Modulational Interaction in a Dusty Plasma of Meteoroid Wakes

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Abstract—This is a study of the possible modulational instability of electromagnetic waves in meteoroid wakes associated with the dust acoustic mode at altitudes of 80–120 km, which is a linear stage of modulational interaction. The parameters of meteoroid wakes at different altitudes in the Earth's ionosphere are considered. It is shown that the charging of dust particles of meteoric matter creates conditions for the occurrence of dust acoustic waves. Dust acoustic disturbances are excited due to the modulational instability of electromagnetic waves from the meteoric trail. The influence of neutrals on the development of modulational interaction is taken into account. The concentration of neutrals in meteoroid wakes is higher than the concentration of neutrals in the Earth's ionosphere. It has been found that the condition for the excitation of a dust acoustic wave is satisfied for the typical parameters of dusty plasma of meteoroid wakes at altitudes of 100–120 km. Due to collisions between dust and neutrals, the development of modulation instability is suppressed at altitudes of 80–90 km, while inelastic collisions of neutrals with electrons and ions do not affect the development of modulational instability. The modulational instability of electromagnetic waves can explain the occurrence of low-frequency noise during the passage of meteoric bodies in a frequency range characteristic of dust acoustic waves. It is shown that the modulation instability has time to develop for characteristic temperatures and particle concentrations in meteoroid wakes. Equations for the charging of dust particles in meteoroid wakes are given. It has been found that the dust is positively charged, both in the daytime and at night, due to intense emission currents from the surface of dust particles.

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1. INTRODUCTION

Meteoric matter can break up, melt down, and evaporate due to the collision of ionospheric atoms with a meteoric body when meteoroids enter into the atmosphere. Collisions between the molecules of meteoric matter and atmospheric air at high speeds can lead to the ionization and excitation of both meteoric and atmospheric atoms. These processes generate a meteoric trail with vapors of meteoric matter, broken fragments of meteoric body, molecules, and ionized atoms of atmospheric gases and meteoric matter. Meteors are glowing trails of meteoroid vapor.

The passage of meteoric bodies is associated with various effects, such as electromagnetic and acoustic effects. The passage of meteors is accompanied by noises recorded in a wide frequency range up to 12 kHz (Spalding et al., 2017; Trautner et al., 2002; Verveer et al., 2000; Zgrablić et al., 2002). The physical phenomena and effects arising from the passage of meteors can affect the operation of radar systems, radio telescopes, geolocation devices, and rocket-passing experiments, which is important for the operation of these systems and the elimination of their failures. There were sounds heard during the passage of bright bolides, after their passage, and during meteor show-

ers. Abnormal sounds heard simultaneously with the meteor passage, which are called electrophonic sounds, are obviously associated with electromagnetic phenomena. The nanoscale charged dust that enters the Earth's atmosphere due to meteoric-body combustion can occur in the ionosphere for up to several months (*Meteornaya materiya...*, 1966) and can lead to various natural phenomena (e.g., noctilucent clouds and polar mesosphere summer echoes) (Popel, 2012).

When a meteoric body enters the atmosphere, a shock wave forms in front of it. The wave emits in the visible range and in a radio range from several Hz to hundreds of MHz (Filonenko, 2018; Keay, 1993; Spalding et al., 2017; Trautner et al., 2002; Verveer et al., 2000; Zgrablić et al., 2002; Zhang et al., 2018). Therefore, the propagation of electromagnetic waves from the meteor begins prior to visual observation of the trail.

In the scientific literature, there were assumptions on the relationship between the low-frequency noise arising from the passage of meteors and the modulation of a high-frequency electromagnetic wave by low-frequency waves; there were prerequisites for the construction of a theory of modulation of electromagnetic waves from the passage of meteors in the Earth's atmosphere (Zamozdra, 2014; Tatum and Stumpf,

2000, Spalding et al., 2017). The low-frequency range, at frequencies up to 60 Hz, is typical for dust acoustic waves, and processes associated with charged dust particles can cause these oscillations. Therefore, this mechanism may explain the low-frequency oscillations recorded during the passage of meteoric bodies. In this regard, it is necessary to consider the mechanisms of dust-particle charging and to study the possible formation of dust acoustic oscillations and their excitation due to the modulational instability, the linear stage of the modulational interaction. Kopnin and Popel (2008), Kopnin et al. (2015), and Borisov et al. (2019) considered the relationship of the formation of low-frequency noise in the ionosphere due to the development of the modulational interaction of electromagnetic waves associated with the excitation of disturbances with frequencies in the region of dust acoustic waves.

Earlier, low-frequency perturbations were assumed to generate only bright meteors, but later data showed that they accompany the passage of small meteoric bodies as well (*Meteoraya materiya ...*, 1966). Recorded data on oscillations from meteor showers, such as the Perseids, showed that, even in the absence of significant meteoroids, there are noises at low frequencies in the range of 10–300 Hz and an amplified electric field observed in a wide range from 5 Hz to 12.6 kHz (Trautner et al., 2002). At present, experiments on the recording of noise from the passage of meteoric bodies are actively being conducted. Oscillations were recorded in sufficiently wide frequency ranges: 40–100 Hz (Spalding et al., 2017), 0–10 Hz (Verveer et al., 2000), and 0–250 Hz (Zgrablić et al., 2002).

