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FLUXES OF COSMIC RAYS IN THE MAXIMUM OF ABSORPTION CURVE IN THE ATMOSPHERE AND AT THE ATMOSPHERE BOUNDARY (1957–2007)

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Introduction

In the 50ies of the 20th century academician S.N. Vernov suggested to perform the regular measurements of cosmic ray (CR) fluxes in the Earth's atmosphere by means of regular radio sound launching. The main goals of this experiment included study of galactic CR modulation processes, acceleration mechanism of charged particles in powerful solar flares and their propagation in the interplanetary space. In the middle of 1957, S.N. Vernov, together with professor A.N. Charakhchyan, started this experiment. Since then till the present time the regular measurements of charged particle fluxes in the atmosphere of polar and middle latitudes have been carried out. At present about 80 thousands of radio sounds have been launched.

A large amount of experimental data on charged particle fluxes in the atmosphere at different latitudes and altitudes was obtained by the workers of Lebedev Physical Institute of Russian Academy of Sciences (LPI RAS) in cooperation with other academic and non-academic institutions. This cooperation included Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University (under the charge of professor T.N. Charakhchyan), Kasakh State University, Alma-Ata (charge of professor E.V. Kolomeetz), Polar Geophysical Institute, RAS, Apatity (charge of professor E.V. Vashenyik), Alikhanyan Physical Institute, Yerevan, Armenia (charge of doctor G.A. Asatryan), Cosmophysical Observatory of Shafer Institute of Cosmophysical Research and Aeronomy, RAS, Tixie (charge of head A.M. Novikov), Institute of Solar-Terrestrial Physics, RAS , Irkutsk (charge of V.P. Karpov), Leningrad branch of Institute of the Earth's Magnetism, Ionosphere and Radio Wave Propagation, RAS, Voyeikovo (charge of professor M.I. Tyasto), Crimean Astrophysical Observatory, Crimea (Simeiz, charge of professor A.A. Stepanyan), Fedorov Institute of Applied Physics, Moscow, Roshydromet (charge of professor N.K. Pereyaslova), Campinas University, Campinas, Brasil (charge of professor I.M. Martin). From 1963, the measurements have been made at the Antarctic station Mirny supported by Arctic and Antarctic Scientific Research Institute, Roshydromet, St. Petersburg.

After disintegration, of the USSR, the financial support of scientific research in Russia was virtually stopped. Regular measurements of charged particles in the atmosphere were saved due to academician A.E. Chudakov efforts. He persuaded the officials of RAS to support this experiment. The management of Lebedev Physical Institute has been of inestimable value in the fulfillment of research. The financial support has been given by the Russian Foundation for Basic Research and by the special program "Neutrino Physics" of the Presidium of RAS.

Description of observations

For the CR measurements in the atmosphere the special radio sounds for the charged particle detection, ground-based receiver, and calibration stands for particle detectors and atmospheric pressure sensors were developed. A valuable contribution in development of these devices and performance of measurements was made by the engineers of Dolgoprudny scientific station of LPI: P.N. Ageshin, V.V. Bayarevich, A.E. Golenkov, A.F. Krasotkin, V.N. Makunin and others.

A gas-discharge counter of STS-6 type is used to detect omnidirectional flux of charged particles, and a telescope with two such counters is used to detect vertical flux of charged particles. A cylindrical counter of STS-6 type is 98 mm in effective length and 19 mm in diameter. The thickness of steal walls equals 50 mg·cm^{-2}. Energy cutoff of detected particles is E_{ec} = 200–300 keV for electrons and E_{pc} = 5 MeV for protons. A single counter response to γ-rays is less than 0.1%. A telescope has a 7-mm aluminum absorber between counters, which gives with account of the counter walls the energy cutoff of E_{ec} = 5 MeV for electrons and E_{pc} = 30 MeV for protons. The telescope does not detect γ-rays at all. The distance between centers of the upper and bottom counters is 26 mm. The geometrical factors of a single counter G_c and a telescope G_t depend on the angular distribution of detected particles. For isotropic angular distribution of particles in the upper hemisphere these values equal G_c = 16.4 cm^2 and G_t = 17.8

$cm^2 \cdot sr^{-1}$. The quasi isotropic distribution of charged particles is realized for the primary particles at the top of the atmosphere and for the particles in the maximum of absorption curve in the atmosphere. The experiment description is given in [1–5].

During 60ies the regular measurements of γ-rays with energy $E_\gamma \geq 20$ keV in the atmosphere of the northern polar and middle latitudes were made also. The standard radio sounds with *NaJ*(*Tl*) crystal as a γ-ray detector was used. The crystal was of cylindrical form with diameter of 20 mm and length of 20 mm [6].

