Electrophonic noises from meteors and dust acoustic modulational perturbations

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Abstract. The article discusses dusty plasmas processes in the Earth’s ionosphere associated with the passages of meteoroids and the spread of the meteor tail. Mechanisms explaining the occurrence of electrophonic noises recorded simultaneously with the passage of meteor bodies are suggested for extremely low frequencies range. It is explained by modulational instability of electromagnetic waves from meteor associated with the dust acoustic mode with characteristic frequencies 0.03–60 Hz. As electromagnetic waves propagate in the dusty plasmas of the meteor tail or in the dusty ionospheric plasmas, dust acoustic waves are excited as a result of the development of modulational instability of electromagnetic waves at characteristic frequencies and as a result, the electromagnetic waves become modulated. At the surface, these perturbations can be converted into sound waves by means of receivers. The growth rates of modulational instability at which the modulational excitation of extremely low-frequency dust acoustic disturbances occur are calculated. The conditions of the development of modulational instability are given. The correlation between observations of ionospheric radio noises and passages of meteors is noticed. Observed data of electrophonic noises include discussing range of frequencies 0.03–60 Hz.

1. Introduction
The passage of meteors is a natural phenomenon outside of human control that is difficult to predict. It is necessary to study these phenomena in detail in order to understand the processes they cause and the consequences of the passage of meteors for nature and man. Physical phenomena and effects that arise as a result of meteor flights can affect the operation of radar systems, radio telescopes, geolocation devices and flight missile experiments. It is important to take it into account for operation of the above systems and eliminating failures.

If a meteor body (or meteoroid) interacts with the atmosphere of the Earth it can cause a glow called meteor. Meteors are a glow of meteoroid vapor.

Electrophonic sounds from meteors are not fully understandable phenomena. They cover a wide range of frequencies: from 0 to several kHz [1–3]. It is assumed that they can be described by several physical mechanisms. Abnormal sounds heard simultaneously with the passage of meteors are obviously associated with electromagnetic phenomena. When a meteor reaches a certain height in the atmosphere at which it is crushed and burned, observers can hear various sounds, such as whistling, crackling, hissing, and hum. In the second half of the 20th century, there were a lot of attempts to explain the nature of these phenomena and build theoretical models. However, self-consistent theory describing the appearance of electrophonic noises for all
range of frequencies has not been developed. But there have been proposed a lot of models and assumptions.

There are various theories of such noises: the electrostatic nature of the sounds, similar to the nature of the sounds of the auroras [4]; fluctuations in potential between two plates of the capacitor (one is the Earth and another is the meteor tail), which lead to production of noises, the origin of which has not been explained [5]; transformation of electromagnetic waves in the auricle and their perception as sound waves [6]; meteor tail turbulence and geomagnetic field displacement [7, 8]; radiation of waves at the frequencies of meteor tail plasma; breakdown mechanism [9]; displacement of the dipole moment of the Earth [10].

Experiments of C Keay [11] indicates that the disturbance from the meteor is transmitted with a speed of light and is transformed into sound waves at the surface of the Earth. The possibility of this is confirmed by his experiments, in which he sat probationers in a soundproofed room and exposed them to an alternating electric field with a voltage of 130 V/m and a sound frequency of several kilohertz. Those probationers who had metal-framed glasses or long hair heard sounds. The temples and hair in this case were antennas that detected electromagnetic vibrations and, together with the auricle, turned them into sound waves heard by the human ear.

Presuppositions of building a theory of modulation of electromagnetic waves from meteors in the atmosphere of the Earth were made in different variations. The mechanism of converting a modulated electromagnetic signal from a meteor into sound waves is given in [12]. In [1], processes describing the conversion of heat emitted by bodies into sound waves as a result of heating by electromagnetic waves from meteors into air vibrations are shown. The correlation between the occurrence of extremely low-frequency noise in the ionosphere [13] as a result of the development of modulational interaction of electromagnetic waves associated with the excitation of disturbances with frequencies in the range of dust acoustic waves is considered in [14].

