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Evolution of weather forming ULF electromagnetic structures in the ionospheric shear flows

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Abstract

This work is devoted to study of transient growth and further linear and nonlinear dynamics of planetary electromagnetic (EM) ultra-low-frequency internal waves (ULFW) in the rotating dissipative ionosphere due to non-normal mechanism, stipulated by presence of inhomogeneous zonal wind (shear flow). Planetary EM ULFW appears as a result of interaction of the ionospheric medium with the spatially inhomogeneous geomagnetic field. An effective linear mechanism responsible for the generation and transient intensification of large scale EM ULF waves in the shear flow is found. It has been shown that the shear flow driven wave perturbations effectively extract energy of the shear flow and temporally algebraic increasing own amplitude and energy (by several orders). With amplitude growth the nonlinear mechanism of self-localization is turned on and these perturbations undergo self organization in the form of the nonlinear solitary vortex structures due to nonlinear twisting of the perturbation's front. Depending on the features of the velocity profiles of the shear flows the nonlinear vortex structures can be either monopole vortices, or dipole vortex, or vortex streets and vortex chains. From analytical calculation and plots we note that the formation of stationary nonlinear vortex structure requires some threshold value of translation velocity for both non-dissipation and dissipation complex ionospheric plasma. The space and time attenuation specification of the vortices is studied. The characteristic time of vortex longevity in dissipative ionosphere is estimated. The long-lived vortex structures transfer the trapped particles of medium and also energy and heat. Thus the structures under study may represent the ULF electromagnetic wave macro turbulence structural element in the ionosphere.

Keywords: *ULF electromagnetic wave, Inhomogeneous geomagnetic field, Shear flow, non-modal approach, Nonlinear solitary vortex structures.*

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1. Introduction

In the work presented here, we continue to study a special type of internal waves, which appear in the ionosphere under the influence of the spatially inhomogeneous geomagnetic field and the Earth's rotation velocity (Aburjania *et al* 2002, 2003, 2004, 2007). So, we are interested in large-scale (planetary) ultra-low-frequency (ULF) electromagnetic (EM) slow and fast wave motions in the ionospheric medium (consisting of electrons, ions and neutral particles), which have a horizontal linear scale L_h of order 10^3 km and higher, a vertical scale $\mathrm{L_v}$ of altitude scale order H ($\mathrm{L_v} \approx \mathrm{H}$). In the mid-latitude E-layer, slow ULF waves have phase velocities of 1-100 m/s along the parallels, and period variations from several hours to tens of days, i.e. they have the frequencies in the range of $(10^{-4} - 10^{-6})$ s^{-1}, as it is obvious from the long-term observations (Cavalieri et al. 1974; Manson et al. 1981; Sharadze et al. 1989; Zhou et al. 1997). In contrast to conventional planetary Rossby waves, they give rise to a perturbation of the geomagnetic field (a few nanoteslas (nT)) − a circumstance that gives evidence of their electromagnetic nature. These waves are generated by the electrostatic dynamo electric field of polarization $\mathbf{E_d} = \mathbf{V}\times\mathbf{H}_0 / c$, where $\mathbf{H}_0$ is the strength of the geomagnetic field, $\boldsymbol{V}$ is velocity, c is light speed. Observations also show, that at temperate and mid-latitudes of the ionospheric E-region there are large-scale, relatively fast planetary electromagnetic wave perturbations, which propagate along the parallels with velocity of order of 2-20 km/s, their periods vary from several of minutes to a few hours, i.e. they have the frequencies in the range of $(10^{-1} - 10^{-4})$ s^{-1}, and an amplitude from hundreds to thousand of nT, as it is obvious from the observations (Al'perovich et al. 1982; Sharadze et al. 1988; Burmaka et al. 2004; Georgieva et al. 2005). Fast waves are generated by the latitudinal gradient of the geomagnetic field and the Hall effect and represent a variation of the vortical electric field $-$ $\mathbf{E_v} = \mathbf{V_D}\times\mathbf{H}_0 / c$, where $\mathbf{V_D} = \mathbf{E}\times\mathbf{H}_0\, c / H_0^2$ is an electron drift velocity. The fast waves are caused by the oscillations of electrons, completely frozen in the geomagnetic field. The phase velocities of these perturbations differ by magnitude at daily and nightly conditions in the E-layer of the ionosphere. In the mid-latitude F-layer the fast planetary electromagnetic wave perturbations propagate east-west along lines of constant latitude with a phase velocity of several units-tens of km/s; the periods range from a few seconds to several minutes, i.e. they have the frequencies in the range of $(10^{1} - 10^{-3})$ s^{-1}and accompanied by strong pulsation of the geomagnetic field ($20 - 10^{3}$ nT), as it is obvious from the observations (Sorokin, 1988; Sharadze et al. 1988; Burmaka et al. 2004; Georgieva et al. 2005; Fagundas et al. 2005). The phase velocity of the fast magneto-ionospheric wave perturbations in the F-layer does not vary noticeably on the period of a day, but depends on the ionospheric ionization levels.

These perturbations represent the eigen oscillations of the E and F-regions of the ionosphere and they are responsible for ionospheric electromagnetic weather formation. Such forced oscillations are observed at impulse action on the ionosphere from above - at magnetic storms (Haykowicz, 1991), from bellow – at seismic activity, volcano eruption and anthropogenic activities (Pokhotelov et al. 1995; Shaefer et al. 1999). So, at external influences these oscillations will be excited or amplified first in the ionosphere as eigen modes of the ionospheric resonator. Thus, these waves may be represented also ionospheric electromagnetic response on natural and artificial activities.

Observations (Gershman, 1975; Gossard and Hooke, 1975; Kamide and Chian, 2007) show also, that spatially inhomogeneous zonal winds (shear flows), produced by nonuniform heating of the atmospheric layers by solar radiation, permanently exist in the atmosphere and ionosphere layers. Herewith, investigation of the problem of generation and evolution of ionospheric EM ULF electromagnetic waves at interaction with the inhomogeneous zonal wind (shear flow) becomes important.

2. The governing equations

We choose our model as a two-dimensional $\beta -$ plane with sheared flow. Since the length of planetary waves ($\lambda \geq 10^{3}\,\mathrm{km}$) is comparable with the Earth's radius R, we investigate such notions in approximation of the $\beta -$plane, which was specially developed for analysis of large-scale processes (Pedlosky, 1978), in the "standard" coordinate system. In this system, the x-axis is directed along the parallel to the east, the y-axis along the meridian to the north and the z-axis $-$ vertically upwards (the local Cartesian system). For simplicity, the equilibrium velocity $\boldsymbol{V}_0$, geomagnetic field H_0, perturbed magnetic field $\mathbf{h}$ and frequency of Earth's rotation $\boldsymbol{\Omega}_0$ are given by $\boldsymbol{V}_0 =\ V_0(y)\,\mathbf{e_x}$, $\boldsymbol{H}_0\,(0,0,-H_p\cos\theta)$, $\boldsymbol{h}\,(0,0,h_z)$, $\Omega_0\,(0,0,\Omega_0\cos\theta)$. Here and elsewhere $\mathbf{e}\,(\mathbf{e_x},\mathbf{e_y},\mathbf{e_z})$ denotes a unit vector, $H_p = 5\times10^{-5}$ T is the value of geomagnetic field strength in the pole and we suppose that geomagnetic colatitude θ coincides with a geographical colatitude θ'. In the ionosphere the large-scale motions are quasi-horizontal (two-dimensional) (Aburjania et al. 2002; 2003; 2006) and hydrodynamic velocity of the particles $\mathbf{V} = (V_{x,}, V_y, 0)$. The fluid is assumed to be incompressible and therefore a stream function ψ can be defined trough $\boldsymbol{V} = [\nabla\boldsymbol{\psi}, \boldsymbol{e_z}]$. Medium motion is considered near the latitude $\varphi_0 = \pi/2 - \theta_0$.