This paper proposes that low-frequency noise from meteoroid passages can be explained by the development of modulational instability of electromagnetic waves from meteoric bodies associated with dust acoustic mode (Kopnin and Popel, 2008; Borisov et al., 2019; Kopnin et al., 2015). We consider electromagnetic waves in the radio frequency range of tens and hundreds of megahertz modulated by low-frequency disturbances.

The concentration of dust in meteoroid wakes is several orders of magnitude higher than that in the Earth's ionosphere; the concentration of neutrals in meteoroid wakes is an order of magnitude higher than that at the corresponding ionospheric altitude. This leads to a high frequency of dust collisions with neutrals, which suppresses the occurrence of modulational instability at some altitudes. We locate the heights at which the development of modulational instability of electromagnetic waves associated with dust acoustic mode in meteoric wakes is possible.

Dusty plasma processes in meteoroid wakes and the related possibility of modulational instability of electromagnetic waves for different altitudes of the meteoroid passage in the Earth's ionosphere were not previously considered for collisions of dust with neu-

trals and inelastic collisions of electrons and plasma ions with neutrals. In view of this, the problem is novel and important.

The study has the following structure. The first (introductory) section describes the current state of research in this field. The second section presents the main parameters of dusty plasma in meteoroid wakes and describes the mechanisms of meteoroid breakup and formation of dusty plasma in the meteoroid wake. The third section describes the charging of dust particles in meteoroid wakes. The fourth section considers the modulation of an electromagnetic wave from the plasma of a meteor trail due to dust acoustic oscillations. The final section formulates the main results and conclusions.

2. PARAMETERS OF DUSTY PLASMA OF METEOROID WAKES

The meteoric trail is the trail in the atmosphere that remains after the passage of a meteoric body. Along the meteoroid flight trajectory, the ionization of air molecules and meteoric matter occurs to form an ion trail. This trail can be observed up to several minutes for especially bright meteors and up to a fraction of a second for weak meteors. The so-called meteoroid wake is directly behind the meteoroid. The glow of the wake and of the meteoric body itself occurs due to the excitation of atoms and ions of meteoric matter and atmospheric gases (Bronshen, 1981). The excitation potentials of metal lines in the meteor spectrum are 3–5 eV, which is much lower than the excitation potentials of gases. Therefore, the glow of meteors is largely produced by the elements that constitute meteoric bodies (metals Na, Mg, Ca, Al, Fe, and Ni and single ions) (Meteory, 1959).

Meteor trails can be ionized or dusty. Ionized meteor trails include electrons, ions, and dust particles created by the breakup of the main meteoroid or its breakaway parts. The ionized trail reflects meter- and decameter-range radio waves. Meteoric ionization is most intense at altitudes of 80–120 km, where most meteoric bodies disappear. However, large and slow bodies can penetrate deeper into the Earth's atmosphere, and ionization occurs at lower altitudes for them. Evaporation, melting, and breakup of the meteoric body leads to ablation of the meteor, i.e. the loss of its mass.

Dust trails form as a result of the cooling of jets of melted meteoric matter from the meteor head and the condensation of meteoric matter in the meteoroid tail. Cylindrical particles mainly form during the solidification of melted jets, while spherical particles form during the condensation of meteoric matter. Thus, the trail includes dust particles of less than 10^{-4} cm in size, liquid drops of meteoric matter, and gases. Meteoric dust trails can be observed for a very long time (up to

several hours). At dusk, they glow due to the scattering of sunlight, mainly on dust particles.

The powerful radiation of the shock wave ionizes the air, and the meteoric matter melts and evaporates; it is an agent of meteoroid-tail heating. With increasing pressures in the meteor trail, conditions are created for mechanical and thermomechanical meltdown of the meteoric body and the separation of dust particles and small structural grains from it. Depending on the meteoroid parameters, several melting types can be distinguished with respect to the different sizes of flying fragments: splitting, crumbling, flaking, splashing, and spraying (Bronshthen, 1981). Larger fragments can undergo progressive fragmentation during flight and disintegrate into smaller pieces (mainly through sputtering, which generates submicron particles). The temperature in the meteoroid tail changes with distance from the meteoric body and ranges from 1000 to 200 000 K (Bronshthen, 1981; Levitskii, 1981; *Meteor-naya materiya* ..., 1966; Silber et al., 2017, 2018). The temperature also depends on the flight altitude and the size of the meteoroid itself. The dust temperature is much lower than the electron temperature and is lower than the melting point of the meteoric matter; therefore, the dust in the meteoroid tail at some distance from the meteoric body will not melt.

The masses of observed meteoric bodies range widely from 10^{-7} to 10^7 g. For example, the characteristic meteor masses for meteor showers such as Perseids, Leonids, Orionids, and Draconids are small: from fractions of a gram to several hundred grams, with sizes 0.1–10 cm (Popova, 2000). The densities of meteoric bodies are around 0.5–3 g/cm³. According to the dust-lump hypothesis (Bronshthen, 1981), some meteoric bodies have a porous structure with individual inclusions of small-sized particles. This hypothesis is in good agreement with data on the altitudes at which the meteors disappear and the meteor-brightness data (Öpik, 1955). Due to their loose structure, meteoric bodies have a lower mass, glow more brightly (since the surface area of the body is larger), and break up more intensively. According to Seizinger et al. (2013), the strength characteristics of these porous particles fall by two orders of magnitude.

