NONLINEAR EVOLUTION OF PLANETARY-SCALE ELECTROMAGNETIC WAVES IN E-REGION OF THE IONOSPHERE FOR A SPHERICAL EARTH MODEL

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Abstract

Physical mechanism of generation of slow and fast planetary waves of electromagnetic type in dissipative $E-$ region of the ionosphere is suggested. The waves are caused by a constantly acting factor - a latitude variation of geomagnetic field. It is shown that slow waves are generated by the dynamo field in the ionosphere and fast waves - by vortical electric field. Slow electromagnetic wave is analogous to the Rossby planetary wave, fast one is a new mode of proper oscillation of $E-$layer. Linear waves propagate both to the east and west directions in dynamo region of the ionosphere along parallel against a background of the mean zonal flow.

Nonlinear theory of fast and slow planetary electromagnetic waves in $E-$ region of the ionosphere is developed for the first time in this paper. It was established that these perturbations are self-localized in the form of nonlinear solitary vortical structures in dynamo-region of the ionosphere and they move to the east (slow) and west (fast) directions against a background of the mean zonal flow. Nonlinear structure consists of a couple of cyclone-anticyclone type vortices, which rotate in the opposite directions and transfer trapped particles of the medium. Energy and enstrophy of large-scale vortices attenuate weakly and are long-lived. Vortical structures generate magnetic fields greater by an order of magnitude than the corresponding linear waves. The features and parameters of the theoretically investigated electromagnetic wave structures are in conformity with the features and parameters of the experimentally observed large-scale ultralow frequent wave perturbations in the ionosphere.

Key words and phrases: Planetary waves, Nonlinear vortex, Geomagnetic field, Ionosphere.

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1. *Introduction*

There exists an increasing interest in the problems related to the large-scale wave perturbations, since many ionospheric phenomena, such as superrotation of the Earth's atmosphere [22], ionospheric precursors of natural processes [18,19,32], ionospheric response on anthropogenic action [37,38,40], fall in the range of such waves.

It is supposed now, that the Earth's atmosphere is a united dynamic system in which a close connection occurs between the processes at different altitudes by means of atmospheric planetary waves. Moreover, connection between litosphere-ionosphere-magnetosphere can be successfully realized by means of wave processes of different scales if neutral components of the medium are essentially participating in the process [31]. It is supposed that in the natural conditions planetary waves are generated in the troposphere-stratosphere and penetrate to ionospheric altitudes. However, theoretical investigations of wave processes as bases of energy transformation from a lower atmosphere to the upper one point out that the system of stable zonal winds reliably shields (especially in summer) upper atmosphere from influence of large-scale planetary waves generated in the troposphere-stratosphere [25,27]. In the period of equinox, when zonal winds reverse their directions, more favorable conditions for penetration the ionosphere appear only for very long planetary waves (wave number 1-2) [25].

Nevertheless, a great number of experimental data confirm an existence of slow (long-period) planetary waves with wave number 2-10 (phase velocity is close to the local wind's velocity - $20 \div 200\ m \cdot s^{-1}$, wavelength-$10^3 km$ and more, period-a few days) in $E-$region of the ionosphere [7,41,42] in any season of the year. Unlike the ordinary planetary Rossby waves they cause substantial perturbation of geomagnetic field (from few to several tens nanotesla (nT)), that points out electromagnetic nature of these waves. Experimental observations of the ionospheric perturbations convincingly indicate [43,44,45] that fast large-scale perturbations are generated at middle and high latitudes of $E-$region of the ionosphere, which move along the Earth's surface with the velocities of order $2 \div 20\ km \cdot s^{-1}$ [44]. Their periods range from one to a few tens minutes, wavelength is of order $10^3 km$ and more, amplitude is from tens to hundreds nT. Phase velocity of these perturbations differs almost by an order of magnitude for day and night conditions in $E-$region of the ionosphere. Big phase velocities and high variations from day to night eliminate a possibility to identify these perturbations with magnetohydrodynamic waves. They show themselves as background vibrations in the natural conditions. Observations show that the forced oscillations of such type arise at pulse action on the ionosphere either due to magnetic storm [18], or due to earthquake, volcanic eruption or artificial explosion [8,14,44]. In the last case perturbations are revealed as solitary wave structures, which are registered by observatories remote from each other by thousand kilometers with retardation in time, that indicates their motion. In this connection it is necessary to investigate a possibility of generation of planetary electromagnetic waves in the thermosphere. At the same time, for proper comprehension of the processes taking place in the ionosphere medium during the formation and propagation of the waves, it is necessary to investigate nonlinear effects taking into account the dispersion and dissipation of the medium.

In this paper we investigate a possibility of generation and propagation of slow and fast planetary (linear and nonlinear) waves of electromagnetic type in dynamo region of the ionosphere on the bases of nonlinear dynamic equations for wave perturbations in $E-$ region of the ionosphere taking into account the latitude gradient of the geomagnetic field.

2. *Model dynamical equations for large-scale perturbations*

In the investigation of large-scale processes in the conductive atmosphere (ionosphere) it is necessary to select Magnetohydrodynamic (MHD) (Alfven and magneto-acoustical) waves as well as small-scale waves. From the analysis of the system of MHD equations it follows that MHD oscillations are possible if the effective magnetic Reynolds number is $R_{em} = 4\pi\sigma_{eff}VL \ / \ C^2 \gg 1$. Here σ_{eff} is effective conductivity of the ionosphere; L and V are characteristic linear size and velocity of perturbations, respectively; C is a light speed. At the same time lines of magnetic force are as if stuck to the substance and inductive magnetic field $\overrightarrow{h}$, as well as an external geomagnetic field $\overrightarrow{H}_0$, plays an important role in liquid motion [6,11]. At $R_{em} \ll 1$ the inductive field is negligible and the influence of quasi-elastic magnetic forces may be neglected. In this case, magnetic field is considered as predetermined and equal to the external geomagnetic field $\overrightarrow{H}_0$. Its influence on liquid motion is reduced to inductive braking and gyroscopic Hall effect similarly to action of Coriolis force [13,20,24].

For the processes with the characteristic period of several hours and more in the Earth's atmosphere Coriolis force (and geomagnetic field $\overrightarrow{H}_0$) has an importance. In this case, as it is well known, so called long waves or Rossby waves may be generated in the atmosphere taking into account spatial variations of the angular velocity of the Earth's rotation. Wavelengths of these waves reaches $10^4 km$ and the velocities of their propagation do not exceed typical values of the local wind velocities, the pressure amplitude reaches $100mb$ [24,35].

