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ELECTRODE EFFECT AS AN EARTHQUAKE PRECURSOR

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The authors propose a mechanism for the formation of an anomalous electric field by the ionization of the near-surface air layer. Such an ionization is caused by radon-daughter small ions and submicron metal aerosols released from the Earth's seismoactive zones.

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1. Vertical electrostatic field disturbances of $50-150\,\mathrm{V\cdot m^{-1}}$ near the Earth's surface are often observed before earthquakes and major volcanic eruptions. Before strong earthquakes, such disturbances may reach $1000\,\mathrm{V\cdot m^{-1}}$. Specifically, the authors of [1,2] pointed out an unusual electric field behavior, in particular, a decrease or even sign reversal of the vertical field several hours before strong earthquakes. On the other hand, anomalous variations in the electron density, temperature, and composition arise in higher atmosphere and ionosphere (at altitudes of 60–200 km, i.e., within D, E, and F regions) also before strong earthquakes [3–6]. These effects are attributed to variations in the electric potential gradient and conductivity of the near-surface atmosphere. Thus, we encounter an urgent problem of accounting for anomalous electric field behavior near the Earth's seismoactive zone before earthquakes.

Earthquake epicenters are usually located near crust fractures, where considerable amounts of metal aerosols, such as Cu, Fe, Ni, Zn, Pb, Co, Cr, etc. [7], as well as radon which is the main source of α particles, are emitted into the near-surface atmosphere layer. The radioactive ^{238}U, ^{235}U, and ^{232}Th decay in the crust results in the formation of radon isotopes, including $^{222}_{86}$Rn, thoron $^{220}_{86}$Rn (Tn), and action $^{219}_{86}$Rn (An). Produced in the crust, these isotopes diffuse into the atmosphere. The radon emanation flow from the soil to the atmosphere is approximately two orders of magnitude higher than that for thoron. Therefore, radon and its secondary products provide the most contribution to the air ionization near the Earth's surface. However, since the halftime of radon isotopes decay is small (3.83 days at most), a considerable concentration of ions is observed above the crust faults and uranium-containing rocks. Each ^{222}Rn α-particle with a mean energy of $E_\alpha = 6$ MeV can theoretically produce about $2\cdot10^5$ electron–ion pairs. According to the experimental data [8], the radon yield before an earthquake can reach 12 emans which corresponds to the ionization rate $Q_0 \simeq 7.6\cdot10^3\,\mathrm{cm^{-3}\cdot s^{-1}}$.

In this paper, we propose a mechanism of the electric field formation in the lower atmosphere induced by radon and metal aerosols emanation from the Earth's crust faults.

2. Initially, radiation generates a great number of O_2^+ ions in the near-surface atmosphere. This process occurs through both direct ionization and recharging of primary N_2^+ ions,

$$N_2^+ + O_2 \rightarrow O_2^+ + N_2,$$

and electrons, which rapidly attach to oxygen atoms, because these are characterized by a high affinity to electrons. The relevant three-body reaction most probable in the dense lower atmosphere is written as

$$e + O_2 + O_2 \rightarrow O_2^- + O_2,$$

where an oxygen molecule is involved as the third body. The efficiency of nitrogen molecules is lower by a factor of 40 in this case. Free electrons also attach to metal atoms released from the faults to form negative ions. Negative metal ions with closed electronic shells are characterized by the highest affinity energy.

Thus, primary free electrons, as well as positive and negative elementary ions arise in the near-surface air. Then various ion–molecular reactions take place. The characteristics time of these reactions is of the order 10^{-5} s, resulting in a stable content of elementary ions in the lower atmosphere [9,10]. Since the troposphere contains a tremendous concentration of water-vapor molecules (about $10^{17}\,cm^{-3}$) with a noticeable dipole moment $p_{H_2O} = 1.87\,D$, elementary ions rapidly hydrate to produce ion complexes, such as $CO_3^- \cdot (H_2O)_n$, $NO_3^- \cdot (H_2O)_n$, $H_3O^+ \cdot (H_2O)_m$, and $HN_4^+ \cdot (H_2O)_m$. The values $n = 2-3$ and $m = 3-6$ are typical for the troposphere, and the lifetimes of these complexes may reach several hours [11]. Numerical simulations with real contents of impurity gases indicate that even more complicated structures, for instance, $NO_3^- \cdot (HNO_3)_n \cdot (H_2O)_m$ and $HSO_4^- \cdot (H_2SO_4)_n \cdot (H_2O)_m$, can be produced in the troposphere [12].

