

Investigation into effect of cosmic radiation on microstructural parameters and optical properties of the lower atmosphere in middle and high latitudes.

Part 2. Heterogeneous processes under the effect of a flow of high-energy particles

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The effect of the flow of high-energy protons on the lower atmosphere is considered. The analytical equations are derived for the ionization rate of molecules and aerosol particles in the processes of both impact ionization and ambipolar diffusion. The ionization rate of aerosol particles is calculated for some cases. Variations of the optical depth are estimated for the atmospheric layer of 8–10 km. A good agreement between the calculated and observed values is achieved.

Introduction

The effect of high-energy particles of cosmic origin on the processes in the lower atmosphere is an important and, at the same time, poorly studied problem.¹ The most significant component of galactic (GCR) and solar (SCR) cosmic rays is high-energy protons (energy up to 1 GeV and higher). Solar flashes, one of the causes of solar proton events (SPE) or the polar top absorption (PTA), stimulate splashes of solar cosmic rays, during which flows of charged particles, as well as their energy increase by several orders of magnitude.

A correlation between SCR splashes and variations of some parameters of the lower atmosphere has been revealed in Refs. 2–5. It was found that the next day after an SCR splash the optical transparency of the atmosphere in the visible spectral range decreases by 6–10%, and variations of the vertical temperature profile are observed in the lower troposphere. In the authors' opinion, this is caused by the change in the atmospheric transparency. In Ref. 5, it was supposed that a cloud layer appears in the layer of 8–10 km as a consequence of the SCR splash. At the same time, the mechanisms of the processes leading to formation of the disperse phase of a cloud layer were not considered in that papers. In this paper, we discuss the mechanisms of formation of such a medium under the effect of high-energy particles and consider the conditions under which these processes are possible.

1. Formation of electric charge in an aerosol particle

One of the kinds of ionospheric disturbance is connected with penetration of high-energy particles into

the Earth's atmosphere, in particular, the SCR phenomenon. In this phenomenon, high-energy solar protons with the energy up to 1000 MeV and higher enter the Earth's atmosphere. In the framework of the earlier developed model,⁹ the equation relating the energy of primary protons E_{p0} and the residual mean free path ξ_m was obtained:

$$\xi_m = \frac{3E_{p0}^2}{2Q_0^p \ln(E_{p0}/E_i) [\ln(E_{e0}/E_i)]^{1/4}}. \quad (1)$$

Here Q_0^p is a constant in the cross section of the process of non-elastic losses of protons (it is calculated in Ref. 8); E_i is the energy of ionization of atmospheric molecules (it was taken to be equal to 15 eV), and $E_{e0} = 4(m_e/m_p) E_{p0}$ (m_e and m_p are the electron and proton masses, respectively). Using the model of the atmosphere and knowing ξ_m , one can calculate the minimum height h of penetration of the primary proton flow with the energy E_{p0} . The results of such calculation are shown in Fig. 1. As is seen from the figure, the energy of the primary proton flow E_{p0} should be higher than 800 MeV for the flow to penetrate to the height of 10 km. The magnetic field increases this energy approximately $\sqrt{\text{cosec}(\varphi)}$ times (φ is the angle between the direction of the flow and the vector of magnetic induction).

As the flow of fast protons passes through the atmosphere, it undergoes not only energy degradation, but also the change in the composition. The primary flow becomes a complex system of both protons p and other components formed due to interaction of the flow with molecules of the medium. Among these components, hydrogen atoms H and electrons e are most important. Thus, for solution of the formulated problem, the set of kinetic equations should be solved

for deriving the functions of distribution of the formed particles over velocities \mathbf{v} and coordinates \mathbf{r} for each component. The technique for solving the set of equations is considered in detail in Refs. 8 and 9. It is shown that as the flow penetrates into the atmosphere, the fractions of different components change essentially, and the principal component near the end of the mean free path is formed by secondary electrons.