Not considering any more detail in the new under review branches of planetary waves (see Aburjania et al , (2002-2004, 2007)) we would like to note that beginning with the altitude of 80 km and higher, the upper atmosphere of the Earth is a strongly dissipative medium. Often when modelling large-scale processes for this region of the upper atmosphere, effective coefficient of Rayleigh friction between the ionospheric layers is introduced. The role of the ion friction rapidly increases at the altitudes above 120 km (Kelley, 1989, Kamide and Chian, 2007) and its analytical expression coincides with the Rayleigh friction formula (Aburjania and Chargazia, 2007). Therefore, often during a study of large-scale $(10^3 - 10^4)$ km, ULF $(10 - 10^{-6})\mathrm{s}^{-1}$ wavy structures in the ionosphere, we will apply the well-known Rayleigh formula to dissipative force $\boldsymbol{F} = -\Lambda \boldsymbol{V}$, assuming the altitudes above $(80-130)$ km $\Lambda \approx 10^{-5}$ s^{-1}(Dickinson, 1969; Gosard and Hooke, 1975), and the altitudes above 130 km $\Lambda = N\nu_{in}/\mathrm{N_n}$, where N and N_n denote concentrations of the charged particles and neutral particles, ν_{in} is frequency of collision of ions with molecules (Gershman, 1974; Kelley, 1989; Al'perovich and Fedorov, 2007).

The governing equations of the considered problem are the closed system of magnetohydrodynamic equations of the electrically conducting ionosphere (Gershman, 1974; Kelley, 1989; Aburjania et al. 2004; 2007; Al'perovich and Fedorov, 2007). The solution of the temporal evolution of inhomogeneously sheared flow reduces to solution of the set of nonlinear partial differential equations for ψ and magnetic field perturbation, h_z (see Aburjania et al. 2002):

$$\left(\frac{\partial}{\partial t} + V_0(y)\frac{\partial}{\partial x}\right)\Delta\psi + \left(\beta - V_0''\right)\frac{\partial\psi}{\partial x} + C_H\frac{\partial h}{\partial x} + \Lambda\Delta\psi = J(\psi,\Delta\psi)\,, \tag{1}$$

$$\left(\frac{\partial}{\partial t} + V_0(y)\frac{\partial}{\partial x}\right)h - \beta_H\frac{\partial\psi}{\partial x} + \delta\cdot C_H\frac{\partial h}{\partial x} = J(\psi,h)\,. \tag{2}$$

Here

$$\beta = \frac{\partial 2\Omega_0}{\partial y} = -\frac{1}{R}\frac{\partial}{\partial\theta}(2\Omega_0) = \frac{2\Omega_0\sin\theta_0}{R}\,,$$

$$\beta_H = \frac{eN}{\rho c}\frac{\partial H_{0z}}{\partial y} = -\frac{N}{N_n}\frac{eH_p}{MRc}\sin\theta_0 < 0\,,\quad V_0''(y) = \frac{d^2V_0(y)}{d^2y}\,,$$

$$h = \frac{eN}{N_nMc}h_z\,,\quad C_H = \frac{c}{4\pi eN}\frac{\partial H_{0z}}{\partial y} = -\frac{cH_p}{4\pi eNR}\sin\theta_0 < 0\,,$$

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\,,\quad J(a,b) = \frac{\partial a}{\partial x}\cdot\frac{\partial b}{\partial y} - \frac{\partial a}{\partial y}\cdot\frac{\partial b}{\partial x}\,. \tag{3}$$

$\rho = N_nM$ is density of neutral particles; m and M are masses of electrons and ions (molecules); e is the magnitude of the electron charge; c is the light speed. Further we consider a motion in neighborhood of fixed latitude ($\theta = \theta_0$). The dimensionless parameter δ is introduced here for convenience. In the ionospheric E region $(80-150)$ km, where the Hall effect plays an important role, this parameter is equal to unity ($\delta = 1$). In the F region $(200-600)$ km, where the Hall effect is absent, δ turns to zero ($\delta = 0$).

The system of Eqs. (1), (2), at corresponding initial and boundary conditions, describes nonlinear evolution of the spatial two-dimensional large-scale ULF electromagnetic perturbations in sheared incompressible ionospheric E- and F-regions.

From the equations (1), (2) we determine the temporal evolution of the energy of wavy structures, $E(x,y,t)$

$$\frac{\partial E}{\partial t} = \int V_0'(y)\frac{\partial\psi}{\partial x}\frac{\partial\psi}{\partial y}dxdy - \Lambda\int|\nabla\psi|^2dxdy\,, \tag{4}$$

where

$$E = \frac{1}{2}\int\left(|\nabla\psi| + k\,|h|\right)dxdy\,,\quad V_0'(y) = \frac{dV_0(y)}{dy}\,,\quad k_0^2 = \frac{N}{N_n}\frac{\omega_{\mathrm{Pi}}^2}{c^2}\,,\quad \omega_{\mathrm{Pi}}^2 = \frac{4\pi e^2N}{M}\,; \tag{5}$$

and the potential enstrophy Q of wave perturbations:

$$\frac{\partial Q}{\partial t} = \frac{\partial}{\partial t}\left[\frac{1}{2}\int\left(|\Delta\psi|^2 + \frac{|\nabla h|^2}{k_0^2}\right)dxdy\right] = -\int V_0'\frac{\partial h}{\partial x}\frac{\partial h}{\partial y}dxdy - \int V_0'''\frac{\partial\psi}{\partial x}\frac{\partial\psi}{\partial y}dxdy - \Lambda\int|\Delta\psi|^2dxdy\,. \tag{6}$$

We note that in the absence of zonal flow ($V_0 = 0$) and Rayleigh friction ($\Lambda = 0$) the wavy structure energy and enstrophy are conserved.

Therefore, the existence of sheared zonal flow can be considered as the presence of an external energy source. One can see, that presented zonal shear flow (term with $V_0(y)$ in (4)) feeds the medium with external source of energy for generation of the wave structures (development of the shear flow instability). In this case it is necessary the velocity of the shear flow to have at least the first derivative according to meridional coordinate different from zero ($V_0'(y) \neq 0$). This conclusion can be made by virtue of above used modal (local - spectral) approach, which can't give much information about the features of the shear flow instability. But this doesn't mean that such instability always arises and remains in such form. This is exactly due to non-adequacy of modal approach at investigation of the features of shear flows, which is already considered in the introduction. In shear flows the modal approach can detect only possibility of instability. But for investigation of instability generation conditions and its temporal development in the ionosphere an alternative approach, namely, non-modal mathematical analysis becomes necessary. As it will be shown in the section 4 on the basis of more adequate method for such problems –nonmodal approximation, shear flows can become unstable transiently till the condition of the strong relationship between the shear flows and wave perturbations is satisfied (Chagelishvili et al. 1996; Aburjania et al. 2006), e. i. the perturbation falls into amplification region in the wave number space. Leaving this region, e. i. when the perturbation passes to the damping region in the wave vector space, it returns an energy to the shear flow and so on (if the nonlinear processes and self-organization of the vortex structure will not develop before) (Aburjania et al. 2006). The experimental and observation data shows the same (Gossard and Hooke, 1975; Pedlosky, 1979; Gill, 1982). Thus, non-uniform zonal wind or shear flow can generate and/or intensify the internal gravity waves in the ionosphere and provoke transient growth of amplitude, i.e. transient transport the medium into an unstable state. In the section 4 we confirm this view by using a different, more self-consistent method for the shear flow.