In E - region of the ionosphere, where $\omega_{Hi} \ll \nu_{in}$ (where $\overrightarrow{\omega}_{Hi} = e\overrightarrow{H}_0/MC$ is the ion cyclotron frequency; ν_{in} is the collision frequency between ions and neutral particles; M - mass of ions or neutral component) Ampere electromagnetic force acting on a neutral component becomes equal to $\overrightarrow{F}_A = \left[\overrightarrow{u}, \overrightarrow{\Omega}_i\right]$ (see Section 5). Here $\overrightarrow{u} = \overrightarrow{V} - \overrightarrow{V}_D; \overrightarrow{V}$ is a vector of perturbation of hydrodynamic velocity of neutral particles, $\overrightarrow{V}_D = C\left[\overrightarrow{E}, \overrightarrow{H}\right]/H^2$ - electric drift velocity, $\overrightarrow{H} = \overrightarrow{H}_0 + \overrightarrow{h}$; $\overrightarrow{E}$ - tension of electric field, $\overrightarrow{\Omega_i} = N\overrightarrow{\omega}_{Hi}/N_n; N$ *and* N_n- concentration of ionospheric plasma and neutral particles. Similarity of Ampere's force $\overrightarrow{F}_A$ with the Coriolis force $\overrightarrow{F}_C = \left[\overrightarrow{V}, \overrightarrow{f}\right]$ (where $\overrightarrow{f} = 2\overrightarrow{\Omega}_0$; $\overrightarrow{\Omega}_0$ is the angular velocity of the Earth rotation) and equality $\Omega_i \approx f$ in $E-$ region point to the fact that new branches of large-scale electromagnetic oscillations must generate in the ionospheric medium due to inhomogeneity of geomagnetic field $\overrightarrow{H}_0$, as ordinary planetary Rossby waves generate due to inhomogeneity of the angular velocity $\overrightarrow{\Omega}_0$ of the Earth's rotation [17,24].

Large-scale (planetary) waves are weakly fading due to turbulent, molecular viscosity and heat conductivity, since for such motions Reynolds number is too big $Re = VL/\nu \gg 1$ (where ν is a kinematic typical value of viscosity or temperature conductivity). Besides, the ion velocity of large-scale motion V_i coincides with the velocity of the neutral component $V_i = V$; i.e. full entrainment of ions by neutral particles takes place in the lower $E-$ region of the ionosphere or dynamo region (the range of the altitudes is $(90 \div 130)\,km$). Accordingly, the influence of ion friction on large-scale motion in dynamo-region of the ionosphere can also be neglected [17,24] (we must emphasize that the role of ion friction becomes more noticeable only at heights more than $140km$).

Rossby waves, as it is well known, strongly attenuate only due to friction on the Earth's surface [16,17]. Therefore for large-scale flows many authors thought it useful to substitute the term with turbulent friction in the motion equation by Rayleigh friction, which is proportional to the velocity $\overrightarrow{F} = -\Lambda\overrightarrow{V}$ [12,17], where Λ is a constant coefficient of surface friction of atmospheric layers which reaches the value of $10^{-5}s^{-1}$ at a height of $E-$ region [28].

Further we shall be interested in large-scale flows in $E-$ region of the ionosphere with the horizontal spatial scale L of order of magnitude 10^3km and more. Vertical scale D is of order of the scale of altitudes of homogeneous atmosphere, temporal scale is of order of ten minutes, few hours and more. Exactly such perturbations are related with global distributions of the ionosphere and its large-scale variations - diurnal, seasonal and etc. In accordance with the experimental data [24] at a height of $100 \div 150km$

the ratio of characteristic vertical velocity of the wind V_v to horizontal one V_h is $V_v/V_h \leq D/L \quad 10^{-2}$. Thus large-scale motions in dynamo region of the ionosphere are quasi-horizontal on the whole and hence in this approximation the principal theoretical problem is the determination of horizontal components of ionospheric parameters .

Electric currents that cause variations of the tension of geomagnetic field are located in a comparatively narrow strip - dynamo layer of $E-$ region of the ionosphere, where Hall electric conductivity σ_H has the maximum value $\sigma_H \approx 40\sigma_P$ (where $\sigma_P = 4,5 \quad 10^5 \quad s^{-1}$ is Pedersen conductivity) [13,39]. In this region the effective electric conductivity is determined by Cowling conductivity $\sigma_C = \sigma_{eff} = \sigma_P + \sigma_H^2/\sigma_P \sim 10^9 s^{-1}$. Magnetic Reynolds number is big $R_{em} > 10^2$ for these processes (having characteristic spatial scale $L \sim 2000km$ and more, period T – few tens minutes and more) in the ionosphere. From nondimensional Maxwell equation $R_{em} \ \overrightarrow{\bar{j}} = rot \ \overrightarrow{\bar{h}}$ (bar points to non-dimensionality of variables and operator) it follows that in the ionosphere induced magnetic field $\overrightarrow{h}$ must play an important role even at infinitesimal currents $\overrightarrow{j}$. In this case the problem of dynamic large-scale low-frequent ionospheric perturbations of electromagnetic type could be solved on the basis of equations of magnetic hydrodynamics of the ionosphere.

Now we investigate a possibility of generation of planetary waves in dynamo layer of the ionosphere, where Hall-conductivity is dominant due to constantly acting factors such as the latitude gradient of geomagnetic field and angular velocity of the Earth's rotation. Using magnetohydrodynamic equations for the ionosphere and generalized Ohm law for $E-$ region, after eliminating the acoustic-gravitational and MHD waves and taking into account that large-scale flows almost do not perturb density and concentration of medium component particles [17,24], we can write a set of equations:

$$\frac{\partial \overrightarrow{\Omega}}{\partial t} - rot\left[\overrightarrow{V}\left(2\overrightarrow{\Omega}_0 + \overrightarrow{\Omega}\right)\right] - \frac{1}{4\pi\rho} rot\left[rot\overrightarrow{H}, \overrightarrow{H}\right] + \Lambda\overrightarrow{\Omega} = 0, \qquad (2.1)$$

$$\frac{\partial \overrightarrow{H}}{\partial t} + \left(\overrightarrow{V}\nabla\right)\overrightarrow{H} - \left(\overrightarrow{h}\nabla\right)\overrightarrow{V} + \frac{C}{4\pi eN} rot\left[rot\overrightarrow{H}, \overrightarrow{H}\right] = 0, \qquad (2.2)$$

where $\overrightarrow{\Omega} = rot\overrightarrow{V}$, $\quad \overrightarrow{H} = \overrightarrow{H}_0 + \overrightarrow{h}$, $\quad \rho = MN_n$ is the density of neutral particles.

Now we consider horizontal incompressible flow in a spherical coordinate system related to rotating Earth. Let us denote an addition to the latitude by $\varphi^{'} \left(\theta = \pi/2 - \varphi^{'}\right)$, to the longitude - by λ, a distance from the center of the Earth - by r. We consider velocity component on r axis equal to zero $V_r = 0$. $V_\theta(\theta, \lambda, t)$ is a velocity component directed along meridian (it is positive if the velocity is directed to the north), $V_\lambda(\theta, \lambda, t)$ - a velocity component along the circle of latitude (it is positive if the velocity is directed to the east). Let, for simplicity, geomagnetic field have only a vertical component $H_{or} = -H_\rho \cos\theta$, i.e. we consider moderate and high latitudes, where $H_p = 5 \cdot 10^4 nT$ is the tension of geomagnetic field near Pole. Accordingly, the perturbed geomagnetic field has only vertical component $h_r(\theta, \lambda, t)$. We choose the direction of the angular velocity as the vertical axis $\overrightarrow{r}$ $\Omega_r = \Omega_0 \cos\theta$.