The modulational instability of electromagnetic waves from meteors associated with the dust acoustic mode, as a mechanism describing the appearance of electrophonic sounds, has not been previously considered in the scientific literature. Thus, the proposed method in this article is rather new. It describes the appearance of electrophones at frequency range 0.03–60 Hz. As electromagnetic waves from meteor propagate in dusty plasmas of the meteor tail or in dusty plasmas of the ionosphere of the Earth, modulational interaction can excite electrostatic perturbations with frequencies below 60 Hz close to the range of dust acoustic waves. As a result, the electromagnetic waves become modulated. Since dust acoustic waves are longitudinal, they can exist only in the plasma of the meteor tail or in the ionospheric plasma and cannot reach the surface of the Earth. Therefore, only electromagnetic waves can be observed at the surface of the Earth.

The present work is devoted to the consideration of the modulational interaction associated with electrostatic perturbations with frequencies below 60 Hz. This range is characteristic for the dust acoustic mode. Dust presents in the meteor tail due to its fragmentation and can reach rather high concentrations (see section 2). During the Perseid, Orionid, Leonid, and Gemenid meteor showers, the background radio noise fluctuations with frequencies below 60 Hz can be substantially enhanced by modulational interaction of the electromagnetic waves from the meteors in the plasma of the meteor tail or in the ionospheric plasma where dust particles are present. It is suggested that the observed radio noise fluctuations (dust lines) occur directly from the modulational interaction.

2. Dusty plasmas in meteor tails
Dusty plasmas in meteor tails occurs due to meteor body fragmentation and further charging of dust fragments under the action of different currents. A meteor tail is a trace in the atmosphere that remains after the passage of a meteor. There are two types of meteor tails: dusty tails and ionized tails. The so-called meteor wake stretches directly behind the meteoroid. Dusty tails
are formed as a result of cooling jets of molten meteor material in the head of the meteor trace and condensation of meteor material in the meteor wake. The evaporation of meteorites occurs as a result of the action of heat fluxes associated with the radiation of a shock wave, convective heat transfer due to hydrodynamic flow around the body and electron thermal conductivity [15]. When the molten jets become solid, cylindrical particles are mainly formed, and during the condensation of meteor matter, they are spherical. Thus, the trace includes dust particles smaller than $10^{-4}$ cm, liquid drops of meteorite matter and gases. At dusk they shine due to the scattering of sunlight mainly on dust particles. Dusty meteor trails from bright meteors can be observed for a very long time, up to several hours. Ionized meteor tracks are observed from fractions of a second to several minutes (depending on the mass and brightness of the meteor). They also include dust particles from crushing meteoroid, molten and evaporated meteor matter. The ionized trace emits radio waves of meter and decameter range mainly. Meteor ionization is most intense at altitudes of 80–120 km [15]. In this paper we consider ionized meteor tails with the presence of the dust particles (where dusty plasmas exist).

The composition of dust particles depends on the composition of the meteoroid. Particles of meteor dust can consist of metals Na, Ma, Ca, Al, Fe, Ni and other compounds, as well as Si, FeS and oxides $\text{SiO}_2$, $\text{MgO}$, $\text{FeO}$.

There are several mechanisms of meteor fragmentation: mechanical, thermomechanical, and electrostatic. The picture of the dynamics of meteor body crushing and the charging of its dust fragments is following. Then the meteor enters the dense layers of the atmosphere (below 120 km), the pressure and the temperature in shock wave in front of meteor body increase. The radiation of a shock wave creates the conditions for the emission of electrons and ions from its surface. So, due to mechanical, thermal and electrostatic effects, the granular structure of the body ensures intensive fragmentation of the meteor body into small fragments and dust particles, and then, with increasing the temperature, the meteoroid melts and evaporates (for silicates when the temperature becomes more then 1500 K). At the initial stage of melting, stresses can occur in the neighboring material, which leads to rapid crushing of the meteoroid. As a result of the separation of the parts, uncompensated charges are formed at the surface of the body. There are a possibility of the appearance of cracks with sizes of $10^{-3}$–$10^{-4}$ cm, in which an electric field can occur. It can lead to mechanoemission from the crack, dust charging and to fragmentation when electrostatic pressure exceeds strength of meteor material.

