Effective cross-sections and ionization rates of cosmic rays in the atmosphere

Victor Ermakov, Yuri Stozhkov, and Nikolai Svirzhevsky

***Abstract*—From the data on cosmic ray fluxes measured in the atmosphere the effective cross-sections of ionization and ionization rates of cosmic rays as functions of atmospheric pressure and geomagnetic cutoff are calculated for periods of low and high solar activity levels.**

1. Introduction

From the middle of 1957 till the present time Lebedev Physical Institute of the Russian Academy of Sciences has carried out monitoring of charged particles in the atmosphere at several latitudes with different geomagnetic cutoffs R_c including polar northern and southern latitudes [1].

To measure charged particle fluxes the standard radiosondes have been used with gas-discharge counters as detectors of particles (see Fig. 1). For the period of 1957 - 2007 about 80000 altitude profiles of cosmic ray (CR) fluxes have been obtained in the interval of altitudes from the ground level up to (30 - 35) km [1].

Radiosonde measures global and vertical fluxes of charged particles with a single gas-discharge counter (electrons with energy E > 0.2 MeV, protons with E > 5 MeV) and with a counter telescope (electrons with energy E > 5 MeV, protons with E > 30 Mev) respectively. The weight of a radiosonde is about 600 grams.

In each flight of radiosonde the altitudinal dependence of CR flux vs. atmospheric pressure *x* or altitude *h* is obtained. In Fig. 2 altitudinal profiles measured at the latitudes with different values of R_c are shown [1]. Time dependences of CR fluxes at a number of altitudes in the northern polar atmosphere (R_c = 0.6 GV) are given in Fig. 3. The peaks in 1962 and 1963 were due to the tests of nuclear weapons in the atmosphere.

The data shown in Figs. 2, 3 serve as a base for calculations of effective cross-sections and ionization rates of cosmic rays in the atmosphere.

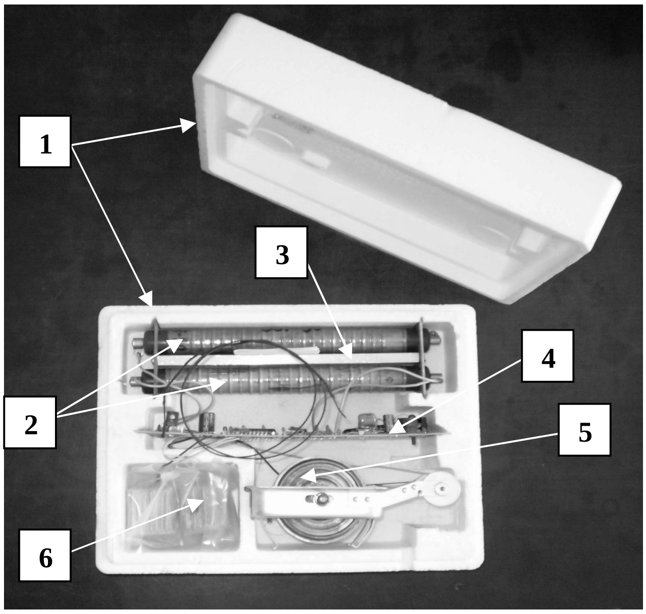

Fig. 1. A standard radiosonde for measurements of charged particle flux in the atmosphere: 1 – a foamed plastic box; 2 – detectors of charged particles (gas-discharged counters); 3 –an aluminum plate of 7 mm thickness; 4 – electronic scheme with high voltage power and radiotransmitter; 5 – atmospheric pressure sensor; 6 – chemical batteries.

