ISSN 1063-780X, Plasma Physics Reports, 2007, Vol. 33, No. 2, pp. 138–145. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © Yu.N. Besedina, S.I. Popel, 2007, published in Fizika Plazmy, 2007, Vol. 33, No. 2, pp. 159–167.

SPACE PLASMA

# Nano- and Microscale Particles and Global Electromagnetic Resonances in the Earth–Ionosphere Cavity

**Yu. N. Besedina and S. I. Popel**

*Institute of Geosphere Dynamics, Russian Academy of Sciences, Leninskiĭ pr. 38-1, Moscow, 119334 Russia*

Received April 5, 2006

**Abstract**—The influence of nano- and microscale particles (dust grains) on the global electromagnetic (Schumann) cavity has been studied in the context of two possible mechanisms. First, the presence of charged microscale particles in the ionospheric plasma modifies the dispersion properties of the upper boundary of the Schumann cavity and, thus, affects its eigenfrequencies and quality factor. Second, there is a relation between the dust concentration in the atmosphere and lightning discharges, which excite Schumann resonances. Therefore, dust grains can enhance the energy pumping of the cavity, thereby increasing the amplitude of electromagnetic oscillations in it.

PACS numbers: 52.27.Lw, 94.20.-y, 92.60.Kc, 92.70.Bc, 91.40.Dr

**DOI:** 10.1134/S1063780X07020079

## 1. INTRODUCTION

In recent years, processes in dusty (complex) plasmas have received much attention [1–3], primarily because of their widespread occurrence in nature. Charged dust grains are present in planetary magnetospheres and ionospheres, atmospheres of comets, and interstellar medium. Many investigations have been devoted to natural processes involving nano- and microscale particles [4]. In the Earth's atmosphere, dust from natural and anthropogenic sources is present at different altitudes. In the near-Earth layer, this is anthropogenic dust, mineral aerosols, ice and snow grains, sea salt, volcanic dust, and organic microscale particles. Anthropogenic particles include industrial dust and soot (with grains larger than 1 μm), as well as submicrometer sulfate and nitrate grains and anthropogenic organic molecules. Sea-salt and mineral aerosols and volcanic dust grains are, as a rule, larger than one micrometer in size, whereas the sizes of natural sulfate and nitrate grains are less than 1 μm. The dust can ascend to the stratosphere and ionosphere in the course of violent volcanic eruptions, rocket launchings, and high-altitude flights and also as a result of convective processes [1, 5, 6]. Into the ionosphere, microscale particles get due to the bombardment of the Earth by micrometeorites, which are burnt in the upper part of the middle atmosphere, at altitudes of 80–100 km. The dust present in the mesosphere and lower ionosphere manifests itself in the form of noctilucent clouds, polar mesospheric summer echoes, and meteorite traces [1, 7]. In the ionosphere, dust grains are charged due to photoelectric effect and the absorption of electrons and ions from the surrounding plasma. Therefore, the plasma of the dusty ionosphere can be considered as a dusty (complex) plasma [1, 7]. This also concerns the plasma of lightning discharges containing nano- and microscale particles. In the present paper, we consider the influence of nano- and microscale particles occurring at different altitudes on the characteristics of electromagnetic oscillations in the Schumann cavity (SC).

Schumann resonances (SRs) represent global electromagnetic oscillations excited by lightning discharges in a concentric spherical cavity formed by the Earth's surface and the lower ionosphere [8]. About one hundred lightning discharges per second occur in the Earth's atmosphere. As a rule, four or five first resonance peaks are recorded. The peak frequencies vary within several tenths of a hertz near frequencies of about 8, 14, 20, and 26 Hz.

The propagation of VLF and ULF electromagnetic waves in the Earth–ionosphere cavity is of interest from the standpoint of investigating the lower ionosphere, radio wave propagation, sources of electromagnetic radiation, and resonance phenomena. The fact that the eigenfrequencies of the cavity depend on the electromagnetic properties of its walls allows the ionosphere to be investigated by analyzing SRs. Interest in SRs increased in the early 1990s, after it had been found that they can be used as a global tropical thermometer [9]. SRs are stable, rather long, global oscillations, which represent the typical natural daytime background of the biosphere. They are also of interest because their frequencies fall within the range of eigen oscillations of the brain biocurrents, specifically, the alpha (8–13 Hz) and beta (13–30 Hz) rhythms, and, therefore, may be of biological significance [10]. SRs can also be observed on other planets, in particular, on Mars, where they can be excited by electric discharges in dust storms or as a result of geological activity [11].

It is of considerable interest to investigate the influence of nano- and microscale particles, which are present in all of the atmospheric regions, on the SC parameters. First of all, the presence of dust affects thunderstorm activity, which is the source of SRs. Thunderstorm activity is related to the processes of charge separation in clouds and the accumulation of dust particles in the atmosphere. Second, charged nano- and microscale particles can substantially modify the dispersion properties of the plasma [1–3]. A change in the dielectric permittivity of the ionospheric plasma can alter the properties of the SC. The influence of nano- and microscale particles on the SC parameters has not yet been studied.