Besides, we take into account that in the Earth's atmosphere there always exists east-west zonal motion along latitude circles $\overline{V}_\lambda(\theta)$ (atmosphere as if outdistances the Earth at West-East rotation) [29] beginning from some altitude. Thus the motion consists of basic, stationary, pure zonal east-west flow $\overline{V}_\lambda(\theta)$, on which non-zonal perturbations $V'_\lambda(\theta, \lambda, t)$ are applied. Hence we have

$$V_\theta = V'_\theta(\theta, \lambda, t), \qquad V'_\lambda = \overline{V}_\lambda(\theta) + V'_\lambda(\theta, \lambda, t). \tag{2.3}$$

We suppose that zonal wind is determined by a well-known expression obtained from experiments $\overline{V}_\lambda = \alpha r \sin\theta$, where α is a constant angular velocity of zonal rotation of the atmosphere (so called circulation index). α varies from season to season: in winter $\alpha = 0,05\Omega_0$, in summer $\alpha = 0,025\Omega_0$. Stream function is submitted in the form $\Psi = \bar{\Psi}(\theta) + \Psi'(\theta, \lambda, t)$. We shall determine the velocity components as a stream function from continuity equation due to absence of V_r and condition of incompressibility

$$V'_\theta = -\frac{1}{r\sin\theta}\frac{\partial \Psi'}{\partial \lambda}, \qquad V'_\lambda = \frac{1}{r}\frac{\partial \Psi'}{\partial \lambda}, \tag{2.4}$$

$$\bar{\Psi}(\theta) = -\alpha r^2 \cos\theta. \tag{2.5}$$

Using these expressions, eqns (2.1) and (2.2) may be rewritten in the form

$$\frac{\partial \triangle\Psi}{\partial t} + 2(\alpha + \Omega_0)\frac{\partial \Psi}{\partial \lambda} + \alpha\frac{\partial \triangle\Psi}{\partial \lambda} + \alpha_H\frac{\partial h}{\partial \lambda} + \Lambda\triangle\Psi = -\frac{1}{R^2\sin\theta}J(\Psi, \triangle\Psi), \tag{2.6}$$

$$\frac{\partial h}{\partial t} - \Omega_H\frac{\partial \Psi}{\partial \lambda} + (\alpha - \alpha_H)\frac{\partial h}{\partial \lambda} = \frac{1}{R^2\sin\theta}J(\Psi, h). \tag{2.7}$$

Here, for simplicity, we do not write prime for Ψ function and introduce designations:

$$\alpha_H = \frac{C_H}{R\sin\theta}, \qquad C_H = -\frac{C}{4\pi eN}\frac{1}{R}\frac{\partial H_{0r}}{\partial \theta} = -\frac{CH_p\sin\theta}{4\pi eNR}, \tag{2.8}$$

$$\Omega_H = \frac{N}{N_n}\frac{e}{MC\sin\theta}\frac{\partial H_{or}}{\partial\theta} = \frac{N}{N_n}\frac{eH_\rho}{MC}, \qquad h = \frac{N}{N_n}\frac{eR^2}{MC}h_r,$$

$$\triangle = \frac{1}{\sin\theta}\left[\frac{\partial}{\partial\theta}(\sin\theta\frac{\partial}{\partial\theta}) + \frac{1}{\sin\theta}\frac{\partial^2}{\partial\lambda^2}\right], \quad J(a,b) = \frac{\partial a}{\partial\theta}\frac{\partial b}{\partial\lambda} - \frac{\partial a}{\partial\lambda}\frac{\partial b}{\partial\theta}.$$

In our problem r exists parametrically and therefore, taking into account the thinness of atmospheric layer, we replace r by the Earth's radius R in the eqns (2.6)-(2.8). Further for investigation of dynamics of large-scale (planetary) zonal flows in dynamo region of the ionosphere we shall use a set of nonlinear eqns (2.6) and (2.7) .

3. *Linear planetary electromagnetic waves*

We begin an investigation of eqns (2.6) and (2.7) from the analysis of motion with the small amplitude. It is expedient to analyze a necessary group of solutions of linear dynamic equations on the sphere at investigation of planetary waves, which have a horizontal spatial scale of order of Earth's radius $L \sim R$. Therefore, in linear approximation we seek the solution of evolution equations in the form $\Psi, h \approx f\ (\theta)\exp\left(im\lambda - i\omega t\right)$, where m is a whole number; ω— frequency of perturbations and $f\left(\theta\right)$ is an unknown function of θ . For such a solution eqns (2.6) and (2.7) give us the following equation defining f

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\frac{df}{d\theta}) + \left[-\frac{m^2}{\sin^2\theta} + \frac{2(\alpha+\Omega_0)m}{\alpha m - \omega - i\Lambda} + \frac{\alpha_H\Omega_H m^2}{((\alpha-\alpha_H)m-\omega)(\alpha m - \omega - i\Lambda)}\right]f = 0. \tag{3.1}$$

We obtain the equation for associated Legendre polynomial. At the same time this is a unique possibility for everywhere bounded solution if a sum of last two terms in square brackets is equal to $n(n+1)$, where n is a whole number. Hence, the dispersion equation may be written in the form

$$\frac{2(\alpha+\Omega_0)m}{\alpha m - \omega - i\Lambda} + \frac{\alpha_H\Omega_H m^2}{((\alpha-\alpha_H)m-\omega)(\alpha m - \omega - i\Lambda)} = n(n+1). \tag{3.2}$$

Solving this equation with respect to the frequency $\omega = \omega_0 + i\gamma$, we obtain two branches of the wave

$$\omega^{\pm} = \alpha m - \frac{\alpha_H m}{2}\left(1 + \frac{\sigma_R + i\Lambda}{\alpha_H m}\right)\left\{1 \pm \left[1 - \frac{4\left(\sigma_R - \sigma_H + i\Lambda\right)}{\alpha_H m\left(1 + \left(\sigma_R + i\Lambda\right)/\left(\alpha_H m\right)\right)^2}\right]^{1/2}\right\},$$

where $\sigma_R = 2(\alpha + \Omega_0) m/n(n+1)$, $\sigma_H = \Omega_H m/n(n+1)$; $n = m, m+1...$ The " + " sign corresponds to fast waves, " − " - to slow waves. Now we estimate all the parameters in eqn (3.3): taking into account that $\Omega_0 = 7,3 \cdot 10^{-5} s^{-1}$, Earth's radius $R \approx 6,4 \cdot 10^6 m$, $\alpha \approx 0,04\Omega_0 \sim 3 \cdot 10^{-6} s^{-1}$, $H_p = 5 \cdot 10^{-5} T$, for moderate latitudes at a height of $120 km$ $N \sim 10^{10} m^{-3}$ at night and $N \sim 10^{11} m^{-3}$ in the day-time; hence, $C_H \approx 2 \div 20 km \cdot s^{-1}$, $\alpha_H \approx 10^{-3} \div 10^{-4} s^{-1}$, $2\Omega_H \approx 10^{-4} \div 10^{-5} s^{-1}$, $\Lambda = 10^{-5} s^{-1}$. From these estimations it follows that $\alpha_H m \gg \sigma_R, \sigma_H, \Lambda$ and if these correlations are fulfilled for fast wave, from the eqn (3.3) we have

$$\omega_0^+ = -\alpha_H m, \qquad \gamma^+ = -\Lambda \frac{[4(\alpha + \Omega_0) - \Omega_H]}{n(n+1)\alpha_H}, \tag{3.3}$$

for the slow wave we obtain

$$\omega_0^- = \alpha m - \frac{[2(\alpha + \Omega_0) - \Omega_H] m}{n(n+1)}, \qquad \gamma^- = -\Lambda. \tag{3.4}$$