Treatment of experimental data has been made at Dolgoprudny scientific station of LPI RAS. A large amount of work was done by engineers, technicians, and laboratory assistants G.V. Yastrebtseva, A.F. Biryukova, K.A. Bogatskaya, A.M. Istratova, V.I. Obryvalova, G.V. Klishina, O.A. Shishkova, E.G. Plotnikova, G.I. Plugar, and many others.

In Table 1, the sites of regular measurements of charged particle and γ-ray fluxes in the atmosphere are shown. The measurements have been done at the latitudes with different geomagnetic cutoff rigidities R_c and span the interval of altitudes from the ground level up to 30–35 km. At each level of measurements in the atmosphere the counting rate of detectors is defined by primary particles with rigidity above some cutoff value, so-called atmospheric cutoff rigidity R_a if $R_a > R_c$. Otherwise, if $R_a < R_c$, the cutoff is defined by geomagnetic cutoff rigidity R_c. For the data obtained with a single counter the dependence of R_a on atmospheric pressure is expressed as $R_a = 4 \cdot 10^{-2} \cdot x^{0.8}$ where R_a is in GV and x is in $g \cdot cm^{-2}$ [7].

Table 1. The sites and periods of measurements of CR and γ-ray fluxes in the atmosphere

Site of measurements	Geographical coordinates	R_c, GV	Period of measurements
Loparskaya station, Olenya station, Apatity, Murmansk region	68°57′N; 33°03′E 67°33′N; 33°20′E	0. 6	07.1957–present time 03.1965–12.1968 (γ)
Dolgoprudny, Moscow region	55°56′N; 37°31′E	2.4	07.1957–present time 10.1964–12.1969 (γ)
Alma-Ata, Kazakhstan	43°15′N; 76°55′E	6.7	03.1962–04.1993
Mirny observatory, Antarctica	66°34′S; 92°55′E	0.03	03.1963–present time
Simeiz, Crimea	44°00′N; 34°00′E	5.9	03.1958–12.1961 03.1964–04.1970 10.1964–12.1969 (γ)
Voyeikovo, Leningrad region	60°00′N; 30°42′E	1.7	11.1964–03.1970
Norilsk, Krasnoyarsk Territory	69°00′N; 88°00′E	0.6	11.1974–06.1982
Yerevan, Armenia	40°10′N; 44°30′E	7.6	01.1976–05.1989
Tixie, Yakutiya	71°36′N; 128°54′E	0.5	02.1978–09.1987
Dalnerechensk, Khabarovsk Territory	45°52′N; 133°44′E	7.35	08.1978–05.1982
Vostok station, Antarctica	78°47′S; 106°87′E	0.00	01.1980–02.1980
Barentzburg, Norway	78°36′N; 16°24′E	0.06	05.1982, 03–07.1983
Campinas, Brasil	23°00′S; 47°08′W	10.9	01.1988–02.1991

During the whole period of measurements, the identical detectors of charged particles (gas-discharged tubes of STS-6 type) and γ-rays (*NaJ*(*Tl*) crystal) and identical devices for calibration of detectors have been used. Therefore, the sets of data given in Tables 3-32 are homogeneous.

The most long-lasting data series were obtained at the northern polar stations (Murmansk region) and at the midlatitude station (Dolgoprudny, Moscow region). These series span the period from the middle of 1957 up to now.

As an example in Figs. 1a, b monthly averaged counting rates of a single counter $N_1(x)$ and a telescope $N_2(x)$ at various latitudes are shown. The maxima in the counting rates $N_{1m}(x)$ and $N_{2m}(x)$ are distinctly seen. In comparison with the data obtained at other altitudes ($N_1(x)$ and $N_2(x)$) the values of N_{1m} and N_{2m} have minimal statistical errors and do not depend on the accuracy of altitude or atmospheric pressure measurement. Fluxes of γ-rays have similar dependence on the atmospheric pressure [6].