The paper is organized as follows. In Section 2, basic relations describing SRs are presented. In Section 3, the relation between global electromagnetic oscillations and the presence of nano- and microscale particles in the Earth–ionosphere cavity is discussed and the influence of these particles on the dispersion properties of the ionosphere and the SC parameters is considered. In Section 4, we discuss the results obtained. Finally, in the Conclusions, the main results of this study are summarized.

## 2. BASIC RELATIONS FOR SCHUMANN RESONANCES

The equations describing SRs can be derived in a standard way [12]. The basic equations are Maxwell's equations in spherical coordinates. The boundary conditions correspond to the zero tangential component of the electric field on the Earth's surface and continuous tangential components of the electric field **E** and magnetic field **H** on the cavity–ionosphere interface ($r = b$, where $b$ is the distance between the Earth's center and the lower boundary of the ionosphere). Moreover, the emission condition at $r > b$ is imposed, which means that, in this region, there are only waves propagating away from the lower boundary of the ionosphere, while waves arriving from infinity are absent.

In order to estimate the quality of the cavity, it is necessary to take into account the finite conductivity of the ionosphere and its dispersion properties (in this case, the approximation of a perfectly conducting Earth's surface is quite appropriate). In the simplest model of a homogeneous cavity [12], the dielectric permittivity is described by the formula

$$\varepsilon(r) = \begin{cases} 1, & \text{for} \quad a \le r \le b, \\ \varepsilon, & \text{for} \quad r \ge b, \end{cases} \tag{1}$$

where $a$ is the Earth's radius and $\varepsilon$ is the dielectric permittivity of the lower ionosphere (which is assumed to be homogeneous and isotropic).

The properties of the medium are taken into account through the dielectric permittivity $\varepsilon(\omega, r)$, entering into the equation $\mathbf{D} = \varepsilon(\omega, r)\mathbf{E}$.

In spherical coordinates, the basic equation determining the eigenfrequencies and quality of the SC has the form

$$k_n a \approx \left\{ n(n+1)\left[1 - \frac{b-a}{a}\right] - \frac{Z^2}{4}\frac{a^2}{(b-a)^2} \right\}^{1/2} + \frac{iZ}{2}\frac{a}{b-a}, \tag{2}$$

where $Z \equiv 1/\sqrt{\varepsilon}$, $k_n = \omega_n/c$, and $\omega_n = 2\pi f_n$. The quality is defined by the formula $Q_n = \mathrm{Re} f_n/2\mathrm{Im} f_n$. Equation (2) implies that the resonant frequency $f_n$ has a real and an imaginary part.

The quality can be estimated by the approximate formula $Q_n \approx 2V/(dS)$ [13], where $V$ is the cavity volume, $S$ is the surface area of the ionospheric wall, and $d = \mathrm{Im}(1/(k_n\sqrt{\varepsilon}))$ is the skin depth.

The dielectric permittivity of a homogeneous isotropic ionosphere is defined as

$$\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega(\omega - i\nu_{\mathrm{eff}})}, \tag{3}$$

where $\omega_{pe}$ is the electron plasma frequency, $\omega$ is the SR frequency, and $\nu_{\mathrm{eff}}$ is the frequency characterizing the dissipation rate in the system (in the absence of dust, this rate is determined by electron–neutral collisions). The presence of charged dust can change the dissipative properties of the lower ionosphere. To find the parameters of the cavity, it is necessary to determine $\varepsilon$ for a homogeneous isotropic dusty ionosphere.

Let us consider forced oscillations in the SC [12]. Since the impedance of the ionosphere in the frequency range under study is low (on the order of $10^{-2}$), we can employ the perturbation method. We denote by $\mathbf{E}_{nm}$ and $\mathbf{H}_{nm}$ the normalized fields of a perfect cavity (a cavity bounded by perfectly conducting walls); by $\omega_n$ the resonant frequencies of the perfect cavity; and by **E**, **H**, and $\omega$ the corresponding parameters of the actual cavity. We expand the fields **E** and **H** in the complete orthonormal system of the basis functions $\mathbf{E}_{nm}$ and $\mathbf{H}_{nm}$,

$$\mathbf{H} = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \alpha_{nm}\mathbf{H}_{nm}, \qquad \mathbf{E} = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \beta_{nm}\mathbf{E}_{nm}. \tag{4}$$

Integrating the system of Maxwell's equations over the volume with allowance for the currents **j** and the boundary conditions, we obtain a set of equations, which, in the case of a homogeneous isotropic cavity, yields (hereafter, we are interested only in the electric component of the cavity field)

$$\alpha_{nm} = -\frac{\omega_n J_{nm}}{\omega_n^2 + \frac{ic}{b-a}\omega Z(\omega) - \omega^2}, \quad (5)$$

where $J_{nm} = 4\pi i \int_V \mathbf{J}(\mathbf{r}) \cdot \mathbf{E}^*_{nm} dV$ is the function of the field sources, $\mathbf{J}(\mathbf{r}) = \int_{-\infty}^{\infty} \mathbf{j}(\mathbf{r}, t) e^{-i\omega t} dt$ is the Fourier component of the field source, and $Z(\omega)$ is the impedance of the ionosphere.