We must emphasize that an existence of linear large-scale electromagnetic slow waves in the ionosphere was theoretically predicted using plane geometry for the first time in [23,46] and an existence of fast linear waves in [26,28]. Introducing the angular velocity of wave motion $d\lambda^\pm/dt = \omega_0^\pm/m$ and using eqns (3.4) and (3.5), it is possible to determine linear (phase) velocities of wave motion along latitude circles $V_\lambda^\pm = V_{ph}^\pm = R \sin\theta d\lambda^\pm/dt$. Consequently, for fast and slow waves we obtain

$$V_{ph}^+ = V_\lambda^+ = -C_H, \quad V_{ph}^- = V_\lambda^- = \left\{ \alpha - \frac{[2(\alpha + \Omega_0) - \Omega_H]}{n(n+1)} \right\} R \sin\theta \ . \tag{3.5}$$

It is evident that in the high-latitude $E-$region of the ionosphere linear fast wave of electromagnetic nature together with zonal flow $\overline{V}_\lambda(\theta)$ will move from the east to the west ($V_\lambda^+ < 0, \alpha_H > 0$) weakly attenuating ($|\gamma^+| \approx 0,08\Lambda \ll \Lambda$), though, taking into account vertical H_{0r} and horizontal $H_{0\theta}$ components of geomagnetic field, fast waves can move both to the west and east directions [28]. Since the phase velocity of fast waves C_H is inversely proportional to the concentration of charged particles, phase velocity of these waves V_{ph}^+ at night side will exceed phase velocity at daily side by an order of $10 \div 10^2$. Period of fast waves $T^+ = 2\pi/\omega_0^+$ varies from 10 to 50 minutes at night and from 2 to 8 hours in the day-time, when wavelength varies from $10^3 km$ $(m = 10)$ to $10^4 km$ $(m = 2)$ and the waves have the phase velocity of propagation $C_H = 2 \div 20 km \cdot s^{-1}$ along latitude circles. So, fast waves of electromagnetic type, generated in the ionosphere due to constantly acting factor (such as a gradient of geomagnetic field), are a new branch of the ionosphere's proper oscillations [26].

They are weakly fading at high-latitude $E-$ region of the ionosphere and ionospheric and magnetic observatories remote by thousand kilometers can register them with retardation in time, that points to their motion. The features and parameters of these waves are in conformity with experimental data [43,44,45] for fast large-scale electromagnetic perturbations in dynamo region of the ionosphere.

Formulae (3.5) and (3.6) have large meteorological application. In particular, they show that slow electromagnetic wave (wave of Rossby-type forming the weather) together with the mean zonal flow $\overline{V}_\lambda(\theta)$ moves along the latitude circles with the velocity (from ten to a few hundred $m \cdot s^{-1}$ which is typical for zonal winds) depending on circulation index and wavelength (on m and n characterizing this wave). Period of this wave $T^- = 2\pi/\omega_0^-$ varies from 2 to 10 days (at variation of the wavelength from $10^3 km$ to $10^4 km$). Dispersion of these waves occurs due to both gradient of the angular velocity of the Earth's rotation and gradient of geomagnetic field ($\Omega_H \sim \partial H_{or}/\partial r$; so-called gradient hydromagnetic waves [23,46]). In accordance with (3.5) and (3.6) slow waves corresponding to big n (perturbations having small spatial scales) will move from the west to the east ($V_\lambda > 0$); at small n waves will move opposite to the zonal flow direction. These waves strongly damp in $E-$ region of the ionosphere due to Rayleigh friction $\left(|\gamma^-| = \Lambda \sim 10^{-5}s^{-1}\right)$. Attenuation will be weaker for waves with the big wavelength (greater than 10^4 km) and large periods (a week and more). Parameters of slow waves coincide with the parameters presented in the experimental works [7,41,42] about planetary electromagnetic waves.

4. *Nonlinear large-scale wave structures*

It was shown in the previous section that fast large-scale ω_0^+ and slow ω_0^- electromagnetic waves in $E-$region of the ionosphere have dispersion (dependence on the direction of propagation of there frequency). It is well-known from the general theory of nonlinear waves [36,47] that a competition between dispersion and non-linearity may lead to the creation of non-harmonic (solitary) regular profiles propagating without changing forms, which is impossible in both linear and non-dispersive nonlinear cases. Moreover, numerous experiments and observations show [10,21,34,36] that nonlinear solitary vortex structures may be generated at different layers of the Earth's atmosphere. Captured rotating particles are transferred by these structures. Ratio of characteristic velocity U_c of rotation of these particles to the vortex motion velocity U satisfies the following condition $U_c/U \geqslant 1$.

Designate temporal and spatial scales by L and T. In accordance with

(2.4), from eqn (2.6) we have $J(\Psi,\Delta\Psi)/\partial\Delta\Psi/\partial t \sim \Psi T/L^2 \sim U_c/U$, as $U_c \sim \Psi/L$, $U \sim L/T$. Hence, non-linearity is important for wave processes satisfying the condition $U_c \geq U$ [33]. After all characteristic features of both large-scale waves and medium are taken into account in eqns (2.6) and (2.7), with the purpose to simplify the analysis of dynamics of wave structures in a nonlinear regime we shall suppose further that motion occurs in the neighbourhood of the latitude $\varphi_0 = \pi/2 - \theta_0$. It is convenient to introduce new latitude and longitude coordinates $x = \lambda R \sin\theta_0$, $y = -(\theta-\theta_0)R$, that allows us to keep the variable coefficients in eqns (2.6) and (2.7) and reduce them to the following form:

$$\frac{\partial}{\partial t}\Delta_\perp\Psi + \alpha_1\frac{\partial\Psi}{\partial x} + \alpha_2\frac{\partial\Delta_\perp\Psi}{\partial x} + \alpha_3\frac{\partial h}{\partial x} - \Lambda\Delta_\perp\Psi = J(\Psi,\Delta_\perp\Psi), \tag{4.1}$$

$$\frac{\partial h}{\partial t} - \alpha_4\frac{\partial\Psi}{\partial x} + \left(\alpha_2 - \alpha_3 R^2\right)\frac{\partial h}{\partial x} = J(\Psi,h), \tag{4.2}$$

where positive coefficients α_i $(i = 1,2,3,4)$ are equal to $\alpha_1 = 2(\alpha+\Omega_0)\sin\theta_0/R$, $\alpha_2 = \alpha R\sin\theta_0$, $\alpha_3 = \alpha_H\sin\theta_0/R$, $\alpha_4 = \Omega_H R\sin\theta_0$, $\Delta_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is Laplacian along horizontal surface of the Earth.

From the set of eqns (4.1) and (4.2) follows the law of evolution of energy conservation

$$\frac{\partial E}{\partial t} = \frac{\partial}{\partial t}\left\{\frac{1}{2}\int\left[(\nabla_\perp\Psi)^2 + \frac{h^2}{k_0^2R^2}\right]dxdy\right\} = -\Lambda\int(\nabla_\perp\Psi)^2\,dxdy,$$

and potential enstrophy of wave perturbations.

$$\frac{\partial K}{\partial t} = \frac{\partial}{\partial t}\left\{\frac{1}{2}\int\left[(\Delta_\perp\Psi)^2 + \frac{(\nabla_\perp h)^2}{k_0^2R^2}\right]dxdy\right\} = -\Lambda\int(\Delta_\perp\Psi)^2\,dxdy, \tag{4.3}$$

Here $k_0^2 = N\omega_{pi}^2/\left(N_nC^2\right)$, $\omega_{pi}^2 = 4\pi e^2N/M$, $\nabla_\perp$ is the two-dimensional nabla operator. Energy E and enstrophy K of the waves are preserved in a non-dissipative approximation ($\Lambda = 0$).