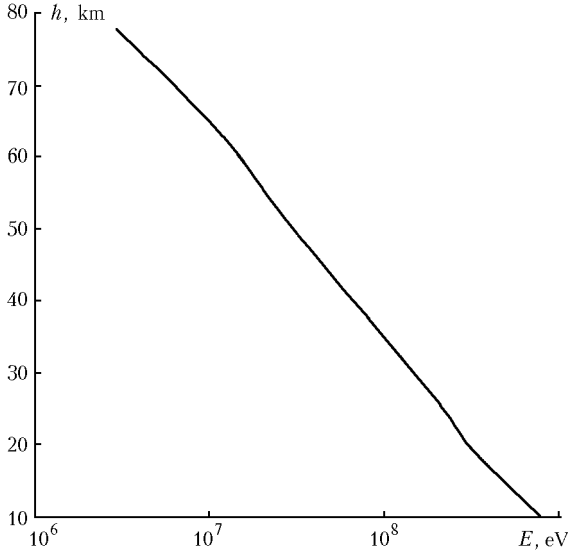


Fig. 1. Dependence of the maximum penetration depth of protons into the atmosphere h on initial proton energy E .

The energy distribution function of secondary electrons was calculated in Ref. 9 and has a complex form. Approximately, it can be presented as

$$f_e = \frac{I_0(E_{p0}) m_e^2}{4\pi E Q_e(E)} \Phi[E(\xi)] \frac{C}{E + E_i}, \quad (2)$$

where $I_0(E_{p0})$ is the flow of primary protons in the unit energy range (as measured from a satellite at the height $h_m \approx 300\text{--}500$ km),

$$E(\xi) = E_{p0} [(1 - (\xi/\xi_m)^{4/3})^{1/2}], \quad (3)$$

$$\xi = \int_h^{h_m} N_{\text{mol}}(h') dh', \quad (4)$$

$N_{\text{mol}}(h)$ is the concentration of molecules at the height h ;

$$\Phi[E(\xi)] \cong \frac{Q_0^p [E(\xi)] \ln[E(\xi)/E_i]}{E(\xi)}; \quad (5)$$

the constant C is approximately equal to the number e ; $Q_e(E)$ is the electron deceleration cross section. It is supposed that an aerosol particle can acquire the charge due to such processes as:

1) direct impact ionization of an aerosol particle at its collision with particles of one of the flow components;

2) ionization of atmospheric molecules and attachment of formed ions to a surface of an aerosol particle in the process of diffusion.

The rate of ionization at collision of an electron with a molecule is calculated as

$$z_i = \frac{8\pi N}{m_e^2} \int_{E_i}^{E_{c0}} E S_i f_e(E, \xi) dE, \quad (6)$$

where $S_i(E)$ is the cross section of direct ionization of a particle by electron impact. Let us assume that the ionization cross section of an aerosol particle is

$$S_i^a(E) = S_0,$$

where S_0 is the geometric area of the aerosol particle cross section (if the particle is shaped like a sphere of radius a , then $S_0 = \pi a^2$). The ionization cross section of atmospheric molecules was calculated by the equation

$$S_i^m(E) = \frac{Q_0^e \ln(E/E_i)}{E_i E} \left(1 - \frac{E}{E_i}\right), \quad (7)$$

where Q_0^e is the coefficient determined so that the ionization cross section calculated by Eq. (7) is in the closest agreement with the measured one.