Let the source of oscillations be a thunderstorm center. We represent it as a vertical electric dipole with the current moment $M$, which is defined as the integral of the discharge current over altitudes. We choose the spherical coordinate system in such a way that the source is situated at the pole ($r = a$, $\theta = 0$). Substituting expression (5) into the second of Eqs. (4), we obtain the expression for the electric field of this dipole,

$$E_r \propto \frac{M(\omega)\nu(\nu+1)}{\omega(b-a)a^2}\left[\frac{P_\nu(-\cos\theta)}{\sin\nu\pi}\right]. \quad (6)$$

This formula implies that, for a solitary discharge, the SR amplitude is proportional to the current moment of the discharge, $E \propto M(\omega)$. Each $i$th discharge supplies the SC with an energy proportional to $E_i^2$, so the energy supplied by $n$ discharges is proportional to $nM^2$.

## 3. INFLUENCE OF NANO- AND MICROSCALE PARTICLES ON THE PARAMETERS OF SCHUMANN RESONANCES

Let us consider possible mechanisms for the influence of nano- and microscale particles in the atmosphere on the SC parameters.

SRs are mainly excited by vertical (cloud-to-ground and intracloud) thunderstorm lightnings. The length of lightning is typically several kilometers. Lightning usually develops in two stages. It starts as a leader, which propagates from a cloud to the ground along the path corresponding to the maximum field strength or the maximum number density of water drops. After the leader reaches the Earth's surface, the main stage of lightning—the return stroke—begins. Lightnings most often occur in cumulonimbus clouds; however, they can also occur during snow or sand storms, volcanic eruptions, earthquakes, and even nuclear explosions [12]. At middle latitudes, the height of a thundercloud is 8–12 km, whereas in tropical regions, it can reach 20 km. Clouds form in regions dominated by intense convective processes. The electric charges are separated due to the motion of cloud particles (ice, snow, and aerosols) relative to one another. When the electrostatic field strength reaches the breakdown value, a thunderstorm discharge occurs. Thus, a change in the parameters and number density of dust grains in the atmosphere can affect the intensity of thunderstorms.

The SC upper boundary is located in the ionosphere. Nano- and microscale particles can be present there due to meteorite bombardment, violent volcanic eruptions, or convective particle transfer from the lower atmosphere. Dust grains in the ionosphere are charged due to microscopic electron and ion currents to them, photoelectric effect, collisions with other grains, and so on. Charged nano- and microscale particles substantially enhance the dissipative properties of the system [2]. Thus, the presence of dust grains in the lower ionosphere can influence the SC quality, which characterizes the efficiency of energy supply to the cavity and its dissipative properties.

### *3.1. Eigenfrequencies and Quality of the SC*

The eigenfrequencies and quality of the SC are mainly influenced by processes involving nano- and microscale particles in the ionosphere. Charged dust in the ionospheric plasma provides new dissipation mechanisms, such as charging of dust grains, absorption of electrons and ions by them, and transfer of the electron and ion momentum to a dust grain due to absorption and Coulomb scattering of plasma particles (electrons and ions) by the grain. Microscopic electron and ion currents to dust grains can be calculated using the orbit-limited model [1, 2, 14, 15]. In this model, cross sections for the interaction of ions and electrons with a charged dust grain are determined from the conservation laws of energy and angular momentum. The condition for the electron and ion currents to a dust grain to be equal to one another determines its equilibrium charge, while the equation of the dynamic charging of a grain yields the charging frequency, which characterizes the time during which the grain charge relaxes to its equilibrium value.

The set of linearized hydrodynamic equations for a plasma consisting of electrons, ions, and dust grains has the form [2]

$$
\begin{aligned}
&(i\omega + \bar{\nu}_e)\frac{\delta n_e}{n_e} - i(\mathbf{k}\cdot\mathbf{u}_e) + \bar{\nu}_e\frac{\delta n_d}{n_d} = -\delta\bar{\nu}_e,\\
&(i\omega + \bar{\nu}_i)\frac{\delta n_i}{n_i} - i(\mathbf{k}\cdot\mathbf{u}_i) + \bar{\nu}_i\frac{\delta n_d}{n_d} = -\delta\bar{\nu}_i,\\
&i\omega\frac{\delta n_d}{n_d} - i(\mathbf{k}\cdot\mathbf{u}_d) = 0,\\
&(i\omega + \bar{\bar{\nu}}_e)\mathbf{u}_e - v_{Te}^2 i\mathbf{k}\frac{\delta n_e}{n_e} + \frac{e}{m_e}\mathbf{E} = 0,\\
&(i\omega + \bar{\bar{\nu}}_i)\mathbf{u}_i - v_{Ti}^2 i\mathbf{k}\frac{\delta n_i}{n_i} - \frac{e}{m_i}\mathbf{E} = 0,\\
&(i\omega + \bar{\bar{\nu}}_d)\mathbf{u}_d - \frac{m_e}{m_d}\bar{\bar{\nu}}_e\mathbf{u}_e - \frac{m_i}{m_d}\bar{\bar{\nu}}_i\mathbf{u}_i - \frac{q_d}{m_e}\mathbf{E} = 0,
\end{aligned}
\quad (7)
$$

