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GENERATION OF MAGNETIC NOISE BURSTS DURING DISTANT ROCKET LAUNCHES

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Introduction

Any intense impact on the ionosphere, e.g. acoustic blast waves from natural or artificial sources, is accompanied by occurrence of electromagnetic disturbances. Injection of plasma ionizing (Ba, Li, Na) or suppressive (H_2O) compounds also results in a whole complex of phenomena: generation of MHD impulse [*Kelley et al.,* 1980], burst of ELF electromagnetic noise, plasma turbulization, and stimulation of energetic particle precipitation. Powerful source of the ionosphere modification is rocket launches. The mechanisms of the rocket-induced distortions of the ionosphere studied so far were related to acoustic disturbances from fast flying rocket [*Gorelyi et al.,* 1994] or enhanced plasma recombination due to waste products [*Mendillo,* 1988]. In this paper we draw attention to another possible effect of an impact on the ionosphere from rocket engine - excitation of magnetosonic waveguide in the ionosphere, which transmits electromagnetic disturbances in the Hz frequency band to considerable distances.

Bursts of magnetic noises during rocket launches

For the study of the possibility of geomagnetic pulsations generation we made a retrospective analysis of geomagnetic data according to the list of powerful strategic missile launches from the rocket site Plesetzk (180 km southward from Arkhangelsk, Northern Russia) from February 1989 to February 1991. We analyzed the data of the nearest available observatories Sodankylä (SOD, geographic coordinates 67.37°, 26.63°) and Oulu (OUL, 64.52°, 27.23°), situated about 103km to west-south from launching site. At these observatories the high frequency pulsations are recorded with the use of search-coil magnetometers with high sensitivity, ~ 1 pT.

We excluded from the consideration the events during substorm activity at higher latitudes in a given LT sector. Keeping in mind the uncertainty of take-off moments about few minutes, we suppose that an onset of probable stimulated emission should be within 10 min interval after a nominal take-off. In a few events remained the occurrence of weak signals in Hz frequency range after rocket launches were noticed.

Fig. 1 shows the H component magnetogram and sonogram produced by electronic sonograph analyzer for SOD during the launch (1930 UT) on November 01, 1989. About 10 min after the take-off a short-lived isolated burst of emission with ~ 5 min duration is observed. The signal is detected on a quite background. Only about 2 hours later, at 2120 UT a series of regular Pi1c emission begins. At more distant observatory OUL no signal could be reliably retrieved in this time interval. Similar weak anomalous emissions were revealed shortly after several other launches as well.

Modification of the ionospheric plasma and excitation of MHD modes

The movement of rocket with running engine through the ionosphere can be visualized as a continuous sequence of neutral gas injections along the trajectory. The effectiveness of the hydromagnetic disturbances excitation at different stages of the fly apart of rocket engine waste depends on the dynamics of the movement of the neutral gas component introduced into the ionosphere. The injected neutral component involves into movement both the electron and ion constituents of the background plasma. When the energy of the expelled plasma becomes comparable with the energy of injection, the gas expansion stops and then the diffusion of this gas into the ionospheric plasma takes place. For the description of the neutral component dynamics it may be supposed for simplicity that expanding gas is a cylindrical cloud with time-varying radius.

The dynamics of ionospheric ionized components can be described with the use of three-fluid hydrodynamics of collisional plasma, consisting from electrons, ions and neutrals. The analysis of the three-fluid plasma dynamics shows that there are three stages of plasma dynamics.

