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Lower Hybrid Waves upon Interaction of Meteor Wakes with the Earth's Ionosphere

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Abstract—The possibility of generation of lower hybrid waves in meteoroid wakes upon their interaction with the Earth's ionosphere is analyzed. The lower hybrid waves are driven as a result of development of the Buneman-type instability due to motion of meteoroid-wake plasma relative to the Earth's magnetic field. Magneto-modulational processes that are induced by existence of the lower hybrid waves in plasma and leading to generation of quasi-stationary perturbations of magnetic field are discussed. It is demonstrated that these perturbations are of the same order of magnitude as magnetic fields induced by meteoroids passing through the Earth's atmosphere.

Keywords: Earth's ionosphere, meteoroid tails, lower hybrid waves, magnetic fields, modulational interaction
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1. INTRODUCTION

Passage of meteoroid bodies as natural phenomena independent of humans and hardly predictable must be studied in detail in order to understand processes that they induce, along with consequences that they can have for nature and humans. Physical phenomena and effects accompanying passage of meteor bodies can influence operation of radars, radio telescopes, remote-sensing devices, and experiments involving sounding rockets, which should be taken into consideration in the course operation of the systems listed above and correction of their malfunctioning.

Meteors represent a glow of meteoroid vapor (meteor body). Meteoroids appear either individually (predominantly, fragments of an asteroid) or as meteor showers (shooting stars) that are related to the Earth's crossing an orbit of a comet. Up to several meteors per hour can be observed during meteor showers. A meteor body entering the Earth's atmosphere creates a meteor trail as a result of collision of atoms of ionosphere and the meteor body. The trail contains vapor of meteoroid material, fragments of meteor body, molecules, ionized atoms of atmospheric gases and meteor material.

Methods of plasma physics are frequently used for explanation of meteor phenomena. For example, the mechanism of generation of low-frequency radio noise during Perseid, Leonid, Genimid, and Orionid meteor showers is related to development of modulational interaction in dusty plasma of the Earth's ionosphere [1, 2]. Modulational interaction is also important for explanation of acoustic waves generated by meteor showers [3–5].

Generation of magnetic fields appearing during meteoroid passage is an important aspect of physics of meteor phenomena that can also be related to development of modulational interaction in plasma [6]. The magnitude of such magnetic fields reaches $\sim 10^{-4}$ G [7–9]. Hitherto, there is no generally accepted concept regarding the main mechanism of the magnetic effect indiced in the Earth's atmosphere by celestial bodies, which is related to small amount of available observational data in the first place.

It is well known that development of modulational interaction of high-frequency waves that leads to generation of low-frequency transverse electric fields is accompanied by a relatively intense generation of quasi-stationary magnetic fields [6]. Modulational interaction of lower hybrid (LH) waves that describes random walks of the lines of magnetic field created in the process of plasma heating by high-intensity HF field and imposes restrictions on application of HF fields (especially, in the range of frequencies close to the LH resonance) for plasma heating [10] frequently plays an important role. Similar phenomena influence lower hybrid current drive at fusion facilities [11]. The LH waves play substantial role in various natural plasma systems, such as the magnetosphere of the Earth [12, 13], the lunar exosphere [14], etc.

The present work aims at exploring the possibility of generation of LH waves upon interaction of meteor wakes with the Earth's ionosphere, determining quasi-stationary magnetic fields formed as a result of development of modulational interaction of the LH waves, and comparing them with magnetic fields appearing during meteoroid passage. The mechanism of generation of the LH waves upon propagation of meteor-wake plasma in ionosphere relative to the Earth's magnetic field is described in Section 2. Section 3 deals with analysis of magneto-modulational processes with participation of LH waves and associated with them generation of quasi-stationary magnetic fields. The conclusions are briefly summarized in Section 4.

2. EXCITATION OF LH WAVES

The so-called meteoroid wake appears immediately behind the meteor body [15]. The nature of the wake luminocity is the same as that of the meteor itself: light is emitted by excited atoms and ions of the meteor material and atmospheric gases. Meteoroid wake can also contain dust particles formed as a result of fragmentation of the main meteor body or its parts. Meteor ionization is most intense at altitudes of 80–120 km, i.e., it occurs upon interaction of meteoroid wake with the Earth's ionosphere.

