation in the energy range from tens of MeV up to several hundreds of GeV [7]. The instrument operated from the middle of 2006 till the beginning of 2016 on board of Resurs-DK1 satellite which had a semi-polar (70° inclination) 350 — 610 km altitude orbit. The satellite's (and then the instrument's) orientation was calculated by the star trackers with an accuracy better than 1°. This along with the high instrumental angular resolution (0.1° – 2.5° depending on energy) of the PAMELA spectrometer, makes it marvelously suitable for angular measurements and quite unique for IRB.

The satellite crossed the inner edge of the IRB in the South Atlantic Anomaly (SAA) region several times a day. For the instrument's altitudes and typical orientations, direct measurements of the trapped radiation were available at B<0.216 G and L-shells <1.22 Re, where L is McIlwain's parameter [8]. Figure 1a shows the live time for one second during a typical passage of the SAA region. It is seen that though the value lowers significantly it does not drop to zero indicating the absence of saturation.

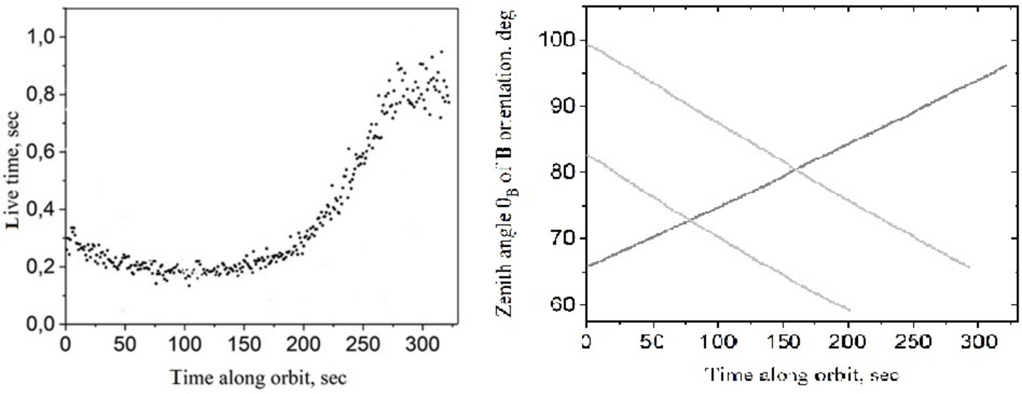

Figure 1: a) Live time per 1 second during a typical passage through the IRB. b) The values of zenith angle θ_B of the local magnetic field vector in IRB changing with time as the satellite crosses the SAA region for several passages.

3. Proposed method of reconstruction of the trapped particle flux

The instrument's count rate is related to the flux through a proportionality factor. Its value and form depend on the instrument's geometry, efficiency, and characteristics of the flux itself. According to the classical definition by J.D. Sullivan [9] this coefficient is called gathering power (GP) Γ for the anisotropic flux and geometrical factor (GF) G for isotropic. In the latter case, it does not depend on the flux's characteristics. The fluxes in IRB are well known to be highly anisotropic [10, 11] and therefore require an accurate calculation of GP. Commonly, for real devices, it is calculated by means of Monte-Carlo (MC) simulations:

$$\Gamma = \frac{N_{TRIG}}{N_0}\Gamma_{oa} \tag{1}$$

where N_{TRIG} —- a number of simulated trajectories passing within the instrument's aperture and surpassing the selection criteria; N_0 —- the total number of simulated trajectories; Γ_{oa} —- gathering power of the open aperture. In the case of the isotropic flux simulation from a hemisphere through a square S placed above the detector $\Gamma_{oi} = G_{oa} = \pi S$ and

The flux then is calculated as:

$$J = \frac{N_{sel}}{G\Delta E\Delta t} \tag{2}$$

where N_{sel} is the number of selected events in an experiment of energies ΔE during time Δt.

This characteristic although is not convenient and, for the tracking instruments which are able to reconstruct the incident particles' direction and operating in the event-by-event mode, an approach based on the calculation of so-called effective area had been proposed [3], evolved in [10] and used in [1, 12]. According to it the number of particles hitting the i^{th} energy bin from E_i to $E_{(i+1)}$, k^{th} equatorial pitch-angle bin from $\alpha_{(eq,k)}$ to $\alpha_{(eq,k+1)}$, and n^{th} L-shell bin from L_n to $L_{(n+1)}$, during the m^{th} temporal bin from t_m to $t_{(m+1)}$, is related to the flux $J(E, L, \alpha_{eq}, t)$ through the following expression:

$$N_{iknm} = \int_0^{2\pi} \int_{\alpha_{eq,k}}^{\alpha_{eq_k+1}} \int_{E_i}^{E_{i+1}} \int_{t_m}^{t_{m+1}} A^*(E, \theta(\alpha, \beta, \theta_B(t), \phi_B(t)), \phi(\alpha, \beta, \theta_B(t), \phi_B(t)), \epsilon(\theta, \phi, E))\times$$
$$\times \cos\theta(\alpha, \beta, \theta_B(t), \phi_B(t)) \times J(E, L, \alpha_{eq}, t) \times \sin\alpha \times \frac{d\alpha}{d\alpha_{eq}} \times dtdEd\alpha_{eq}d\beta \quad (3)$$

where α, β — pitch and gyrophase angles, respectively i.e. the spherical angles of the incident particle flight direction with respect to the local magnetic field vector B; θ_B, ϕ_B —- spherical angles of local magnetic field vector in the IRF; θ, ϕ — the spherical angles of incident particle flight direction in the IRF; A^* —- the detector's effective area including the instrument's detection efficiency $\epsilon(\theta, \phi, E)$ for particles with energy E; α_{eq} —- pitch angle of the trapped particle at the geomagnetic equator, it is related to the local pitch angle α through the first adiabatic invariant conservation law [13].

On one hand, the main advantage of this approach is that the proportionality factor, which in this case is the effective area A, does not depend on the flux properties anymore. On the other hand, it depends on the instrument's orientation and needs independent calculations for all possible orientations and pitch-angles what requires MC simulation for each of them. In fig 1,b θ_B changing with time is shown measured along several orbits of the PAMELA instrument just for one day as it crossed the SAA region. It is seen that it is changing significantly, and to cover even a one-day set of orientations one needs a large amount of simulation.

The main idea of the proposed method is the following. If one outlines a quite small solid-angle domain within the instrument's FOV, the flux within it can be treated as isotropic. In fig 2b an accurate representation of the PAMELA detectors' sensitive areas and confined by it FOV is shown. The FOV is divided into segments according to the spherical angles θ, ϕ in the IRF so that each ω_{pq} domain corresponds to p^{th} bin over θ and q^{th} bin over ϕ. If ω_{pq} is smaller than the anisotropy scale then GF G_{pq} corresponding to it will represent the instrument's response function to the flux within the domain. We will call it partial geometric factor (PGF). It can be calculated using MC simulation of the isotropic flux passing through the instrument with 1 where one needs to use the number of selected simulated events within ω_{pq} as N_{TRIG}. The flux measured within the domain ω_{pq} of the instrument's FOV can be calculated then with 2 where one needs to use the number of selected experimental events within ω_{pq} as N_{sel}. The most important advantage of this approach is that now for each domain a single set of isotropic flux simulations can be used.

Actually, the shape of domains is not constrained to $\Delta\theta, \Delta\phi$ spherical segments and can be any within which the isotropy of the flux is expected. In the IRB the flux to a first approximation depends only on pitch-angle α, that is the angle between the local magnetic field vector B and the incoming particle direction. Thus, the solid angle domain should correspond to a small enough range over pitch-angle $\Delta\alpha_k$. It is schematically shown in fig. 2a where Z_{IRF} is a z-axis in the IRF, B is a vector of the magnetic field, θ_B is the zenithal angle of B in the IRF, α_k —- local pitch angle and $\Delta\alpha_k$ —- a pitch-angle band and corresponding to it the solid angle domain ω_k. In fig. 2b an overlapping of the domain ω_k with the instrument's FOV is shown. Geometrical factor G_k relative to ω_k in this case is a simple sum of G_{pq}'s within it. Alternatively, one can describe analytically the boundaries of the ω_k domain in the IRF and select the events within it at once using it then in 1 and 2 to derive the flux. GF for this domain is also called partial GF since it does not cover