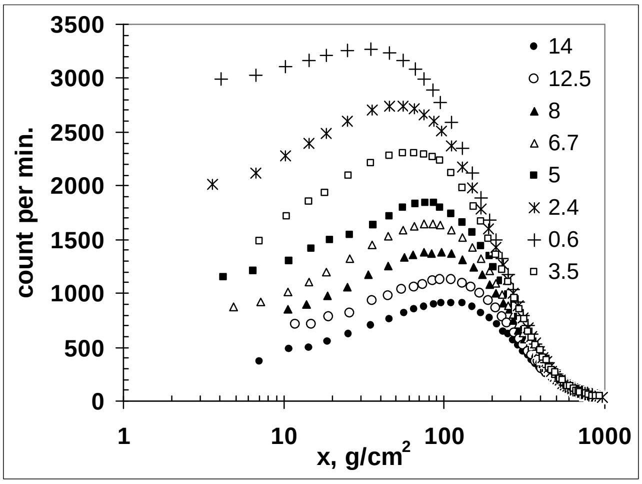

Fig. 2. Altitudinal profiles of CR fluxes obtained with single counters at the latitudes from equatorial to polar in the solar activity minimum of 1987. The values of R_c in GV are given in the right side of this figure [1].

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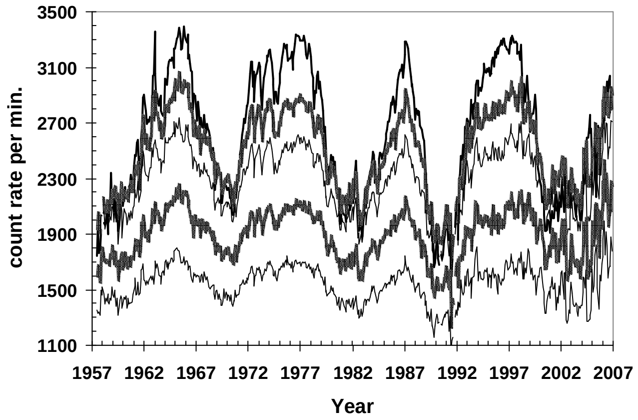

Fig. 3. Time dependences of the global CR flux in the northern polar atmosphere (R_c = 0.6 GV) at several altitudes from 25 km (upper curve) till 12 km (lower curve).

2. Ionization in the Atmosphere

CRs are the main source of the ionization in the atmosphere in the range of altitudes of (0 – 50) km. Over continents at the altitudes from the Earth's surface up to 3 km natural radioactive gases (mainly radon) emanating from soil produce additional ionization.

CRs give so-called column ionization of air when ions and electrons are distributed along the ionized track that the charged particle makes in air (see Fig. 4).

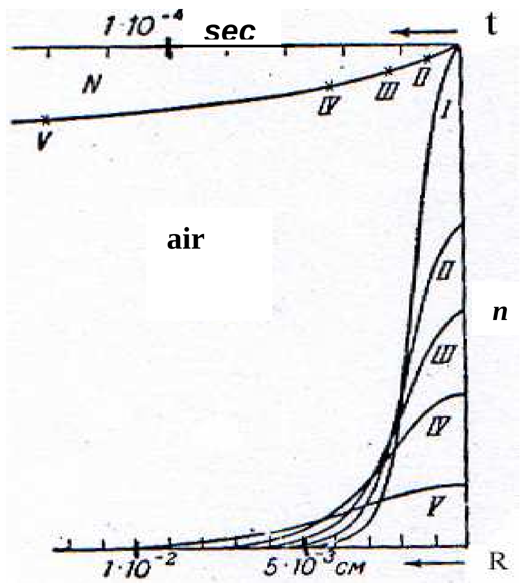

Fig. 4. Dependence of ion density *n* (relative units) and radius *R* of ionized track in air from the time *t* [2].

As a result of diffusion, with time the width of columns increases and some part of ions recombines. In the end the diffusion process gives chaotic ion distribution. The ion density distribution is described by Gauss law decreasing from the maximum in the center of tracks to outside.

3. Effective Cross-Section of Air Ionization

The ionization rate of the atmosphere by cosmic rays $q(x)$ at different altitudes and latitudes is defined from the expression $q(x) = J(x, R_c)\cdot\sigma(x)\cdot N(x)$, where $J(x, R_c)$ is CR flux at atmospheric pressure level x (in g cm^{-2}) and latitude with the geomagnetic cutoff rigidity R_c, $\sigma(x)$ is effective cross-section of air ionization, $N(x)$ is concentration of air molecules.

