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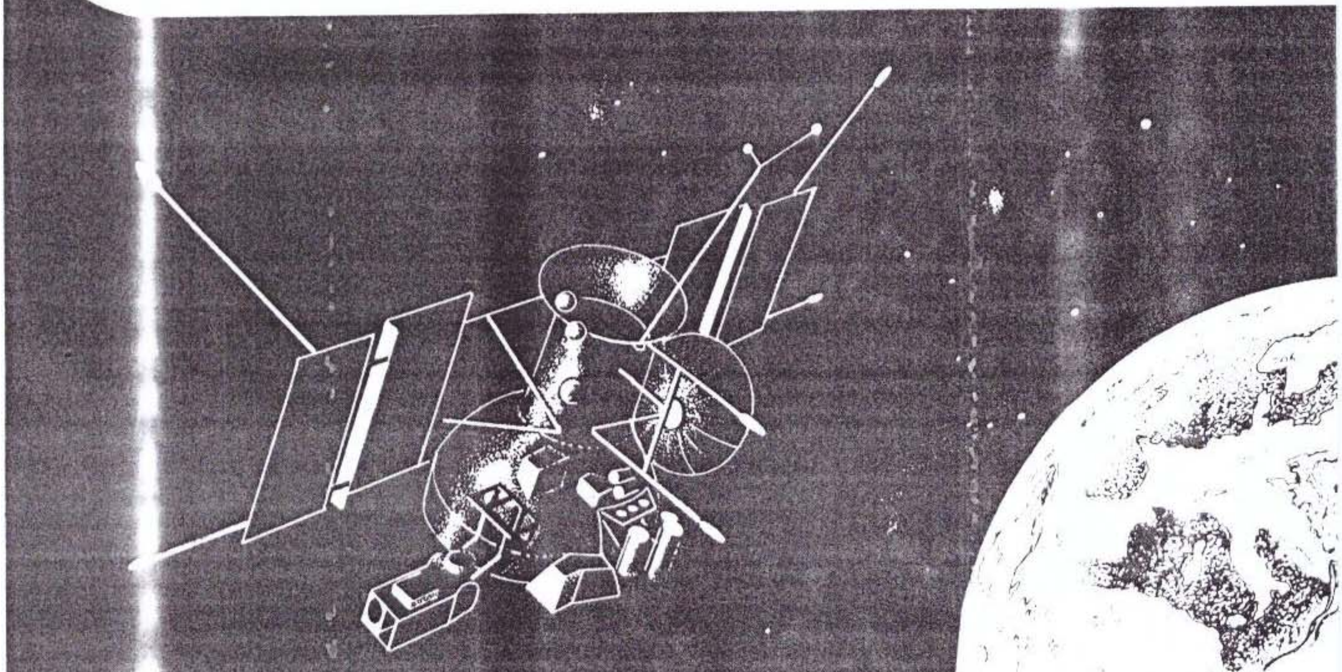

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Generation of Low-Frequency Whistlers by Infrasonic Waves in the Ionospheric E-Region During Disturbances of a Various Nature*

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It is well known that during severe thunderstorms, explosions, earthquakes, and other disturbances infrasonic waves are generated in the frequency range $0.1 < f_a < 20$ Hz (for example, see [1, 2]). These waves reach the ionospheric E-region (the height range $z \approx 100$–170 km) without hindrance; this causes additional currents and electric and magnetic field disturbances, i.e., the generation and the strengthening of various waves. It is also well known that the whistlers (the whistling modes) are the electromagnetic waves propagating in weakly ionized plasma for which the following conditions are satisfied:

$$\nu_{en} \ll \omega_{Be}, \qquad \nu_{in} \ll \omega_{Bi}, \tag{1}$$

where ω_{Be} and ω_{Bi} are the gyrofrequencies and ν_{en} and ν_{in} are the frequencies of collisions of neutrals with electrons and ions. Such waves arise when the electrons are magnetized and drift in the crossed fields, but the ions are retarded by neutrals and are at rest. These conditions are satisfied at the heights of the ionospheric E-region. The presence of such waves in the epicentral zone and at a certain distance from the source of the disturbance was discovered experimentally (for example, see [3]). The propagation of low-frequency whistlers in the above-mentioned region was discussed in detail in [4]. The solution to the problem of generating these waves in the E-region by acoustic waves was given in [5].

In this paper we show that the generation of a low-frequency whistler by infrasound is feasible.