Velocity $\mathbf{u}$ of meteoroid-wake plasma relative to ionospheric plasma can be comparable to velocity of the main meteor body that is quite high (Fig. 1) [16]. Concentration of electrons and ions per centimeter of travelled distance is an important parameter characterizing meteor trails [15, 17]. Characteristic values of linear concentrations are $n_e = 10^{12}$–10^{16} cm^{-1} (depending on mass and brightness of the meteor body ranging from 5^m to -5^m) and $n_i = 10^{12}$–10^{13} cm^{-1}. Using linear concentration, it becomes possible estimating the total concentration per unit solid angle of the meteor trail that also depends on diffusion coefficient (see [15], page 297). Typical values of thus found concentrations are $n_{e\mathrm{M}} = 10^9$–10^{13} cm^{-3} and $n_{i\mathrm{M}} = 10^8$–10^{12} cm^{-3}. Electron and ion temperatures are equal to $T_{e\mathrm{M}} = T_{i\mathrm{M}} = 2$ eV. The characteristic size a of dust particles in a meteor trail falls in the range from 80 nm to 1 μm [18], and concentration n_d of dust particles varies from 10^6 to 10^8 cm^{-3}. Typical parameters of ionospheric plasma at, say, altitude of 90 km are: electron and ion concentrations of $n_{e\mathrm{I}} \sim n_{i\mathrm{I}} \sim 3 \times 10^4$ cm^{-3}; electron and ion temperatures of $T_{e\mathrm{I}} \approx T_{i\mathrm{I}} \approx 140$ K.

Concentrations of ionospheric electrons and ions upon interaction of meteor wake with ionosphere are thus substantially lower than concentrations of electrons and ions in the meteor wake. It turns out that interaction of wake electrons and ions with the Earth's magnetic field plays the dominant role upon propagation of meteor-wake plasma relative to ionosphere. Motion of electrons and ions of the meteor wake relative to magnetic field of the Earth $\mathbf{B}_0$ ($|\mathbf{B}_0| \sim 0.5$ G)

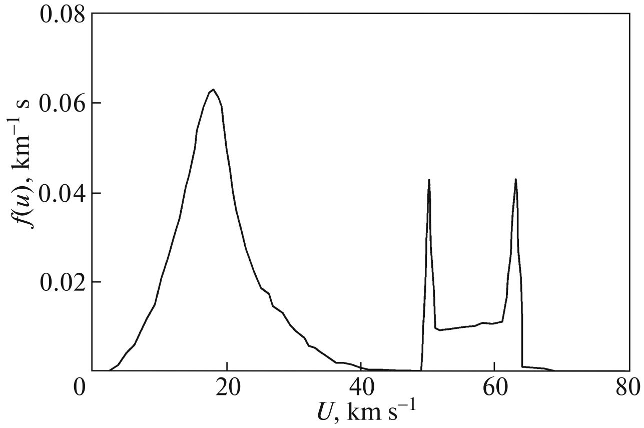

Fig. 1. Distribution function of meteoroids near the Earth with respect to velocity u (according to [16]).

leads to development of the Buneman-type instability [19]. Indeed, using expressions describing magnetoactive cold plasma (see, e.g., Eq. (56.12) in [20]), taking into account the Doppler effect for electrons and ions moving relative to the Earth's magnetic field (in the same way as this effect is taken into account in the case of hydrodynamic beam instability, see, e.g., [21]), magnetization of electrons and lack of magnetization of ions, and retaining the leading-order terms at $\cos\Theta \ll 1$, we obtain the following linear dispersion relation in the Earth's coordinate system:

$$1 + \frac{\omega_{pe\mathrm{M}}^2}{\omega_{Be}^2} - \frac{\omega_{pe\mathrm{M}}^2 \cos^2\Theta}{(\omega - k_\parallel u_\parallel)^2} - \frac{\omega_{pi\mathrm{M}}^2}{(\omega - \mathbf{k}\cdot\mathbf{u})^2} = 0, \qquad (1)$$

where index $\parallel$ characterizes vector component parallel to external magnetic field $\mathbf{B}_0$, $\cos\Theta = k_\parallel/|\mathbf{k}|$, $\omega_{pe(i)\mathrm{M}}$ is the electron (ion) plasma frequency in the meteoroid wake, $\omega_{Be} = e|\mathbf{B}_0|/m_e c$ is the electron gyrofrequency, $-e$ is the electron charge, m_e is the electron mass, and c is the speed of light.