We seek the solution of nonlinear eqns (4.1) and (4.2) in the non-dissipative approximation ($\Lambda = 0$) in the form of stationary regular waves $\Psi = \Psi(\eta,y)$, $h = h(\eta,y)$ propagating along latitude circles x with the velocity $U = const$ without changing the shape, where $\eta = x - Ut$. It is easy to show that eqns (4.1) and (4.2) are equivalent to the following equation of variables η and y

$$\Delta_\perp\Psi - \beta_2\Psi = f(\Psi+\beta_1 y), \tag{4.4}$$

where f is an arbitrary differentiable function of its own argument,

$$\beta_1 = C_R - U, \qquad \beta_2 = \frac{\sin\theta_0\left[2(\alpha+\Omega_0)(C_R - C_H - U) + C_H\Omega_H\right]}{R(C_R - C_H - U)},$$

$C_R = \alpha R \sin\theta_0$ is the characteristic phase velocity of Rossby waves.

In accordance with [2,4] we introduce polar coordinates along the Earth's surface $r = \left(\eta^2 + y^2\right)^{1/2}$, $tg\varphi = y/\eta$ and a circle with radius a. We demand that functions $\Psi(r,\varphi)$ and $h(r,\varphi)$exponentially tend to zero at $r \to \infty$ and are twice continuously differentiable (including the circle $r = a$) with respect to their arguments. Then the solution of (4.5) has the following form

$$\Psi(r,\varphi,t) = \frac{C_R - C_H - U}{\Omega_H R \sin\theta_0} h(r,\varphi,t) = a\beta_1 F(r)\sin\varphi,$$

where

$$F(r) = \begin{cases} (p/\varkappa)^2 J_1(\varkappa r)/J_1(\varkappa a) - \left(\varkappa^2 + p^2\right) r/a\varkappa^2, & at \quad r < a, \\ -K_1(pr)/K_1(pa), & at \quad r \geq a, \end{cases} \tag{4.5}$$

here J_n is Bessel function of the first order; K_n is McDonald function, parameters p and $\varkappa$ are connected by dispersion relation

$$\frac{J_2(\varkappa a)}{\varkappa J_1(\varkappa a)} = -\frac{K_2(pa)}{pK_1(pa)}, \qquad p^2 = -\frac{\beta_2}{\beta_1} > 0. \tag{4.6}$$

Total field Ψ consists of a given flow (2.5) and a stationary vortical structure (4.6)

$$\Psi(r,\theta,\varphi,t) = -aR^2\cos\theta_0 + \Psi(r,\varphi,t). \tag{4.7}$$

As we construct the perturbed solutions exponentially decreasing at infinity, parameter p^2 must be positive. This condition imposes the restriction on possible phase velocity U of nonlinear vortex structures. Phase velocity $U^- > C_R\left(\sim 10m \cdot s^{-1}\right)$ is positive for slow vortices (vortex of Rossby type. i.e. Rossby type solitary electromagnetic waves can move along latitude only to the east direction). Phase velocity of fast nonlinear electromagnetic vortices $-C_H < U^+ < -C_H\left[1 - \Omega_H/\left(2\left(\alpha + \Omega_0\right)\right)\right]$ and exists in the interval $|\Delta U| = C_H\Omega_H/\left(2\left(\alpha + \Omega_0\right)\right)$ (i.e. fast vortices can move along latitude circles only to the west direction with the velocity of $|U^+| \cong 0,9C_H \sim 9km \cdot s^{-1}$). Hence, the phase velocity of nonlinear vortical structures takes the value outside this interval and inside it there are all the possible phase velocities of appropriate linear periodic waves (see formulae (3.6)).

Taking into account the dispersion eqn (4.8), the solution of eqn (4.6) has two free parameters U and a (although U is defined by the inequality above). As it follows from (4.6), perturbed solution has the asymptotic $\Psi, h \sim r^{-1/2}\exp(-pr)$ at $r \to \infty$. Hence, the wave is localized along the Earth's surface (η, y). Perturbed level lines of stream function have dipole form. Therefore, such structures represent a couple of vortices (cyclone-anticyclone type) rotating in the opposite directions with the same intensity and moving along latitude circles against a background of the mean pure zonal west-east flow. The motion of particles in nonlinear vortical structures (4.6)-(4.8) has nonzero vorticity $rot\overrightarrow{V} \neq 0$, i.e. particles rotate in a vortex. Characteristic velocity of this rotation, as it follows from (2.4) and (4.6), is proportional to $U_c \sim U$. At the same time vortex traps a group of particles (their number are of order of transient particles). While rotating, the particles move with the vortical structure. Characteristic spatial scale d of these vortices is equal to $d \sim a \sim p^{-1} \approx [UR/(\alpha+\Omega_0)]^{1/2}$. For slow vortices $d^- \geq 10^3 km$ and for fast one $d^+ \geq 10^4 km$.

Now we determine the amplitude of magnetic field h_{vr} generated by vortical structures. Taking into account that $a \sim d \approx [UR/(\alpha+\Omega_0)]^{1/2}$, $U > C_R$, from eqns (4.6) and (2.8) we obtain

$$h_{vr} = \frac{N_n}{N}\frac{U}{C_H+U}\frac{\Omega_H}{\omega_{Hi}}\left[\frac{U}{R(\alpha+\Omega_0)}\right]^{1/2} \cdot H_0. \qquad (4.8)$$

For estimation of the amplitude (4.10) we use the mean diurnal values of medium parameters and geomagnetic field in $E-$ region of the ionosphere at a height of $100 \div 200 km$ [24,39]: $N \approx 0,5 \cdot 10^{11} m^{-3}$, $N_n \approx 6 \cdot 10^{17} m^{-3}$, $C_H \approx 10^4 m \cdot s^{-1}$, $\alpha + \Omega_0 \approx 7,6 \cdot 10^{-5} s^{-1}$, $\Omega_H \approx 2,7 \cdot 10^{-5} s^{-1}$, $\omega_{Hi} \approx 3 \cdot 10^2 s^{-1}$. If we take into account that the phase velocity of fast nonlinear vortices is equal to $|U^+| \approx 0,9 C_H = 9 \cdot 10^3 m \cdot s^{-1}$, from (4.10) we have $h^+_{vr} \approx 0,2 H_0 = 10^4 nT$. For slow vortices with mean phase velocity $U^- \approx 50 m \cdot s^{-1} > C_R$, we obtain $h^-_{vr} \approx 1,6 \cdot 10^{-3} H_0 = 10^2 nT$. Hence, large-scale electromagnetic vortices generate intensive magnetic fields in dynamo region of the ionosphere. Such fields emerge on the Earth surface with a value lower by an order of magnitude [15], but they may be easily registered by the surface equipments.