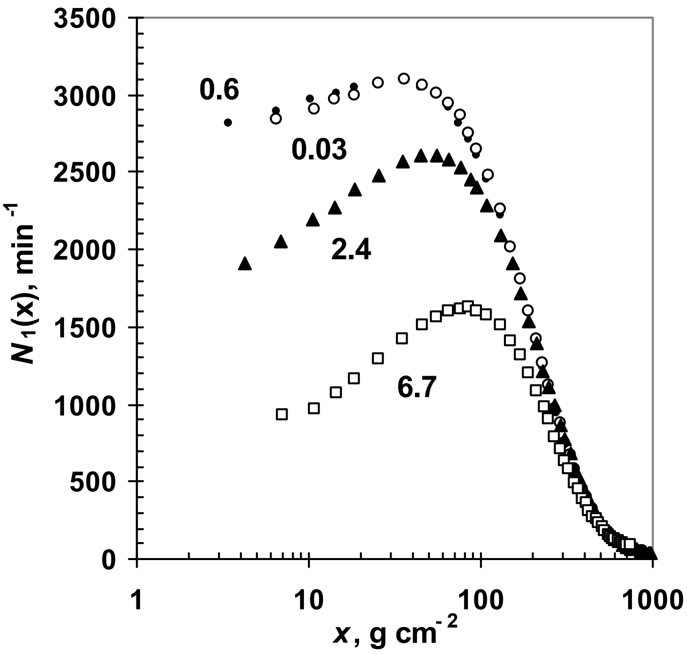

Fig. 1a. Monthly averaged counting rates of a single counter $N_1(x)$ vs. atmospheric pressure value x (so called absorption curves). The measurements were made during solar activity minimum in July 1987 at the northern polar latitude with the geomagnetic cutoff rigidity $R_c = 0.6$ GV (black circles), at the southern polar latitude with $R_c = 0.03$ GV (open circles), at the northern middle latitude with $R_c = 2.4$ GV (black triangles), and at the northern low latitude with $R_c = 6.7$ GV (open squares). The values of R_c are shown by figures near curves. The root-mean-square errors do not exceed sizes of the symbols.

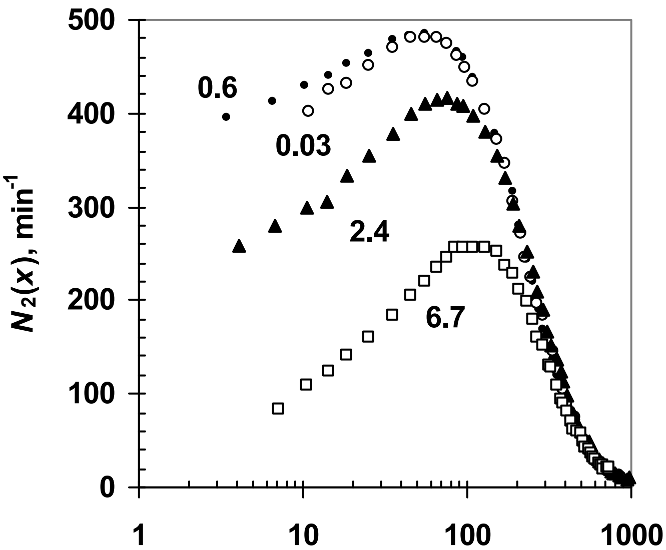

Fig. 1b. The same as in Fig. 1a but for data obtained with a telescope.

The following Tables 3–27 give the monthly averaged values of CR fluxes (galactic CRs and their secondaries in the atmosphere) measured with a single counter and a telescope in the maximum of absorption curve (N_{1m} and N_{2m}) with the root-mean-square errors σ_1 and σ_2 at the sites and for periods shown in Table 1. Tables 28–30 give the monthly averaged values of the γ-rays fluxes of $N_{\gamma m}$ with energy $E_\gamma \geq 20$ keV measured with crystal *NaJ*(*Tl*) in the maximum of absorption curve at the sites and for periods according to Table 1.

Determination of the particle fluxes at the atmospheric boundary

a) technique of extrapolation of particle flux values to the atmospheric boundary

From the altitude dependences of particle fluxes (see examples in Figs. 1a, b) one can find charged particle fluxes at the top of the atmosphere where atmospheric pressure $x = 0$. Let us take the differences between the counting rates at the latitudes with the geomagnetic cutoff rigidities $R_c = 0.6$ GV and $R_c = 2.4$ GV, as well as between $R_c = 0.6$ GV and $R_c = 6.7$ GV vs. residual pressure (or altitude) dN(x). For values of $4 < x \leq 85$ g·cm^{-2} these differences can be fitted to an exponential. As examples, in Figs. 2a, b and 3a, b these differences vs. x are plotted as obtained from the data presented in Figs. 1a, b for the solar activity minimum period (July 1987).

In Figs. 2a, b the approximation of differences obtained for a single counter and a telescope is shown together with the corresponding energy interval of primary protons ($0.1 \leq E \leq 1.5$ GeV). The logarithmic scale for the vertical axis is used. In Figs. 3a, b the differences for the second pair of altitude dependences ($0.1 \leq E \leq 5.8$ GeV) are shown. In this case the scale of both axes have linear and the differences are fitted to straight lines.