The higher the meteor speed is, the more intense is its breakup. The Leonids (70–72 km/s) and the Geminids (35–40 km/s) are among high-speed showers. The density of dust particles in the meteoroid wake is $n_d = 10^6$ – 10^8 cm⁻³ (Simonenko, 1968) for micron and submicron particles. An important parameter of meteor trails is the concentration of electrons and ions per centimeter of path (Bronshthen, 1981; Furman, 1960). The typical values of the linear concentrations are $n_e = 10^{12}$ – 10^{16} cm⁻¹ (depending on the mass and brightness of the meteoric body from 5^m to –5^m) and $n_i = 10^{12}$ – 10^{13} cm⁻¹. The total electron density for a meteoric body with a radius of 5 cm and a velocity of 40 km/s at altitudes from 120 to 80 km ranges from

$n_e = 10^8$ – 10^{14} cm⁻³, respectively. The neutral concentration in the meteoroid wake is higher than that at the corresponding ionospheric altitude due to the removal of meteoric atoms and varies in the range $n_n = 10^{12}$ – 10^{16} cm⁻³ at altitudes of 120 to 80 km. In addition to emissions, which contribute to the density of particles in the meteor trail and affect the ionization processes, the mechanisms of kinetic removal of meteoric electrons, ions, and neutral atoms due to their collision with air molecules, as well as the mechanisms of the potential extraction of electrons from the meteoric body by gas molecules, were also taken into account. The energy of meteoric body collision with air particles depends on the velocity of meteoric bodies and ranges from 16.6 to 1675 eV for typical meteor velocities of 11–72 km/h (Furman, 1960).

3. DUST-PARTICLE CHARGING

Let us consider the charging of dust particles in the meteoroid wake under the action of different currents. For typical parameters of the dusty plasma of meteoroid wakes, dust particles almost always acquire positive charges both in the daytime and at night.

Dust particles are affected by currents of electrons and ions of the surrounding plasma, photocurrent, and emission currents (the thermal electron emission current, thermionic emission current, autoelectronic emission current, and mechanical emission current). Autoelectronic emission is negligible due to low values of the external electric field strength in the wake (up to 10 V/m (Bronstein, 1991)). Secondary electron emission and ion emission can be disregarded in comparison with thermal electron emission, since the electron concentration is higher than the ion concentration and the coefficient of secondary electron emission is small for energies of almost several eV. Mechanical emission is accompanied by a high voltage in the crack of the meteoric body and the removal of electrons with energies of 1–100 keV, which can generate up to 300 secondary electrons of lower energies removed from the surface (Medvedev and Khokhlov, 1975). Further, these electrons can intensely ionize the ambient air at the meteoroid wake and affect the discharge of dust particles. The electrons emitted from the surface of cracks due to mechanical emission create positive charges on dust particles. The current of mechanical emission from the crack surface on dust particles rapidly decreases stepwise with time; the typical values of charged particle fluxes during mechanical emission for metals were given by Molotskii (1977). The photocurrent arising from the influence of the meteor radiation and daytime solar radiation on dust particles is smaller than the emission currents in meteoroid wakes.

The charging of dust particles is governed by the equation

$$\frac{\partial q_d}{\partial t} = \sum I, \quad (1)$$

where the right-hand side is the sum of all currents acting on the dust particle and q_d is the dust-particle charge.

Since the ion concentration is significantly lower than the electron concentration in the meteor trail (Furman, 1960), the current of ions to dust particles can be disregarded.

According to the Orbital Motion Limited (OML) model, the current of trail electrons to a dust particle in the case of positively charged particles (for spherical dust particles) can be expressed as (Vladimirov, 1994; Klumov et al., 2000)

$$I_e(q_d) = -en_e\pi a^2 \sqrt{\frac{8T_e}{\pi m_e}} \left(1 + \frac{q_d e}{a T_e}\right). \quad (2)$$

Here, $n_{(e)i}$ is the electron (ion) concentration, $T_{(e)i}$ is the electron (ion) temperature, $m_{(e)i}$ is the electron (ion) mass, a is the dust-particle radius, v_i is the hydrodynamic ion velocity, $V_{Ti} = (T_i/m_i)^{1/2}$ is the thermal velocity of ions, $V_{\min(q_d)} = (2eq_m/am_i)^{1/2}$, and $q_d = eZ_d$, where Z_d is the charge number.

The reverse current of mechanical electrons to neighboring dust particles depends on the dust-particle concentration and actually has a nature similar to the current of reverse photoelectrons to dust particles in the case of particle irradiation with X-rays (Vladimirov 1994; Klumov et al., 2000; Morozova et al., 2012). The expression for the current of reverse mechanical electrons has the form

$$I_{eM}(q_d) = -en_d Z_d \pi a^2 N_M \alpha \beta \sqrt{\frac{8T_e}{\pi m_e}} \left(1 + \frac{q_d e}{a T_e}\right), \quad (3)$$

where N_M is the coefficient of mechanical emission, which describes the number of electrons removed by a single mechanical electron, α is a coefficient showing the ratio of the crack area in which mechanical electrons are generated to the surface area of a spherical dust particle, and β is the probability of crack formation. In this study, it is assumed that $N_M = 300$, $\beta = 0.5$, and $\alpha = 1/5$.

The thermionic emission current was given by Kopnin et al. (2017)

$$I_T = \frac{4\pi m_e}{h^3} T^2 e^{-\chi/T}, \quad (4)$$

where χ is the work function of the meteoric matter, T is the temperature, and h is Planck's constant.

The thermionic-emission current is much less than the thermal electron-emission current, since the energies required for the emission of heavy ions from the particle surface have large orders of magnitude.