3. Local dispersion relation

Equations (1) and (2) are partial differential equations the variable coefficients of which depend on the spatial coordinate y. An analysis of the existence of nontrivial solutions by direct expansion of the physical quantities in Fourier integrals it is impossible even for the initial stage of the evolution of wave perturbations. This is why we have to use a local approximation by assuming that the coefficients of Eqs. (1) and (2) are locally uniform (constant), ($v_0 = const$). This approach justifies the use of the Fourier expansion in spatial and time variables to analyze the spectrum of the perturbations described by these equations (Mikhailovskii, 1974).

We represent the solution to Eqs. (1) and (2) in terms of the spatiotemporal Fourier expansion of the wave perturbations:

$$[\psi(x,y,t),h(x,y,t)] = \int [(\psi(k_x,k_y),h(k_x,k_y)]\, exp\left\{i\left[k_x x + k_y y - \omega t\right]\right\} dk_x dk_z\,, \tag{7}$$

where $\boldsymbol{k}$ is the wave vector and ω is the frequency. Substituting representation (7) into Eqs. (1) and (2) yields the dispersion relation

$$\tilde{\omega}^2 + \left(\frac{k_x}{k^2}\beta - \delta\cdot k_x C_H + i\Lambda\right)\tilde{\omega} - \delta\cdot\frac{k_x C_H}{k^2}\left(k_x\beta + i\Lambda k^2\right) - \frac{k_x^2}{k^2}C_H\beta_H = 0\,. \tag{8}$$

Here $\tilde{\omega} = \omega - k_x V_0$. Assuming that the wave number $k = \left(k_x^2 + k_y^2\right)^{1/2}$ is real, and the frequency is complex, $\tilde{\omega} = \omega_0 - k_x V_0 + i\gamma = \omega_1 + i\gamma$, $|\gamma| << \omega_0$, and taking in to account that the velocity $C_H < 0$ and $\beta_H < 0$, we obtain from dispersion relation (8) the spectrum of linear perturbations

$$\omega_1^2 + \left(\delta\cdot k_x|C_H| + \frac{k_x}{k^2}\beta\right)\omega_1 + \frac{k_x^2}{k^2}|C_H|\,[\,\delta\cdot\beta - |\beta_H|\,] = 0\,. \tag{9}$$

where $\omega_1 = \omega_0 - k_x V_0$, and the damping rate

$$\gamma = -\frac{(\delta\cdot k_x|C_H| + \omega_1)\Lambda}{\left(2\omega_1 + \dfrac{k_x\beta}{k^2} + \delta\cdot k_x|C_H|\right)}\,. \tag{10}$$

From formula (9) we can determine two wave branches:

$$\omega_0^{(1,2)} = k_x V_0 + \frac{k_x}{2k^2}\left\{-\delta|C_H|k^2 - \beta \pm \left[\left(\delta|C_H|k^2 + \beta\right)^2 - 4k^2|C_H|\left(\delta\beta - |\beta_H|\right)\right]^{1/2}\right\}. \tag{11}$$

(i) <u>*E-region*</u>$(\delta = 1)$.

For E region of the ionosphere, where the Hall effect plays an essential role $(\delta = 1)$, the equations (11) and (10) obtain the following form respectively:

$$\frac{\omega_0^{(1,2)}}{k_x} = V_0 - \frac{|C_H|k^2 + \beta}{2k^2} \pm \frac{1}{2k^2}\left\{\left(|C_H|k^2 + \beta\right)^2 - 4|C_H|k^2\beta'\right\}^{1/2}, \tag{12}$$

$$\gamma = -\frac{(k_x|C_H| + \omega_1)\Lambda}{\left(2\omega_1 + \dfrac{k_x\beta}{k^2} + k_x|C_H|\right)} \tag{13}$$

Here $\beta' = \beta - |\beta_H|$.

Equation (12) describes the propagation ULF planetary electromagnetic waves in the ionospheric E-layer having two branches of oscillations fast $\omega_0^{(1)}$ (with "+" sign before the radical) and slow $\omega_0^{(2)}$ (with "$-$" sign before the radical). The fast and slow mode (12) is an eigen oscillation of E-region of the ionospheric resonator. Wave is of electromagnetic origin and can exist in the presence of latitudinal gradient of the equilibrium geomagnetic field. It is seen that at $\beta \approx |\beta_H|$, the first branch $\omega_0^{(1)} = k_x V_0$ and for second branch we get

$$\omega_0^{(2)} = k_x V_0 - k_x|C_H| - \frac{k_x\beta}{k^2}. \tag{14}$$

In case long wave-length perturbations $k^2 \ll \beta/|C_H|$, we get from (12) and (13)

$$\omega_0^{(1)} = k_x V_0 - k_x\left[|C_H| - \frac{|C_H \cdot \beta_H|}{\beta} - \frac{k^2 C_H^2|\beta_H|}{\beta^2}\left(1 - \frac{|\beta_H|}{\beta}\right)\right], \quad \left|\gamma^{(1)}\right| = \frac{k^2|C_H\beta_H|}{\beta^2}\Lambda \ll \Lambda, \tag{15}$$

and

$$\omega_0^{(2)} = k_x V_0 - k_x\left[\frac{\beta}{k^2} + \frac{|C_H \cdot \beta_H|}{\beta} + \frac{k^2 C_H^2|\beta_H|}{\beta^2}\left(1 - \frac{|\beta_H|}{\beta}\right)\right], \qquad \gamma^{(2)} = -\Lambda. \tag{16}$$

From these expressions we see that depending on the sign of $(\beta - |\beta_H|)$, fast $\omega_0^{(1)}$ waves can propagate both westward and eastward virtually without damping, while slow $\omega_0^{(2)}$ waves are propagating only westward and are damping substantially (but for more large-scale waves the damping can be weak).

In case of relatively short wave-length perturbations $k^2 \gg \beta/|C_H|$, we get

$$\omega_0^{(1)} = k_x V_0 - \frac{k_x}{k^2}\left[\beta - |\beta_H| + \frac{|\beta_H|}{|C_H|k^2}\left(\beta - |\beta_H|\right)\right], \quad \gamma^{(1)} = -\Lambda, \tag{17}$$

and

$$\omega_0^{(2)} = k_x V_0 - k_x\left[|C_H| + \frac{|\beta_H|}{k^2} - \frac{2|\beta_H|}{|C_H|k^4}\left(\beta - |\beta_H|\right)\right], \quad \left|\gamma^{(2)}\right| \approx \frac{|\beta_H|}{k^2|C_H|}\Lambda \ll \Lambda. \tag{18}$$

As before, we see that depending on the sign $(\beta - |\beta_H|)$, slow $\omega_0^{(1)}$ waves can propagate both westward and eastward and are damping substantially, while fast $\omega_0^{(2)}$ waves are propagating only westward without damping.

(ii) _F-region_ $(\delta = 0)$.

