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Latitude Effect of Muons in the Earth's Atmosphere during Solar Activity Minimum

**V. S. Makhmutov[a], Yu. I. Stozhkov[a], G. A. Bazilevskaya[a],
N. S. Svirzhevsky[a], and A. K. Morzabayev[b]**
[a] *Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia*
[b] *Gumilev Eurasian National University, Astana, Kazakhstan*
e-mail: vms1@fian.fiandns.mipt.ru

Abstract—The results of muon flux measurements ($E \geq 70$ MeV) in the atmosphere during solar activity minimum are reported. The measurements were performed during Antarctic sea expedition in 1975–1976 at several geomagnetic locations (from 1 to 14 GV). The experimental data obtained made it possible to determine the latitude effect of muons in the distribution at different levels in the atmosphere. The Geant4 program was used to simulate the galactic cosmic ray transport in the Earth's atmosphere and evaluate the angular and spectral distributions (p, e^-/e^+, photons, muons) at different atmospheric levels. The experimental and simulated results are in satisfactory agreement.

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INTRODUCTION

Muon flux measurements in the atmosphere were performed by researchers of the Lebedev Physical Institute during the Antarctic sea expedition in a solar activity minimum (November 1975–March 1976). The measurements were performed on balloons on different geographic (geomagnetic) latitudes at several geomagnetic locations, $R_c \approx 1$–14 GV, at altitudes from 0 to 30 km, which correspond to the residual atmospheric pressure range ~10–1000 g cm^{-2}.

To analyze the experimental data, the transport of galactic cosmic ray (GCR) flux through the Earth's atmosphere was simulated by the Monte Carlo method based on the PLANETOCOSMICS/Geant4 software package [1–3]. We calculated the spatial and energy characteristics of the muon flux distribution at different latitudes with different R_c values. The obtained experimental data on the muon flux in the atmosphere and the simulation results are important for studying GCR flux variations, GCR interactions in the Earth's atmosphere, geomagnetic effect on the muon flux distribution in the atmosphere, etc. [4–8].

EXPERIMENTAL DATA

Muon flux measurements in the Earth's atmosphere were performed using a detector composed of eight STS-6 cylindrical Geiger counters (Fig. 1). A counter has a diameter of 1.9 cm and a length of 9.8 cm; the thickness of its steel walls corresponds to 0.05 g cm^{-2}. These counters were combined into a telescope using a lead filter with a thickness of 2.5 cm (28.4 g cm^{-2}). Charged particles were counted in three channels: (i) CH1 (count rate per minute of single counter *2*), (ii) CH2 (count rate of particles passing through counter *2*, lead filter, and counter *7*), and (iii) CH$_3$ (coincidence count rate of signals recorded in counters *2* and *7* and in any lateral counter (*1, 3, 4–6*, or *8*)). Thus, these data made it possible to separate omnidirectional charged-particle fluxes (channel CH1) and shower particles (CH3) and select the hard (high-energy) cosmic ray (CR) component (mainly muons) in the atmosphere, using the difference in the records of channels CH2 and CH3.

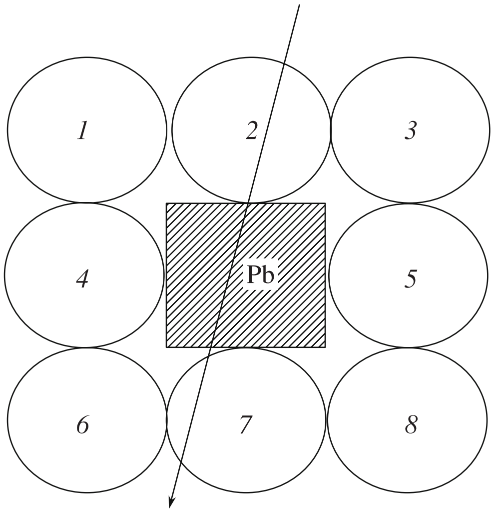

Fig. 1. Schematic of the detector for measuring the muon flux in the atmosphere (aside view): STS-6 Geiger counters (*1–8*) separated by a 2.5-cm-thick lead filter.