Substituting Eqs. (2)–(5) into Eq. (6), we obtain the ionization rate of aerosol particles

$$z_i^a = 2C \frac{I_0 N_1 S_0 Q_0^p E_{c0} \ln \left[\frac{E_{p0}}{E_i} (1 - X^{4/3})^{1/2} \right]}{Q_0^e E_{p0} (1 - X^{4/3})^{1/2} \left[\ln \left(\frac{E_{c0}}{E_i} \right) \right]},$$

where N_1 is the number density of aerosol particles, N_{1a} is the value calculated from the equation

$$\int_{E_i}^{E_{c0} - 2E_i} \frac{dE}{\ln \left(\frac{E}{E_i} \right) \ln \left(\frac{E_{c0} - E}{E_i} \right)} = \frac{E_{c0}}{\left[\ln \left(\frac{E_{c0}}{E_i} \right) \right]^{n_1}}.$$

Taking into account that

1) aerosol particles have some size distribution $n(a)$ and their number density is

$$N_1 = \int_0^\infty n(a) da,$$

assuming that particles are spherical, we can calculate the product

$$N_1 S_0 = \pi \int_0^\infty n(a) a^2 da;$$

2) in the framework of the used model it is true that

$$Q_0^p \approx (m_p/m_e) Q_0^e$$

and, hence,

$$Q_0^p E_{c0} / (Q_0^e E_{p0}) \cong 4,$$

then we obtain

$$z_i^a = 8C \frac{I_0 N_1 S_0 \ln \left[\frac{E_{p0}}{E_i} (1 - X^{4/3})^{1/2} \right]}{(1 - X^{4/3})^{1/2} \left[\ln \left(\frac{E_{e0}}{E_i} \right) \right]^{n_1}}. \quad (8)$$

The ionization rate at collision of electrons with atmospheric molecules can be calculated by substituting Eqs. (2)–(5) into Eq. (7)

$$z_i^m = 2C \frac{I_0 N_{\text{mol}} Q_0^p [E(\xi)] \ln \left(\frac{E_{p0}}{E_i} \right) \left[\ln \left(\frac{E_{e0}}{E_i} \right) \right]^{n_2}}{E_i E_{p0}}, \quad (9)$$

where N_{mol} is the number density of atmospheric molecules. Taking into account that the ionization cross section of oxygen and nitrogen molecules are close to each other and that of atomic oxygen is approximately two times less, the value of N_{mol} was calculated as

$$N_{\text{mol}} = [N_2] + [O_2] + \frac{1}{2} [O].$$

The value of N_2 was calculated by the equation

$$\int_{E_i}^{E_{e0}-2E_i} \frac{dE}{(E + E_i) \ln \left(\frac{E_{e0} - E}{E_i} \right)} = \left[\ln \left(\frac{E_{e0}}{E_i} \right) \right]^{n_2}.$$

For the conditions under consideration, we can assume that

$$Q_0^p [E(\xi)] \cong Q_0^p = \text{const.}$$

The values of z_i^a and z_i^m were determined supposing that the primary proton flow is monoenergetic. Under actual conditions, the value of I_0 depends on E_{p0} , and in this case the total ionization (ion formation) rate at the height h can be calculated by the general equation

$$Z_i(h) = \int_{E_m}^{\infty} z_i(E_{p0}) dE_{p0}, \quad (10)$$

where E_m is determined by the equation

$$\xi(h) = \frac{3E_m^2}{2Q_0^p \ln \left(\frac{E_m}{E_i} \right) \left[\ln \left(\frac{4m_e E_m}{m_p E_i} \right) \right]^{1.4}}, \quad (11)$$

derived from Eq. (1) under the condition that

$$E_{p0} = E_m, \quad \xi_m = \xi(h).$$

Substituting Eqs. (8) and (9) into Eq. (10) we obtain

$$Z_i^a = 8C N_1 S_0 \times \int_{E_m}^{\infty} \frac{I_0(E_{p0}) \ln \left\{ \frac{E_{p0}}{E_i} \left[1 - \left(\frac{\xi(h)}{\xi_m} \right)^{4/3} \right]^{1/2} \right\} dE_{p0}}{\left[1 - \left(\frac{\xi(h)}{\xi_m} \right)^{4/3} \right]^{1/2} \left[\ln \left(\frac{4m_e E_{p0}}{m_p E_i} \right) \right]^{n_1}}, \quad (12)$$

$$Z_i^m = \frac{2C N Q_0^p}{E_i} \times \int_{E_m}^{\infty} \frac{I_0(E_{p0}) \ln \left\{ \frac{E_{p0}}{E_i} \left[1 - \left(\frac{\xi(h)}{\xi_m} \right)^{4/3} \right]^{1/2} \right\}}{\left[1 - \left(\frac{\xi(h)}{\xi_m} \right)^{4/3} \right]^{1/2} E_{p0}} \times \left[\ln \left(\frac{4m_e E_{p0}}{m_p E_i} \right) \right]^{n_2} dE_{p0}. \quad (13)$$