According to calculations, the magnitude of the dust-particle charge is largely affected by the current of thermal-electron emission due to high temperatures in the meteoroid wakes. As a result, dust particles become positively charged, both in the daytime and at night.

According to the OML model for spherical dust particles (Vladimirov, 1994; Klumov et al., 2000; Tsyrovich et al., 2008), the dust-particle charges in the stationary case can be estimated as

$$\frac{Z_d e^2}{a T} \sim 2-4, \quad (5)$$

the charge numbers are between 1 to 10^5 for particles ranging in size from nanometers to hundreds of micrometers.

4. MODULATIONAL INTERACTION OF ELECTROMAGNETIC WAVES IN THE METEOROID WAKE

The heated plasma of the meteor trail generates radio waves at frequencies of several to hundreds of megahertz. The breakup of the meteoric body and dust-particle charging can generate dust acoustic oscillations, which leads to modulational instability of electromagnetic waves.

Under conditions of diffusion equilibrium, the system of basic equations describing modulational instability has the form (Borisov et al., 2019; Kopnin et al., 2015)

$$en_{e0} \nabla \varphi - T_{e0} \nabla n_{e1} - n_{e0} \nabla T_{e1} - \frac{n_{e0} e^2}{2m_e \omega_0^2} \nabla |E|^2 = 0, \quad (6)$$

$$en_{i0} \nabla \varphi + \kappa T_{i0} \nabla n_{i1} + \kappa n_{i0} \nabla T_{i1} = 0, \quad (7)$$

$$\frac{\partial^2 n_{d1}}{\partial t^2} + v_{dn} \frac{\partial n_{d1}}{\partial t} = \frac{n_{d0} q_{d0} \Delta \varphi}{m_d}, \quad (8)$$

$$\begin{aligned} \frac{3}{2} \frac{\partial T_{e1}}{\partial t} - \frac{\chi_e}{2} \Delta T_{e1} + \bar{v}_{ei} (T_{i1} - T_{e1}) \\ + \bar{v}_{en} T_{e1} - \frac{T_{e0}}{n_{e0}} \frac{\partial n_{e1}}{\partial t} = 0, \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{3}{2} \frac{\partial T_{i1}}{\partial t} - \frac{\chi_i}{2} \Delta T_{i1} + \bar{v}_{ei} (T_{e1} - T_{i1}) \\ + \bar{v}_{in} T_{i1} - \frac{T_{i0}}{n_{i0}} \frac{\partial n_{i1}}{\partial t} = \frac{2v_e e^2 |E|^2}{m_e \omega_0^2}, \end{aligned} \quad (10)$$

$$\Delta \varphi = 4\pi(n_{e1}e - n_{i1}e - q_{d0}n_{d1} - n_{d0}q_{d1}). \quad (11)$$

Hereafter, all formulas and quantities are given in the centimeter-gram-second (CGS) system; m_ξ is the mass of particles of the type ξ , n_ξ is the concentration of particles of the type ξ ; $\xi = e, i, d$ for electrons, ions, and dust particles, respectively; $T_{(e)i}$ is the temperature of electrons (ions) measured in units of energy; e is the electron charge (ions are assumed to be

singly charged); q_d is the charge of dust particles; ϕ is the potential of low-frequency perturbation; $\mathbf{E}_0$ is the electric field of the electromagnetic pump wave; ω_0 is the frequency of this wave; and κ is the adiabatic index ($\kappa = 1$ for an isothermal process and $\kappa = 3$ for an adiabatic process). The subscript “0” corresponds to unperturbed parameters, and the subscript “1” corresponds to perturbed quantities of the first order of smallness. $\bar{\nu}_{e(i)} = \sum_{\xi=i(e),n,d} 3(m_{e(i)}/m_\xi) \nu_{e(i)\xi}$ is the effective collision rate, $\nu_{\xi\eta}$ is the rate of collisions of particles of the type $\xi = e, i, n, d$ with particles of the type $\eta = e, i, d$, which characterizes the rate of equalization of the temperatures of electrons and ions. $\chi_e = 3.16T_e/(m_e \nu_e)$ and $\chi_i = 3.9T_i/(m_i \nu_i)$ are the electron and ion thermal diffusivities, respectively; here, $\nu_{e(i)} = \sum_{\xi=i(e),n,d} \nu_{e(i)\xi}$ and Δ is the Laplace operator.

It can be seen from Eqs. (6)–(11) that the development of modulational instability is caused by Joule heating, ponderomotive force, and the charging and dynamics of dust particles.

$$\frac{|\mathbf{E}_0|^2}{4\pi n_{e0} T_{e0}} \gg \max \left\{ \frac{3 C_{sd} K \omega_0^2 \nu_e^2 + K^4 c^4}{8 \nu_e K^2 c^2} \frac{\omega_0^2}{\omega_{pe}^4}, \frac{3 (\omega_{\chi e} + \bar{\nu}_{en})^3 \omega_0^2 \nu_e^2 + K^4 c^4}{8 \nu_e C_{sd}^2 K^2} \frac{\omega_0^2}{\omega_{pe}^4} \right\}. \quad (13)$$

Here, $C_{sd} = |q_{d0}/e| \sqrt{n_d T_e / n_e T_d}$ is the dust acoustic speed; $K = |\mathbf{K}|$ is the length of the wave vector of modulational perturbations; c is the speed of light; $\omega_{\chi e} = \chi_e K^2/2$, and $\omega_{\chi i} = \chi_i K^2/2$.