3. On the average, the negative ion mobility is 1.3–1.4 times higher than that of positive ions. Apparently, this difference can be attributed to an asymmetrical arrangement of oppositely charged ions, related to the oxygen atom in the water molecule. Consequently, negative ions are characterized by a lower energy, i. e., by a smaller number of attached water molecules, than positive ions [13]. Based on the ion classification [11], we can assign the considered ion complexes to the class of small or intermediate ions with mobilities of $0.05-5\,cm^2 \cdot (V \cdot s)^{-1}$.

Thus, due to the difference in mobilities of oppositely charged ions, the atmospheric electric field E under certain conditions may induce an uncompensated space charge near the Earth's surface.

Let us consider a simplified model of this effect in the case of weak turbulent diffusion, e. g., in early morning, when a radioactive gas cloud spreads within a thin near-surface layer where ions are produced (Fig. 1). In the electric field E, positive ions move toward the Earth's surface, where they recombine. However, for a low mobility, these ions produce a near-surface layer within a certain time. Meanwhile, negative ions move upward (within the model, we neglect electrons near the Earth's surface because of their small concentration [9]). The near-surface electrode layer induces a local field E_l which compensates for the main field. In other words, within the layer, the field decreases and, under definite conditions, can even reverse its sign. Due to a considerable uncompensated negative charge, the field is enhanced above this layer [14].

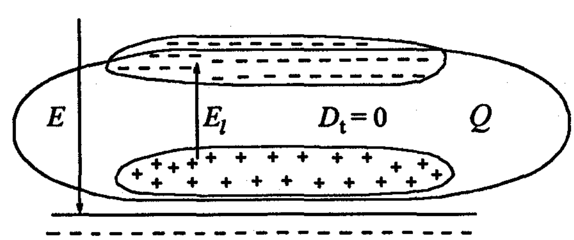

Figure 1. Positive and negative space charges near the Earth's surface.

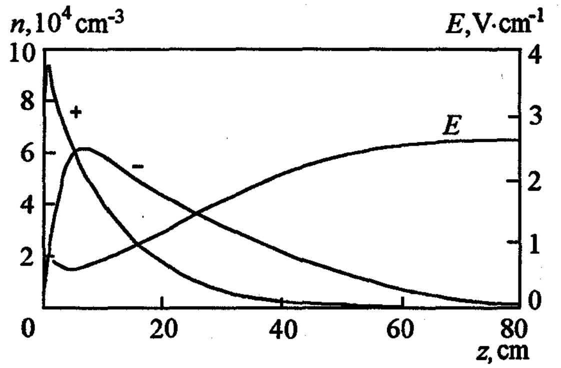

Figure 2. Concentrations n of positive (+) and negative (−) ions and the electrostatic field E as functions of the altitude z near the surface 50 s after the radon emanation onset. The mobilities of negative and positive ions are $b_- = 3.8 \cdot 10^{-1}\,\mathrm{cm^2 \cdot (V \cdot s)^{-1}}$ and $b_+ = 2.4 \cdot 10^{-1}\,\mathrm{cm^2 \cdot (V \cdot s)^{-1}}$, respectively; $D_+ = 2.8 \cdot 10^{-2}\,\mathrm{cm^2 \cdot s^{-1}}$ and $D_- = 4.3 \cdot 10^{-2}\,\mathrm{cm^2 \cdot s^{-1}}$ at weak turbulent diffusion ($K = 0.1\,\mathrm{m^2 \cdot s^{-1}}$) and $h = 10$ cm.

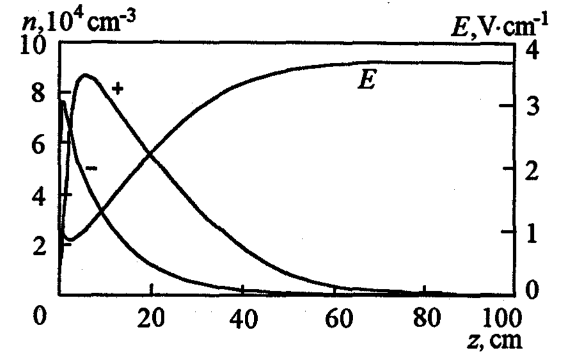

Figure 3. Concentrations n of positive (+) and negative (−) ions and the electrostatic field E as functions of the altitude z near the surface 30 s after the radon emanation onset with the additional flow of metal aerosols from the Earth's surface.