Dispersion relation (1) has unstable solutions. Instability causes an increase in the amplitude of longitudinal electrostatic plasma oscillations with a growth rate on the order of the LH-resonance frequency. Indeed, since $k_\parallel \ll k$ and $u_\parallel \le u$, we have $|k_\parallel u_\parallel| \ll |\mathbf{k}\cdot\mathbf{u}|$. In this case, when finding solution to the dispersion equation, the latter can be recast in the form

$$1 + \frac{\omega_{pe\mathrm{M}}^2}{\omega_{Be}^2} - \frac{\omega_{pe\mathrm{M}}^2 \cos^2\Theta}{\omega^2} - \frac{\omega_{pi\mathrm{M}}^2}{(\omega - \mathbf{k}\cdot\mathbf{u})^2} = 0 \qquad (2)$$

that is typical of the Buneman-type instability. Let $\cos\Theta \gg \sqrt{m_e/m_i}$, where m_i is the ion mass. In this case, the fourth term on the left-hand side of (2) is significant only for values of $\mathbf{k}\cdot\mathbf{u}$ close to ω. Maximum value of the growth rate of instability can be found using the method described in [21], according to which

$$\omega = \frac{\omega_{peM}\cos\Theta}{\sqrt{1+\omega_{peM}^2/\omega_{Be}^2}} + \delta\omega \approx \omega_{LH}(\cos\Theta) + \delta\omega, \quad \delta\omega \ll \omega_{LH}(\cos\Theta), \tag{3}$$

$$\omega = \mathbf{k}\cdot\mathbf{u} + \delta\omega, \quad \delta\omega \ll |\mathbf{k}\cdot\mathbf{u}|. \tag{4}$$

Here, $\omega_{LH}(\cos\Theta) = \sqrt{\omega_{piM}^2 + \omega_{peM}^2\cos^2\Theta}/\sqrt{1+\omega_{peM}^2/\omega_{Be}^2}$ is the LH-wave frequency in the wake of a meteoroid propagating at angle Θ relative to the Earth's magnetic field. Under the condition of $|k_\parallel u_\parallel| \ll |\mathbf{k}\cdot\mathbf{u}|$, relation (4) justifies transition from (1) to (2) when searching for solution to the dispersion equation.

Assuming that

$$\omega_{LH}(\cos\Theta) \approx \mathbf{k}\cdot\mathbf{u}, \tag{5}$$

we thus obtain a cubic equation of the form

$$\frac{2\delta\omega\sqrt{1+\omega_{peM}^2/\omega_{Be}^2}}{\omega_{peM}\cos\Theta} - \frac{\omega_{piM}^2}{(\delta\omega)^2\left(1+\omega_{peM}^2/\omega_{Be}^2\right)} = 0 \tag{6}$$

that has an unstable solution characterized by the growth rate of

$$\gamma_{\max}^{\rm Hydro} = \frac{\sqrt{3}}{2^{4/3}}\frac{\omega_{piM}}{\sqrt{1+\omega_{peM}^2/\omega_{Be}^2}}\left(\frac{\omega_{peM}^2\cos^2\Theta}{\omega_{piM}^2}\right)^{1/6}. \tag{7}$$

Dispersion relation (3) is typical of LH waves propagating at angles Θ relative to the earth's magnetic field that satisfy the condition $\cos\Theta \gg \sqrt{m_e/m_i}$. The presence of exponent 1/6 in the last multiplier on the right-hand side of (7) means that excitation of discussed oscillations upon propagation of a meteoroid in the Earth's ionosphere for typical parameters of plasma in the meteoroid wake is characterized by the growth rate on the order of frequency $\omega_{LH0} \equiv \omega_{piM}/\sqrt{1+\omega_{peM}^2/\omega_{Be}^2}$ of the LH resonance.

The time interval during which plasma of a meteoroid wake is present in the Earth's ionosphere is $t_M > 0.1$ s, while characteristic time of development of LH instability

$$\tau = \left(\gamma_{\max}^{\rm Hydro}\right)^{-1} \tag{8}$$

for typical parameters of the meteoroid-wake plasma is on the order of 10^{-5}–10^{-4} s. The time of existence of the meteoroid-wake plasma in the ionosphere is thus sufficient for generation of LH waves due to the instability described above. Moreover, efficient development of nonlinear processes can be expected since $t_M \gg \tau$.