For a positive dust-particle charge, the frequency of low-frequency perturbations excited from modulational instability under the condition $\omega_{\chi e} \gg \Omega \gg C_{sd} K$ can be expressed as (Kopnin et al., 2015)

$$\Omega \sim \Gamma \sim \left(\omega_0 \frac{C_{sd}^2 \omega_{pe}^4}{\chi_e \omega_0^4} \right)^{1/2} \left(\frac{|\mathbf{E}_0|^2}{4\pi n_{e0} T_{e0}} \right)^{1/2}, \quad (14)$$

where Γ is the maximum growth rate of modulational instability and ω_{pe} is the plasma electron frequency.

If $\omega_{\chi e} \gg \Omega \gg C_{sd} K$ (which is satisfied for plasma parameters of meteoroids wakes), the instability growth rate has the form

$$\gamma(K) \approx 2\sqrt{2} \left(\nu_e \frac{C_{sd}^2 K^2}{\omega_{\chi e}(K) + \bar{\nu}_{en}} \right)^{1/2} \frac{\omega_{pe}^2}{\omega_0} \times \frac{Kc}{\sqrt{\omega_0^2 \nu_e^2 + K^4 c^4}} \left(\frac{|\mathbf{E}_0|^2}{4\pi n_{e0} T_{e0}} \right)^{1/2}. \quad (15)$$

Due to the high electron temperature and high thermal diffusivity, inelastic collisions of electrons and

Modulational instability leads to an increase in low-frequency perturbations of the electric field associated with the dust acoustic mode.

Assuming that variation of low-frequency oscillations in plasma is $\exp(-i\Omega t + i\mathbf{K}\mathbf{r})$, where Ω and $\mathbf{K}$ are the frequency and wave vector associated with low-frequency perturbations, we can write the equations for the evolution of the high-frequency electromagnetic field as

$$\epsilon_{\pm} \mathbf{E}_{\pm} - \frac{c^2}{\omega_{\pm}^2} \mathbf{k}_{\pm} \times (\mathbf{k}_{\pm} \times \mathbf{E}_{\pm}) = \frac{n_{e1}}{n_{e0}} \frac{\omega_{pe}^2}{\omega_{\pm}^2} \mathbf{E}_{0\pm}, \quad (12)$$

where $\omega_{\pm} = \Omega \pm \omega_0$ and $\mathbf{k}_{\pm} = \mathbf{k} \pm \mathbf{K}_0$; ω_0 and $\mathbf{K}_0$ are the frequency and wave vector corresponding to the pump wave; $\mathbf{k}_{\pm}$ is the wave vector of the amplitude modulation of the electromagnetic pump wave; $\omega_{pe}^2 = 4\pi n_{e0} e^2 / m_e$ is the electron plasma frequency; $\epsilon_{\pm} = 1 - \omega_{pe}^2 / \omega_{\pm}^2$ is the high-frequency dielectric function of ionospheric plasma; $\mathbf{E}_{+} = \mathbf{E}$, $\mathbf{E}_{-} = \mathbf{E}^*$, $\mathbf{E}_{0+} = \mathbf{E}_0$, $\mathbf{E}_{0-} = \mathbf{E}_0^*$ (* denotes the complex conjugate).

In the case considered in this study, when $q_d > 0$, modulational instability develops if

neutrals do not affect the development of modulational instability in meteoroid wakes at altitudes of 80–120 km. For all possible wave vectors that can lead to dust acoustic oscillations, these collisions can be disregarded. The minimum values of wave vectors K of low-frequency perturbations that can lead to excited dust acoustic oscillations at altitudes from 120 to 80 km have a range of 0.004– $6 \times 10^3 \text{ cm}^{-1}$, respectively; the characteristic values of wave vectors at altitudes from 120 to 80 km are in the range 10^2 – 10^4 cm^{-1} , respectively.

The law for the dispersion of dust acoustic waves has the form

$$\omega_{sd}(K) = \text{Re } \omega_{sd}(K) + i \text{Im } \omega_{sd}(K), \quad (16)$$

where

$$\text{Re } \omega_{sd}(K) = \sqrt{\frac{C_{sd}^2 K^2}{1 + \lambda_d^2 K^2} - \frac{\nu_{dn}^2}{4}}, \quad (17)$$

$$\text{Im } \omega_{sd}(K) = -\frac{\nu_{dn}}{2} - \frac{(\text{Re } \omega_{sd}(K))^2}{2} \left(\frac{\nu_{en}}{K^2 \nu_{Te}^2} + \frac{\nu_{in}}{K^2 \nu_{Ti}^2} \right). \quad (18)$$

Here, K is the length of the wave vector of dust acoustic perturbations, $\nu_{dn} = (4/3) \pi a^2 \sqrt{8T_{n0}/\pi m_n n_n} (m_n/m_d)$ is the rate of dust collisions with neutrals,

Table 1. Parameters of dusty plasma of meteoroid wakes and quantities characterizing the modulational instability of electromagnetic waves in meteoroid wakes for a meteoroid with a radius of 5 cm and a velocity of 40 km/s

h , km	T_e , eV	T_n , eV	n_n , cm ⁻³	n_d , cm ⁻³	n_e , cm ⁻³	K_{ch} , cm ⁻¹	C_{sd}/λ_d , c ⁻¹	Γ , s ⁻¹	$v_{dn}/2$, c ⁻¹
80	2	1.5	10 ¹⁶	10 ⁹	5 × 10 ¹⁴	10 ⁴	5 × 10 ⁵	360	6 × 10 ⁴
90	1	0.9	10 ¹⁵	10 ⁸	10 ¹³	5 × 10 ³	2 × 10 ⁴	60	300
100	0.8	0.7	10 ¹⁴	4 × 10 ⁷	10 ¹²	1.7 × 10 ³	6 × 10 ⁴	15	7.8
110	0.6	0.5	10 ¹³	10 ⁷	10 ¹⁰	2 × 10 ³	5 × 10 ³	9	3.6
120	0.4	0.4	10 ¹²	10 ⁶	10 ⁸	33	1.5 × 10 ⁴	2.4	0.4

The concentrations and temperatures are given for a distance of more than 40 m from the meteoric body.