The initial set of the equations involves the Maxwell equations (2), the dynamics equations, i.e., the linear momentum equations for particles, (3), (4), and the continuity equations (5)

$$\operatorname{rot}\vec{B} = \left(\frac{4\pi}{c}\right)\vec{j}, \qquad \operatorname{rot}\vec{E} = -\left(\frac{1}{c}\right)\frac{\partial \vec{B}}{\partial t}, \qquad \vec{j} = \sigma\vec{E}, \tag{2}$$

$$\frac{\partial \vec{V}_i}{\partial t} + (\vec{V}_i\nabla)\vec{V}_i = \frac{q}{m_i}\left(\vec{E} + \frac{1}{c}[\vec{V}_i\vec{B}]\right) - \nu_{in}(\vec{V}_i - \vec{V}_n) - \nu_{ei}\frac{m_e}{m_i}(\vec{V}_i - \vec{V}_e), \tag{3}$$

$$\frac{\partial \vec{V}_e}{\partial t} + (\vec{V}_e\nabla)\vec{V}_e = -\frac{q}{m_e}\left(\vec{E} + \frac{1}{c}[\vec{V}_e\vec{B}]\right) - \nu_{en}(\vec{V}_e - \vec{V}_n) - \nu_{ei}(\vec{V}_e - \vec{V}_i), \tag{4}$$

$$\frac{\partial N_\alpha}{\partial t} + \operatorname{div} N_\alpha \vec{V}_\alpha = 0. \tag{5}$$

Here q and m_e are the electron charge and mass, m_i is the ion mass, and $\vec{V}_\alpha$ are the hydrodynamic velocities of electrons and ions, where $\alpha = e, i$. Consider a two-component plasma. In solving equations (2)–(5), we use a linear approximation for the equations in the Gaussian coordinate system, which is chosen in the following way: the wave vector $\vec{k}$ coincides with the z-axis, the magnetic induction vector $\vec{B}$ is in the xy-plane, and the angle $\vec{k}\vec{B}$ is equal to θ. The variations in both $\vec{V}_\alpha$ and the electric field strength $\vec{E}$

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are wavelike in character, i.e., $\vec{V}_\alpha, \vec{E} \sim \exp i(\omega t - \vec{k}\vec{r})$. Assume that the ion mass is sufficiently large; this enables the action of the magnetic field on ions to be neglected. The forced vibrations of the ionospheric plasma resulting from the action of an infrasonic wave on it are regarded as a quasistationary background for the natural plasma vibrations. For the ionospheric E-region, these assumptions are justified from a physical viewpoint.

The procedure for obtaining the dispersion equation is similar to the one in [6]; for this reason, the cumbersome intermediate computations are omitted. The expression for the current strength $\vec{j}$ in matrix form is derived from equations (3), (4) in the linear approximation

$$\vec{j} = \hat{\sigma}(\vec{E} + a_\alpha \vec{A}_\alpha). \tag{6}$$

Here $a_\alpha = m_\alpha / q_\alpha$, where m_α and q_α are the particle mass and charge and $\vec{A}_\alpha = \vec{A}_\alpha(\omega, \omega_{Bi}, \omega_e, q_\alpha)$. The variable $\hat{\sigma}$ is given by

$$\hat{\sigma} = -\frac{i\omega}{4\pi}\begin{vmatrix} A & -iB\cos\theta & iB\sin\theta \\ iB\cos\theta & A - C\sin^2\theta & -0.5C\sin 2\theta \\ -iB\cos\theta & -0.5C\sin 2\theta & D - C\sin^2\theta \end{vmatrix}, \tag{7}$$

where $A, B, C, D = f(\omega, \omega_{Bi}, \omega_{Be}, a_\alpha, \nu_\alpha)$. In order not to make the text of this paper cumbersome, the corresponding expressions are not given here.

As in [6], the solution of (2) gives the equation

$$k^2\vec{E} - (\vec{k}\vec{E})\vec{k} - (\omega^2/c^2)\vec{E} + (i4\pi\omega/c^2)\vec{j} = 0. \tag{8}$$

Substitution of the expression for the current strength (6) into (8) makes the latter nonhomogeneous. In this case, the general solution of (8) is reduced to the solution of a homogeneous equation, since, in view of the above assumptions, the particular solution of the nonhomogeneous equation can be neglected. As in [6], this enables the dispersion equation to be found in general form: $n^2 = (B_1 \pm C_1)/A_1$, where $A_1, B_1, C_1 = f(\omega, \omega_{Be}, \omega_{Bi}, a_\alpha, \nu_\alpha)$. For waves with frequencies $\omega_{Bi} \ll \omega \ll \omega_{Be}$ (the low-frequency whistlers), the following dispersion equation can be obtained (the consideration of two other well-known cases is beyond the scope of our problem):