In this paper, we report the results of analysis of the data on the distribution of high-energy particles in the atmosphere (CH2 – CH3 difference) at different geomagnetic latitudes. The chosen thickness of the lead filter made it possible to select penetrating particles (mainly muons) with energies above 70 MeV; the telescope acceptance factor $G = 9$ cm^2 sr for the angular particle distribution $J(>E) \sim \cos^2\Theta$ (Θ is the zenith angle). The CH2 – CH3 difference at a given altitude x, $N_{tot}(x)$, is related to detection of the total muon flux $N(x)$ and nuclear-active CR component $N_{pr}(x)$. The contribution of the latter to the measurement results at a given level x can be determined from the relation $N_{pr}(x) = N_0\exp(-x/x_0)$, where N_0 is the primary-particle flux at the atmospheric boundary (for example, for measurements at $R_c = 13.6$ GV, $N_0 = 100$ m^{-2} s^{-1} sr^{-1}) and $x_0 = 120$ g cm^{-2} is the particle free path in the atmosphere before absorption. Then, the difference $N(x) = N_{tot}(x) - N_{pr}(x)$ is the muon flux ($E > 70$ MeV) at a given level x. Thus, the results of each flight were used to determine the muon absorption curve $N(x)$ in the atmosphere, after which the average dependences $N(x)$ were calculated, related to the muon flux measurements at points with similar R_c.

SIMULATION OF GCR TRANSPORT IN THE EARTH'S ATMOSPHERE

The GCR proton transport in the Earth's atmosphere was simulated by the Monte Carlo method using the PLANETOCOSMICS/Geant4 code [1–3]. Ionization, multiple scattering of particles, bremsstrahlung, formation of pairs, photoelectric effect, Compton effect, elastic and inelastic nuclear interactions, and particle decay were taken into account. It was previously shown that PLANETOCOSMICS/Geant4 adequately describes the propagation of magnetospheric electrons and solar protons in the Earth's atmosphere in analysis of CR stratospheric experimental data [9, 10].

In the calculations, the differential energy spectrum of the GCR protons at the atmospheric boundary during solar activity minimum was taken in the form $J(E)$[m^{-2} s^{-1} sr^{-1} MeV^{-1}] $= DE^{\alpha}/(0.01E + B)^4 + C\exp(-0.1E)$, where E is the proton kinetic energy in MeV, $D = 16$, $B = 8$, $\alpha = 1.3$, and $C = 1.1$ [11]. The primary proton energies ranged from 500 to 10^6 MeV. The calculations were performed using the standard model of the atmosphere (applied also in analysis of stratospheric data [12]). For 28 levels of the residual atmosphere ($x = 0.05$–1000 g cm^{-2}), we calculated the energy and angular distributions of the particles (protons, electrons, positrons, photons, and muons) formed during transport of primary protons in the atmosphere. The simulation results show that the maximum of the atmospheric muon energy spectra at different altitudes and measurement points is rather wide and locates on average in the energy range $E \approx 100$–1000 MeV, while the muon flux is maximum in the range $x \approx 70$–250 g cm^{-2} (height $h \approx 11$–18 km).

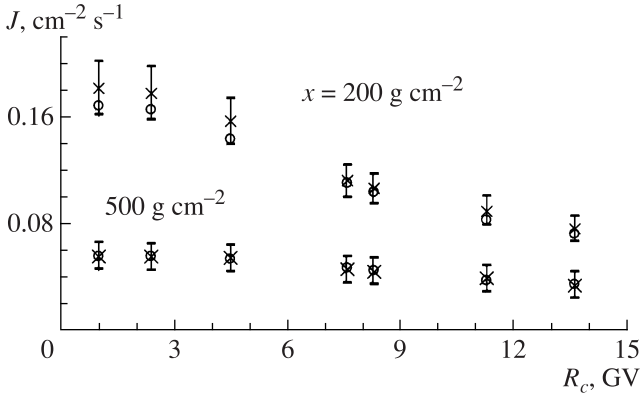

Fig. 2. Latitude effect of muon flux ($E > 70$ MeV) at two levels of the Earth's atmosphere: $x = 200$ and 500 g cm^{-2}: (×) experiment and (○) calculation. The vertical bars indicate experimental errors.