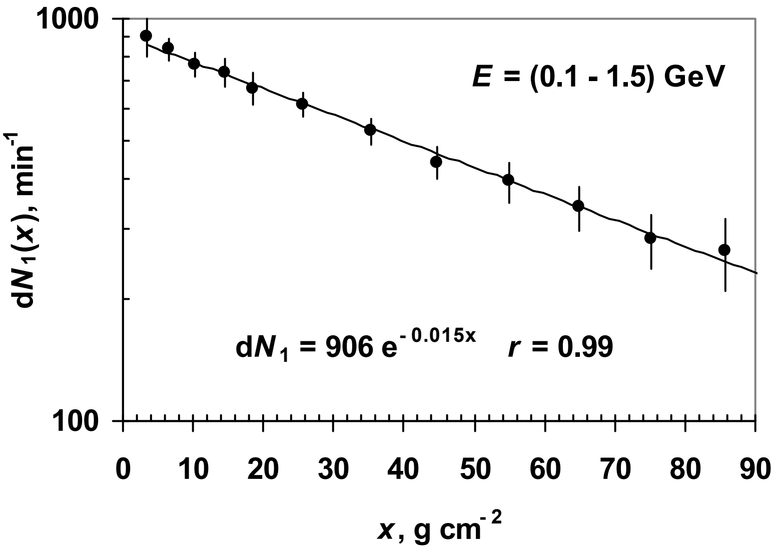

Fig. 2a. Differences dN_1(x) between the counting rates of a single counter at the northern polar latitude ($R_c = 0.6$ GV) and that at the middle latitude ($R_c = 2.4$ GV) vs. atmospheric pressure x for the period of July 1987 (differences between the data of upper and middle absorption curves given in Fig. 1a). The scale of vertical axis is logarithmic. The vertical bars equal three root-mean-square errors (3σ). The fitting law (see the figure) was calculated by the method of least squares, r – correlation coefficient between the experimental points and the approximation.

The approximating functions given $x = 0$ yield the fluxes of charged particles at the top of the atmosphere (see examples in Figs. 2a, b and 3a, b). These fluxes include primary CRs J_0 and secondary albedo particles J_A. Subtracting the albedo particle flux J_A from the values of charged particle fluxes at the top of the atmosphere yields the fluxes of primary CRs J_0. The values of J_A can be found in [8, 9]. An isotropic angular distribution of primary particles at the top of the atmosphere was assumed. In this case the geometrical factors G_{count} = 16.4 cm^2 for a single counter and G_{tel} = 17.8 cm^2·sr for a telescope. Tables 31–32 give monthly averaged values of primary CR fluxes at the top of the atmosphere $J_0(E \geq 0.1$ GeV) and $J_0(0.1 \leq E \leq 1.5$ GeV).

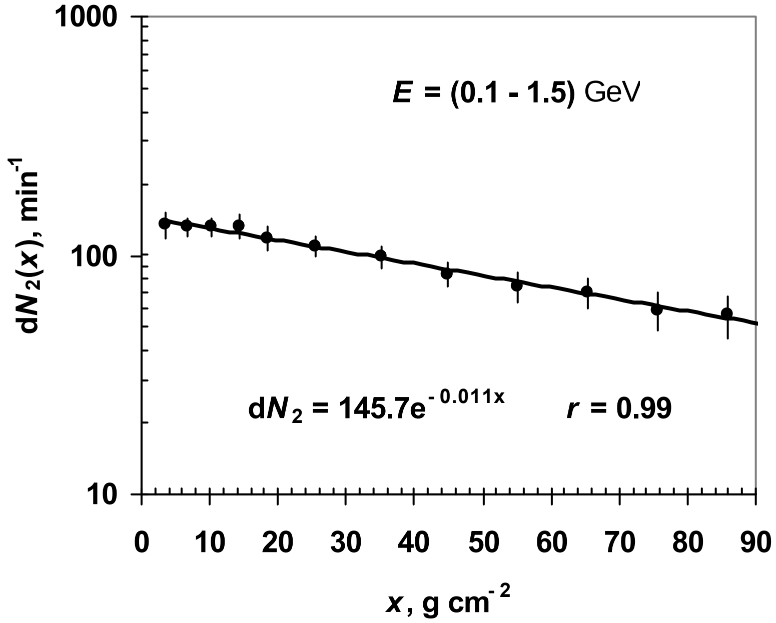

Fig. 2b. The same as in Fig. 2a but for the data obtained with a telescope at the northern polar latitude (R_c = 0.6 GV) and the northern middle latitude (R_c = 2.4 GV) for July 1987 (differences between the data of upper and middle absorption curves presented in Fig. 1b).