where $\mathbf{u}_e$ and $\mathbf{u}_i$ are the electron and ion flow velocities; $v_{Te}$ and $v_{Ti}$ are the electron and ion thermal velocities; $\bar{\nu}_e$ and $\bar{\nu}_i$ are the frequencies characterizing absorption of electrons and ions by dust grains,

$$\bar{\nu}_e = \frac{\nu_{ch}P(\tau+z)}{z(1+\tau+z)}, \quad \bar{\nu}_i = \frac{\bar{\nu}_e}{1+P}; \tag{8}$$

and $\bar{\bar{\nu}}_e$ and $\bar{\bar{\nu}}_i$ are the frequencies characterizing momentum transfer between electrons and ions and dust grains,

$$\begin{aligned}\bar{\bar{\nu}}_e &= \nu_{ch}\frac{P}{z}\frac{(\tau+z)}{(1+\tau+z)}\left(4+z+\frac{2z^2}{3}\exp(z)\ln\left(\frac{d}{a}\right)\right),\\ \bar{\bar{\nu}}_i &= \nu_{ch}\frac{P}{(1+P)z(1+\tau+z)}\left(z+\frac{4}{3}\tau+\frac{2z^2}{3\tau}\ln\left(\frac{d}{a}\right)\right).\end{aligned} \tag{9}$$

Here, $P = N_dZ_d/N_e$, $N_{e(d)}$ is the electron (dust) number density; $d$ is the Debye radius of the dusty plasma; and $\nu_{ch}$ is the charging frequency of dust grains,

$$\nu_{ch} = \frac{\omega_{pi}a}{\sqrt{2\pi}\lambda_{Di}}(1+\tau+z), \tag{10}$$

where $\omega_{pi}$ is the ion plasma frequency, $a$ is the dust grain size, $\lambda_{Di}$ is the ion Debye radius, $\tau = T_i/T_e$, $T_{e(i)}$ is the electron (ion) temperature, $z = Z_de^2/aT_e$, $-e$ is the electron charge, and $q_d = -Z_de$ is the grain charge. It should be noted that these formulas are valid either for the nocturnal ionosphere or when the photoelectric work function is sufficiently large (larger than 7.3 eV), i.e., when photoelectric effect is absent. In the presence of photoelectric effect (i.e., when the photoelectric work function of dust grains is smaller than 7.3 eV [1]), the problem is solved in a similar way.

Supplementing set of Eqs. (7) with the equation

$$-\frac{4\pi i}{\omega}en_e\mathbf{u}_e + \frac{4\pi i}{\omega}en_i\mathbf{u}_i + \frac{4\pi i}{\omega}q_dn_d\mathbf{u}_d + (\varepsilon-1)\mathbf{E} = 0, \tag{11}$$

which is a consequence of Maxwell's equations, we obtain the expression for $\varepsilon(\omega)$:

$$\begin{aligned}\varepsilon = 1 &- \frac{\omega_{pe}^2}{\omega(\omega-i\bar{\bar{\nu}}_e)} - \frac{\omega_{pi}^2}{\omega(\omega-i\bar{\bar{\nu}}_i)} - \frac{\omega_{pd}^2}{\omega(\omega-i\bar{\bar{\nu}}_d)}\\ &- \frac{\omega_{pd}^2\bar{\bar{\nu}}_e}{Z_d\omega(\omega-i\bar{\bar{\nu}}_d)(i\omega+\bar{\bar{\nu}}_e)} + \frac{\omega_{pd}^2\bar{\bar{\nu}}_i}{Z_d\omega(\omega-i\bar{\bar{\nu}}_d)(i\omega+\bar{\bar{\nu}}_i)},\end{aligned} \tag{12}$$

where $\omega_{pd}$ is the dust plasma frequency. Finally, ignoring small quantities, we obtain the following expression for the dielectric permittivity of a homogeneous isotropic dusty ionosphere:

$$\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega(\omega-i\bar{\bar{\nu}}_e)}. \tag{13}$$

This expression has the same form as Eq. (3); however, in a dusty ionosphere, dissipation is determined by the frequency $\bar{\bar{\nu}}_e$, which characterizes momentum transfer between electrons and dust grains. Thus, in order to estimate the effect of nano- and microscale particles, it is necessary to compare the electron–neutral collision frequency with the frequency $\bar{\bar{\nu}}_e$. These frequencies become comparable at a dust density on the order of $10^3$ cm$^{-3}$, the dust grain size being on the order of 10 μm. The frequency $\bar{\bar{\nu}}_e$ increases with increasing number density and size of dust grains. Hence, for the dust to significantly affect dissipation, the grain size should exceed a certain critical value. The dust density can reach sufficiently large values in noctilucent clouds [7]. Catastrophic events, such as volcanic eruptions, can also increase the dust density in the lower ionosphere to values substantially exceeding the critical density. In the model of a homogeneous ionosphere, the presence of dust with critical parameters in the lower ionosphere can reduce the resonant frequencies by several percent: from 7.8 to 7.0 Hz for the first mode and from 14.5 to 13.3 Hz for the second mode. Simultaneously, the SC quality decreases from 1.1 to 0.8 for the first mode and from 1.5 to 1.1 for the second mode.

