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PROPOGATION OF MHD DISTURBANCES ALONG THE IONOSPHERE

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1. Introduction

Comprehensive understanding of propagation features of ultra-low-frequency (1 - 100 mHz) MHD disturbances along the ionosphere is still absent. On the one hand, some authors [*Webster et al.*, 1989] following the early idea of *Rostoker* [1965] believe that propagation of Pi2 pulsations along the ionosphere is similar to the electromagnetic wave propagation in a conductive slab and is limited by an skin-length $\delta_P = (2/\mu_o \omega \sigma_P)^{1/2}$, determined by Pedersen conductivity σ_P. On the other hand, in a series of papers the hypothesis of *Sorokin and Fedorovich* [1982] has been developed that along the E-layer of the ionosphere, where Hall conductivity $\sigma_H \gg \sigma_P$, long-range propagation of specific MHD mode (called gyrotropic wave) becomes possible. Further researches showed that in the real ionosphere a gyrotropic mode can propagate at the high and middle latitudes only in a diffusive way [*Borisov*, 1988; *Mazur*, 1988]. Resent results cannot be applied directly to the ionosphere with a small inclination I of the geomagnetic field $\mathbf{H}$.

The goal of the present paper is to supplement the existing physical picture of ionospheric MHD propagation with the analysis of wave properties of the near-equatorial ionosphere. *Saito* [1983] noticed the existence of an additional maximum in diurnal distribution of Pc3 pulsations, observed at the near-equatorial stations only. At the meridional profile of low-latitude stations ULF signals propagating outwards the equator have been detected [*Rao*, 1995]. The above experimental facts bring us to the hypothesis that ULF fluctuations of the equatorial electrojet may induce geomagnetic disturbances, which then propagate along the ionosphere.

2. MHD wave model of the near-equatorial ionosphere

For the theoretical analysis we use the multi-layer model of the ionosphere with axis X directed to the North, Y - to the West and Z - upward. The conductive layer with constant Hall and Pedersen conductivities is bounded at z=0 and z=l. Magnetic fluctuations are induced by an external current (electrojet) $\mathbf{J}_o$, which flows along Y. Taking into account that in the ionospheric plasma $\sigma_\parallel \to \infty$ and the field-aligned electric component $E_\parallel \to 0$, we have for the transverse electric field $\mathbf{E}_\perp$

$$rot_\perp rot \mathbf{E}_\perp = -\mu_o \partial_t \hat{\sigma_\perp} \mathbf{E}_\perp - \mu_o \partial_t \mathbf{J}_o$$

where $\hat{\sigma_\perp} \mathbf{E}_\perp = \sigma_P \mathbf{E}_\perp + \sigma_H (\mathbf{H} \times \mathbf{E}_\perp)/H$. For the Fourier harmonics e_x, $e_y(z, k, \omega)$ of disturbances propagating along the meridian this equation results in the system

$$\begin{gathered} \left(\nabla_\parallel^2 + k_P^2\right) \frac{e_x}{\sin I} - i k_H^2 e_y = 0 \\ i k_H^2 \frac{e_x}{\sin I} + \left(\nabla^2 + k_P^2\right) e_y = -i\omega \mu_o j_o \end{gathered}$$

Here we introduce the following notations: $k_P^2 = i\omega\mu_o\sigma_P$, $k_H^2 = \omega\mu_o\sigma_H$. The operators in the above equations are: $\nabla_\parallel = ik\cos I + \sin I \partial_z$ and $\nabla^2 = \partial_z^2 - k^2$. Substituting the electric field components with the vertical magnetic component h_z, we obtain

$$\left(\nabla_\parallel^2 + k_P^2\right)\left(\nabla^2 + k_P^2\right) h_z - k_H^4 h_z = -ik\left(\nabla_\parallel^2 + k_P^2\right) j_o$$

To simplify the calculations we neglect the influence of the Earth. With account for the continuity of h_z, $\partial_z h_z$ and vanishing of normal component of current at $z = (0, l)$ we come to the boundary condition

$$\nabla_\parallel \left(\nabla^2 + k_P^2\right) h_z \,(z = 0, l) = -ik \nabla_\parallel j_o \,(z = 0, l)$$

Within a conductive layer a general solution of the above equation can be searched for in the form

$$h_z(z) = \sum C_n \exp(\lambda_n z) + h_*$$

where C_n $(n = 1 - 4)$ are arbitrary constants, and h_* is some particular solution of the equation. The spectral parameters λ are found from the characteristic equation

$$\triangle(k,\lambda) = (k_{\parallel}^2 - k_P^2)(q^2 - k_P^2) - k_H^4 = 0$$

Here $k_{\parallel} = k\cos I - i\lambda\sin I$ is the field-aligned projection of wave vector $\mathbf{k}$, $q^2 = k^2 - \lambda^2 = \mathbf{k^2}$. The above equation is actually an algebraic equation of the 4-th order of λ and its solution has a cumbersome form. So, we'll look for an approximate solution, using inclination angle I as a small parameter. In the first approximation we obtain

$$\lambda_{1,2} = (-ik \mp ik_P)I^{-1} + O(I)$$
$$\lambda_{3,4} = \pm\left[k^2 - k_P^2 - k_H^4/(k^2 - k_P^2)\right]^{1/2} + O(I)$$

The first equation can be re-written in the form $k_P^2 = k_{\parallel}^2$, which proves that (λ_1, λ_2) modes correspond to Alfven waves. The (λ_3, λ_4) modes in a plasma with $\sigma_H = 0$ are isotropic and correspond to compressional (magnetosonic) waves. In plasma with anisotropic conductivity $\sigma_H \neq 0$ compressional waves were called gyrotropic modes by *Sorokin and Fedorovich* [1982].