Vortex is not a stationary wave in the dissipative ionosphere ($\Lambda \neq 0$) and it is necessary to use corresponding transfer equation for investigation of dynamics of nonlinear structures. In this case integral characteristics of structures, in particular, the energy E and enstrophy K are not preserved in eqns (4.3) and (4.4) and change in time due to dissipation. Solutions (4.6) - (4.8) may be inserted in (4.3) and (4.4) with the parameters U and a changing slowly in time within the limits of small dissipation in accordance with [1]. We estimate the order of integrals in these equations to analyze the evolution of energy and enstrophy (4.3) and (4.4) in the dissipative medium: $\int (\nabla\Psi)^2 dxdy \sim d^{-2} \int \Psi^2 dxdy$, $\int (\triangle\Psi)^2 dxdy \sim d^{-2} \int (\nabla\Psi)^2 dxdy$; where $d \sim [UR/(\alpha+\Omega_0)]^{1/2}$ is a characteristic spatial scale of the vortices. Taking into account that in dynamo region of the ionosphere $d^2/\left[k_0 R\left(C_H+U\right)/\Omega_H\right] \sim 10^{-3} \ll 1$, for structures of moderate spatial scales $\left(d \sim 10^3 km\right)$, energy and enstrophy are of order of magnitude of the dissipative term and therefore eqns (4.3) and (4.4) may be rewritten as

$$\partial E/\partial t = -2\Lambda E, \qquad \partial K/\partial t = -2\Lambda E. \tag{4.9}$$

This means that energy and enstrophy of such vortices exponentially attenuate. Dissipative term in the transfer eqns (4.3) and (4.4) is less than energy and enstrophy for large-scale vortices ($d > k_0 R\left[\left(C_H+U\right)/\Omega_H\right]$) and relaxation of vortices occurs more slowly.

Thus, electromagnetic large-scale nonlinear vortical structures are long-lived in dynamo region and therefore they can play an important role in transfer processes of substance, heat and energy and formation of strong turbulent state of the medium [3].

5. *Discussion of the results and conclusion*

It was established that large-scale (planetary) linear and nonlinear electromagnetic slow and fast wave structures might be generated in dynamo-region of the ionosphere due to the constantly acting factor - the latitude variation of geomagnetic field. For large-scale flows having a characteristic spatial scale $10^3 km$ and more it is impossible to neglect a variation of geomagnetic field with latitude, as it is impossible to neglect latitude variations of the angular velocity of the Earth's rotation for planetary Rossby waves (since ordinary Rossby parameter $\beta = \partial 2\Omega_{or}/\partial\theta$ and its magnetic analog $\beta_H = eN/\left(\rho c\right)\partial H_{or}/\partial\theta$ have the same order $\beta \approx \beta_H \sim 10^{-11} m^{-1} \cdot s^{-1}$) [24].

The existence of these waves follows from general Ohm's law $\left[\vec{j}\vec{H}\right]/C = eN\left(\vec{E} + \left[\vec{V}\vec{H}_0\right]/C\right)$ for dynamo region of the ionosphere, where $\vec{j}$ is a current density. Ampere force is

$$\vec{F}_A = \frac{1}{\rho C}\left[\vec{j}\vec{H}\right] = \left[\vec{u}\vec{\Omega}_i\right] \approx \frac{eN}{\rho}\left\{-\frac{1}{C}\left[\vec{V}_D\vec{H}\right] + \frac{1}{C}\left[\vec{V}\vec{H}\right]\right\}. \tag{5.1}$$

The expression (5.1) exactly coincides with Coriolis force $\vec{F}_C = \left[\vec{V}\vec{f}\right]$ by appearance.. This similarity and also the condition $\Omega_i \approx f$ points out that electromagnetic waves are generated in dynamo region due to inhomogeneous geomagnetic field $\left(\nabla\vec{H}_0 \neq 0\right)$in the same way as Rossby type planetary waves are generated due to inhomogeneous angular velocity of the Earth rotation $\left(\nabla 2\vec{\Omega}_0 \neq 0\right)$. In this case the first part of electromagnetic force $\overrightarrow{F}_A$ (5.1) caused by the vortical electric field $\overrightarrow{E}_v = -\left[\overrightarrow{V}_D\overrightarrow{H}\right]/C$ (by electric drift velocity $\overrightarrow{V}_D$) generates a fast wave. The second part of electromagnetic force $\overrightarrow{F}_A$ caused by velocity of flow of the medium (by dynamo field $\overrightarrow{E}_d = \left[\overrightarrow{V}\overrightarrow{H}\right]/C$) generates Rossby type slow electromagnetic wave.

It is shown that slow linear electromagnetic waves are generated by a gradient of the geomagnetic field, depend on the wavelength propagate in $E-$ region along latitude circles both to the west and east directions against a background of a stationary pure zonal flow and are Rossby-type waves. Frequency bandwidth of slow waves is $10^{-4}\div 10^{-5}s^{-1}$, wavelength is of order of $10^3 km$ and more, phase velocity of these waves is of order of magnitude of local wind velocity (from several tens to a few hundreds meters per second). Slow waves attenuate more strongly due to Rayleigh friction between the layers of the local atmosphere with the decrement $|\gamma^-| = \Lambda \sim 10^{-5}s^{-1}$, though large-scale waves (with wavelength $10^4 km$ and period from a few week and more) attenuate weaker. Linear slow waves generate magnetic field, which as it follows from the Maxwell's equation and the expression (5.1) for the current $\overrightarrow{j^-} = eN\overrightarrow{V^-}$ has an order of $h_r^- = \left|4\pi eNV_{ph}^-\xi\right|/C$, where ξ is the transversal displacement of charged particles. If $V_{ph}^- = 50m\cdot s^{-1}, \xi = 1km$, we obtain $h_r^- \approx 1 \quad nT$. This estimate increases up to $20nT$ if transversal displacement of the system is about ten kilometers and phase velocity is $V_{ph} \sim 10^2 m\cdot s^{-1}$. Thus, linear slow electromagnetic waves are accompanied by the noticeable micropulsation of geomagnetic field in dynamo region and have a similar order of magnitude as the micropulsation caused by currents S_q in dynamo region.

It is established that linear fast electromagnetic waves are caused by a gradient of geomagnetic field and Hall effect and propagate along latitudes in dynamo region of the ionosphere against a background of mean zonal flow. They move both to the west and east directions with the velocities of several km/s $\left(V_{ph}^+ = C_H \approx 2\div 20 \quad km\cdot s^{-1}\right)$. Frequency bandwidth is of order of magnitude $10^{-2}\div 10^{-4}s^{-1}$, wavelength - $10^3 km$ and more, and the waves weakly fade $|\gamma^+| \sim 0.08\Lambda \sim 10^{-6}s^{-1}$. In accordance with Maxwell's equation and expression (5.1) for the current $\overrightarrow{j^+} = eN\overrightarrow{V}_D$, fast waves cause substantial micropulsation of geomagnetic field and are equal to $h_r^+ \approx \left|2eNV_{ph}^+\lambda^+\right|/C$ by the order of magnitude , where $\lambda^+ \sim 10^3 km$ is the wavelength of fast waves, so that $h_r^+ \approx 10^3 \ nT$. They could be considered as a new mode of proper oscillations of $E-$ region of the ionosphere [26,28]

Now we explain a physical reason of emergence of nonlinear planetary electromagnetic structures and generation of induced strong magnetic field

$\overrightarrow{h}$ in $E-$ region of the ionosphere. Using the expression for Ampere's force (5.1) and Maxwell's equation $\partial\overrightarrow{H}/\partial t = -Crot\overrightarrow{E}$, taking into account the equation of motion $d\overrightarrow{V}/dt = \overrightarrow{F}_A$, it is easy to obtain a condition when geomagnetic field $\overrightarrow{H}_0$ is partially frozen in the neutral component for $E-$region of the ionosphere

$$helm\left(rot\overrightarrow{V} + \frac{N}{N_n}\frac{e\overrightarrow{H}_0}{MC}\right) = 0. \qquad (5.2)$$