For F-region of the ionosphere, where the Hall effect is absent $(\delta = 0)$, from (11) and (10) we obtain following solutions:

$$\omega_0^{(1,2)} = k_x V_0 + \frac{k_x}{2k^2}\left[-\beta \pm \left(\beta^2 + 4k^2\left|C_H \cdot \beta_H\right|\right)^{1/2}\right], \tag{19}$$

and

$$\gamma^{(1,2)} = -\frac{\omega_I^{(1,2)}}{2\omega_I^{(1,2)} + k_x\beta / k^2}\Lambda . \tag{20}$$

In case long wave-length perturbations $k^2 \ll \beta^2 / \left|C_H \cdot \beta_H\right|$, we get from (19) and (20)

$$\omega_0^{(1)} = k_x V_0 + \frac{k_x\left|C_H \cdot \beta_H\right|}{\beta}\left[1 - \frac{\left|C_H \cdot \beta_H\right|}{\beta^2}k^2\right], \quad \left|\gamma^{(1)}\right| \approx \frac{k^2\left|C_H\beta_H\right|}{\beta^2}\Lambda \ll \Lambda , \tag{21}$$

and

$$\omega_0^{(2)} = k_x V_0 - k_x\left[\frac{\beta}{k^2} + \frac{\left|C_H \cdot \beta_H\right|}{\beta}\left(1 - \frac{k^2\left|C_H \cdot \beta_H\right|}{\beta^2}\right)\right], \left|\gamma^{(2)}\right| \approx \frac{\beta^2}{4k^2\sqrt{C_H\beta_H}}\Lambda \gg \Lambda . \tag{22}$$

From these expressions we see that fast $\omega_0^{(1)}$ waves can propagate only eastward virtually without damping, while slow $\omega_0^{(2)}$ waves are propagating only westward and are damping substantially.

In case of relatively short wave-length perturbations $k^2 \gg \beta^2 / \left|C_H \cdot \beta_H\right|$, we get

$$\omega_0^{(1)} = k_x V_0 + \frac{k_x}{k}\left\{\sqrt{C_H\beta_H} - \frac{\beta}{2k} + \frac{\beta^2}{8\sqrt{\left|C_H\beta_H\right|}k^2}\left(1 - \frac{\beta^2}{16\left|C_H\beta_H\right|k^2}\right)\right\}, \quad \left|\gamma^{(1)}\right| = \frac{\Lambda}{2}, \tag{23}$$

and

$$\omega_0^{(2)} = k_x V_0 - \frac{k_x}{k}\left\{\sqrt{C_H\beta_H} + \frac{\beta}{2k} + \frac{\beta^2}{8\sqrt{\left|C_H\beta_H\right|}k^2}\left(1 - \frac{\beta^2}{16\left|C_H\beta_H\right|k^2}\right)\right\}, \quad \left|\gamma^{(1)}\right| = \frac{\Lambda}{2}. \tag{24}$$

We see that $\omega_0^{(1)}$ waves can propagate only eastward, while $\omega_0^{(2)}$ waves are propagating only westward. These waves are weakly damping.

The wave branches (15) and (18) represent the dispersion relations for fast EM planetary waves stipulated by Hall conductivity ($\delta = 1$) and the permanently acting factors in the E-region of the ionosphere $-$latitudinal gradient of the geomagnetic field and angular velocity of the Earth's rotation. The wave branches (21), (23) and (24) represent also fast EM planetary waves caused by the global factors, acting permanently in the F-region of the ionosphere$-$inhomogeneity of the geomagnetic field and angular velocity of the Earth's rotation. As to the wave branches (16), (17) and (22), they are of slow magnetized Rossby (MR)-type. In the dispersion of the slow waves (16), (17) and (22) along with the latitudinal gradient of the Earth's angular velocity latitudinal gradient of the geomagnetic field plays the important role, which reduces the phase velocity. The same for the fast waves (15), (18), (21), (23) and (24) $-$non-uniform nature of the angular velocity of the Earth rotation stipulates the mutual coupling of the fast and slow waves, which causes intensification of the dispersion of the fast waves. Without such couplings, for example, the fast waves (15), (23) and (24) become non-dispersive.

4. Non-modal analysis of the linear evolution of disturbances

In deriving dispersion relations (8)-(11), we used a local approximation; i.e., we assumed that the quantities V_0 and V_0'' are locally uniform (as well as β, β_{H} and C_H, as is usually done in the β-plane approximation) and expanded the physical quantities in Fourier integrals. The applicability of the local approximation to nonuniform medium and sheared flows is limited (Mikhailovskii, 1974). The results obtained by using this approximation are valid only for the initial stage of the evolution of perturbations. In particular, when the background flow is spatially nonuniform in the meridional direction, applying the Fourier expansion in the y coordinate is unjustified. According to (Reddy et al. 1993; Trefenthen et al. 1993; Chagelishvili et al, 1996; Aburjania et al. 2006), a more adequate approach to investigating the evolution of wave perturbations in sheared flows in the linear stage is provided by a nonmodal (rather than modal, i.e., direct Fourier expansion) mathematical analysis.

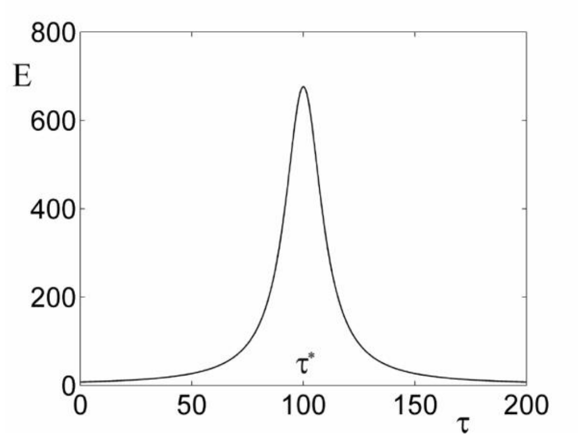

Fig. 1. Evolution of the non-dimensional energy density $E(\tau)$ (formulae (45)) to the initial parameters: $|\beta_H| = 0.1$, $\beta = 0.06$, $k_x = 0.01$, $k_y(0) = 0.1$, $S = 0.1$, $C_H = 1$.

Therefore, for adequate description of the dynamics of ULF waves interaction with inhomogeneous ionospheric winds on the basis of dynamical equations (1), (2), the non-modal mathematical analysis will be used below, which accounts non self-adjointness of the operators in this equations and non-orthogonality of the corresponding eigen-functions (Aburjania et al. 2006).

In this section, for definiteness, we choose the velocity profile of the sheared flow (nonuniform wind) to have the simplest form $V_0(y) = A \cdot y$, where $A > 0$ is the constant parameter of the wind shear, which we take to be positive and independent of y. The non-modal approach begins with a transformation to the convective coordinates $x_1 = x - v_0(y)t,\ y_1 = y,\ t_1 = t,$ that are the coordinates in the local rest frame of the mean flow.

In our problem, this is equivalent to the following change of variables:

$$x_1 = x - Ayt, \quad y_1 = y, \quad t_1 = t, \tag{25}$$

or

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial t_1} - Ay\frac{\partial}{\partial x_1}, \quad \frac{\partial}{\partial x} = \frac{\partial}{\partial x_1}, \quad \frac{\partial}{\partial y} = \frac{\partial}{\partial y_1} - At_1\frac{\partial}{\partial x_1}. \tag{26}$$

In terms of the new variables, Eqs. (1) and (2) read

$$\frac{\partial}{\partial t_1}\left\{\left[\frac{\partial^2}{\partial x^2} + \left(\frac{\partial}{\partial y_1} - At_1\frac{\partial}{\partial x_1}\right)^2\right]\psi\right\} + \beta\frac{\partial \psi}{\partial x_1} + C_H\frac{\partial h}{\partial x_1} + \nu\left\{\frac{\partial^2}{\partial x^2} + \left(\frac{\partial}{\partial y_1} - At_1\frac{\partial}{\partial x_1}\right)^2\right\}\psi = 0, \tag{27}$$

$$\frac{\partial}{\partial t_1}h - \beta\frac{\partial \psi}{\partial x} + C_H\frac{\partial h}{\partial x} = 0. \tag{28}$$

The coefficients of the initial set of linear equations (1) and (2) depend on the spatial coordinate y. Having made the above charge of variables, we switch from this spatial nonuniformity Eqs. (1) and (2) to the temporal nonuniformity in Eqs.(27) and (28).