Then the pressure in shock wave increases during meteor fall, mechanical fragmentation also begins to dominate. For small bodies, liquid mass loss plays an important role. As we can see from experiments [15], jets and droplets with sizes less than 0.3 mm are knocked out from the melted meteor during its gasification. As a result, after cooling the matter, spherical particles and elongated particles are formed, resembling droplets (rounded on the head side and with a tail cut off on the other), which were separated by expelling the gases from the melted meteoroid and then they move further in the meteor wake, they become solid due to decreasing the temperature. Several types of particles should be considered in order to study the conditions of their splitting and crushing. Mainly, spherical particles and particles with the shape of elongated droplets close to cylinders can be distinguished. It is easy to break a cylindrical particle than spherical one.

The characteristic values for strength $\sigma$ of porous silicate substance are $(1–3) \times 10^4$ dyne/cm$^2$ [16], for granites are $(0.5–3) \times 10^8$ dyne/cm$^2$, for stone meteors have a range from $2 \times 10^7$ to $5 \times 10^8$ dyne/cm$^2$ [15]. In the meteor tail after decreasing the temperature, evaporating meteor matter begins to condensate and mostly spherical dust particles are formed. Heat transfer due to electronic thermal conductivity is much greater than as a result of electron diffusion [17]. This is especially evident at high altitudes of 100–120 km. In the daytime, at an altitude of 100 km, the electrons are cooled in a time of $10^{-3}$ s to an ionosphere temperature of 200 K and during the night in a time of $10^{-1}$ s. The time of condensation of evaporated meteor matter is less than the time of meteor passage and charged condensed dust can influence on rising of electrophonic
sounds but taking into account low temperature of electrons in meteor wake (due to its cooling in result of heat transfer connected with electronic thermal conductivity), condensed dust will obtain low electric charges and frequencies of dust acoustic waves will be rather small.

Dust particles near the meteor body obtain higher charges than condensed matter in meteor wake. Charging of dust leads to fragmentation of dust particles in case when electrostatic pressure exceeds strength of meteor material. Dust particles in the meteor tail are influenced by ion current, electron current, mechanoemission current, reverse current of mechanoelectrons and thermoelectron current. It leads to positive particle charges for typical parameters of dusty plasmas of the meteor tail mainly due to emission currents. Estimation of the charges according to the probe model for spherical dust particles \[18\] in a stationary situation which is present in the concrete point of the meteor tail (taking into account that number of particles is constant in there) gives

\[
\frac{z_d e^2}{aT_e} \approx 2-4,
\]  

the range of the charge numbers \(z_d\) is from \(10^2\) to \(10^3\) for particles with sizes from tens to hundreds of nanometers (\(10^4\) for particles of 1 \(\mu\)m size and \(4 \times 10^2\) for particles with a size of 80 nm).

Progressive fragmentation also takes place in any cases of fragmentation.

The masses of the observed meteoroids have a wide range of values: from \(10^{-7}\) to \(10^7\) g. For example, for meteor showers, such as Perseids, Leonids, Orionides, Draconids, the characteristic sizes of meteors are small, from fractions of a gram to several grams. However, individual meteors have rather large masses. The characteristic densities of meteoroids lie in the range 0.5–3 g/cm\(^3\). The total mass dropped by a 1 cm meteoroid during one flash is 0.3 g. Considering a meteor density of 1 g/cm\(^3\), the mass of a spherical particle with a radius of 80 nm is \(10^{-13}\) g. Then the number of dust particles that a meteoroid with a radius of 1 cm drops will be \(10^{12}\) [19]. The dust concentration in the cylindrical wake will be \(10^4\) cm\(^{-3}\) for a radius of the meteoroid 10 cm and a length of the meteor tail 10 km. However, closer to the meteoroid itself, the dust concentration will be greater, and further will fall from the trace length \(r\) as \(1/r\). If we assume that the flash lasts 1 ms which is according to the observations at a meteor speed of 50 km/h, then the meteor passes a distance of 50 m. Thus, the concentration of dust dropped during the flash will be \(n_d = 2 \times 10^8\) cm\(^{-3}\) for a 1 cm meteor body and a meteor tail radius 10 cm (assuming that a meteor body drops a 1/10 of mass during a flash). Smaller and larger meteoroids give similar estimates of dust concentration taking into account that smaller or larger numbers of dust particles spread in smaller or larger volume of the meteor tail. On average, the range of concentration of dust particles in the meteor trace close to the meteor body \(n_d\) is from \(\sim 10^6\) to \(\sim 10^8\) cm\(^{-3}\). This situation will be considered for the rising of the electrophonic sounds. According to the “dust lump hypothesis”, some meteor bodies have a porous structure with individual inclusions of micron particles. This hypothesis is in good agreement with the altitude data at which meteors disappear and with their brightness [20]. Due to the porous structure, meteor bodies have a smaller mass, glow brighter (since the surface area of the body is larger) and crush more intensively.