The values of $\sigma(x)$ can be evaluated in the following way. It is known that in the atmosphere CRs represent the flux of relativistic single charged particles. In air such a relativistic particle loses 1.8 MeV g $^{-1}$ cm^2. In air to produce one ion pair it is necessary to spend ~ 35 eV. Near the ground level air density is $\rho \approx 1.24\cdot10^{-3}$ g cm^{-3}, $N(x) = 2.6\cdot10^{19}$ cm^{-3}. The number of electron-ion pairs produced by one relativistic single charged particle along the path of 1 cm equals to ~75. From the expression given above we can get that the value of σ is ~$2.5\cdot10^{-18}$ cm^2.

To find the values of $\sigma(x)$ as a function of atmospheric pressure x we have used the data obtained with ionization chambers in the atmosphere at different latitudes [3], [4]. From these data we have got the values of $q(x)$ and from our experiments we have the data on $J(x)$. Thus, using these two sets of data we can calculate the values of $\sigma(x)$ from the expression given above. In Fig. 5 the dependence $\sigma(x)$ as a function of x is shown for latitudes with different values of R_c.

It is worth to note that CR fluxes falling on the flat surface of 1 cm^2 and on the sphere surface with radius $r = (1/\pi)^{0.5}$ will differ in 2 times. So, to calculate the ionization rates $q(h)$ one needs to multiply the values of $J(h)$ by 2 because the values of $q(h)$ were obtained with spherical ionization chamber.

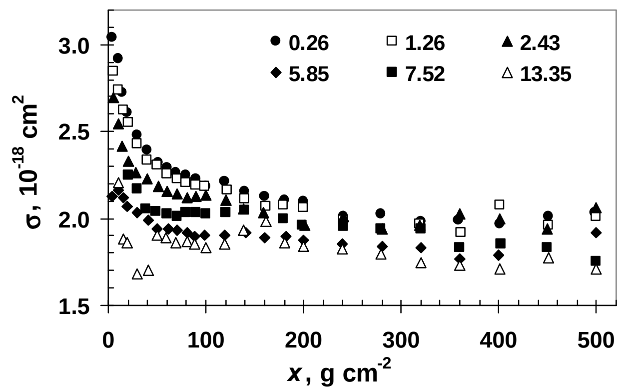

Fig. 5. The values of effective cross-section σ vs. atmospheric pressure x at the latitudes with different geomagnetic cutoff rigidities R_c (given in GV in the upper part of this figure).

It is seen that $\sigma(x)$ is almost constant and $\sigma(x) \approx 2\cdot10^{-18}$ cm^2 at all latitudes for $x > 50$ g/cm2. In the polar regions at $x < 50$ g cm^{-2} the value of $\sigma(x)$ increases as a result of the increase of ionization by helium nuclei and non-relativistic protons.

In Fig. 6 the values of $\sigma(x)$ are given for various phases of

11-year solar activity cycle. These values of σ(*x*) were derived from the data on ionization rates *q*(*x*) obtained by Neher in the polar atmosphere over the Thule station, Greenland, and from our data on *J*(*x*) obtained in the northern polar atmosphere in Murmansk region [1], [3]-[5].