If the energy of primary protons exceeds 200 MeV, the differential energy spectrum of the primary flow can be approximately presented as

$$I_0(E_{p0}) = I_0 / (E_{p0})^\gamma. \quad (14)$$

Taking into account the above-said and substituting Eq. (14) into Eqs. (12) and (13), we have

$$Z_i^a = 8C N_1 S_0 \beta_a \ln \left(\frac{E_m}{E_i} \right) \frac{I_0(E_m) E_m}{(\gamma - 1)} \left/ \left[\ln \left(\frac{4m_e E_m}{m_p E_i} \right) \right]^{n_1} \right.,$$

$$Z_i^m = 2CN \frac{Q_0^p \ln \left(\frac{E_m}{E_i} \right) \left[\ln \left(\frac{4m_e E_m}{m_p E_i} \right) \right]^{n_2}}{E_i E_m} \times \beta_m \frac{I_0(E_m) E_m}{\gamma}, \quad (15)$$

where the numerically calculated coefficients β_a and β_m are close to unity.

The balance equations of particles (charged aerosol particles and molecular ions) have the form

$$\frac{dN_{1a}}{dt} = Z_i^a + \frac{N_i}{\tau_d}, \quad (16)$$

$$\frac{dN_i}{dt} = Z_i^m - \alpha N_i^2 - \frac{N_i}{\tau_d}, \quad (17)$$

where α is the loss coefficient (effective recombination coefficient); τ_d is the mean time of diffusion of molecular ions to the surface of an aerosol particle. The loss coefficient under the considered conditions is much larger than the effective recombination coefficient, and the number densities of positive and negative ions can be considered equal ($N_i = N_+ = N_-$). The value of τ_d can be approximately calculated by the equation

$$\tau_d = 4l^2 / D,$$

where l is the mean distance between aerosol particles,

$$l = N_1^{-1/3},$$

D is the diffusion coefficient of molecular ions. It was assumed that this coefficient is approximately equal to the coefficient of molecular diffusion, and, hence,

$$D = \frac{1}{3NS_{\text{tr}}} \sqrt{\frac{3RT}{\mu}},$$

where R is the universal gas constant, T is atmospheric temperature, μ is the mean molar mass, S_{tr} is the transport cross section of elastic collisions of molecules.

It should be noted that the given set of equations is valid only for the time interval when the number density n_i is stationary, the equilibrium value of n_i is still not achieved, and the number of aerosol particles carrying a charge increases (it is assumed that the nucleation time is long). On this assumption, Eq. (17) takes the form

$$Z_i^m - \alpha N_i^2 - N_i/\tau_d = 0. \quad (18)$$

Solving Eq. (18), we obtain the stationary number density of molecular ions

$$N_i = \frac{1}{2\alpha\tau_d} (\sqrt{1 + 4\alpha\tau_d^2 Z_i^m} - 1).$$

Upon substitution of the result into Eq. (16) and integration, we obtain

$$N_i = \left[Z_i^a + \frac{1}{2\alpha\tau_d} (\sqrt{1 + 4\alpha\tau_d^2 Z_i^m} - 1) \right] t.$$

Using the obtained equation, we can calculate the mean time, needed for formation of one charged particle in the unit volume:

$$t_{\text{mean}} = \left[Z_i^a + \frac{1}{2\alpha\tau_d} (\sqrt{1 + 4\alpha\tau_d^2 Z_i^m} - 1) \right]^{-1}.$$