### *3.2. Effect of Volcanic Eruptions on the SR Amplitude*

Nano- and microscale particles get into the atmosphere as a result of various natural and anthropogenic processes. Let us consider volcanic eruptions, which can pollute sufficiently large regions with high-density dust. During the Krakatoa eruption (1883), a hot gas–ash cloud ascended to altitudes corresponding to the lower ionosphere (up to 80 km). The most violent eruption among those previously observed was the Mount Tambora eruption (1815), during which about 150 km$^3$ of pyroclastic material [16] was thrown into the atmosphere.

The formation and propagation of volcanic clouds can be accompanied by intense electric processes. Electric phenomena can also occur during dust storms. For instance, on Mars, SRs are excited just in this way [11]. In a cloud of volcanic ash, the following mechanisms for charge separation can operate: thermoemission and thermoelectric emission in the initial stage of ejection, contact and induction charging in the interaction of grains in a cooled cloud, and ion charging by atmospheric ions. Space charge in an ash cloud is accumulated due to charging of large and small grains with charges of opposite signs and their subsequent spatial separation under the action of gravity [17]. At sufficiently large volumes of the erupted material, the electric field voltage in a volcanic cloud reaches a few hundred megavolts. The frequency of powerful lightnings in thunderclouds is on the order of 0.1 s$^{-1}$. During volcanic eruptions, powerful lightnings can occur every second. In regions covered by a volcanic cloud, more frequent spark discharges with a length about 10 m and intense corona radiation can also be observed [18]. Electric processes in volcanic clouds are very similar to those in thunderclouds; therefore, one can use quantitative characteristics of the processes occurring in thunderclouds to estimate the discharge parameters in volcanic clouds.

For an electric discharge to occur in a volcanic cloud, it is necessary that the electric field strength in some macroscopic volume become larger than the breakdown value. Charges are macroscopically separated due to gravitational separation of grains with different masses. Larger grains in a volcanic cloud usually carry a positive charge. Thus, a positively charged region forms in the lower part of the cloud.

The frequency of discharges is to a large extent a random value because it depends on local field fluctuations. The time during which the breakdown electric field is restored after lightning can be estimated from the following considerations. Let us assume that the charge carried away from the cloud by lightning is restored by the flux of positive particles to the lower part of the cloud. The charge transferred over the time $t$ is equal to $\rho v S t$, where $\rho$ is the space charge density, $v$ is the sedimentation rate of larger grains, and $S$ is the area of the active region of the cloud. Then, the discharge frequency can be estimated as follows:

$$n = \frac{QvS}{\Delta Q V} = \frac{Qv}{\Delta Q R}, \quad (14)$$

where $Q$ is the charge of the upper dipole region (the charge of the lower region is the same in magnitude but opposite in sign), $\Delta Q$ is the charge carried away by lightning, $V$ is the cloud volume, and $R$ is the radius of the charged region in the cloud. In order to determine the sedimentation rate of dust grains, let us consider the equation of motion of a grain. The equation describing stationary motion of a grain with allowance for the electric field, which is directed from top to bottom (the upper part of the cloud is charged negatively), has the form

$$3\pi\eta v D + \frac{9}{4}\rho v^2 \frac{\pi D^2}{4} - mg - keE = 0, \quad (15)$$

where $D$ is the grain diameter, $\eta$ is the gas viscosity, and $\rho$ is the gas mass density. Here, the first term is the Stokes viscous force, the second term is the gas drag force, the third term is the gravity force, and the fourth term is the Coulomb force acting on a grain containing $k$ excess electrons. The solution to this equation,

$$v = \frac{8\eta}{3\rho D}\left(\sqrt{1 + \frac{\rho}{4\pi\eta^2}(mg + keE)} - 1\right), \quad (16)$$

allows one to determine the sedimentation rate of dust grains. The correction caused by the electric field is significant only for the smallest particles. From Eq. (15), we find that, e.g., a grain with a size of 100 μm descends with a velocity of about 1 m/s.

The charge carried away from the cloud by lightning can be estimated from the following considerations. Simultaneously with a descending leader, an ascending leader of opposite polarity develops [19]. Thus, when a negative leader originates in the lower part of a negatively charged region of the cloud, it propagates downward, whereas the positive leader propagates upward and traverses the charged region. When treating the current flowing along a solitary leader channel, the charged region of the cloud cannot be considered conducting. However, most lightnings are branched. In the case of a highly branched lightning, the negatively charged part of the cloud is penetrated by many conducting channels; therefore, it be regarded as a solid conducting sphere, whose charge is displaced to its surface. The total charge of the system comprised of such a sphere and a descending leader attached to it remains unchanged and equal to the initial charge $Q$. If we ignore the voltage drop along the channel of the descending leader, then the electric potential $U$ is the same over the entire system. When the leader contacts the positively charged sphere (or the ground), this potential is equal to $U = Q/(C_C + C_L)$, where $C_C = R$ is the capacitance of the charged sphere and $C_L = mL/[2\ln L/r(L/d)^{m-1}]$ is the capacitance of the branched descending leader, which can be represented as $m$ similar conductors of radius $r$ and length $L$, separated from one another by the distance $d$.