An important parameter for meteor tails is the number of electrons and ions per centimeter of path [15, 21]. A range of characteristic values of linear concentration of electrons \(n_e\) is from \(\sim 10^{12}\) to \(\sim 10^{16}\) cm\(^{-1}\) (depending on the mass and brightness of the meteor from \(5^m\) to \(-5^m\)), a range of characteristic values of linear concentration of ions \(n_i\) is from \(\sim 10^{12}\) to \(\sim 10^{13}\) cm\(^{-1}\).

The linear electron density can be used to estimate the total electron density at the solid angle of the meteor shower, the formula of which also includes the diffusion coefficient [15]. For example, for a meteor with parameters \(T = 30 000\) K and brightness \(-5^m\), total electron density is \(10^{16}\) cm\(^{-3}\). In addition to emissions of electrons and ions, which contribute to the particle
density in the meteor wake and ionization processes, the mechanisms of kinetic knocking of electrons, ions and neutral atoms of the meteor due to their collision with air molecules and the potential ejection of electrons from the meteoroid by gas molecules were also taken into account. The collision energy of a meteoroid with air particles depends on the speed of the meteorite and ranges from 16.6 to 1675 eV for characteristic meteor velocities 11–72 km/h [21].

The electron temperature behind the front of the shock wave (in the meteor tail) for a typical meteor is 30 000 K [8], however, it can vary from 20 000 to 200 000 K depending on the mass and speed of the meteor body [10], data on lower temperatures for traces of the intermediate type (\(n_e = 10^{12} \text{ cm}^{-3}\)) about 10 000 K [17]. The temperatures of electrons and ions have the same values.

3. Modulational excitation of low frequency perturbations from meteors

The plasma of the meteor tail generates radio waves with frequencies of the order of several MHz. Dust occurs in the atmosphere of the Earth as a result of the burning of the meteoroid and presents in the meteor wake itself. Under the action of different currents dust particles obtain electric charges and dust acoustic waves can exist. So, radio waves from the meteor tail become modulated at frequencies characteristic to the dust acoustic mode. Thus, one can expect connection between charged dust in the meteor tail and rising of the electrophonic sounds. As a result of the mechanisms of fragmentation and charging of dust particles in the wake, nanoscale charged dust with a sufficiently high concentration is present in the atmosphere of the Earth during a flight from a meteor and for a sufficiently long time after a flight from a meteor (up to several months). The typical time of the meteor passage is a few seconds. The time during which the electrophonic sounds are heard is around 6 s (with a peak intensity of 5–6 s). When the meteor is almost burned out (before the last meteor flash), the intensity of the electromagnetic radiation from the ionized wake increases and, as a result, the signal modulated by sound frequencies has great strength. Observers at the surface of the Earth can perceive such a modulated signal as sound waves by means of radio wave receivers (hair, leaves, temples, fir tree needles [1, 7, 11]).

Hereinafter, all formulas and quantities are used in the CGS. Let us introduce parameters and designations: \(K = k ± K_0\) is the wave vector of modulated electromagnetic wave, \(K_0\) is the wave vector of the pump electromagnetic wave, \(k\) is the wave vector of low frequency disturbances; \(m_\xi\) is the mass of particles of sort \(\xi\); \(n_\xi\) is the concentration of particles of sort \(\xi\); \(\xi = e, i, d\) for electrons, ions and dust particles respectively. \(T_{e(i)}\) is the temperature of electrons (ions) in the energy means, \(-e\) is the electron charge, ions are supposed to have charge equals 1, \(q_d = z_d e\) is the dust particles charge, \(E_0\) is the electric field of the electromagnetic pump wave, \(\omega_0\) is the frequency of this wave. Index “0” corresponds to unperturbed parameters, index “1” to perturbed parameters of the first order of smallness; the effective collision frequency \(\nu_{\xi(i)} = \sum_{\xi = i, d} 3(m_{\xi}/m_i)\nu_{\xi(i)}\), \(\nu_{\xi(i)}\) is the collision frequency of particles of sort \(\xi = e, i, d\) with particles of sort \(\eta = e, i, d\), which characterizes rate of electrons and ions going to equilibrium: \(\chi_e = 3.16T_e/(m_e e)\), \(\chi_i = 3.97T_i/(m_i n_i)\) are electron and ion thermal diffusivity coefficients, respectively, here \(\nu_{e(i)} = \sum_{\xi = i, d} \nu_{\xi(i)}\), \(\nabla\) is the Laplace operator.