It should be noted that the non-equality $Z_i^a \ll Z_i^m$ is fulfilled even for the maximum estimate of N_i as about 1000 cm^{-3} . Taking into account that $\alpha\tau_d^2 Z_i^m \ll 1$, we obtain

$$t_{\text{mean}} = 2/Z_i^m.$$

Obviously, on the above assumptions, most aerosol particles acquire a charge, if the time of the flow action

$$t \gg t_{\text{mean}}.$$

For calculation we used the energy spectra of protons from Ref. 10 (Fig. 2).

To facilitate the calculations, Eq. (15) was transformed, taking into account Eq. (11), to the form

$$Z_i^m = \frac{3C \beta_m N(h)}{E_i \xi(h)} \times \left\{ I_0(E_m) E_m^2 / \gamma \left[\ln \left(\frac{4m_e E_m}{m_p E_i} \right) \right]^{1.4-n_2} \right\}.$$

In this equation, the altitude dependence of the ionization rate enters only into the expression in braces, and it is related to the form of the energy spectrum by an analytical function. The calculated results on Z^m are shown in Fig. 3. From this figure it is seen that at the height of 8–10 km charged aerosol particles are formed

quite quickly not in all cases. Attention is drawn to the fact that charged aerosol in the most intense flow (see Fig. 2, curve 1, highest integral energy of the flow) is formed slowly (mean time about 10 s), whereas for the second and third spectra this time is 10^{-3} and 10^{-2} s, respectively.

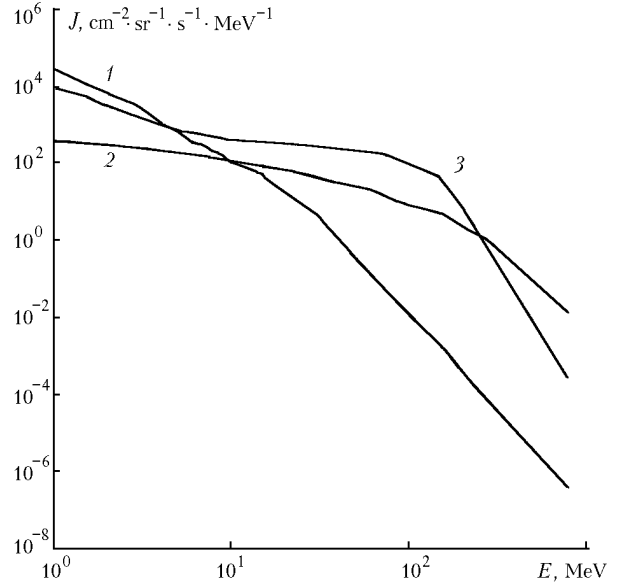


Fig. 2. Differential energy spectra of proton flow for the events on July 13, 1982 (curve 1), July 16, 1959 (curve 2), and August 4, 1972 (curve 3).

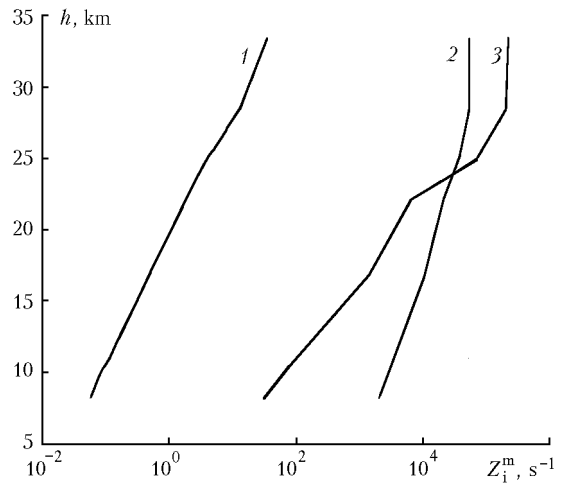


Fig. 3. Vertical distribution of the ionization rate Z_i^m for the events on July 13, 1982 (curve 1), July 16, 1959 (curve 2), and August 4, 1972 (curve 3).