$\lambda_D^{-2} = \lambda_{De}^{-2} + \lambda_{Di}^{-2}$, $\lambda_{De(i)} = \sqrt{T_{e(i)}/4\pi n_{e(i)}e^2}$ is the Debye length for electrons (ions), and $\omega_d = \sqrt{4\pi n_{d0}q_d^2/m_d}$ is the dust plasma frequency.

The expression for the imaginary part was obtained under the assumptions $\omega_{sd} \gg v_{dn}, K v_{Td}$, $v_{en} \gg \omega_{sd}, K v_{Te}$, $v_{in} \gg \omega_{sd}, K v_{Ti}$, $\omega_{sd} v_{en} \gg K^2 v_{Te}^2$, and $\omega_{sd} v_{in} \gg K^2 v_{Ti}^2$, which are normally satisfied for meteor trail plasmas.

The method described here can be applied for meteor trails if the length λ of the electromagnetic wave from the meteor is much less than the meteoroid wake width L . Otherwise, the inhomogeneity effects must be taken into account. It should be noted that the frequencies of electromagnetic radio waves recorded on the Earth's surface from meteoroids range widely from several hertz to hundreds of megahertz. However, based on the applicability of the method and the meteoroid wake parameters in this problem, we explain the occurrence of low-frequency oscillations due to modulational instability by considering radio waves of the meter and decimeter ranges (which correspond to frequencies of around tens and hundreds of MHz (Zhang et al., 2018)), because meteors with a size of 1–10 cm generate a wake with a radius from meter to tens of meters.

Dust acoustic perturbations are excited from the modulational instability of electromagnetic waves. If the instability growth rate Γ , which includes the electromagnetic pump wave, is less than half the rate of collisions of neutrals with dust (v_{dn}), modulational instability (which is the linear stage of modulation interaction) can develop. A propagating dust acoustic wave can exist if $\omega_d \approx C_{sd}/\lambda_d > v_{dn}/2$. Based on the allowable wave vectors of dust acoustic perturbations and Eqs. (16)–(18), one can find that the dust acoustic frequencies belong to the low-frequency range.

Since the concentrations of electrons and ions in meteor trails are almost the same for nocturnal and daytime parameters, the instability growth rates are calculated for one case. Let us find the growth rates of modulational instability for different parameters of the

dusty plasma of meteor trails (at temperature $T_e = 2$ eV) for dust particles with a size of $a = 140$ nm and a charge of $Z_d = 10^3$ (viable particles for monodisperse silicates, and granite and stony meteoric bodies). The electric field strength E_0 in the meteoroid wake is taken to be 10 V/m (Bronshen, 1991).

Table 1 presents the parameters of dusty plasma of meteoroid wakes depending on height, the calculated instability growth rates of electromagnetic waves, and the conditions for the propagation of dust acoustic waves. Dust particles with a size of 140 nm and a charge number $Z_d = 10^3$ are considered.

It can be seen from Table 1 that the instability growth rates are $\Gamma > v_{dn}/2$ for altitudes of 100–120 km and $\omega_d \approx C_{sd}/\lambda_d > v_{dn}/2$ for altitudes of 80–120 km. Consequently, the development of modulational instability of the electromagnetic wave from the meteor trail and the excitation of dust acoustic oscillations in the meteor trail due to the development of modulational instability occur at altitudes of 100–120 km. At lower altitudes, modulational instability is suppressed due to collisions of dust with neutrals.

Calculations conducted by Silber et al. (2017) show that the temperature in the meteoroid wake decreases very quickly and drops in the first 10⁻³ s of the flight by half an order of magnitude, which is in good agreement with the data obtained by Levitskii and Abrikhmanov (1981). They showed that heat transfer from the plasma of the meteoric body wake occurs mainly due to electron thermal conductivity, especially at altitudes of 100–120 km. The temperature in the meteoroid wake changes according to a power law with time: $T \sim t^{1/2}$ (Jenniskens and Stenbaek-Nielsen, 2004).

Table 1 gives the particle temperatures and concentrations in the meteoroid for distances above 40 m from the meteoric body. At this distance, the temperatures retain for ~0.1 s at the wake periphery and for a longer time at its center (Silber et al., 2017). It can be seen from Table 1 that the instability development time ($\sim 1/\Gamma$) is less than 0.1 s, which means that modulational instability should be expected for the given section of the meteor wake at altitudes of 100–120 km. At the same time, the instability does not have time to

develop for a wake head up to 40 m (corresponding to 10^{-3} s and higher electron temperatures and, as a consequence, lower instability growth rates).