$$n_3^2(\omega) = \omega_p^2/\omega\omega_{Be}\cos\theta. \tag{9}$$

The spectrum of such waves is found from (9), according to the equality

$$\omega_3(k) = |\omega_{Be}\cos\theta| k^2c^2/\omega_p^2. \tag{10}$$

The waves described by the dispersion relation (10) are purely electron ones and can propagate in ionospheric plasma in the narrow cone of angles with axis along the magnetic field [4, 6]. The solution of (10) allows one to determine the relationship between f_a and the frequencies f_3 of the low-frequency whistlers generated in this height range

$$f_3 = \frac{c^2}{v_\alpha^2}\frac{f_a^2 f_{Be}}{f_p^2}\cos\theta\cos^2\theta_1. \tag{11}$$

Here c is the speed of light, v_a is the speed of infrasound, and θ_1 is the angle between the vertical and the direction of the infrasonic wave propagation.

Relation (11) between the frequencies f_a generated for various atmospheric disturbances on the ground and under it and measured experimentally allows one to calculate the frequencies f_3 of the low-frequency whistlers that can be generated and amplified in the ionospheric E-region, as was shown above.

TABLE 1

		f_3, kHz for f_a, Hz				
f_p, MHz	θ_1°	0.05	0.1	1.0	2.0	5.0
3	0	0.130	0.520	52.00	208.0	1300
3	30	0.098	0.450	39.00	156.0	975
5	0	0.047	0.187	18.70	71.9	468
5	30	0.035	0.140	14.04	56.2	351

It should be noted that f_3 depends not only on f_a, but also on the electron density N in the ionospheric E-region since we have $f_p = f_p(N)$. Table 1 shows the calculated results of f_3 for two cases: (a) $\theta_1 = 0^\circ$ and (b) $\theta_1 = 30^\circ$. Here $\theta_1 = 0^\circ$, $v_a = 500$ m/sec, and $\omega_{Be} = 8 \cdot 10^6$ sec^{-1}; the values of the frequencies f_a are taken from the papers presenting the generalized observations of infrasound during thunderstorms, earthquakes, and explosions. Calculations show that for $0.05 < f_a < 5$ Hz the whistler frequencies f_3 vary in the range of hundreds Hz to hundreds kHz. These calculations are confirmed by the experimental data from the scientific literature; they are evidence of the fact that whistlers are strengthened in the epicentral zone of an earthquake, in the regions of severe thunderstorm, etc. Though infrasonic waves with frequencies $f_a > 5$ Hz reach the heights of the ionospheric region under consideration, they attenuate significantly; for this reason, they are not discussed here. It can be suggested that the cited mechanism is suitable for the 170–220 km height range where the penetration of infrasonic waves with frequencies $f_a < 1$ Hz is observed, and the electron density is higher than in the E-region.

Thus, we have shown that in propagating in the Earth's ionosphere infrasonic waves excited in the atmosphere during disturbances of various nature can generate or strengthen low-frequency whistlers in the ionospheric E-region. The relationship between the frequencies of the infrasound and the whistler was obtained using the dispersion equation. The frequency range in which the generation of whistlers is possible was computed using the experimental data from the literature on the infrasound frequency range.

References

1. G. I. Grigor'ev and V. P. Dokuchaev, "Infrasound and internal gravity waves during lightning discharges in the atmosphere," *Izv. AN SSSR. Fizika Atmosfery i Okeana*, **17**, No. 7, 690–697 (1981).
2. A. S. Alperovich, B. O. Bukhmeister, M. B. Gokhberg, et al., "On the experience of simulating the magnetospheric and ionospheric effects for seismic phenomena," *Doklady AN SSSR*, No. 3, 573–578 (1983).
3. Yu. M. Mikhailov, A. G. Mikhailova, and O. V. Kapustina, "The extremely-low-frequency and very-low-frequency electromagnetic background in the external ionosphere over the seismic active regions ('Interkosmos-24' earth satellite)," *Geomagnetism i Aéronomiya*, **37**, No. 4, 78–85 (1997).
4. V. A. Mazur, "The propagation of a low-frequency whistler in the ionosphere," *Izv. Vyssh. Uchebn. Zaved. Radiofizika*, **31**, No. 12, 1423–1430 (1988).
5. V. A. Surkov, *Excitation of Ionospheric Low-Frequency Electromagnetic Disturbances by Acoustic Waves* [in Russian], Preprint 041-89, Mosk. Inzh.-Fiz. Inst. (MIFI), Moscow (1989).
6. V. L. Ginzburg and A. A. Rukhadze, *Waves in Magnetoactive Plasma* [in Russian], Nauka, Moscow (1970).