Equality of operator $helm\overrightarrow{a} = \partial\overrightarrow{a}/\partial t + rot\left[\overrightarrow{V}\,\overrightarrow{a}\right] + \overrightarrow{V}div\overrightarrow{a}$ to zero for arbitrary vector field $\overrightarrow{a}$ means a conservation (frozen condition) of force lines $\overrightarrow{a}$ and corresponding force tubes in the medium [24]. The expression (5.2) at $\overrightarrow{\Omega} = rot\overrightarrow{V} = 0$ means a condition, when geomagnetic field is fully frozen in the medium. From a conservation condition of the vertical component (5.2) we have

$$\Omega_z + \frac{N}{N_n}\frac{e}{MC}H_{oz} \equiv A = const. \qquad (5.3)$$

On the basis of this equation we shall investigate first a behaviour of

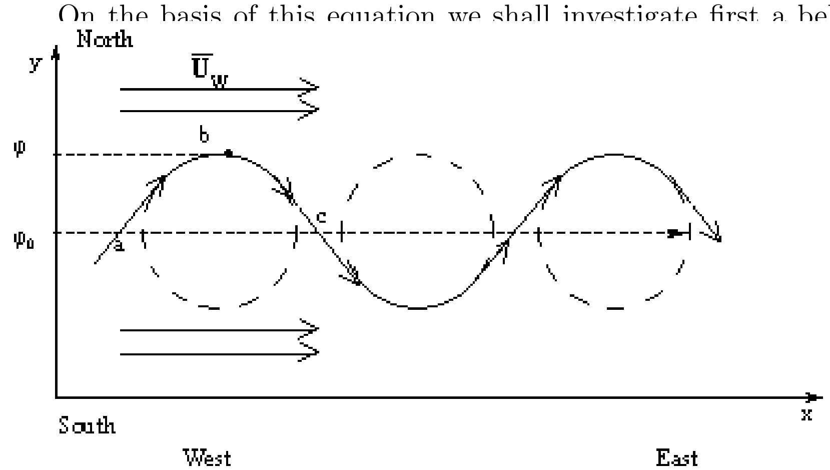

Fig.1. Generation of planetary waves in the west directed flow under the action of geomagnetic field and random external perturbation.

Let velocity $\overline{U}_w$of a particle moving in the west flow receive a north component at some latitude φ_0 (arc ab) under the action of the external perturbation. As soon as the particle starts moving to the pole, value of H_{oz} increases and Ω_z decreases and vortex Ω_z comes down to zero (trajectory pass a flex point) at some latitude φ (point b). Then the velocity of air particle acquires a south component (arc bc) and Ω_z increases due to decreasing of H_z until particle reaches the initial latitude φ_0(point c). West stream directed from left to the right prevent formation of closed vortex and therefore in the west flow there are created planetary-scale wave motions under the action of an external perturbation (without formation of cyclones and anticyclones). These perturbations are called the planetary waves of Rossby type (which has been confirmed by observations [17,20,24,35]).

Now we consider a behaviour of an atmospheric particle under the action of external perturbation in the predominant east-directed stream $\overline{U}_e$(Fig. 2).

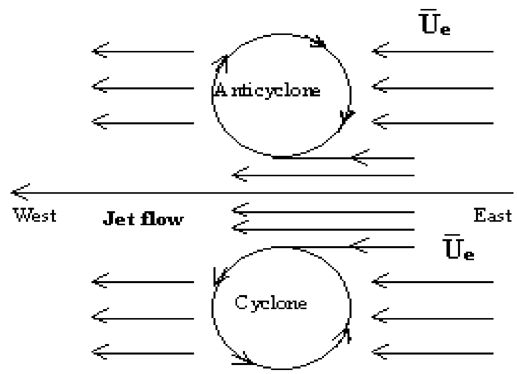

Fig.2. Generation of the vortical structures in the east directed flow under the action of geomagnetic field and randomly external perturbation.

Let a velocity of the particle receive a north component under the action of the external perturbation. As a result of (5.3) Ω_z decreases to zero (in the flex point b). Then the air particle receives a velocity with the south component and the vortex Ω_z increases. Wave motion does not take place in this case as the predominant east-directed stream $\overline{U}$ prevents this process. Trajectory of an air particle is locked under the action of east-directed stream and a vortex is created (anti-cyclone). If the air particle receives the south component of velocity, vortex Ω_z increases due to decrease of H_z. Then it decreases after passing the flex point. East-directed stream $\overline{U}$ prevents here creation of the waves. Trajectory of the particle is locked under the action of east-directed stream and a closed vortex is created (a cyclone). This also is confirmed by an observation [9,34,36].

Thus, due to conservation of an absolute vortex, the latitudinal change of geomagnetic fields generates planetary-scale waves in the west flow and solitary vortices (cyclone-anticyclone) in the east flow under the influence of the external perturbation.

From Fig. 2 it also follows that if generation of cyclone and anticyclone has dipole character (i.e. if they are created simultaneously), then a strong jet flow arises between cyclone and anticyclone and the velocity of the predominant flow $\overline{U}_e$ strongly increases. In accordance with Bernoulli's equation $V^2/2 + P/\rho = const$ (where P is the hydrostatic pressure), this leads to decrease of pressure P in the regions of dipole vortices and hence, surrounding atmospheric particles are drawn into the dipole structures (it is also confirmed by nonlinear solution (4.6) mentioned above).

Moreover, equation (5.3) shows that a motion even linear at the initial time point must become vortical under the action of inhomogeneous geomagnetic field. Actually, let at the initial time point $\Omega_z = rot_z \overrightarrow{V} = 0$, i.e. we have uniform rectilinear motion of air particles from the north to the south (to the direction of negative y; Fig. 3a).

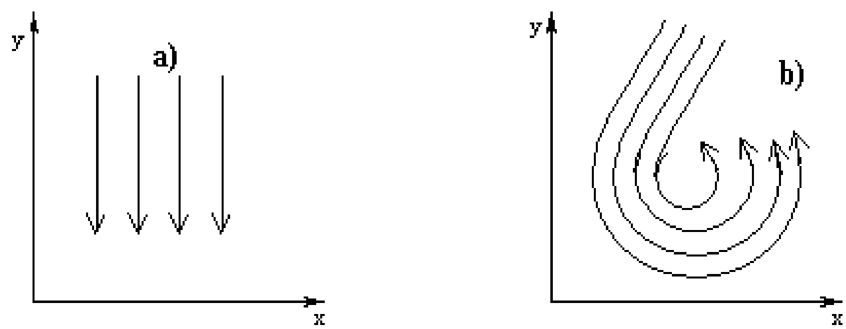

Fig.3a,b. Vortices (cyclone and anti–cyclone) are created even in a straightforward (south, north) flow due to inhomogeneous geomagnetic field.

From (5.3) it follows that $eNH_{oz}/(N_nMC) \equiv A_0 = const > 0$. Since H_{oz} decreases with latitude while moving to the south, a positive vortex $rot_z\overrightarrow{V} > 0$ with cyclonic rotation (counter-clockwise direction; see Fig. 3b) must be generated for conservation of A_0. H_{oz} increases with latitude while moving from the south to the north and a negative vortex $rot_z\overrightarrow{V} < 0$ with anticyclone rotation must be generated for conservation of A_0. Thus, the partially frozen inhomogeneous geomagnetic field naturally leads to generation of large-scale vortical structures in $E-$ region of the ionosphere in the presence of meridional component of horizontal wind in the ionosphere (large-scale condition follows from the estimate $eNH_{oz}/(N_nMC) \sim 10^{-4} \div 10^{-5}s^{-1}$).