Hence, we have reduced the boundary-value problem to the Cauchy problem. Since the coefficients of Eqs. (8) and (9) are now independent of the spatial coordinates x_1 and y_1, we can apply the Fourier expansions in the spatial variables x_1 and y_1 to the equations, without using any local approximations and can independently consider the time evolution of the SFHs:

$$\begin{Bmatrix} \psi(x_1,y_1,t_1) \\ h(x_1,y_1,t_1) \end{Bmatrix} = \int\int_{-\infty}^{\infty}\int dk_{x_1}dk_{z_1} \begin{Bmatrix} \tilde{\psi}(k_{x_1},k_{y_1},t_1) \\ \tilde{h}(k_{x_1},k_{y_1},t_1) \end{Bmatrix} \times exp(ik_{x_1}x_1 + ik_{y_1}z_1). \tag{29}$$

Here, quantities with tilde (e.g., $\tilde{\psi}$]) denote the SFHs of the corresponding physical quantities.

We substitute representation (29) into Eqs. (27) and (28), omit the tilde from the Fourier harmonics of the physical quantities, and switch to the dimensionless variables

$$\tau \Rightarrow \omega_0 t_1; \quad (x,y) \Rightarrow \frac{(x_1,y_1)}{R}; \quad \psi \Rightarrow \frac{\tilde{\psi}}{\omega_0 R^2}; \quad h \Rightarrow \frac{\tilde{h}}{\omega_0};$$

$$S \Rightarrow \frac{A}{\omega_0}; \quad k_{x,y} \Rightarrow k_{x_1,y_1}R; \quad k_z = k_z(0) - k_x S\tau; \quad k^2(\tau) = k_x^2 + k_z^2(\tau);$$

$$\nu \Rightarrow \frac{\Lambda}{\omega_0 R^2}; \quad \beta \Rightarrow \beta\frac{R}{\omega_0}; \quad C_H \Rightarrow \frac{C_H}{\omega_0 R}; \quad \Phi = k^2(\tau)\psi(\tau); \tag{30}$$

As a result, for each SFH of the perturbed quantities, in the non-dissipative case $(\nu = 0)$, we obtain the equations

$$\frac{\partial \Phi}{\partial \tau} - \beta k_x \frac{\Phi}{k^2(\tau)} - ik_x C_H h = 0, \tag{31}$$

$$\frac{\partial h}{\partial \tau} - ik_x \beta \frac{\Phi}{k^2(\tau)} + ik_x C_H h = 0. \tag{32}$$

The closed set of Eqs. (31) and (32) describes the linear interaction of a ULF PEW with a sheared flow and the evolution of the related perturbations in an ionospheric medium. After the above manipulations, the wave vector of the perturbations, $\boldsymbol{k}\ (k_x, k_y(t))$ becomes time-dependent, $k_y(\tau) = k_y(0) - k_x S \cdot \tau; k^2(\tau) = (k_x^2 + k_y^2(\tau))$, that is, the wave vector is subject to a linear drift in wave-number space. Because of the time variation of the wave vector (i.e., the separation of the perturbation scales in the linear stage), the interaction even between the perturbations that occur initially on very different characteristic scales is highly pronounced (Aburjania et al . 2006).

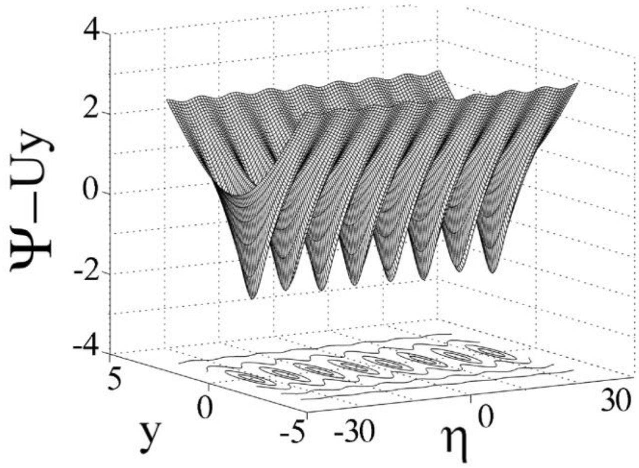

Fig. 2. Relief and level lines in the rest frame of the vortices $\Psi(\eta, y) - Uy$, calculated from formula (55) for $\psi_0^0 = 1$, $k = 1$, $æ_0 = 0.5$ (the longitudinal vortex street).

In wave number space, the total dimensionless energy density E of the wave perturbations, SFHs of which are determined by Eqs. (31) and (32), has the form

$$E[k(\tau)] = \frac{1}{2}\left[|\Phi(\tau)|^2 + \frac{|h(\tau)|^2}{k_0^2} \right]. \tag{33}$$

Correspondingly, from Eq. (4) we can see that, in the presence of a zonal flow with the velocity $V_0(y)$, the energy density of the SFHs evolves according to law

$$\frac{dE(\tau)}{d\tau}=V_0'\frac{\partial\psi}{\partial x}\frac{\partial\psi}{\partial y}=-SV_x(\tau)V_y(\tau). \tag{34}$$

In the absence of a sheared flow ($S=0$), the total energy density of the wave perturbations in the ionosphere is conserved, $dE(\tau)/d\tau=0$.

Let us now turn to Eq. (34) to find out what is the result of the evolution of the energy of a wave perturbation: is it an increase or a decrease in its energy? To do this, we must calculate the right-hand side of Eq. (34), a task that requires solving Eqs. (31) and (32). In this way, differentiating Eq. (31) with respect to time and using Eq. (32), we arrive at the following second-order equation for the generalized stream function $\Phi=k^2(\tau)\psi(\tau)$:

$$\frac{d^2\Phi}{d\tau^2}+P_1(\tau)\frac{d\Phi}{d\tau}+P_2(\tau)\Phi=0, \tag{35}$$

where

$$P_1(\tau)=ik_x\left(C_H-\frac{\beta}{k^2(\tau)}\right),\qquad P_2(\tau)=\frac{k_x^2}{k^2(\tau)}\left[C_H\beta'-2iS\frac{k_y(\tau)}{k^2(\tau)}\beta\right],\ \ \beta'=\beta+\beta_H. \tag{36}$$

Equation (35) can be simplified by introducing a new variable (Magnus 1976). Setting

$$\Phi=Y\,exp\left[-(1/2)\int P_1(\tau')d\tau'\right], \tag{37}$$

we can transform Eq. (35) to the equation of a linear oscillator with time-dependent parameters

$$\ddot{Y}+\Omega^2(\tau)Y=0. \tag{38}$$

Here, the prime denotes the derivative with respect to time and

$$\ddot{Y}=\frac{d^2Y}{d\tau^2};\qquad \Omega^2(\tau)=P_2(\tau)-\frac{1}{2}\dot{P}_1(\tau)-\frac{1}{4}P_1^2(\tau)\approx$$

$$\approx\frac{k_x^2C_H^2}{4}\left(1-\frac{\beta}{k^2(\tau)C_H}\right)^2+\frac{k_x^2}{k^2(\tau)}\left(C_H\beta'-iS\frac{k_y(\tau)}{k^2(\tau)}\beta\right). \tag{39}$$