In this model, we assume that the time required to recover the near-surface charge density is much less than the characteristic times of other atmospheric processes. Therefore, we assume this charge density to be constant. As a consequence, an uncompensated space negative charge is produced. Turbulent and regular air flows can spread this space charge over the atmosphere to form an anomalous electrode layer over vast areas. Actually, such a situation seems to occur only within a short time, because air flows eventually destroy the electrode layer by mixing ions.

Let us write the kinetic equations of such a system

$$\frac{\partial n_+}{\partial t} = \frac{\partial}{\partial z}\left[(D_t + D_+)\frac{\partial n_+}{\partial z}\right] - b_+\frac{\partial}{\partial z}(E n_+) + Q - \alpha n_+ n_- ,$$

$$\frac{\partial n_-}{\partial t} = \frac{\partial}{\partial z}\left[(D_t + D_-)\frac{\partial n_-}{\partial z}\right] + b_-\frac{\partial}{\partial z}(E n_-) + Q - \alpha n_+ n_- ,$$

$$\frac{\partial E}{\partial z} = 4\pi e\,(n_+ - n_-).$$

Here, e is the electron charge; z is the vertical coordinate (we assume that the "capacitor" is infinite in the horizontal plane to consider a one-dimensional problem); $n_\pm$ are the concentrations of positive and negative ions; Q is the ionization rate (we assume that the spatial distribution of the ionization rate due to radon emanation exponentially decays with the altitude, $Q = Q_0 e^{-z/h}$, where h is the ionization layer thickness); $b_\pm$ and $D_\pm$ are the mobility and diffusivity of the relevant ions; $D_t(z) = (Kz + \gamma)/(z + \beta)$ is the turbulent diffusivity [17], where $\beta = 10.0$ m, $\gamma = 5 \cdot 10^{-5}\,\mathrm{m^3 \cdot s^{-1}}$, and K is the turbulence coefficient; and $\alpha \simeq 10^{-6} - 10^{-7}\,\mathrm{cm^3 \cdot s^{-1}}$ is the ion recombination coefficient [9].

The boundary conditions for the field near the Earth's surface and on the upper border of the considered layer are specified as $E_{z=0} = 100\,\mathrm{V \cdot m^{-1}}$ and $\left.\frac{\partial E}{\partial z}\right|_{z=\infty} = 0$. The initial concentrations of positive and negative ions are set equal to the background level (approximately $450\,\mathrm{cm^{-3}}$).

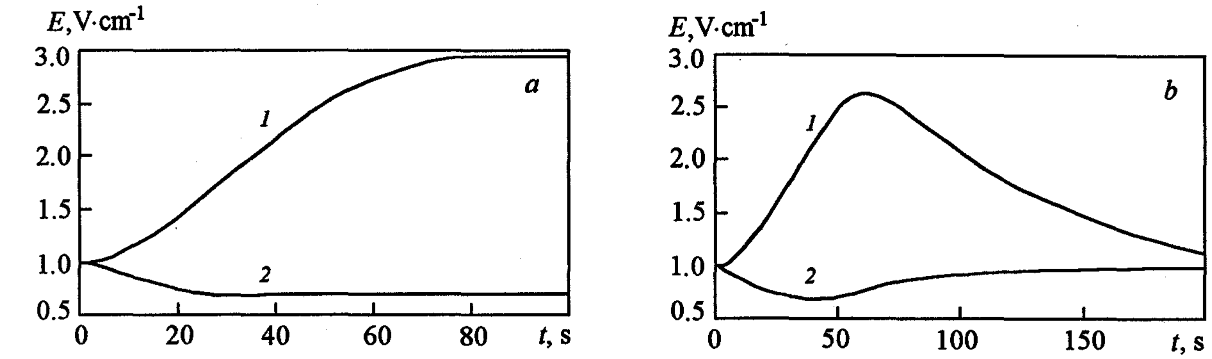

Figure 4. Time evolution of the near-surface electrostatic field at an altitude of (*1*) 60 and (*2*) 3.5 cm: (*a*) permanent ion formation (*b*) time of ion formation is 50 s.

Figure 2 displays the results simulated within the above model. This figure shows the concentrations of positive and negative ions and the electrostatic field as functions of the altitude near the surface 50 s after the ionization (radon emanation) onset. The plots clearly demonstrate the formation of a near-surface electrode layer. The electric field decreases in this layer and noticeably increases above it. This effect is enhanced due to the increased ion mobility and diffusion.