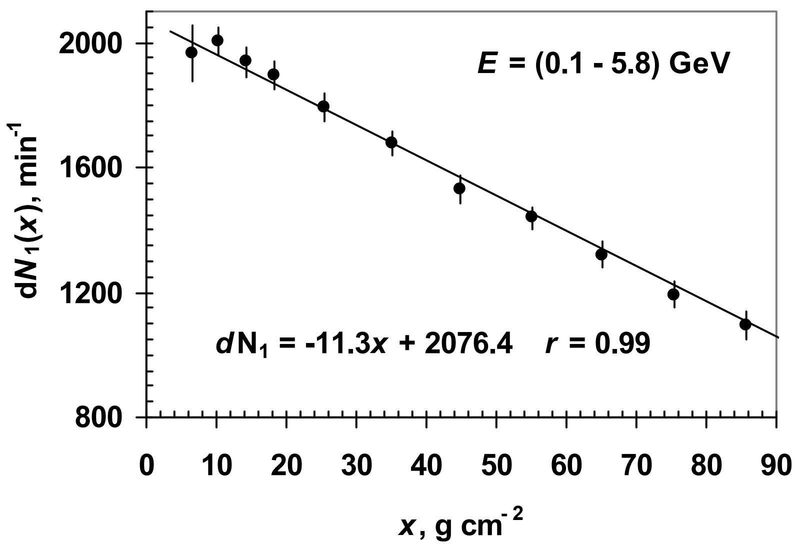

Fig. 3a. Differences of counting rates d$N_1(x)$ of a single counter at the northern polar latitude (R_c = 0.6 GV) and that at the northern low latitude (R_c = 6.7 GV) vs. atmospheric pressure x for the period of July 1987 (differences between the data of upper and bottom absorption curves given in Fig. 1a). The vertical bars equal three standard errors (3σ). The straight line was calculated by the least-squares method, r – correlation coefficient between experimental and the fitting points.

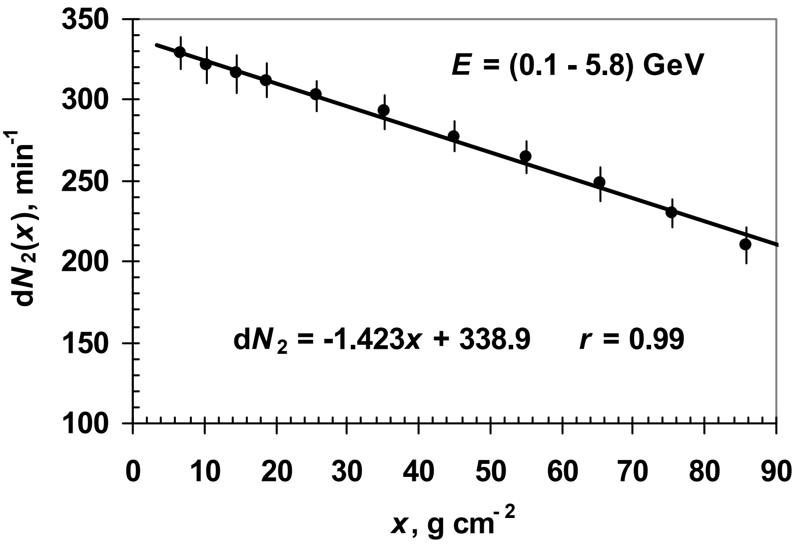

Fig. 3b. The same as in Fig. 3a but for the data obtained with a telescope at the northern polar latitude (R_c = 0.6 GV) and at the northern low one (R_c = 6.7 GV) vs. atmospheric pressure x for the period of July 1987 (differences between upper and bottom absorption curves given in Fig. 1b).

b) relation between the particle fluxes at the atmospheric boundary and fluxes in the maximum of absorption curve

High correlation between experimental data d$N_1(x)$, d$N_2(x)$ and the fitting functions is striking: the correlation coefficient r is ~1. It proves validity of the used approximation. However, high values of r are observed not for all periods under consideration. During the periods of high solar activity, the latitudinal effect (difference between absorption curves) decreases essentially, therefore, the value of d$N_1(x)$ и dN_2) decrease. That leads to growth of errors and fall of correlation coefficients values r. This effect is especially important for the differences of CR fluxes measured at high and middle latitudes with R_c = 0.6 GV and R_c = 2.4 GV, respectively. In this case the method of experimental data extrapolation to the top of the atmosphere becomes inaccurate. In addition, the omnidirectional flux of CRs measured at polar latitudes $N_1(x)$ may contain a contribution from precipitating (solar and/or magnetospheric) particles.