3. NONLINEAR EXCITATION OF MAGNETIC FIELDS

Similar to hydrodynamic instability resulting in excitation of ion-acoustic waves [22], the case in which LH waves are driven as a result of development of the Buneman-type instability should be analyzed from the point of view of strong turbulence. In the process, modulational interaction represents an important nonlinear process [6]. Development of modulational interaction can be accompanied by the process related to increase in spontaneous magnetic fields. Magnetic field $\delta\mathbf{B}$ accidentally induced in plasma locally changes the phase of the waves present in plasma in the first place. Such waves characterized by an inhomogeneous phase distribution interfere with each other thereby inducing an average vortex current that enhances fluctuations of magnetic field $\delta\mathbf{B}$. This, in turn, increases inhomogeneity of phases of oscillations, and so on. Excitation of magnetic fields in accompanied by modulation of phases of oscillations [23, 24].

An equation describing magneto-modulational excitation of magnetic field has the form [10, 11]

$$\Delta\delta\mathbf{B} = \frac{1}{|\mathbf{B}_0|}\frac{\omega_{peM}^2}{\omega_0^2}\nabla\times\nabla\times(\mathbf{E}_\perp(\mathbf{b}\cdot\mathbf{E}^*) + \mathbf{E}_\perp^*(\mathbf{b}\cdot\mathbf{E})), \tag{9}$$

where Δ is the Laplace operator, $\mathbf{b} = \mathbf{B}_0/|\mathbf{B}_0|$ is the unit vector along the direction of unperturbed magnetic field $\mathbf{B}_0$, $\mathbf{E}$ is the complex amplitude of the LH field, asterisk denotes a complex conjugate, ω_0 is the characteristic frequency in the spectrum of LH waves, and index $\perp$ denotes a vector component perpendicular to magnetic field $\mathbf{B}_0$. Equation (9) is valid at $\omega_{LH0} \ll \omega_{Be}$.

Amplitude of quasi-stationary perturbations of magnetic field $\delta\mathbf{B}$ driven by LH waves can be estimated using Eq. (9):

$$|\delta\mathbf{B}| \sim \frac{\omega_{peM}^2}{\omega_0^2}\frac{|\mathbf{E}|^2}{|\mathbf{B}_0|}\cos\Theta_0, \tag{10}$$

where Θ_0 is the characteristic angle between the direction of propagation of the LH wave and the direction of magnetic field $\mathbf{B}_0$. Taking into account relation $W^{\rm LH} = |\mathbf{E}|^2(1+\omega_{peM}^2/\omega_{Be}^2)/2\pi$ between energy density of LH wave $W^{\rm LH}$ and $|\mathbf{E}|^2$ (see, e.g, [25]), we finally obtain that

$$|\delta\mathbf{B}| \sim 2\pi\frac{\omega_{peM}^2/\omega_0^2}{1+\omega_{peM}^2/\omega_{Be}^2}\frac{W^{\rm LH}}{|\mathbf{B}_0|}\cos\Theta_0 \approx \frac{2\pi}{\cos\Theta_0}\frac{W^{\rm LH}}{n_{eM}T_{eM}}\frac{n_{eM}T_{eM}}{|\mathbf{B}_0|}. \tag{11}$$

The latter equation takes into account the fact that $\omega_{Be} \ll \omega_{peM}$ in the case under consideration. At $\cos\Theta_0 = 0.1$, $n_{eM} \sim 10^9$ cm^{-3}, $T_{eM} = 2$ eV, and

$W^{\mathrm{LH}}/n_{e\mathrm{M}}T_{e\mathrm{M}} = 10^{-4}$, we find that $|\delta\mathbf{B}| \sim 3\times10^{-5}$ G, which corresponds to magnitudes of magnetic fields observed during meteoroid passages.

4. CONCLUSIONS

We have demonstrated that LH waves can be driven as a result of development of the Buneman-type instability caused by relative motion of the meteoroid-wake plasma and magnetic field of the Earth upon interaction of meteoroid wakes with the Earth's ionosphere. Conditions facilitating development of magneto-modulational instability of the LH waves that causes generation of quasi-stationary perturbations of magnetic field are created in the discussed system. The magnitude of these perturbations corresponds to the data on magnetic fields obtained in the course of observations of meteoroids passing through the Earth's atmosphere. We analyzed the situation in which the wavelength of the LH wave is much shorter than the trail width. The method used for description of the LH waves and magneto-modulational interaction is applicable in this case.

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