Obviously, various fine impurities in the atmosphere influence the final ion composition, mainly the composition of light negative ions. For example, having the electron affinity energy even higher than that of nitrogen oxides, these impurities may displace the latter from the base of complex ions and become central ions in $M^- \cdot (H_2O)_n$ complexes. Metal aerosols released by faults are characterized by a considerable electron affinity and can serve as a base for negative ion complexes, thus appreciably increasing the negative ion concentration. This effect may be especially important before strong earthquakes, when the aerosol release can be enhanced by up to 1.5 orders of magnitude [7,8].

Figure 3 shows the results of relevant simulations. As is seen from this figure, the space negative charge appreciably increases due to negative ions based on metal aerosols. This charge enhances the field above the electrode layer. However, the layer field decreases to a lower degree.

Figure 4*a* displays the field change at the altitude corresponding to the maximum effect (3.5 cm) and at the altitude above the uncompensated negative charge (60 cm). As is seen from the figure, the process for the anomalous field is stabilized within about 40 s (curve *2*).

We should take into account that ions of one sign are removed by an external field E from the ionization area. Since recombination occurs through the collision of two ions with opposite signs, this process is decelerated and ions are accumulated, which may, in turn, enhance the effect under study.

Figure 4*b* shows the time dependence of the field change for two altitudes under conditions when the ionization is switched off within 50 s after its onset. As is seen, the natural electric field is recovered at a slower time scale and takes more than 200 s.

4. The considered natural formation of atmospheric earthquake precursor can be successfully modeled by techniques such as an artificial atmosphere ionization [15] and by changes in the atmosphere that accompany nuclear weapon tests [16]. In experiments on artificial ionization, the field decreased as X-ray emitters were switched on. The initial field was recovered within 0.5–1.0 min (Fig. 5). The field decrease was observed at considerable distances (up to 1 km) from the emission point. When the X-ray source was switched off, the field slowly (during 5–10 and sometimes 20–40 min) recovered its normal state. Such a low rate of the process can be accounted for by the existence of a long-lived space negative charge, while the positive charge is rapidly neutralized by the Earth's

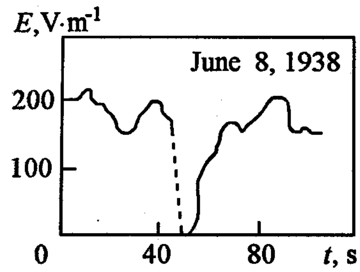

Figure 5. Variation in the electric field E recorded by a Benndorf electrograph during the near-surface air ionization with X-rays (dashed line) and in the absence of X-rays (solid line) [15].

surface [15]. In the case where the electric field is measured in the area of underground nuclear weapon tests, analogous processes are observed: the field drastically decreases at the explosion and then slowly recovers its normal strength (Fig. 6). The near-surface layer is ionized in this case by fission fragments emerging from the soil.

5. The reported results give new explanations of the formation of an atmospheric anomalous electric field near a forthcoming earthquake epicenter. These results allow the following conclusions.

(i) Hypotheses [3,4] concerning the dominant role of radon and metal aerosols in the anomalous electric field generation in a forthcoming earthquake area are theoretically substantiated.

(ii) Since the observed height distribution of the anomalous electric field is nonuniform, it is necessary to modify the procedure for the vertical electric field measuring in seismoactive areas by arranging a few electric field detectors at various altitudes.

(iii) The results of our analysis provide a background for simulating the effects associated with the ionospheric anomalous electric field and for identifying the mechanisms responsible for the generation of seismo-ionospheric earthquake precursors.

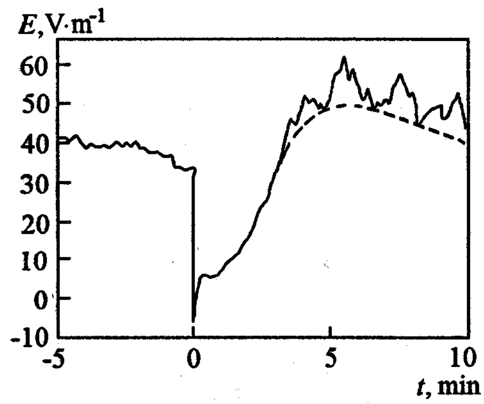

Figure 6. Variation in the electric field E for the nuclear explosion at a distance of 7.8 km [16].

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