Because of this, another technique is used to find primary CR fluxes $J_0(E \geq 0.1$ GeV) and $J_0(0.1 \leq E \leq 1.5$ GeV) at the top of the atmosphere, namely, the relationship between J_0 obtained by extrapolation and CR fluxes in the maximum of absorption curve $N_{1\mathrm{m}}$, $N_{2\mathrm{m}}$ or d$N_{1\mathrm{m}}$, d$N_{2\mathrm{m}}$. As mentioned above, the values of N_m have minimum statistical errors and do not suffer from inaccuracy of atmospheric pressure x determination. We use the values of N_m obtained at the stations with geomagnetic cutoff rigidities R_c equal to 0.6, 2.4 and 6.7 GV. The atmospheric pressure values x_m where N_m are recorded, are different at these latitudes for the periods of solar activity minimum and maximum. It is also necessary to take into account the absorption of particles in the atmosphere. Therefore, CR primary particles with energy $E \geq E_{\min}$ contribute into N_m value, $E_{\min}$ being defined by the values R_c or R_a. In Table 2, the values of x_m and $E_{\min}$ are given for solar activity minimum and maximum periods and aforementioned geomagnetic cutoffs. Values of $E_{\min}$ for atmospheric pressure x_m were calculated from the expression $E_{\min} = \sqrt{R^2 + m_p^2 c^4} - m_p c^2$, where $R = R_a = 4 \cdot 10^{-2} \cdot x_m^{0.8}$, if $R_a > R_c$, otherwise $R = R_c$ if $R_a \leq R_c$, m_p is proton mass, x_m is the atmospheric pressure in g·cm^{-2} [7].

Table 2. Values of x_m in g·cm^{-2} and E_{min} in GeV (for protons) calculated for solar activity minimum and maximum periods according to a single counter data at the stations with the geomagnetic cutoff rigidities R_c, equal to 0.6, 2.4 and 6.7 GV

R_c, GV (E_c, GeV)		0.6 (0.18)	2.4 (1.6)	6.7 (5.8)
Solar activity minimum	x_m, g·cm^{-2}	30	50	80
	E_{min}, GeV	0.18*	1.6*	5.8*
Solar activity maximum	x_m, g·cm^{-2}	60	60	85
	E_{min}, GeV	0.5	1.6*	5.8*

* – the values of E_{min} are defined by geomagnetic cutoff rigidity R_c.

As it is seen from Table 2 the values of E_{min} are defined by atmospheric thickness x only for polar latitudes in the maximum of solar activity. At the middle and low latitudes, the values of E_{min} at the top of the atmosphere are defined by the geomagnetic cutoff R_c.

In Figs. 4a, b relationship between primary CR fluxes at the top of the atmosphere obtained by extrapolation technique $J_0(0.1 \leq E \leq 1.5$ GeV) and differences between the CR fluxes detected by a single counter and a telescope in the maximum of absorption curve in the atmosphere dN_{1m} = $N_{1m}(0.6) - N_{1m}(2.4)$ and dN_{2m} = $N_{2m}(0.6) - N_{2m}(2.4)$ at the latitudes with R_c = 0.6 and 2.4 GV are shown. Here $N_{1m}(0.6)$, $N_{1m}(2.4)$, $N_{2m}(0.6)$ and $N_{2m}(2.4)$ are the CR fluxes in the maximum of absorption curve. Correlation between J_0 and dN_{1m} is high (correlation coefficient r = 0.95) and regression can be expressed as

$$J_0(0.1 < E < 1.5 \text{ GeV}) = (2773 \pm 25)\cdot dN_{1m} + (154 \pm 9), \quad (1)$$

where J_0 is in m^{-2}·s^{-1}·sr^{-1} and dN_{1m} is in cm^{-2}·s^{-1}.

The correlation coefficient for data presented in Fig. 4b r = 0.93 and the relationship between J_0 and dN_{2m} is expressed as