Extra low-frequency perturbations in dusty plasmas of the meteor tail is supposed to change like \(\exp(-i\Omega t + iKr)\), where \(\Omega\) and \(K\) is the frequency and the wave vector of these perturbations.

Wave modulation can result from the modulational interaction between the electromagnetic and dust acoustic waves. The frequency range below 60 Hz is typical of the dust acoustic mode.

The dumping of dust sound waves in the ionospheric dusty plasma and in the dusty plasma of the meteor tail is associated with the collisions of dust particles and neutrals. Dust acoustic disturbances are excited as a result of the development of modulational instability of electromagnetic waves. Modulational instability can develop when growth rate of instability \(\gamma\) less than collision frequency of neutrals and dust particles \(\nu_{\text{dln}}\) divided by two. For the existence
of a propagating of the dust acoustic wave, it is necessary that \( \omega_d \approx C_{sd}/\lambda_D > \nu_{dn} \). Here the dust frequency is

\[
\omega_d = \sqrt{4\pi n_{dn} q_d^2/m_d}.
\] (2)

As we can see from calculations, it is fulfilled for all parameters of dusty plasmas of meteor tails.

Dispersion equation for dust acoustic waves \( \omega_{sd}(k) \) is following:

\[
\omega_{sd}(k) = \mathrm{Re}\omega_{sd}(k) + i\mathrm{Im}\omega_{sd}(k),
\] (3)

where

\[
\mathrm{Re}\omega_{sd}(k) = \sqrt{\frac{C_{sd}^2 k^2}{1 + \lambda_D^2 k^2}} - \frac{\nu_{dn}^2}{4},
\] (4)

\[
\mathrm{Im}\omega_{sd}(k) = -\frac{\nu_{dn}}{2} - \frac{(\mathrm{Re}\omega_{sd}(k))^2}{2} \left( \frac{\nu_{en}}{k^2 v_T^2} + \frac{\nu_{dn}}{k^2 v_D^2} \right).
\] (5)

Here, \( \nu_{dn} = (4/3)\pi e^2 \sqrt{8T_{io}/\pi m_n n_n (m_n/m_d)} \) is the collision frequency of dust s with neutrals; \( k \) is the length of the wave vector of dust acoustic perturbations. The Debye length is

\[
\lambda_D^2 = \lambda_{De}^2 + \lambda_{De(i)}^2, \quad \lambda_{De(i)} = \sqrt{T_e(i)/4\pi n_e(i) e^2}.
\] (6)

The expression for the imaginary part (5) is obtained under the assumptions \( \omega_{sd} \gg \nu_{dn}, k v_T, \omega_{sd} \nu_{en} \ll k^2 v_T^2, \omega_{sd}, \nu_n \ll k^2 v_T^2, \omega_{en} \gg \omega_{sd}, k v_T, \nu_n \gg \omega_{sd}, k v_T, \) which are usually satisfied for dusty plasmas of meteor tails.

Modulational instability for \( q_d > 0 \) occurs when [22]

\[
\frac{|E_0|^2}{4\pi n_0 T_0} \gg \max \left( \frac{3 C_{sd} K \omega_0^2 \nu_e^2 + K^4 c^4 \omega_0^2}{8 \omega_p^2 / \nu_c}, \frac{3 C_{sd} K \omega_0^2 \nu_e^2 + K^4 c^4 \omega_0^2}{8 \omega_p^2 / \nu_c} \right),
\] (7)

where \( C_{sd} = |q_d| e/\sqrt{n_d T_e/n_e m_d} \) is the dust acoustic velocity, \( K \) is the length of the wave vector of modulated electromagnetic wave, \( \omega_c = c e K^2 / 2, \omega_e = c K^2 / 2 \).