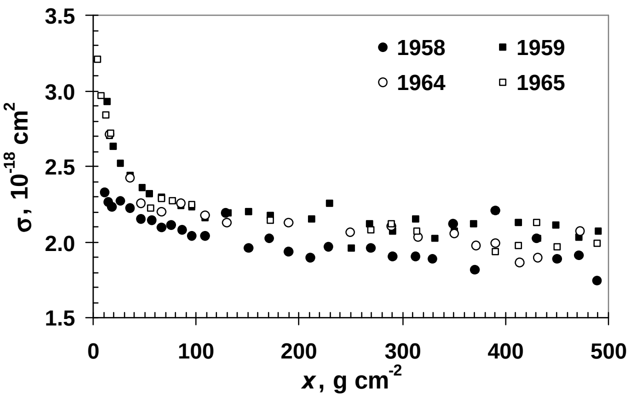

Fig. 6. The values of σ(*x*) in the polar regions vs. atmospheric pressure *x* in various phases of the 11-year solar activity cycle (1958, 1969 – solar activity maxima; 1964, 1965 - solar activity minima).

From Fig. 6 it follows that the value of σ(*x*) weakly depends on the solar activity level at $x > 50$ g/cm^2 and during solar activity minimum at $x < 50$ g/cm^2 the value of σ(*x*) increases.

Thus, at the low and middle latitudes in the interval of atmospheric pressure of $50 < x < 800$ g cm^{-2} the value of σ(*x*) is almost constant and equals to ~ $2 \cdot 10^{-18}$ cм^2. At the polar latitudes for $x < 50$ g cm^{-2} the value of σ(*x*) increases with the altitude increase.

4. Ionization Rate in the Atmosphere

The ionization rates *q*(*h*) are derived from the expression $q(x) = J(x, R_c) \cdot \sigma(x) \cdot N(x)$. The values of $J(x, R_c)$ were taken from our measurements, $\sigma(x) \approx 2 \cdot 10^{-18}$ cм^2. Below we have used altitude *h* instead of atmospheric pressure *x*.

The altitudinal profiles of experimental data on *J*(*h*) and calculated *q*(*h*) for polar, middle, and equatorial latitudes are shown in Fig. 7a, b. As is seen from Fig. 7b, the ionization rate *q*(*h*) increases in ~ 3 times in passing from equatorial to polar latitudes according to the increase of cosmic ray flux (Fig. 7).

CR fluxes shown in Fig. 7a are given for the square in the units of 1 cm^{-2} s^{-1}. The CR fluxes falling on this square and on the sphere surface with radius $r = (1/\pi)^{0.5}$ (see Fig. 7b) will differ in 2 times. So, to calculate the ionization rates *q*(*h*) one needs to multiply the values of *J*(*h*) by 2 because the values of *q*(*h*) were calculated for sphere with 1 cm^3 volume.

5. Ion Concentrations Produced by Cosmic Rays in the Atmosphere

The Central Aerological Observatory, Moscow, made the measurements of light ion concentrations in the atmosphere at different latitudes. The results of these measurements are shown in Fig. 8a. These data and data on CR fluxes in the atmosphere (see Fig. 8b) were analyzed jointly and an important result was obtained.

It was found that in the atmosphere the light ion balance equation has a linear form (not a quadratic one as it is generally agreed): $q(h) = \beta(h) \cdot n(h)$, where *q*(*h*) is the light ion production rate, *n*(*h*) is the light ion concentration, and β(*h*) is the coefficient of linear recombination of ions [6].