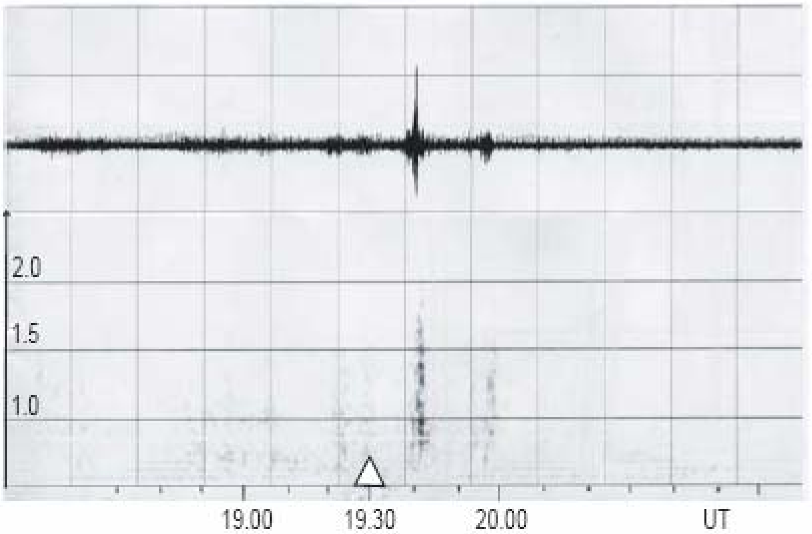

Figure 1. Magnetic signal detected at SOD observatory during the rocket launch on November 01, 1989: H component magnetogram 1800-2200 UT, and corresponding sonogram in the frequency range 0.01 – 1.5 Hz.The take-off moment 1930 UT is marked by a triangle.

At first stage, when the density of neutrals is high, the collision frequencies are large, that is $\nu_{en} >> \Omega_e$, and $\nu_{in} >> \Omega_i$. Plasma particles are dragged by neutral component and the flux caused by dynamo-field is small as compared with the one caused by V_n. In this case the front of an expanding neutral cloud acts as "snow plow" on a background ionospheric plasma. Near the front a closed Pedersen current is generated, which decreases the magnetic field inside the cloud, forming a "magnetic cavern", and increases it outside.

At second stage, up to the moment τ_2~0.5 s, when $\nu_{en} < \Omega_e$ and $\nu_{in} > \Omega_i$, electrons become magnetized, but ions are still dragged by neutrals. Due to a charge separation a polarization electric field arises. This dynamo-field and the electron Hall conductivity produce a radial current and variation of plasma density.

At third stage, both electron and ions become magnetized, while neutral component is still expanding. The Pedersen conductivity is low, whereas the electron and ion Hall conductivities are equal and have opposite signs, hence the plasma concentration does not change noticeably. At this stage a neutral gas weakly interacts with plasma, so diffusion and recombination processes become important.

Intensity of hydromagnetic emission induced by the waste products injection

A characteristic feature of the ionosphere for the propagation of MHD waves is the non-monotonic dependence of Alfven velocity V_A on altitude, that ensures the occurrence of the ionospheric magnetosonic waveguide (IMW) and ionospheric Alfven resonator (IAR) in the F-layer of the ionosphere. The early experiments showed that Pc1 waves trapped into the IMW can propagate with low attenuation to distances up to a few of 103 km.

We consider a feasibility of the IMW excitation and outline the theoretical approach for an analytical description of this process. In a qualitative way the movement of rocket can be visualized as a continuous sequence of micro-injections of neutral gas from rocket engine and an accompanying excitation of short-lived (~ τ_2) bursts of electric currents. The first stage of a fly-apart can be described by the snow-plow model. The movement of a plasma plow excites electric fields and currents which generate hydromagnetic emission from an injection region. The expanding cylindrical shell elongated along a rocket trajectory generates the system of radial Hall currents and azimuthal Pedersen currents [*Borisov et al.,* 1988], as illustrated in Fig.2. The radial Hall current generates Alfvenic disturbances leaking along field lines into the magnetosphere. These

disturbances can be responsible for an excitation of the IAR, but they are spatially localized and cannot be detected at large distances. The system of the azimuthal Pedersen currents forms an effective magnetic dipole, generating a magnetosonic disturbances (M), propagating along the IMW.

The sequence of short-lived impulses of electric currents, generated at the initial stage of waste products fly-apart in conductive ionosphere, results in the excitation of wide-band electromagnetic disturbances in the frequency range $f < \tau_2^{-1} \sim 2$ Hz. Partially these disturbance can be trapped into the IMW.