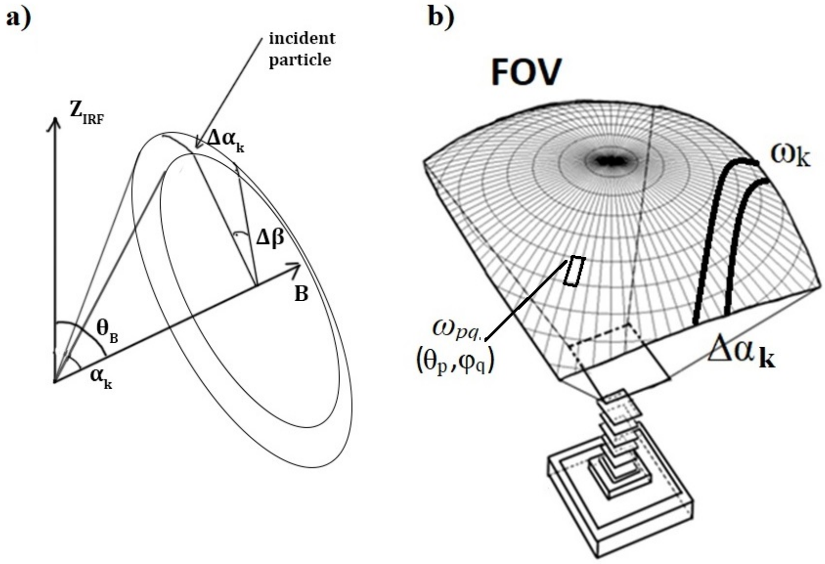

Figure 2: a) Orientation of vector of magnetic field B on the IRF b) The instrument's FOV overlapping with $\Delta_{a}lpha_{k}$ pitch-angle ark and small solid angle domain ω_{pq}.

the whole FOV. In fig 3, the domain corresponding to the local pitch-angle band $\Delta\alpha_k = 89 - 91°$ and $\theta_B = 75°$ (a) and 90° (b) is shown in IRF. The gray area corresponds to the instrument's FOV and the arced shapes depict domain ω_k. To calculate the PGF one needs to count the number of events within the arcs. If it is later necessary to introduce gyrophase angle β dependence, one can additionally divide the pitch-angle arc into segments corresponding to $\Delta\beta$ bins splitting ω_k into subdomains which can be treated the same way. In all these cases again one set of isotropic flux simulation is enough.

All the calculated PGFs relate to a fixed orientation and so can be called the instance PGP. But the measurements usually take a prolonged time during which the shape of the domain for one pitch-angle band $\Delta\alpha_k$ changes significantly. To calculate the flux for such an 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:

$$G_k = G(\Delta\alpha_k) = \sum_{j=1}^{R_m} G_j(\Delta\alpha_k)\frac{\Delta t_j}{\Delta t_m} \quad (4)$$

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

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

$$J_{iknm} = \frac{N_{iknm}}{\Delta E_i \Delta t_m G_{ik}} \quad (5)$$

Here values of G_{ik} can be easily derived with the MC simulation of the isotropic flux.

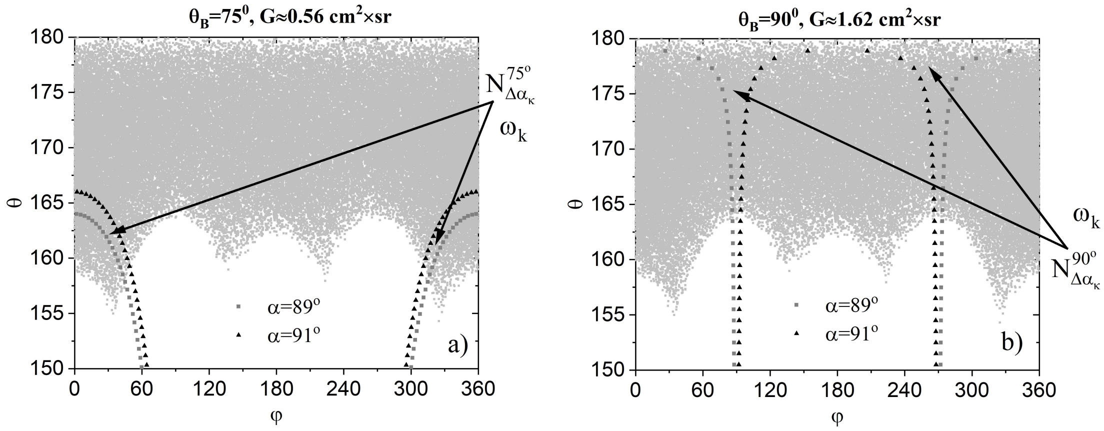

Figure 3: The calculation of partial geometrical factor for the orientations $\theta_B = 75°$(a) and 90°(b), $\phi_B = 0°$ relative to the Earth magnetic field vector B. The light grey area corresponds to the instrument's FOV; the dotted contours outline ω_k solid angle domain corresponding to the pitch-angle band $\Delta\alpha_k = 89 - 91°$ for the two orientations within which the number of events is $N^{75°}_{\Delta\alpha_k}$ and $N^{90°}_{\Delta\alpha_k}$ correspondingly.