Dusty plasma also forms at altitudes below 80 km for large meteoric bodies that do not have time to burn up at these altitudes in the meteor wake; here, the temperatures and concentrations will be higher due to the invasion of the meteoric body into denser layers of the atmosphere.

However, due to the absence of surrounding electrons in the external environment, the wake does not cool as quickly as at ionospheric heights, since there is no electron cooling due to the thermal conductivity of ionospheric plasma, which is the fastest cooling process for electrons. Here, pair collisions with atmospheric molecules and diffuse electron cooling are important.

Modulational instability cannot develop at these altitudes. However, large dust concentrations at altitudes of 90 km or lower can lead to new physical effects that require a more detailed study. One of the effects may be the coagulation of dust particles in the meteoroid wake, even with similarly charged particles, due to the development of gravitational–electrostatic instability.

The mechanism of modulational interaction proposed in this study may qualify as one of the mechanisms explaining the fact that low-frequency noise is recorded simultaneously with the passage of meteoroids and the occurrence of electrophonic sounds in the presence of converters of electromagnetic waves to sound waves at the Earth's surface.

5. CONCLUSIONS

Dusty plasma processes in the Earth's ionosphere associated with the passage of meteoric bodies and the propagation of the meteor trail are considered. An explanation is proposed for the occurrence of low-frequency noise from the passage of meteoroids due to modulational instability of electromagnetic waves associated with dust acoustic mode. As a result of the charging of dust particles of meteoric matter generated from the breakup of the meteoric body and the acquisition of electric charges by the particles, conditions are created for the occurrence of dust acoustic waves. The possibility of the excitation of dust acoustic perturbations due to the development of modulational instability of electromagnetic waves from a meteoroid in the frequency range characteristic of dust acoustic waves is described. A propagating dust acoustic wave can exist if the rate of dust oscillations exceeds the rate of collisions of dust with neutrals. At altitudes of 100–120 km, one should expect the excitation of dust acoustic waves associated with the development of modulational instability for the typical parameters of the dusty plasma of meteoroid wakes.

It is noted that dust formation in the meteoroid wake is due to the breakup of the meteoric body. Mechanisms are described for the charging of dust particles in the meteoroid wakes under the action of currents of electrons and ions of the surrounding plasma and emission currents. The characteristic charge numbers for submicron dust particles are estimated.

The growth rates at which the modulational excitation of low-frequency dust acoustic perturbations occurs are calculated. This paper considers the case in which the length of the electromagnetic wave is much less than the width of the meteoroid wake. In this case, the method to describe the modulational interaction can be used. For typical parameters of meteoroid wakes, the development of modulational instability is possible at altitudes of 100–120 km; at altitudes of 80–90 km, modulational instability is suppressed due to dust collisions with neutrals. It has been shown that modulational instability should be expected for the chosen section of the meteor wake at a distance of at least 40 m from the bow shock wave at altitudes of 100–120 km, since the times of instability development turn out to be shorter than the change in the temperatures and concentrations in the dusty plasma of the meteoroid wake (at this section of the wake). It is noted that large dust concentrations at altitudes of 90 km or lower can lead to new physical effects that require a more detailed study (for example, the coagulation of dust particles in the meteoroid wake).

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REFERENCES

- Borisov, N.D., Kopnin, S.I., Morozova, T.I., and Popel, S.I., Role of collisions with neutrals in the process of modulational excitation of dust acoustic perturbations in dusty ionosphere, *Plasma Phys. Rep.*, 2019, vol. 45, no. 4, pp. 355–360.
- Bronshten, V.A., *Fizika meteornykh yavlenii* (Physics of Meteoric Phenomena), Moscow: Nauka, 1981.