The obtained expressions for λ_n allows to obtain the explicit solution of the problem. Then, the inverse Fourier transform of the relations for components of electromagnetic field gives the spatial distribution of disturbances, excited by external electrojet. The function $h_z(z,k,\omega)$, $h_x(z,k,\omega)$ have poles which are determined by the dispersion relation

$$\tanh\lambda_3 l = -\frac{2\lambda_3\sqrt{k^2}}{\lambda_3^2 + k^2}$$

The roots k_n of this dispersion equation determine the wave numbers of eigen modes in the ionosphere [*Surkov*, 1992]. Here we do not consider the details of this spectrum, but analyze only the most significant mode.

3. Thin ionosphere approximation

Let us consider the case of large-scale disturbances, when the ionosphere can be treated as an optically thin layer for all modes, i.e.$|\lambda_n| \ll 1$ (n=1-4). This condition imposes the restrictions on parameters: $|k|l \ll I \ll 1$, $|k_P|l \ll I \ll 1$. In the thin ionosphere approximation of the infinite discrete spectrum of horizontal wave numbers k_n only the mode with

$$k_s = i\omega/2V_C$$

remains. The velocity $V_C = (\mu_o\Sigma_C)^{-1}$ is determined by a characteristic combination of height-integrated conductivities $\Sigma_C = \Sigma_P + \Sigma_H^2/\Sigma_P$. In the ionospheric plasma with anisotropic conductivity this dispersion relation describes a surface gyrotropic compressional mode.

For the electrojet in the form of an infinitely thin linear current $J_o(x,\omega) = I_0(\omega)\delta(x)$ the components of the disturbed magnetic field at the ionospheric level can be calculated in an explicit form. At small distances of $s \ll 1$ from the source these relations turn into

$$\overline{h_z} = -\frac{I_o}{2\pi x}\left[1 + i\frac{\pi}{2}s\right], \overline{h_x} = \frac{I_o}{2\pi}k_s\left[\ln s + C - i\frac{\pi}{2}\right]$$

Here $s = -ik_s x = (\omega X_C/2c)x$ denotes dimensionless distance from the electrojet, $X_C = \mu_0 c\Sigma_C$ is dimensionless ionospheric impedance. The condition $s \leq 1$ is valid for distances $x \leq \delta_s = |k_s|^{-1} = 10^5 T X_C^{-1}$. For disturbances with period $T = 10^2$ sec and in the dayside ionosphere with the parameter $X_C \simeq 10^4$ the critical distance $\delta_s \simeq 10^3 km$.

4. Discussion

Now we summarize the results, obtained above and elsewhere, and review general properties of surface gyrotropic mode. The situation is considered, when there is no coupling between disturbance in the ionosphere and on the ground, i.e. $kH \gg 1$. We introduce the following characteristic velocities, determined by height-integrated ionospheric conductivities: $V_P = c^2/4\pi\Sigma_P$, $V_H = c^2/4\pi\Sigma_H$ and $V_C = c^2/4\pi\Sigma_C$ (in SI units $V_{P,H,C} = (\mu_o\Sigma_{P,H,C})^{-1}$).

Long-range propagation of the gyrotropic wave is possible along the ionospheric film with the small Pedersen conductivity $\Sigma_P/\Sigma_H \ll (kl)^{1/2}$. The propagation velocity in this case is related with V_H: $\omega/k = (2k)^{1/2} V_H \cos I$ [*Sorokin and Yashenko*, 1988].

However, in the real ionosphere, where $\Sigma_P \simeq \Sigma_H$, the properties of the gyrotropic mode changes drastically. A wave regime of the propagation changes to a diffusive one. Compressional large-scale gyrotropic mode does not "feel" the inclination of geomagnetic field, and the meridional propagation of this mode at all latitudes can be described by the same relation. In the day-side ionosphere, when $\Sigma_P \gg \Sigma_W = c^2/4\pi C_A$, the apparent propagation velocity $\omega/k = -i2V_C$. and the decay length $\delta_s = 2V_C/\omega$ [*Mazur*,1988]. In the night-time ionosphere, where $\Sigma_P \ll \Sigma_W$, the apparent propagation velocity $\omega/k = -i2V_P$ [*Borisov*, 1988].

The skin-effect in the ionosphere ensures the skin-length $\delta_P = |Im(k_P)|^{-1} = (2/\mu_0\omega\sigma_P)^{1/2}$ and phase shifts corresponding to apparent velocity $\omega/k = V_d = c/(\sigma_P T)^{1/2}$ [*Rostoker*, 1965]. Comparison with the above formula shows, that the surface gyrotropic mode can transport magnetic disturbance to larger distance and with greater velocity than the ordinary skin-effect:

$$\frac{\delta_P}{\delta_s} \simeq k_P l(1+\frac{\Sigma_H^2}{\Sigma_P^2}) \ll 1; \frac{V_d}{V_s} \simeq 2k_P l(1+\frac{\Sigma_H^2}{\Sigma_P^2}) \ll 1$$

The geomagnetic disturbances excited by an equatorial electrojet should be observed mainly in H and Z components. The apparent velocity $V_C \simeq$30 km/s at distances about $\delta_s \simeq 10^3$ km provides the phase shift about $\pi/2$. The geomagnetic signals observed by *Rao* [1995] at the near-equatorial latitudes in principle may be induced by ULF fluctuations of the equatorial electrojet, transported by the gyrotropic modes along the ionosphere. The above conclusions concerning the ionospheric propagation of MHD disturbances may be of interest for the studies of Pi2 propagation near the auroral electrojet and for studies of ionospheric response to acoustic impact [*Pokhotelov et al.*, 1995].

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