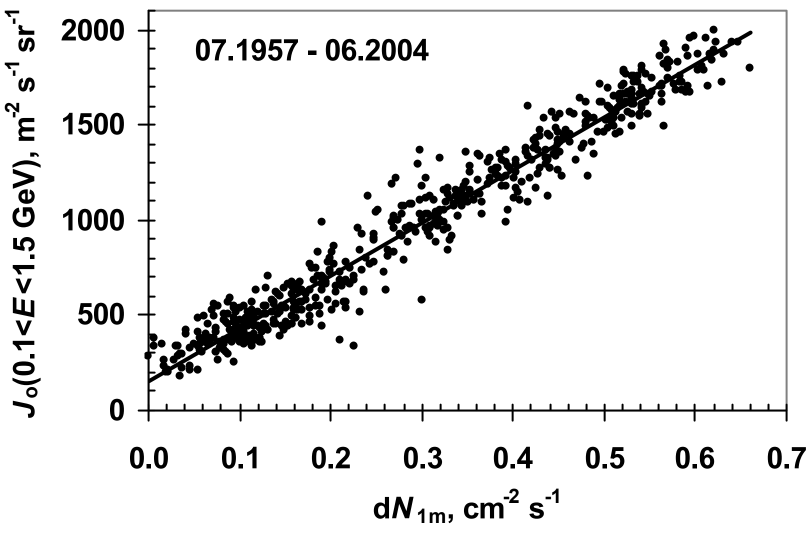

Fig. 4a. Relationship between monthly averaged primary CR fluxes at the top of the atmosphere obtained by extrapolation technique $J_0(0.1 \leq E \leq 1.5$ GeV) and differences of CR fluxes detected by a single counter in the maximum of particle absorption curve in the atmosphere dN_{1m} = $N_{1m}(0.6) - N_{1m}(2.4)$ at the latitudes with R_c = 0.6 and 2.4 GV in the period 07.1957–06.2004. The

straight line was calculated by the least-squares technique.

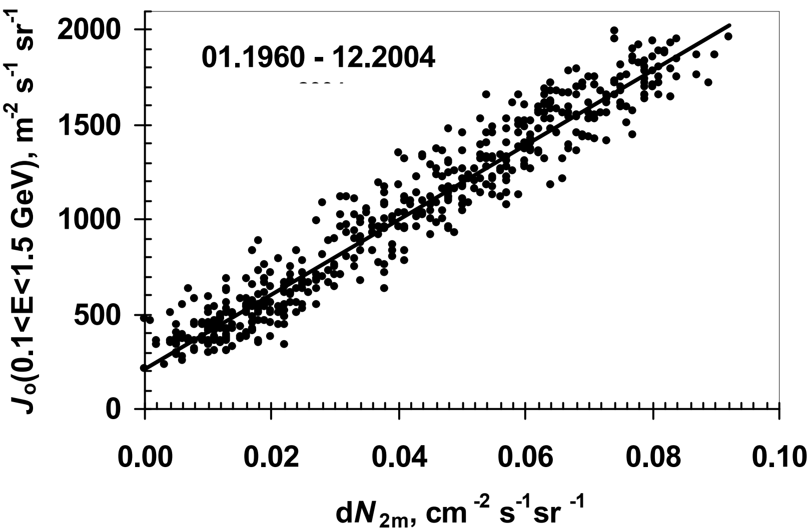

Fig. 4b. The same as in Fig. 4a but for data obtained with telescope in the period from 01.1960 (start of measurement with a telescope) to 12.2004.

$$J_0(0.1 < E < 1.5 \text{ GeV}) = (19715 \pm 239)\cdot dN_{2m} + (216 \pm 11), \quad (2)$$

where J_0 is m^{-2}·s^{-1}·sr^{-1} and dN_{2m} is in cm^{-2}s^{-1}sr^{-1}. The contribution of albedo particles to J_0 defined from telescope data is small. Angular distribution of particles in the maximum of absorption curve is isotropic in the upper hemisphere [3]. The geometrical factor of a telescope in this case is 17.8 cm^2·sr.

Similar regressions can be found between the extrapolated values of primary CR fluxes $J_0(E \geq 0.1$ GeV) and the CR fluxes detected by a single counter N_{1m} and a telescope N_{2m} in the maximum of absorption curve in the atmosphere of polar latitudes with R_c = 0.6 GV. The relations are presented in Figs. 5a, b.