We solve Eq. (38) in the adiabatic approximation (Zel'dovich and Myshkis, 1973) by assuming that the quantity $\Omega(\tau)$ varies adiabatically with time:

$$\left|\dot{\Omega}(\tau)\right|<<\left|\Omega^2(\tau)\right|. \tag{40}$$

Under this assumption, homogeneous equation (38) can be solved approximately. For a flow with $S<<1$, condition (40) is satisfied for a wide range of wave numbers, $\left|k_y(\tau)=k_y(0)-k_xS\tau\right|$. In other words, when the time variation of $\left|k_y(\tau)\right|$ is due to the linear drift of the wave vector in wave number space, condition (40) is valid throughout the entire evolution of the SFHs. The approximate solution to Eq. (38) can then be represented as

$$Y=\frac{C}{\sqrt{\Omega(\tau)}}exp\left[-i\int_0^\tau\Omega(\tau')d\tau'\right], \tag{41}$$

where $C=const$. Substituting representation (41) into formulas (37) and (30), we can construct the solutions to Eqs. (31) and (32):

$$\psi(\tau)=\frac{\Phi(\tau)}{k^2(\tau)}=\frac{C}{k^2(\tau)\sqrt{\Omega(\tau)}}exp\left[-i\phi(\tau)\right], \tag{42}$$

$$h(\tau)=-\frac{k^2(\tau)\psi(\tau)}{k_xC_H}\left[\Omega(\tau)+\frac{k_xC_H}{2}\left(1+\frac{\beta}{k^2(\tau)C_H}\right)\right], \tag{43}$$

Here, with allowance for the obvious inequality $\left|C_H\right|>>\left|\beta'/k^2(\tau)\right|$, we assume that

$$\Omega(\tau)=\frac{k_x C_H}{2}\left(1+\frac{\beta+2\beta_H}{k^2(\tau)C_H}\right),\ \phi(\tau)=k_x C_H\tau+\frac{\beta_H}{k_x S}\left[arct\frac{k_y(\tau)}{k_x}-arct\frac{k_y(0)}{k_x}\right]. \qquad (44)$$

Inserting formulas (42)-(44) into expression (33) and taking into account the inequalities $k_0^2=4\pi^2\times10^{-6}<<1$, $|\beta_H|\geq\beta,\ \beta>0,\ \beta_H<0,\ C_H<0$, we arrive at the following expression for the normalized energy density of the Fourier harmonics:

$$E(\tau)\approx 1+\left|\frac{6|\beta_H|-|\beta|}{8\left[k_x^2+\left(k_y(0)-Sk_x\tau\right)^2\right]C_H}\right|. \qquad (45)$$

In the initial evolutionary stage such that $k_y(0)/k_x>0$ (when $k_y(\tau)>0$), the denominator in expression (45) decreases with time τ, $0<\tau<\tau^*=k_y(0)/(Sk_x)=100$ and, accordingly, the energy density of the SFHs increases monotonically and reaches its maximum (which is several times higher than its initial value) at $\tau=\tau^*=100$. On longer time scales, $\tau^*<\tau<\infty$, the energy density decreases (when $k_y(\tau)<0$) and monotonically approaches a value approximately equal to the initial density. In other words, in the initial evolutionary stage, when $k_y(\tau)>0$ and the SFHs of the perturbations are in the amplification range in wave number space, the perturbations temporarily extract energy from the sheared flow to increase their amplitude several times on the time interval $0<\tau<\tau^*=k_y(0)/(Sk_x)$; in the subsequent stage, when $k_y(\tau)<0$, and the SFHs of the perturbations are in the damping range in wave number space, the perturbations return the energy back to the sheared flow on time scales $\tau^*<\tau<\infty$ (Figure 1), provided that nonlinear processes have not come into play and no self-organization of the wave structures has occurred prior to this stage. In a medium with a sheared flow, such an energy transient redistribution is caused by the fact that the wave vectors of the perturbations become time-dependent, $k=k(\tau)$; that is, the scales of the perturbations are partitioned and the structures occurring on comparable scales efficiently interact with each other, thereby sharing the free energy of the system among themselves.

So, within a time interval $\tau\leq\tau^*$ EM ULF wave disturbances redistribute the mean shear flow energy – draw energy from the main flow (the shear energy) and significantly grow (by several orders).

5. Shear flow driven nonlinear solitary vortex structures

It was shown in previous section, at the zonal flow velocity inhomogeneity, at interaction with the wind the EULF wave perturbations can sufficiently increase own amplitude and energy and in their dynamics the nonlinear effects will be appeared. As a rule, considering nonlinearity, steepness of the wave front increase leading to its breaking or formation of shock wave. However, as it is well known, shock waves do not arise spontaneously in the ionosphere. This indicates that in the real ionosphere for the planetary-scale motions when dissipative forces can be neglected, nonlinear effects of the medium must be essential (Aburjania et al. 2003, 2007). As a result, before breaking the wave must disintegrate either into separate nonlinear waves or into the vortex formations. If nonlinear increase of steepness of wave front will be exactly compensated by dispersion spreading, then stationary vortex structures will appear in the ionosphere. The more so, as experimental data and observations show (Bengtsson and Lighthill, 1982; Cmyrev et al, 1991; Petviashvili and Pokhotelov, 1992; Nezlin, 1994; Aburjania, 2006) that the nonlinear solitary vortex structures may exist in the different layers of Earth's atmosphere. Thus, the shear flow energy accumulation in the ionospheric disturbances may be results in the formation of nonlinear vortex structures. So, the ionosphere medium with sheared flow creates a favorable condition for formation of the nonlinear stationary solitary wave structures.

5.1. The stationary vortex streets in the nondissipative ionosphere

Vortex streets of various shapes can be generated in conventional liquid and plasma media with a sheared flow as a result of the nonlinear saturation of the Kelvin-Helmholtz instability (Gossard and Hooke, 1975; Kamide and Chian, 2007).

Thus, we will seek the solution of the nonlinear dynamic equations (1), (2) (in nondissipative stage, when $\Lambda\approx0$) in the form $\psi=\psi_0(\eta,y)$, $h=h(\eta,y)$, where $\eta=x-U\tau$, i.e. the stationary solitary structures, propagating along x-axis (along the parallels) with velocity $U = const$ without changing its' shape. In accordance to Aburjania and Chargazia (2007), system of equation (1), (2) has the solution

$$h(\eta, y) = \frac{\beta_H}{C_H - U}\Psi , \tag{46}$$

$$\Delta\psi_0 - v_0'(y) - \frac{C_H\beta' - U\beta}{C_H - U} y = F(\psi_0 - \int^{y} v_0(y)dy - Uy) , \tag{47}$$

with $F(\xi)$ being an arbitrary function of its argument and $\Delta = \partial^2 / \partial\eta^2 + \partial^2 / \partial y^2$.Vortex streets have complicated topology and can occur when the function $F(\xi)$ in Eq. (47) is nonlinear (Petviashvili and Pokhotelov, 1992, Aburjania, 2006).