Collision frequency of electrons and neutrals \( \nu_{en} \) much less when \( \omega_{\chi_e}(K) \) in meteor tail due to rather high temperature in spite of high concentration of neutrals in ionosphere and in the meteor tail: \( n_n \) is from 10^{14} to 10^{15} cm^{-3}. So, we can neglect \( \nu_{en} \). So, one can neglect it.

For a positive charge of dust particles, in the case \( \omega_{\chi_e} \gg \Omega \gg C_{sd} K \) (which is performed for the plasma parameters of meteor tails), the growth rate of modulational instability has the following form:

\[
\gamma(K) \approx 2\sqrt{2} \left( \frac{C_{sd}^2 K^2}{\omega_{\chi_e}(K)} \right)^{1/2} \left( \frac{\omega_e^2}{\omega_0^2} + \frac{K c}{\omega_p^2 / \nu_c} \right)^{1/2} \left( \frac{|E_0|^2}{4\pi n_0 T_0} \right)^{1/2}.
\] (8)

The applicability of the method for dusty plasmas of meteor tails is possible in the case when the length of the electromagnetic wave \( \lambda \) from the meteor tail is much less than the width of the tail \( L \). Otherwise, the effects of heterogeneity must be taken into account. This article discusses the situation when the condition \( \lambda \ll L \) is fulfilled. It can be in the case of meteors with the meteor tails which much more than a meter, that is fulfilled for rather big meteors. It is worth to notice that the values of lengths of modulated electromagnetic waves recorded at the surface of the Earth from meteors lie mainly in the meter and decameter ranges. However, these observations correspond to the bright meteors but for small meteors wave lengths can be less than meter. Also, in the tail of the meteor corresponding values of \( K \) can take other meanings and change at the border of the meteor and the ionosphere. In this case described method can be satisfied also for small meteors.
Let us introduce typical values for a wide range of parameters of the dusty plasmas of meteor tails: the characteristic size of dust particles in the meteor wake $a$ is from $\approx 80$ to $10^4$ nm [23], a range of concentrations of dust particles $n_d$ is from $\sim 10^6$ to $10^8$ cm$^{-3}$ and temperature $T_e = 2$ eV, we get a range of $\omega_d$ is from $\sim 10^3$ to $10^4$ rad/s and $\nu_{dn}$ is from $\approx 0.1$ to $\approx 0.2$ 1/s. One can obtain characteristic values of the frequency of dust acoustic perturbations for various wave vectors: $k = 0.1$ cm$^{-1}$, $\omega_{Sd} = 0.27$ Hz; $k = 1$ cm$^{-1}$, $\omega_{Sd} = 1$ Hz; $k = 10$ cm$^{-1}$, $\omega_{Sd} = 60$ Hz. For larger values of the wave vector, spatial scales will not be characteristic for the dust acoustic mode (less than 0.1 cm). The minimum value of $k$ at which dust acoustic waves can occur is $k = 0.003$ cm$^{-1}$.

For possible plasma parameters of meteor tails $C'_{Sd}/\lambda_d > \nu_{dn} \approx 0.1$ 1/s and $\gamma > \nu_{dn} \approx 0.1$ 1/s, therefore, the propagation of dust sound waves and the occurrence of modulational instability of the electromagnetic wave from the meteor associated with dust sound vibrations in the meteor tail is carried out. Growth rates of instabilities $\gamma$ for a range of parameters typical for dusty plasmas of meteor tails (a range of parameter $n_d$ is from $\sim 10^6$ to $10^8$ cm$^{-3}$, $n_e$ is from $\sim 10^{13}$ to $10^{16}$ cm$^{-3}$, $T_e = 2$ eV, $K$ is from $\sim 10^{-1}$ to $10^{-3}$ cm$^{-1}$, $a$ is from $\sim 1$ nm to $10$ $\mu$m, $z_d$ is from $\approx 4$ to $\approx 4 \times 10^5$) have a values from $\sim 10^3$ to $\sim 10^6$ 1/s. All $\gamma > \nu_{dn}$, so it is expected that modulational instability can develop for dusty plasmas of meteor tails (see results of development of modulational instability and growth rates of instability comparing to Borisov for the case of low ionosphere [24]).