The charge flowing through the leader channel in the main stage of lightning is transferred to the positively charged part of the cloud or to the ground. This charge is equal to $\Delta Q = UC_L$. Hence, the relative charge carried away from the cloud by lightning depends only on the geometric parameters of the cloud–lightning system, $\Delta Q/Q = C_L/(C_C + C_L)$. Assuming that the length of lightning is equal to the size of the active region of the cloud and that the number of branchings is equal to 10, we obtain $\Delta Q/Q \approx 0.25$. For $v = 1$ m/s and $R = 10^3$ m, we find that the frequency of discharges is on the order of 0.005. However, the observed frequency of lightnings is much higher; this may be related to the fact that the above model ignores turbulence. Due to turbulent mixing, a thunderstorm cloud is divided into puffs of different size, in which discharges can occur independently.

Due to thermoelectric electrization of ash grains, electrons are transferred from large hot grains to small cooled ones when they touch one another. When two grains with the temperature difference $\Delta T$, corresponding to the thermoelectric voltage $\Delta U$, contact one another, the potential difference decreases due to the transfer of the charge $\Delta q$ from the larger to the smaller grain. If the capacitance of the smaller grain is $C_1$ and that of the larger grain is $C_2$, then we have $\Delta q = \Delta U/(1/C_1 + 1/C_2)$. It can be seen from this formula that the charge transferred due to thermoelectric electrization is mainly determined by the capacitance of the smaller grain. The process of thermoelectric charging is almost completely governed by collisions of grains that are larger than 5–10 μm in size with micron-size grains, whose temperature is equal to the temperature of the surrounding air [20]. Since the rate of electric processes is higher than that of thermal processes, we may assume that, at each instant, the charge of a grain is unambiguously determined by its size and temperature. Thus, the separated charge is proportional to the number of grains $N$ in the active region of the cloud.

Taking into account that the discharge current $I$ is proportional to the separated charge [19] and ignoring turbulent mixing, we find that the discharge current moment $M$ is proportional to the charge of the entire cloud and, therefore, to the number of particles, $N : M \propto I \propto Q \propto N$ (it is assumed that the length of lightning is determined by the geometry of the cloud). When turbulent mixing is taken into account, it is more reasonable to assume that the number of puffs (i.e., the frequency of discharges) increases with number of dust grains, while the average current moment remains unchanged: $n \propto N$ and $M \approx$ const.

Let us estimate the contribution from a volcanic eruption accompanied by thunderstorm discharges to the SR amplitude. For the sake of simplicity, we assume that there is only one thunderstorm center and that the volcanic cloud is located just near this center. The frequency of lightnings in the volcanic cloud is equal to $n_v$, and the average discharge current moment is equal to $M_v$. The energy emitted by lightnings in the volcanic cloud is added to the energy generated by the world thunderstorm activity, $E^2 \propto nM^2 + n_v M_v^2$, and the relative energy increment is on the order of $n_v M_v^2 / nM^2 \propto N$. Thus, the ejection of ash with a total mass of about $10^4$ tons (it is assumed that the number of ash grains is proportional to the mass of the ejected material) can result in a twofold increase in the SR amplitude.

Dust grains obviously influence thunderstorm discharges in meteorological clouds; however, an analysis of all the possible mechanisms for such influence is a subject of a separate study. During the formation of a thunderstorm cloud, dust grains play the role of condensation sites; hence, an increase in their number density promotes the cloud formation. If we assume that the atmospheric humidity is constant, then an increase in the number of condensation sites leads to an increase in the number of small drops that cannot grow to the size of a hailstone; as a result, the probability of a thunderstorm decreases. In experiments on preventing thunderstorms, thunderstorm clouds were seeded by coarsely dispersed aerosols [21]. In this case, large drops form in the upper part of the cloud; as a result, the ascending flows are attenuated, convection is suppressed, and the cloud is dissipated.

### *3.3. Influence of Nano- and Microscale Particles on the Temperature of the Earth's Surface and the SR Amplitude*

There are also mechanisms for the influence of nano- and microscale particles on the SC that are not related to plasma processes. Let us consider the influence of dust on the average temperature near the Earth's surface. On the one hand, the presence of greenhouse gases makes the atmosphere less transparent to long-wavelength radiation, thereby increasing this temperature [4]. On the other hand, the presence of dust, as well as sulfate aerosols, in the atmosphere changes the optical properties of clouds. As a result, the reflecting power of the atmosphere increases and the Earth's surface is less heated. Some organic aerosols can also contribute to a decrease in the temperature near the Earth's surface [4]. Violent volcanic eruptions can lead to a decrease in the average temperature by several tenths of a degree over subsequent years. Such a decrease in the average temperature was observed, e.g., after the Mount Tambora (1815), Krakatoa (1883), and Agung (1963) eruptions. After the Mount Tambora eruption, the average annual temperature in the Northern Hemisphere decreased by 0.7°C [16]. Such a change is comparable with random deviations; however, taking into account the positive trend in the average annual temperature at that time, a decrease in the temperature due to the eruption is estimated to be 0.4–0.7°C. Global changes in weather after this eruption are explained by the fact that about $2 \times 10^4$ tons of aerosols (mainly, sulfur oxide) were suspended in the atmosphere.