- Bronshten, V.A., Electric and electromagnetic phenomena accompanying meteoric flights, *Astron. Vestn.*, 1991, vol. 25, pp. 490–501.
- Filonenko, A.D., High-frequency radio emission from meteors, *Geomagn. Aeron. (Engl. Transl.)*, 2018, vol. 58, no. 5, pp. 693–699.
- Furman, A.M., The theory of meteoric wake ionization, II, *Astron. Zh.*, 1960, vol. 37, no. 4, pp. 746–752.
- Jenniskens, P. and Stenbaek-Nielsen, H.C., Meteor wake in high frame-rate images: Implications for the chemistry of ablated organic compounds, *Astrobiology*, 2004, vol. 4, pp. 95–109.
<https://doi.org/10.1089/153110704773600267>
- Keay, C.S.L., Progress in explaining the mysterious sounds produced by very large meteor fireballs, *J. Sci. Explor.*, 1993, vol. 7, no. 4, pp. 337–351.
- Klumov, B.A., Popel, S.I., and Bingham, R., Dust particle charging and formation of dust structures in the upper atmosphere, *JETP Lett.*, 2000, vol. 72, no. 7, pp. 364–368.
- Kopnin, S.I. and Popel, S.I., Generation of infrasonic waves by low-frequency dust acoustic perturbations in the Earth's lower ionosphere, *Plasma Phys. Rep.*, 2008, vol. 34, no. 6, p. 471–479.
- Kopnin, S.I., Popel, S.I., and Morozova, T.I., Modulational excitation of inhomogeneities in dusty ionospheric plasma, *Plasma Phys. Rep.*, 2015, vol. 41, no. 2, pp. 171–177.
- Kopnin, S.I., Morozova, T.I., Popel, S.I., On the charging of dust plasma particles subjected to the action of an electron beam, *Inzh. Fiz.*, 2017, no. 11, pp. 38–44.
- Levitskii, S.M. and Abrakmanov, N., Cooling of electrons in meteor wakes, *Geomagn. Aeron.*, 1981, vol. 21, pp. 674–677.
- Medvedev, Yu.A. and Khokhlov, V.D., Conditions for the formation of an atmospheric shock wave by a meteoroid, *Astron. Vestn.*, 1975, vol. 9, no. 2, pp. 102–106.
- Meteorная материya v atmosfere Zemli. Sbornik statei* (Meteoric Matter in the Earth's Atmosphere. Collection of Papers), Fedynskii, V.V., Astapovich, I.S., Bronshten, V.A., Zotkin, I.T., and Tsvetkov, V.I., Eds., Moscow: Nauka, 1966.
- Meteor. Sbornik statei* (Meteors. Collection of Papers), Astapovich, I.S., Ed., Moscow: Nauka, 1959.
- Molotskii, M.I., Ion–electron mechanism of mechanism emission, *Fiz. Tverd. Tela*, 1977, vol. 12, no. 2, pp. 642–644.
- Morozova, T.I., Kopnin, S.I., and Popel, S.I., Destruction of microparticles related to dusty plasma processes and possible technological applications, *Probl. At. Sci. Technol., Ser.: Plasma Phys.*, 2012, vol. 82, pp. 84–87.
- Öpik, E.J., Meteor radiation, ionization and atomic luminous efficiency, *Proc. R. Soc. A: Math. Phys. Eng. Sci.*, 1955, vol. 230, pp. 463–501.
- Popel, S.I., *Lektsii po fizike pylevoi plazmy* (Lectures on Dusty Plasma Physics), Moscow: MFTI, 2012.
- Popova, O., Ablation of Leonid meteoroids, in *38th Aerospace Sciences Meeting and Exhibit*, Am. Inst. Aeronaut. Astronaut., 2000, AIAA-2000-0587.
<https://doi.org/10.2514/6.2000-587>
- Seizinger, A., Speith, R., and Kley, W., Tensile and shear of strength of porous agglomerates, *Astron. Astrophys.*, 2013, vol. 559, id A19.
<https://doi.org/10.1051/0004-6361/201322046>
- Silber, E.A., Hocking, W.K., Niculescu, M.L., Gritsevich, M., and Silber, R.E., On shock waves and the role of hyperthermal chemistry in the early diffusion of over dense meteor, *Mon. Not. R. Astron. Soc.*, 2017, vol. 469, pp. 1869–1882.
- Silber, E.A., Boslough, M., Hocking, W.K., Gritsevich, M., and Whitaker, R.W., Physics of meteor generated shock waves in the Earth's atmosphere: A review, *Adv. Space Res.*, 2018, vol. 62, no. 3, pp. 489–532.
- Simonenko, A.N., On the hypothesis of the fragmentation of meteor bodies due to separation of small particles, in *Physics and Dynamics of Meteors*, Kresak, L. and Millman, P.M., Eds., Dordrecht: D. Reidel, 1968, pp. 207–215.
- Spalding, R., Tencer, J., Sweatt, W., Conley, B., Hogan, R., Boslough, M., Gonzales, G., and Spurny, P., Photoacoustic sounds from meteors, *Sci. Rep.*, 2017, vol. 7, pp. 41251–41257.
<https://doi.org/10.1038/srep41251>
- Tatum, J.B. and Stumpf, L.L., The Vancouver Island fireballs of spring 1998, *Publ. Astron. Soc. Pac.*, 2000, vol. 112, no. 777, pp. 1487–1495.
- Trautner, R., Koschny, D., Witasse, O., Zender, J., and Knöfel, A., ULF–VLF electric field measurements during the 2001 Leonid storm, in *Proc. Asteroids, Comets, Meteors, ACM-2002, International Conference*, Warmbein, B., Ed., Noordwijk, Netherlands: ESA, 2002, pp. 161–164.
- Tsyтович, V.N., Morfill, G.E., Vladimirov, S.V., and Thomas, H., *Elementary Physics of Complex Plasmas*, Berlin: Springer, 2008.
- Verveer, P., Bland, A., and Bevan, A.W.R., Electrophonic sounds from the reentry of the Molniya 1–67 satellite over Australia: Confirmation of the electromagnetic link, in *63rd Annual Meteoritical Society Meeting*, 2000, p. A163.
- Vladimirov, S.V., Propagation of waves in dusty plasmas with variable charges on dust particles, *Phys. Plasmas*, 1994, vol. 1, pp. 2762–2767.
- Zamozdra, S.N., On the sound generation by bolide radiation, in *Materialy Vserossiiskoi nauchn. konf. "Meteorit Chelyabinsk—god na Zemle"* (Proceedings of the All-Russian Scientific Conference "The Chelyabinsk Meteorite: A Year on the Earth"), Chelyabinsk, 2014, p. 151.
- Zgrablić, G., Vinković, D., Gradečak, S., Kovačić, D., Biliskov, N., Grbac, N., Andreić, Ž., and Garaj, S., Instrumental recording of electrophonic sounds from Leonid fireballs, *J. Geophys. Res.*, 2002, vol. 107, SIA11–1.
<https://doi.org/10.1029/2001JA000310>
- Zhang, X., Hancock, P., Devillepoix, H.A.R., et al., Limits on radio emission from meteors using the MWA, *Mon. Not. R. Astron. Soc.*, 2018, vol. 477, pp. 5167–5177.

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