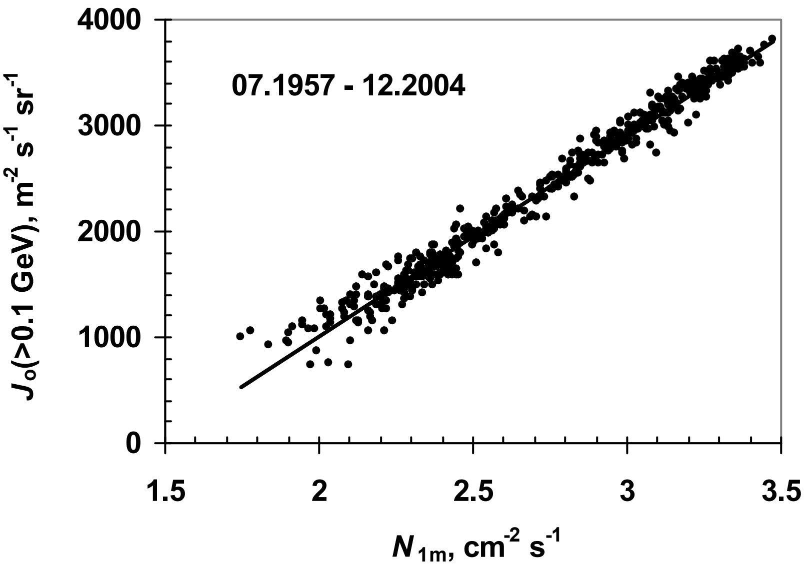

Fig. 5a. Relationship between the primary CR fluxes at the top of the atmosphere obtained by extrapolation method $J_0(E \geq 0.1$ GeV) and the CR fluxes detected by a single counter in the maximum of particle absorption curve in the atmosphere N_{1m} at the latitudes with R_c = 0.6 GV

for the period 07.1957–12.2004. The straight line was calculated by the least-squares technique.

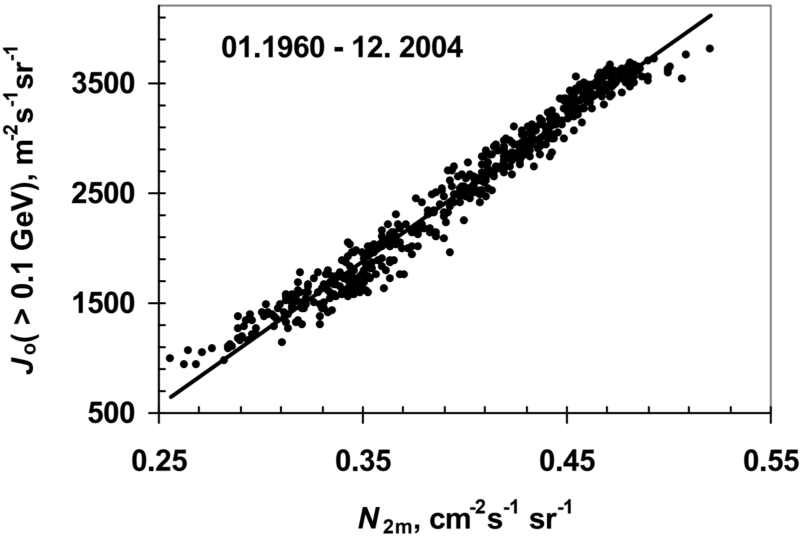

Fig. 5b. The same as in Fig. 5a but for the data obtained with a telescope in 01.1960–12.2004.

For a single counter data in Fig. 5a the correlation coefficient r amounts to 0.99. The relationship between $J_0(E \geq 0.1$ GeV) and N_{1m} can be expressed as

$$J_0(E \geq 0.1 \text{ GeV}) = (1893 \pm 12)\cdot N_{1m} - (2778 \pm 32), \quad (3)$$

where J_0 is in m^{-2}s^{-1}sr^{-1} and N_{1m} is in cm^{-2}·s^{-1}. For the telescope data in Fig. 5b the correlation coefficient r amounts to 0.98. The relationship between $J_0(E \geq 0.1$ GeV) and N_{2m} can be expressed as

$$J_0(E \geq 0.1 \text{ GeV}) = (13051 \pm 98)\cdot N_{2m} - (2698 \pm 39), \quad (4)$$

where J_0 is in m^{-2}s^{-1}·sr^{-1} and N_{2m} is in cm^{-2}·s^{-1}·sr^{-1}.

The values of $J_0(0.1 < E < 1.5$ GeV) and $J_0(E \geq 0.1$ GeV) obtained with the extrapolation technique of a single counter and a telescope data have to coincide with the values obtained from the expressions (1)–(4) within the errors.

In Tables 3–30, monthly averaged charged particle and γ-ray fluxes measured in maximum of absorption curve in the atmosphere are presented for the sites and periods indicated in Table 1. Tables 3–15 give monthly averaged charged particle fluxes measured with a single counter N_{1m}. Tables 16–27 give monthly averaged charged particle fluxes measured with a telescope N_{2m}. Tables 28–30 give monthly averaged γ-ray fluxes N_γ measured with a crystal $NaJ(Tl)$. Tables 31–32 give monthly averaged primary CR fluxes J_0 at the top of the atmosphere for energies $E \geq$ 0.1 GeV and $0.1 \leq E \leq 1.5$ GeV. The values of J_0 were obtained by the both techniques: 1) averaging data of a single counter and a telescope extrapolated to the top of the atmosphere and 2) using the expressions (1)–(4).

This preprint and Tables of the observational data are also presented at the address http://sites.lebedev.ru/DNS_FIAN/.

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