Williams [9] proposed that SRs be used as a global tropical thermometer. He noticed that there is a correlation between variations in the monthly average temperature and the monthly average magnetic field of the SC fundamental mode. According to [9], the intensity of convective processes in the atmosphere depends, first of all, on the temperature near the Earth's surface, rather than on the altitudinal temperature distribution. Charge separation, which leads to thunderstorms, is governed by convective processes. Thus, the temperature near the Earth's surface is related to thunderstorm activity. Figure 1 illustrates fluctuations of the monthly average temperature and the magnetic field of the fundamental mode over 5.5 years, according to the results of observations performed at the University of Rhode Island (Kingston, RI, United State).

## 4. DISCUSSION

There are two mechanisms for the influence of the dust grains present in the atmosphere on global electromagnetic oscillations. First, the presence of nano- and microscale particles can cause additional dissipation. Second, the efficiency of energy pumping of SRs can be enhanced due to an increase in the source intensity. Nano- and microscale particles participate in convective processes in the cloud and intensify charge separa-

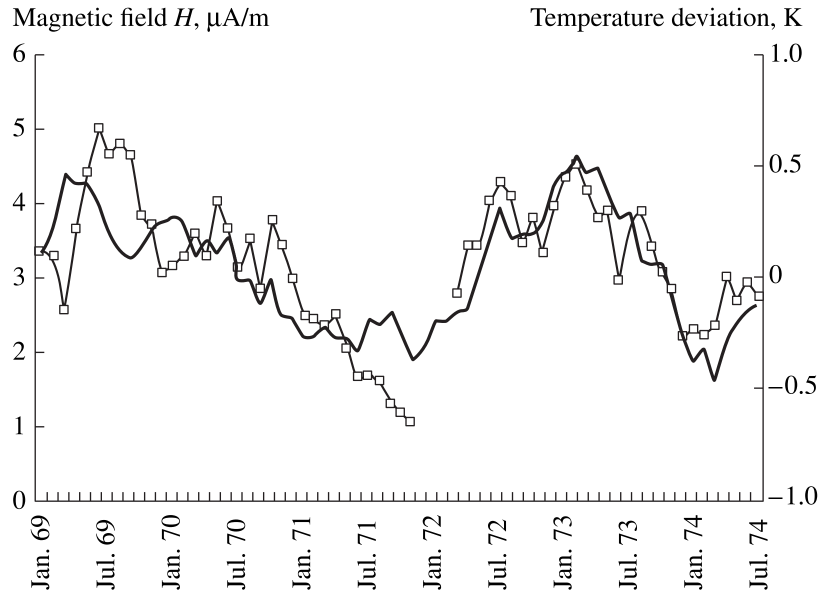


**Fig. 1.** Fluctuations of the monthly average temperature and the magnetic field of the fundamental mode [9].

tion, thereby increasing the number of thunderstorms. Since thunderstorm activity is the main source of SRs, this leads to an increase in the energy density in the cavity and, therefore, in the SR amplitude.

When the number density of nano- and microscale particles in the atmosphere increases abruptly, e.g., during volcanic eruptions, the average temperature on the Earth's surface can decrease by several tenths of a degree over subsequent years. Since there is a correlation between the monthly average temperature and the fundamental mode of the SC magnetic field, the amplitude of the first harmonic should decrease significantly after volcanic eruptions (as the temperature decreases by 1°C, the amplitude halves). Thus, the presence of

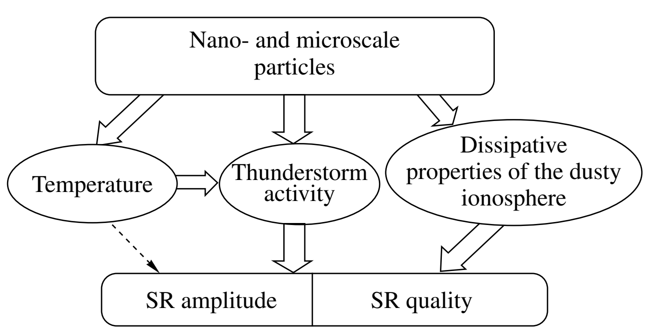


**Fig. 2.** Possible mechanisms for the influence of nano- and microscale particles in the atmosphere on SRs. The dashed arrow indicates correlation between the temperature and the SR amplitude.

nano- and microscale particles in the atmosphere can lead to a decrease in the energy density in the SC.

When dissipation introduced by the dust present in the ionosphere is more intense than that caused by electron–neutral collisions, microscale particles can substantially influence the SC parameters. This takes place when the number density of dust grains is higher than $10^3$ cm$^{-3}$, the grain size being on the order of 10 μm. The presence of dust with such parameters in the lower ionosphere leads to a decrease in the SC quality and an insignificant decrease in the resonant frequencies. In spite of the fact that the number density of microscale particles in the ionosphere is usually lower than the above critical value, situations can occur (e.g., after a volcanic eruption) in which such frequency shifts due to the presence of a finely dispersed phase can be observed.