Then the total muon flux with $E > 70$ MeV was calculated for each atmospheric level taking into account muons produced both by GCR primary protons and helium nuclei [3]. This approach made it possible to calculate the muon absorption curves in the atmosphere, which are in satisfactory agreement with the experimental curves at different R_c. The experimental data and calculation results allowed us to establish the latitude effect in the muon spatial distribution ($E >$ 70 MeV) at different atmospheric levels. Figure 2 shows as an example the latitude effect of muons at two atmospheric levels: $x = 200$ and 500 g cm^{-2}. Its value, determined as the ratio of muon fluxes $J(R_c = 2.4\text{ GV})/J(R_c = 13.6\text{ GV})$, is ~2.3 and 1.6 at levels of $x = 200$ and 500 g cm^{-2}, respectively. Note that the latitude effect in the near-Earth layer ($x = 900$–1000 g cm^{-2}) does not exceed 1.1.

CONCLUSIONS

The results of muon flux measurements in the atmosphere, obtained during the Antarctic sea expedition in November 1975–March 1976, have been analyzed. As a result, the curves of muon absorption in the Earth's atmosphere were determined at different geomagnetic latitudes with cutoff rigidities $R_c \approx 1$–14 GV. The GCR proton transport in the Earth's atmosphere was simulated using the PLANETOCOSMICS/Geant4 program. The spatial and energy characteristics of muons in the atmosphere were determined. Comparative analysis of the experimental data and simulation results was performed and the latitude effect of muons at different atmospheric levels during solar activity minimum was determined.

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REFERENCES

1. Agostinelli, S., Allison, J., Amako, K., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2003, vol. 506, p. 250.
2. Desorgher, L., Flückiger, E.O., Moser, M.R., and Bütikofer, R., in *Proc. 28th ICRC*, Tsukuba, 2003, p. 4277.
3. Desorgher, L., Flückiger, E.O., Gurtner, M., et al., *Int. J. Mod. Phys. A*, 2005, no. 29, p. 6802.
4. Sanuki, Y., Yamomoto, Y., Motoki, M., et al., in *Proc. 27th ICRC*, Hamburg, 2001, p. 950.
5. Krizmanic, J.F., Davis, A.J., Barbier, L.M., et al., in *Proc. 24th ICRC*, Roma, 1995, p. 69.
6. Ageshin, P.N. and Charakhch’yan, T.N., *Vestn. MGU*, 1956, no. 2, p. 77.
7. Kurguzova, A.I. and Charakhch’yan, T.N., *Geomagn. Aeron.*, 1978, vol. 18, no. 4, p. 590.
8. Kurguzova, A.I. and Charakhch’yan, T.N., *Geomagn. Aeron.*, 1983, vol. 23, no. 5, p. 715.
9. Makhmutov, V.S., Bazilevskaya, G.A., Desorgher, L., and Flückiger, E.O., *Adv. Space Res.*, 2006, vol. 38, p. 1642.
10. Makhmutov, V.S., Desorgher, L., Bazilevskaya, G.A., et al., *Adv. Space Res.,* 2007, vol. 39, no. 9, p. 1460.
11. *Luchi kosmicheskie galakticheskie, GOST 25645.122-85* (Cosmic Galactic Rays, State Standard 25645.122-85), Moscow: Izd-vo Standartov, 1986.
12. *Atmosfera: Spravochnik* (Atmosphere: Handbook) Sedunov, Yu.S., Ed., Leningrad: Gidrometeoizdat, 1991, p. 509.