Let us consider the case when the vortex is formed and investigate its dynamics (Fig. $4a, b$).

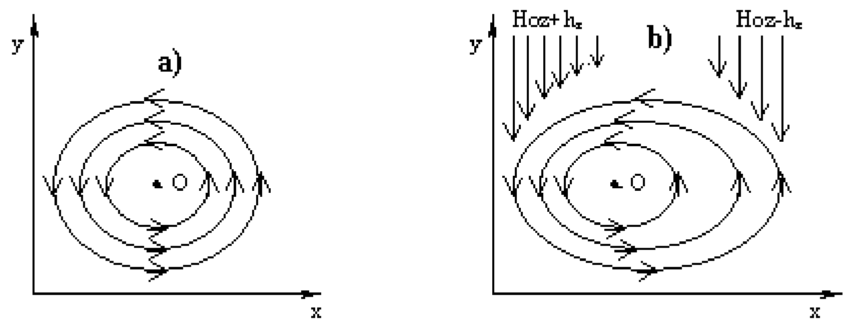

Fig.4a,b. Dynamic of vortices; vortex intensification to the left of instantaneous center of rotation caused by inhomogeneous geomagnetic field.

As it is shown on Fig.4a, the value of $eNH_{oz}/\left(N_nMC\right)$ decreases to the direction of negative y to the left of the instantaneous center of rotation and hence, in accordance with (5.3), Ω_z must increase by an equal magnitude to keep A unchanged. To the right of the instantaneous center of rotation H_{oz} increases and Ω_z decreases while moving to the direction of positive y (to the north). Thus, inhomogeneity of the geomagnetic field leads to the intensification of the vortex to the left of the instantaneous center of rotation, i.e. particles will rotate more rapidly to this side than to the right one (Fig.4b). This effect is similar to the intensification mechanism of flows at the west shores of ocean caused by Coriolis force [33]. It is easy to show that if the basic vortex (Fig. 4a) rotates to the clockwise direction, then an intensification of the vortex will be again to the left of the instantaneous center of rotation.

Two important conclusions follow from this:

a) Atmospheric particles will rotate non-uniformly along circular orbits (rapidly to the left and slowly to the right) in the vortex generated by the inhomogeneous geomagnetic field. Taking into account the full drowning of an ionospheric plasma into $E-$ region, this must lead to generation of law-frequent electromagnetic waves in $E-$ region of the ionosphere due to an additional acceleration of particles in vortices of this type. Hence, $E-$ region (under the conditions of Hall effect) becomes a source of low-frequent electromagnetic waves. Special publication will be devoted to more detailed investigation of this problem.

b) Magnetic field h_z induced by a vortex in the inhomogeneous rotating vortex will amplify to the left of instantaneous center of particles' rotation due to conservation of the condition $\Omega_z + eN\left(H_{oz}+h_z\right)/\left(N_nMC\right) = const$, i.e., a direction of h_z will coincide with the direction of equilibrium geomagnetic field H_{oz}. As a result, lines of magnetic force will be compacted to the left of center of rotation (Fig.4b). Induced magnetic field will be directed opposite of equilibrium geomagnetic field to the right of center of rotation and hence, the total magnetic field will be weakening $(H_{oz}-h_z)$.

Thus, the inhomogeneity of geomagnetic field along latitude generates an inhomogeneous vortex in $E-$ region of the ionosphere that is a source of low-frequent electromagnetic radiation and the reason of amplification or attenuation of induced geomagnetic field h_z in corresponding regions. Amplification of the total field $(H_{oz}+h_z)$ may be easily observed experimentally since an effect of weakening of the total magnetic field $(H_{oz}-h_z)$ will be veiled by basic (equilibrium) field.

Actually, it was shown on the basis of an analytical solution of the set of nonlinear dynamic eqns (2.6), (2.7), that in non-dissipative $E-$ region of the ionosphere planetary electromagnetic waves self-localize as nonlinear solitary vortical structures moving with a constant velocity along the latitude circles without modification against a background of the mean zonal flow. In addition, a motion velocity U of nonlinear structures does not coincide with the velocity of corresponding linear periodic waves. Hence, slow vortices can move only to the east with the velocity $U^- > C_R$ (in contrast to linear periodic slow waves) and fast vortices move only to the west with the velocity $|U^+| \approx 0,9C_H < C_H$. Nonlinear structure consists of a couple of vortices rotating in the opposite directions of cyclone-anticyclone type and it transfers the trapped medium particles. Characteristic spatial scale of slow vortices is $d^- \geq 10^3\ km$ and of fast ones - $d^+ \geq 10^4\ km$. Energy and enstrophy of large-scale vortices weakly attenuate in the dissipative ionosphere, the structures are long-lived and they can be structural elements of strong turbulence of E - region of the ionosphere.

Nonlinear large-scale vortex structures generate more powerful pulsations of geomagnetic field than corresponding linear waves. For example, fast vortices generate geomagnetic fields $h^+_{vr} \approx 10^4 nT$, slow ones - $h^-_{vr} \approx 10^2 nT$. Generation of such intensive perturbations is likely connected with specific features of low-frequent planetary structures. Actually, these structures trap medium particles and the particles are partially frozen in a geomagnetic field in the $E-$ region of the ionosphere. Therefore, a creation of such structures means a noticeable compaction of lines of magnetic force and consequently, an amplification of perturbations of geomagnetic fields in the place of their location. Since a number of trapped (by vortices) particles is of order of the number of transient particles, perturbation of the geomagnetic field in stronger fast vortices will be of order of the background field. On the Earth surface, that is lower by distance $R_0(\sim 10^2 km)$ then the region of generation of these wave structures, a level of geomagnetic pulsations will be less by the factor $\exp(-R_0/\lambda_0)$ (where λ_0 is the characteristic wavelength of electromagnetic perturbations). Magnetic effects on the Earth will be weaker than in dynamo region as $\lambda_0 \sim (10 \div 10^2) R_0 >> R_0$, but they can also be easily observed.

A comparison of theoretical estimates of parameters of two waves investigated above and experimentally observed for slow and fast large-scale electromagnetic perturbations [7,41,42,43,44,45] and their good agreement point to an availability of the sources of proper (background) large-scale wave structures of electromagnetic nature at a height of dynamo region of the ionosphere, where Hall conductivity is dominant. We must note that large-scale low-frequent wave structures fall into the frequency band $10^{-2} \div 10^{-5} s^{-1}$. Electromagnetic perturbations of this frequency range are biologically active [30] and, in particular, may play the role of a starting mechanism of pathological complications in human bodies susceptible to the hypertensional and other diseases. Therefore these wave structures are worthy of attention also in ecological point of view as a source of electromagnetic pollution of the environment.

Since fast and slow electromagnetic planetary waves represent their own degree of freedom in $E-$ region of the ionosphere, then under the influence on the ionosphere from above or from below (magnetic storm, earthquake, artificial explosions and so on) these wave structures will be generated in the first place on these modes (see, for example [5]). At the appointed power of the source nonlinear vortical structures will be generated [4], that is confirmed by observations [9,34,40]. Separate publication will be devoted to more detailed investigation of the problem of forced generation of these wave structures under the extraordinary (natural and artificial) influence on the ionosphere.

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