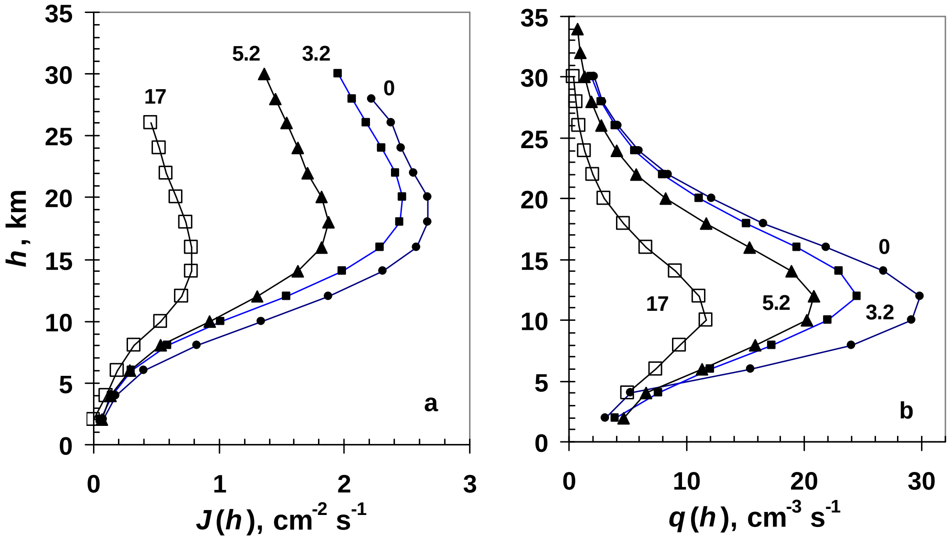

Fig. 7. On the left panel (a): altitudinal profiles of CR fluxes *J*(*h*); on the right panel (b): ion production rate *q*(*h*). The values of *J*(*h*) were measured at the several latitudes with different values of R_c (shown near each curve in GV) during the period of high solar activity level. The values of *q*(*h*) were calculated for the same latitudes. The values of R_c in GV are given near each curve.

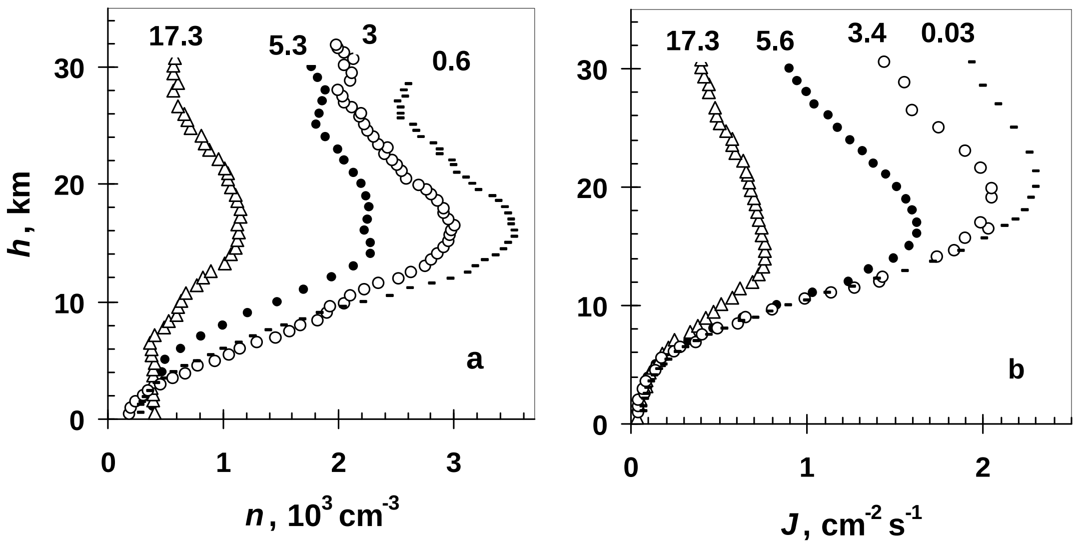

Fig. 8. Left panel (a): Altitudinal profiles of light ion concentrations *n*(*h*); Right panel (b): Altitudinal profiles of CR fluxes *J*(*h*) [6]. These data were obtained during solar activity maximum at the latitudes with different values of geomagnetic cutoff rigidities R_c (shown in GV near curves in the upper parts of each panel).

6. Conclusion

Cosmic ray fluxes are the main source of ionization in the atmosphere at the altitudes from the ground up to ~ 50 km.

From the altitudinal dependences of CR fluxes (Lebedev Physical Institute data) and ionization rates in the atmosphere (Neher data) the effective cross-sections of ionization were derived.

From the altitudinal dependences of CR fluxes and light ion concentrations (Central Aerological Observatory data) a linear relationship between ion production rate and ion concentration in air was found.

References

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