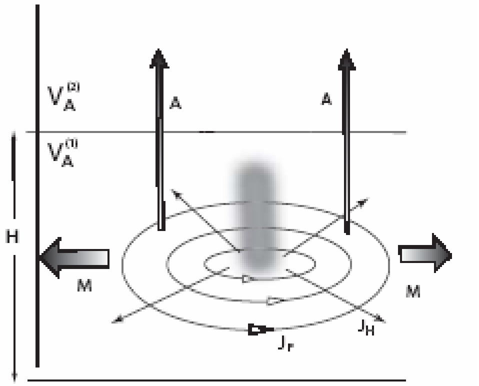

Figure 2. A sketch of ionospheric currents generated by a radial expansion of a cylindrical rocket waste column. The radial Hall currents (J_H) produce Alfven type disturbances (A), and vortex Pedersen currents (J_P) produce magnetosonic type disturbances (M).

As a result, one may expect to observe the signals with frequencies above the IMW cut-off frequency $f^{(M)}$ ~ 0.5 Hz at large distances from a point of rocket entry into the conductive ionosphere.

For the analytical consideration of the IMW excitation by non-steady currents, produced by neutral gas injection into the ionosphere, we consider the following model (Fig. 2). The axis z is oriented along the vertical geomagnetic field, $\mathbf{B}_0 = B_0\mathbf{e}_z$ ($B_0 > 0$). The ionosphere is assumed to be a horizontally stratified, that is V_A and $\hat{\sigma}$ depend on altitude z only. For this model the Maxwell's equations are as follows

$$(\nabla \times\mathbf{B})_\perp = V_A^{-2}\,\partial_t\mathbf{E}_\perp + \mu_0\,\hat{\sigma}_\perp\,\mathbf{E}_\perp + \mu_0\mathbf{j}^{(d)},\quad \nabla \times\mathbf{E}_\perp = -\partial t\mathbf{B} \quad (1)$$

where $\hat{\sigma}_\perp\,\mathbf{E}_\perp = \sigma_P\mathbf{E}_\perp + \sigma_H[\mathbf{e}_z \times \mathbf{E}_\perp]$. The external current $\mathbf{j}^{(d)}$, induced by the gas expansion is assumed to be axially symmetric.

For the description of electric and magnetic fields of MHD waves we introduce the scalar Φ and vector **A** potentials: $\mathbf{B} = \nabla\times\mathbf{A}$, and $\mathbf{E} = -\nabla\Phi - \partial_t\mathbf{A}$. The scalar potential Φ and vertical component of the vector potential $\mathbf{A}_z = A\,\hat{e}_z$ characterize a shear Alfven mode, whereas perpendicular component of the vector potential $\mathbf{A}_\perp$ characterizes a magnetosonic (compressional) mode.

We introduce a potential $U^{(d)}$ for the external current $\mathbf{j}^{(d)}$ as follows $\mathbf{j}^{(d)} = \hat{e}_z \times\nabla_\perp U^{(d)}$. The equations system (1) can be transformed into the following system for the Alfven and magnetosonic wave potentials

$$\partial_z^2\Phi - V_A^{-2}\partial_t^2\Phi - \mu_0\sigma_P\partial_t\Phi - \mu_0\sigma_H\partial_t^2\Psi = 0$$

$$\nabla^2\Psi - V_A^{-2}\partial_t^2\Psi - \mu_0\sigma_P\partial_t\Psi - \mu_0\sigma_H\Phi = \mu_0 U^{(d)} \quad (2)$$

This system shows that two MHD modes are coupled in the ionosphere owing to the Hall conductivity $\sigma_H \neq 0$.