Summarizing the aforesaid, we present a scheme illustrating possible mechanisms for the influence of nano- and microscale particles on SRs (see Fig. 2).

## 5. CONCLUSIONS

Thus, we have studied the influence of nano- and microscale particles on the SC parameters. It is shown that the presence of dust grains in the Earth–ionosphere cavity can significantly enhance thunderstorm activity. Since this activity is directly related to the SR amplitude, an increase in the concentration of nano- and microscale particles in the atmosphere can raise the efficiency of energy pumping of the cavity. For example, during violent volcanic eruptions, the SR amplitude can increase severalfold. The presence of dust particles in the atmosphere also influences the annual average temperature near the Earth's surface. For instance, violent volcanic eruptions are accompanied by an appreciable decrease in the annual average temperature. Since the SR amplitude is related to the surface temperature, a decrease in the temperature can lead to a decrease in the energy density in the cavity. It is shown that the presence of microscale particles in the lower ionosphere affects its dispersion properties, decreasing the frequencies and quality of the resonances. The first modes of SRs, probably, have a biological effect; therefore, changes in their parameters may influence human health.

## ACKNOWLEDGMENTS

We are grateful to R. Bingham for fruitful discussions. This work was supported by the Department of the Earth Sciences of the Russian Academy of Sciences under the program "Nanoscale Particles in Natural and Technogenic Systems" and the Russian Foundation for Basic Research (project no. 06-05-64826). Yu.N. Besedina acknowledges the financial support of the Dynasty Foundation, and S.I. Popel is grateful to the Russian Science Support Foundation (grant in the nomination "Doctors of Sciences of the Russian Academy of Sciences").

## REFERENCES

1. B. A. Klumov, G. E. Morfill, and S. I. Popel, Zh. Éksp. Teor. Fiz. **127**, 171 (2005) [JETP **100**, 152 (2005)].
2. V. N. Tsytovich, Usp. Fiz. Nauk **167**, 57 (1997) [Phys. Usp. **40**, 53 (1997)].
3. V. E. Fortov, A. G. Khrapak, S. A. Khrapak, et al., Usp. Fiz. Nauk **174**, 495 (2004) [Phys. Usp. **47**, 447 (2004)].
4. C. Anastasio and S. T. Martin, in *Nanoparticles and the Environment*, Ed by J. F. Banfield and A. Navrotskiy (Mineralogical Society of America, Washington, DC, 2001), p. 293.
5. D. Fromm and R. Servranckx, Geophys. Rev. Lett. **30**, 1542 (2003).
6. J. R. Holton, P. H. Haynes, M. E. McIntre, et al., Rev. Geophys. **33**, 403 (1995).
7. O. Havnes, in *Dusty Plasma in the New Millenium*, Ed. by R. Bharuthram, M. A. Hellberg, P. K. Shukla, and F. Verheest (AIP, New York, 2002), p. 13.
8. W. O. Schumann, Z. Naturforsch. **7A**, 149 (1952).
9. E. R. Williams, Science **256**, 1184 (1992).
10. N. Cherry, Natural Hazards **26**, 279 (2002).
11. G. J. Molina-Cuberos, J. A. Morente, B. P. Besser, et al., Radio Sci. **41**, RS1003 (2006).
12. P. V. Bliokh, A. P. Nikolaenko, and Yu. F. Filippov, *Global Electromagnetic Resonances in the Earth–Ionosphera Cavity* (Naukova Dumka, Kiev, 1977) [in Russian].
13. L. A. Vaĭnshteĭn, *Electromagnetic Waves* (Radio i Svyaz', Moscow, 1988) [in Russian].
14. F. F. Chen, in *Plasma Diagnostic Techniques*, Ed by R. H. Huddelstone and S. L. Leonard (Acadimic, New York, 1965; Mir, Moscow, 1967), Chap. 4.
15. M. S. Barnes, J. H. Keller, J. C. Forster, et al., Phys. Rev. Lett. **68**, 313 (1992).
16. V. V. Shuvalov and I. A. Trubetskaya, in *Geophysical Processes in the Lower and Upper Envelopes of the Earth*, Ed. by S. B. Turuntaev (IDG RAN, Moscow, 2004), p. 336 [in Russian].
17. O. P. Rulenko, N. N. Klimin, I. N. D'yakonova, et al., Vulkanol. Seĭsmol., No. 2, 17 (1986).
18. O. P. Rulenko, Vulkanol. Seĭsmol., No. 5, 71 (1985).
19. E. M. Bazelyan and Yu. P. Raizer, *Lightning Physics and Lightning Protection* (Nauka, Moscow, 2001; IOP, Bristol, 2000).
20. Yu. V. Adamchuk and V. V. Titov, Preprint No. 4016/1 (Kurchatov Institute, Moscow, 1984).
21. V. M. Muchnik, *Physics of Thunderstorms* (Gidrometeoizdat, Moscow, 1974) [in Russian].

*Translated by É. G. Baldina*