4. Results

At first, the proposed algorithm of partial geometry factor calculation and subsequent flux intensity reconstruction was tested on the galactic cosmic ray proton fluxes detected in the Earth's polar regions (L>6) with the PAMELA spectrometer. In fig 4 reconstructed flux intensities of protons in the rigidity range 0.75˘1.25 GV in arbitrary units (without normalization on the exposure time) are shown as a function of pitch angle calculated relative to two arbitrarily assigned directions of $B(\theta_B, \phi_B)$ in IRF: (20°, 0°) (a) and (85°, 45°)(b).

The flux intensities of geomagnetically trapped protons detected at $L = 1.16$ in the energy range 70˘140 MeV in the PAMELA and NOAA-17 experiments are presented in fig. 5 as a function of equatorial pitch angle. The PAMELA data were obtained in July-September 2006, — the NOAA-17 data were collected in April 2005 [5, 6]. Taking into account that NOAA-17 measurements are averaged over the whole FOV (which is about 60°) while PAMELA's ones are within its angular resolution $(0.1 - 2.5°)$; and considering the stability of the intensity of trapped protons fluxes in the IRB [14], the agreement between PAMELA and NOAA-17 data is quite well.

5. Conclusion

A simple and robust method of reconstruction of the flux intensity of geomagnetically trapped particles is proposed. Instead of multiple calculations of the effective area for different pitch angles and instrument orientations respective to the magnetic field vector, the value of the effective geometrical factor is estimated from one simulation sample. In this procedure, the additivity of partial geometrical factors within the Instrument's field of view is used. The proposed method was tested on PAMELA experimental data for galactic cosmic rays, which are known to be isotropic. The reconstructed flux intensity of geomagnetically trapped particles, detected by the PAMELA instrument, is consistent with the measurements of other instruments. The method provides the

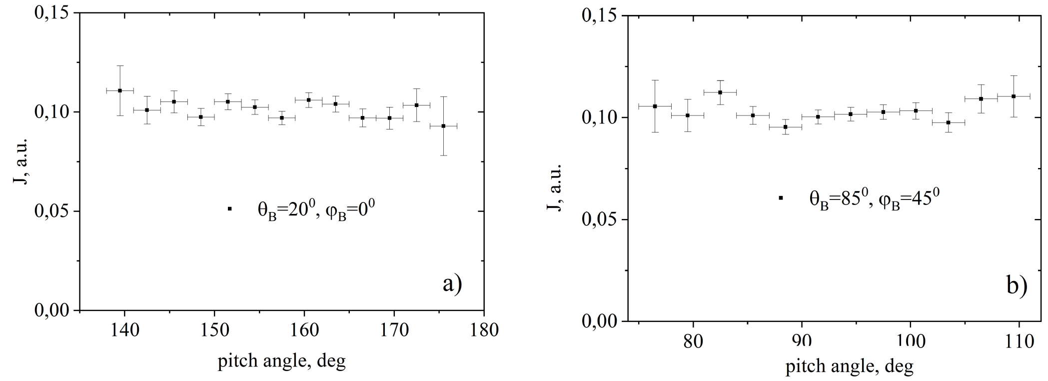

Figure 4: Distribution over the angle between two (a and b) arbitrary assigned directions of *B* in the IRF of galactic cosmic ray proton fluxes in the rigidity range 0.75˘1.25 GV in arbitrary units reconstructed with the PAMELA spectrometer data.

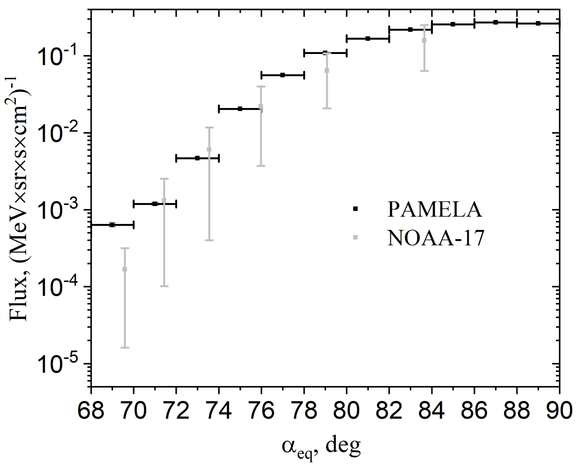

Figure 5: The flux of geomagnetically trapped protons detected at L=1.16 in the energy range 70˘140 MeV in the PAMELA (black squares) and NOAA-17 (gray squares) experiments depending on equatorial pitch angles. The PAMELA data were obtained in July-September, 2006, the NOAA-17 —- in April, 2005

possibility to reconstruct the flux intensity of geomagnetically trapped particles for each instrument passage across SAA.

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