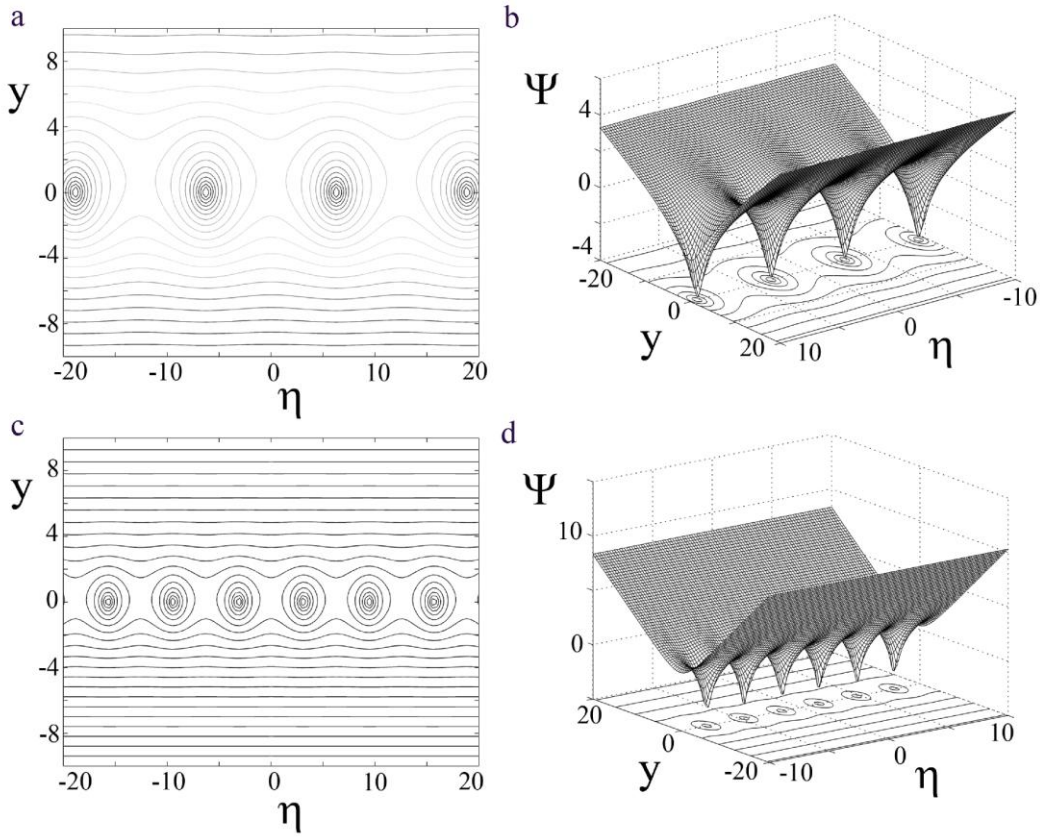

Figure 3. The level lines and relief of the stream function of vortex solution (55) in the moving system of coordinates to the parameters: a). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.2$, $\kappa = 0.5$; b). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.2$, $\kappa = 1$; c). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.2$, $\kappa = 0.5$; d). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.2$, $\kappa = 1$.

In (47) we assume that a nonlinear structure propagates with the velocity U satisfying the condition

$$U = \frac{\beta'}{\beta} C_H . \tag{48}$$

For this case, choosing F to be a nonlinear function, $F(\xi) = \psi_0^0 \kappa^2 (exp(-2\xi / \psi_0^0)$ (Petviashvili and Pokhotelov, 1992; Aburjania, 2006), we can reduce Eq. (47) to

$$\Delta(\psi_0 - Uy) = \psi_0^0 k^2 \, exp\left[-2(\psi_0 - Uy) / \psi_0^0\right] . \tag{49}$$

Then we introduce the new stream function

$$\Psi_0(\eta, y) = \Phi_0(y) + \psi_0(x, y) , \tag{50}$$

and the velocity potential $\Phi_0(y)$ of the background sheared zonal flow,

$$V_0(y) = \frac{d\Phi_0(y)}{dy} . \tag{51}$$

The stream function of the background sheared flow $\Phi_0(y)$ can be chosen to have the form

$$\Phi_0(y) = Uy + \psi_0^0 \, ln(æ_0 y). \tag{52}$$

Here, ψ_0^0 is the amplitude of the vortex structure, $2\pi/\kappa$ kappa is its characteristic size, and $2\pi/æ_0$ is the nonuniformity parameter of the background sheared flow.

Taking into account formula (50) and using stream function (52), we can write vortex equation (49) as

$$\Delta\psi_0 = \psi_0^0 æ_0^2 \left[\frac{\kappa^2}{æ_0^2} e^{-2\psi_0/\psi_0^0} - 1\right]. \tag{53}$$

This equation has the solution (Mallier and Maslowe, 1993)

$$\psi_0(\eta, y) = \psi_0^0 \, ln\left[\frac{ch(\kappa y) + \sqrt{1-æ_0^2}\, cos(\kappa\eta)}{ch(æ_0 y)}\right], \tag{54}$$

which describes a street of oppositely circulating vortices. Substituting solution (54) and stream function (52) into formula (50), we arrive at the final solution

$$\Psi_0(\eta, y) = Uy + \psi_0^0 \, ln[ch(\kappa y) + \sqrt{1-æ_0^2}\, cos(\kappa\eta)]. \tag{55}$$

Formulas (54), (52), and (51) yield the following expressions for the velocity components of the medium and sheared flow:

$$V_x(\eta, y) = U + \psi_0^0 \kappa \frac{sh(\kappa y)}{ch(\kappa y) + \sqrt{1-æ_0^2}\, cos(\kappa\eta)}, \tag{56}$$

$$V_y(\eta, y) = \psi_0^0 \kappa \frac{\sqrt{1-æ_0^2}\, sin(\kappa\eta)}{ch(\kappa y) + \sqrt{1-æ_0^2}\, cos(\kappa\eta)}, \tag{57}$$

$$V_0(y) = U + \psi_0^0 æ_0 th(æ_0 y). \tag{58}$$

For $æ_0 = 1$, solution (56) describes a background flow of the type of sheared zonal flow with velocity (58). For $æ_0^2 < 1$, a street of cyclonic-type vortices forms in the middle of the zonal flow with velocity (58) (Figure 2). A solution like that described by formulas (56) and (57), with closed current lines in the form of cat's eyes, was for the first time obtained by Kelvin.

The vortex structures move with velocity (48). If we take into account that $\beta_H < 0$, $\beta' = \beta - |\beta_H| < 0$ as far as $|\beta_H| > \beta > 0$, $C_H < 0$ from expression (48) follows $U > 0$. For E-region the characteristic parameters $\mathrm{N/N}_n = 5\times10^{-7}$, $\Omega_H = eH_p/(Mc) \sim 10^3\ \mathrm{s}^{-1}$, $\mathrm{R} = 6.4\times10^6 m$, $2\Omega_0 \cong 10^{-4} rad\cdot s^{-1}$, we get that $\beta = 2\Omega_0 \sin\theta_0 / R \sim 0.8\times10^{-11} m^{-1}s^{-1}$, $|C_H| \approx 10\ km\cdot s^{-1}$, $|\beta_H| = (N/(N_n R))\Omega_H \sin\theta_0 \approx 4\times10^{-11} m^{-1}s^{-1}$. Thus, the vortices move with velocity $U \approx 4|C_H| > |C_H|$ along the parallels to the east. Therefore, this velocity is greater than the phase one of the corresponding linear periodic waves $U > |C_H| \approx 10\ \mathrm{km\cdot s^{-1}}$. So, the vortices don't come into resonance with the linear waves and don't loose energy on their excitation (Stepanyants and Fabrikant 1992).