2. Change of aerosol microstructure and optical properties at intense ejection of high-energy particles

In the quasi-steady equilibrium of aerosol particles and ions in the atmosphere and in the absence of cosmic

rays, the number density of charged, mostly with a unit charge, aerosol particles at the heights of 8 to 15 km at low relative humidity ($f \leq 20\%$) does not exceed 300 cm^{-3} for Aitken nuclei and 0.5 cm^{-3} for coarse aerosol particles ($a \geq 0.1 \text{ }\mu\text{m}$). The particle size increases due to the effect of the electric charge on the diffuse inflow of water vapor (or sulfurous gas) only for particles with $a < 0.05 \text{ }\mu\text{m}$. The time needed for a particle of the size a_0 to grow roughly from 0.01 to $0.02 \text{ }\mu\text{m}$ is about 10^5 s . As compared to the aerosol extinction by an aerosol system of non-charged particles, the extinction by charged particles changes due to this process by no more than 10^{-4} km^{-1} . Even assuming the effective depth of this aerosol layer to be equal to 5 km, we obtain the change of the optical depth $\Delta\tau_a \leq 5 \cdot 10^{-4}$.

Injection of high-energy particles leads to charging practically all aerosol particles, and the charges acquired by aerosol particles exceed that acquired by them in the atmosphere not disturbed by cosmic rays. This intensifies the flow of vapor molecules on a charged particle (the effective radius of the sphere increases).

This effect affects only the growth of aerosol particles up to $a \approx 2 - 5 \cdot 10^{-2} \text{ }\mu\text{m}$. This gives the maximum increase $\tau_a \approx 1.5 \cdot 10^{-3}$ if all background aerosol particles present at the heights from 8 to 15 km are charged by cosmic particles. However, this is insufficient for explanation of the effect observed by a number of investigators, in particular, in Refs. 2–5.

The increasing efficiency of coagulation of charged aerosol particles can essentially affect the increase of the aerosol optical depth, if the initial number density of charged particles is significantly greater than the background one ($N_a > 10^3 \text{ cm}^{-3}$) and the particles are polydisperse ($a_{i \text{ max}}/a_{j \text{ min}} \gg 1$). Then the characteristic time of coagulation t_{coag} is about 10 s and shorter, and the aerosol optical depth τ_a of the layer increases by $\Delta\tau_a \approx 5 \cdot 10^{-3} - 2 \cdot 10^{-2}$, i.e., the value close to the observed effect.

Obviously, the aerosol particle size must increase most strongly at increased relative air humidity, in the presence of vapor of condensing gases that chemically transform to the condensate (sulfur and nitrogen oxides). Such conditions occur after volcanic eruptions.

The concentration of charged aerosols can also increase significantly at interaction of high-energy particles with large and giant aerosol particles. In this case, the charge can achieve $100e$ or even more for particles with $a > 0.1 \text{ }\mu\text{m}$.

Formation of crystal nuclei at bombardment of aerosol particles by high-energy charged particles (causing the increase of the number of aerosol particles by an order of magnitude or more) was experimentally modeled by Avdiev for the mesospheric conditions.¹⁴ We can assume that the similar process takes place at lower heights as well. In this case, crystallization growth of particles occurs with transition of water vapor from liquid droplets^{12,13} to ice crystals at the temperature 20°C higher than the freezing point (Refs. 6 and 7).

Hence, we can conclude that charging aerosol particles in the upper troposphere and stratosphere leads to formation and growth of an ice cover. This process is most efficient for particles with $a < 0.1 \text{ }\mu\text{m}$ (Ref. 14).

Obviously, ambiguity and wide variety of conditions occurring in the atmosphere require transformation of the aerosol microstructure to be considered and calculated for simplified model cases.

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