The dust modulating the electromagnetic wave from the ionized trace of the meteor can be located in the head part of the shock wave behind the crushing meteoroid (the dust concentration is high there), and at sufficiently large distances from the meteoroid in the meteor tail. Also, the modulation of electromagnetic waves from meteors can be affected by charged dust, which is present in the ionosphere from previous burnt meteors or by large dust particles that sediment from the meteor tail to the lower layers of the ionosphere. However, as shown by the works of Musatenko [13], the appearance of dust lines in the spectra of ionospheric radio noises is stronger during meteor showers. Thus, the charged dust that remains in the atmosphere as a result of the passage of meteors has a finite period of life and is not always able to affect the processes associated with the passage of future meteors.

The main results on the development of modulational instability of electromagnetic waves in the dusty plasmas of meteor tails and in the lower dusty ionosphere are the following. There perturbations on the ion acoustic time scale are suppressed by strong ambipolar diffusion. Thus, the modulational instability gives rise to the electromagnetic fields with frequencies of 0.05–60 Hz, which can in turn be associated with modulation by the dust acoustic mode. The modulational instability can be caused by Joule heating, the ponderomotive force, as well as processes related to charging and dynamics of the dust grains. It leads to the modulation of electromagnetic waves from meteors at extra low frequencies. They can reach the surface of the Earth and perceived as electrophonic noises in audible range. It is noticed that only electromagnetic waves can reach surface of the Earth. Dust acoustic oscillations can exist only in dusty plasma.

4. Conclusions
As electromagnetic waves propagate in the dusty plasmas of the meteor tail or in the dusty lower ionosphere, dust acoustic disturbances are excited as a result of the development of modulational instability of electromagnetic waves. Thus, the electromagnetic waves become modulated. When the modulated electromagnetic wave reaches the surface of the Earth, it can be perceived as sound wave by means of receivers. This phenomenon called electrophonic sounds from meteors. It covers wide range of frequencies 0 to 10 kHz. Here, mechanism of formation of electrophones is explained by modulational instability of the electromagnetic wave from the meteor associated with the dust acoustic mode at frequencies 0.03–60 Hz. Dust particles present in the meteor...
tail in result of crushing of meteor body, cooling molten meteor matter and condensation of evaporated meteor matter.

It is shown that as a result of the charging of dust particles of meteoric substance, when high particles charges are reached, conditions for the excitation of dust acoustic waves are created. For the existence of a propagating of the dust acoustic wave, it is necessary that the frequency of dust oscillations be greater than the collision frequency of dust with neutrals divided by two. This condition is satisfied for the characteristic parameters of the dusty plasmas in meteor tails. It is shown that dust acoustic waves modulate a radio wave from a meteor at frequencies characteristic for the dust acoustic mode (0.03–60 Hz). The influence of the modulational instability on the propagation of electromagnetic waves from the plasma of meteor tails is significant at altitudes characteristic to the combustion of meteors (80–120 km for small meteor bodies and lower for big meteoroids). The correlation of observations of extremely low-frequency ionospheric radio noises with frequencies of 0.03–60 Hz with meteor showers of Perseids, Leonids, Geminids, Orionids, Eta Aquarids can be explained by means of generating dusty plasmas from meteor tails at altitudes of 80–120 km and excitation of modulation instability of electromagnetic waves from meteors associated with the dust acoustic mode. It is shown that rising of electrophonic sounds in the range 0.03–60 Hz can be described by modulation of electromagnetic waves from meteors by dust acoustic perturbations in the dusty plasmas of meteor tail or in the ionospheric plasma.

The increments of modulational instability are calculated at which modulational excitation of extremely low-frequency dust acoustic disturbances occurs. The conditions of the development of modulational instability are given. It is noticed that the modulation of electromagnetic waves from meteors can be affected by charged dust, which is present in the ionosphere from previous burnt meteoroids or large dust particles that sediment from the meteor tail to the lower layers of the ionosphere. There is considered charged dust in meteor tails in the vicinity of meteor body which has higher concentration and higher charges then condensed dust in the meteor tail far from meteor body and the dust from previous meteoroids.

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