Let us suppose that the external current potential is $U^{(d)} = -M(t)(2\pi r_0)^{-1}\delta(\mathbf{r} - \mathbf{r}_0)$, where $M(t)$ is its effective magnetic moment. Then, the induced current has the azimuthal component only, namely $j_\varphi^{(d)} = \partial_r U(r) j(d)$. For the study of wave generation in the IMW we consider the excitation of magnetosonic modes, neglecting their coupling with Alfven disturbances due to the Hall conductivity (terms $\propto u_0\sigma_H\Phi$ in (2)). Magnetosonic potential Ψ can be found from the following boundary problem

$$\nabla^2\Psi - V_A^{-2}\partial_t^2\Psi = -\mu_0 M(t)\,\delta(\mathbf{r} - \mathbf{r0}) \qquad \Psi(z = 0) = \alpha\partial_z\Psi \quad (3)$$

where $\alpha = (1/h - i\omega\mu_0\Sigma_P)^{-1}$ for $\nu h < 1$, and h is the height of the ionospheric conductive layer. We Fourier transform (4) over time, and then transfer into cylindrical coordinates. The potential Ψ can be searched as sum of waveguide modes, determined by the boundary Sturm-Liuville problem with eigenvalues ν_n^2 (horizontal wave vectors of n-th mode) and corresponding eigenfunctions $u_n(z)$. The spectrum of this mathematical problem consists of continuous and discrete (waveguide modes) parts, so Ψ can be presented as a sum of normal modes

$$\Psi = \Sigma a_n(r)u_n(z) + \int \{\text{over continuous spectrum}\} \quad (4)$$

Coefficients $a_n(r)$ of the n-th mode excitation are determined by the following equation, stemming from (3,4)

$$r^{-1}\partial_r(r\partial_r a_n) + \nu_n^2\,a_n = -\mu_0 M(\omega)(2\pi r_0)^{-1}\delta(r - r_0)u_n(z_0) \qquad (5)$$

The solution of (5) can be expressed through the Green's function of the Bessel's equation $G(r, r_1)$ as follows

$$a_n(r) = -\mu_0 M(\omega)(2\pi r_0)^{-1}u_n(z_0)\int_0^\infty G(r,r_1)\delta(r - r_0)r_1 dr_1 \qquad (6)$$

Finally, the potential of the n-th waveguide mode can be obtained

$$\Psi n(r, z) = i \frac{\mu_0}{4} M(\omega) u_n(z_0) u_n(z) H_0(\nu_n r) \qquad (7)$$

where H_0 is the Hankel's function. Further we derive the analytical expressions describing the IMW excitation for the simplified vertical two-layer profile of $V_A(z)$.

Let the vertical profile of $V_A(z)$ in the IMW may be modeled with step-wise function (Fig.2). The vertical structure of the wave in such waveguide has the following form

$$u_n(z) = N_n^{-1} \begin{cases} \cos[k_n(z-H)] - \dfrac{q_n}{k_n} \sin[k_n(z-H)] & \text{at } 0 < z < H \\ \exp[-q_n(z-H)] & \text{at } \mathrm{H} < \mathrm{z} < \infty \end{cases} \qquad (8)$$

where $\kappa(\nu) = \sqrt{\omega^2 / V_1^2 - \nu^2}$, and $q(\nu) = \sqrt{\nu^2 - \omega^2 / V_2^2}$ are effective inverse vertical scales in a corresponding layer, and N_n is the normalization factor. The horizontal wavenumbers νn can be obtained from the dispersion equation for waveguide modes. The space-time distribution of the waveguide mode potential $\Psi_n(t, r, z)$ can be found with the inverse Fourier transform of (7). In the far-field zone, at $\nu_n r >> 1$,

$$\Psi_n(t, r, z) \cong \frac{\mu_0}{4\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega M(\omega) u_n(z_0) u_n(z) \sqrt{\frac{2}{\pi \nu_n r}} \exp[i(\nu_n r + \frac{\pi}{4} - \omega t)] \qquad (9)$$

The relationship obtained demonstrates a principal possibility of the IMW excitation by a firing rocket engine. The developed mathematical formalism can be used for quantitative estimate under specific parameters of the rocket engine waste products.

Conclusion

From the wide band electromagnetic noise generated by rocket jet during the entry into the conductive ionospheric layer the emission with the frequencies corresponding to characteristic waveguide frequencies (~ 1 Hz) would be trapped and further propagate at larger distances. We observed the intensification of ULF activity after intercontinental rocket launches just in the frequency band indicated. The presented observational results and theoretical estimates cannot be considered as a convincing evidence of feasibility of this effect, so further studies are necessary to reveal it unambiguously.

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