For estimation of the linear scale of the vortex structures let's remember the general formal relation between the dispersion equation of the linear waves and with so-called modified dispersion equation of the nonlinear structures (Petviashvili and Pokhotelov, 1992; Aburjania, 2006). This is coupling of the phase velocity of linear wave $V_p = \omega/k$ with motion velocity of the nonlinear structures $U : -\omega/k \to U$; relation of the wave vector k of the linear disturbances with the characteristic linear scale of the vortex d : $-\ k \to d^{-1}$. Taking into account this fact for characteristic scale of the fast vortex structures from (14) we get:

$$d^f = \left(\frac{|C_H|}{\beta}\right)^{1/2}. \tag{59}$$

And for the slow Rossby type vortex structures from the equations (16), (17) we get:

$$d^s = \left(\frac{U}{\beta}\right)^{1/2} . \qquad (60)$$

Substituting in these expressions the typical for the Earth's ionosphere numerical values $|C_H| \approx 10 \text{ km s}^{-1}$, $\beta \approx 10^{-11} m^{-1} s^{-1}$, we find for fast structures $d^f \approx 10^4 km$. For slow Rossby-type vortices $U \approx 10 \text{ m s}^{-1}$ and we can obtain $d^s \approx 10^3 km$.

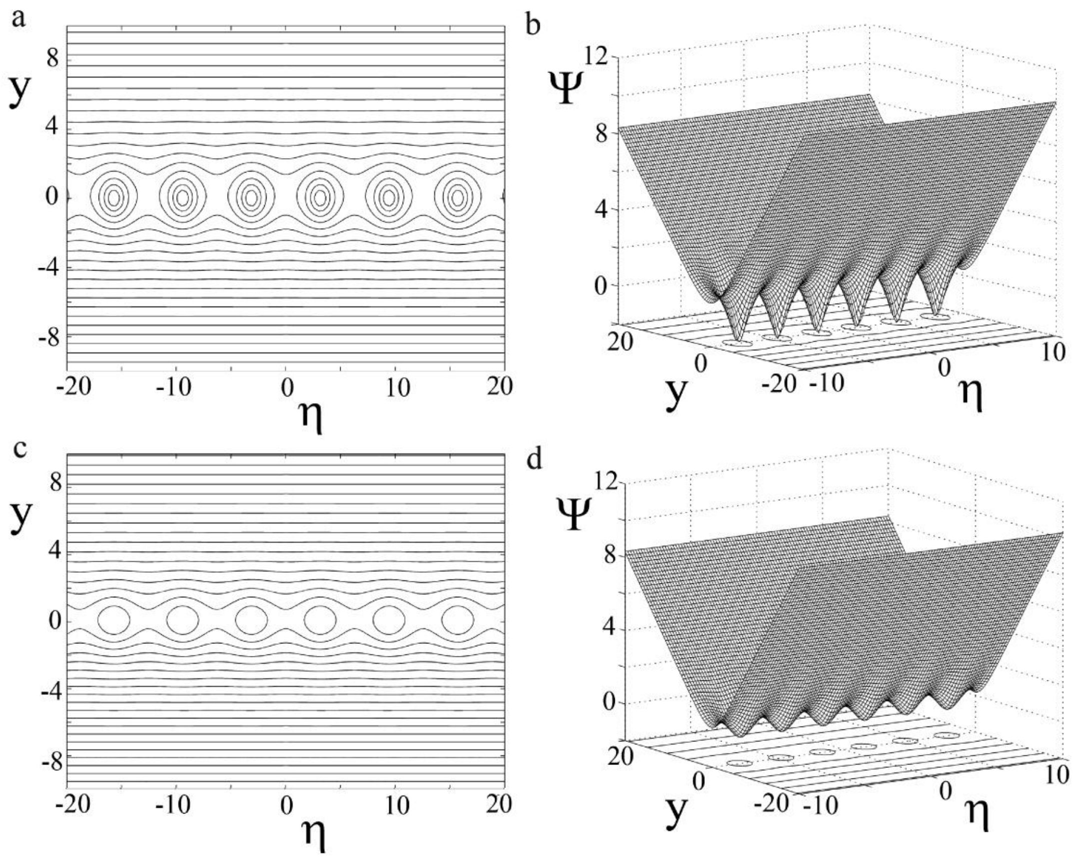

Figure 4. The level lines and relief of the stream function of vortex solution (55) in the moving system of coordinates to the parameters: a). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.5$, $\kappa = 1$; b). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.5$, $\kappa = 1$; c). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.9$, $\kappa = 1$; d). $\psi_0^0 = 1$, $U = 0.1$, $æ_0 = 0.9$, $\kappa = 1$;

For magnetic field perturbation from (46) and (55), we can obtain the following estimation:

$$|h| \approx |\beta_H| \cdot d , \qquad (61)$$

valid for both the fast and slow modes. For the ionospheric conditions $|\beta_H| \approx 4 \times 10^{-11} m^{-1} s^{-1}$, thus using the estimations to carried out above, we my conclude that fast vortical motion generate magnetic pulsations $h^f \approx 10^{-4} T$, while in case slow Rossby-type vortical motions $- h^s \approx 10^{-5} T$.

Note that nonlinear stationary equation (47) also has an analytic solution in the form of a Larichev-Reznik cyclone-anticyclone dipole pair and other class of solitary solutions by different profiles of background shear flows (Petviashvili and Pokhotelov, 1992; Jovanovich et al. 2002; Aburjania, 2006; Aburjania et al. 2003; 2004; 2007).

5.2. Attenuation of the vortex streets in the dissipative ionosphere

In the dissipative approximation ($\Lambda \neq 0$), we switch to the above self-similar variables (η and y) and take into account the relationship $\partial / \partial\tau = -U\partial / \partial\eta$, which then holds. As a result, we can write Eqs. (1) and (2) as

$$-U\frac{\partial}{\partial\eta}\Delta\Psi + \beta\frac{\partial\Psi}{\partial\eta} + C_H\frac{\partial h}{\partial\eta} + \Lambda\Delta\psi - J(\Psi, \Delta\Psi) = 0 , \qquad (62)$$

$$(C_H - U)\frac{\partial h}{\partial \eta} - \beta_H \frac{\partial \Psi}{\partial \eta} - J(\Psi, h) = 0. \tag{63}$$

Equation (63) has the solution

$$h(\eta, y) = \frac{\beta_H}{C_H - U}\Psi. \tag{64}$$

Substituting solution (64) into Eq. (62), take into account the expression (48) and rearranging the term, we arrive at a single nonlinear equation:

$$\left(D_\eta + \frac{\Lambda}{U}\right)\Delta\Psi = 0, \tag{65}$$

where

$$D_\eta = \frac{\partial}{\partial \eta} + \frac{1}{U}\left(\frac{\partial \Psi}{\partial \eta}\frac{\partial}{\partial y} - \frac{\partial \Psi}{\partial y}\frac{\partial}{\partial \eta}\right).$$

The equation (65) yield a solution as

$$\Psi = \Psi_0 \cdot \exp\left(-\frac{\Lambda}{\mathrm{U}}\eta\right). \tag{66}$$

Here the zero$^{\mathrm{th}}$ order Ψ_0 is identified with solution (55) (Figure 2). The incorporation of dissipation effects has modified the solution of the dynamical non-linear differential equation. It can be seen from (66) that friction (or collision) is responsible for exponential decay of stationary nonlinear vortex structures in space. This street of vortices can be studied by plotting the stream line function $\Psi(\eta, y)$(Eqs. (66) and (55)). We have free parameters Ψ_0^0, κ and $æ_0$, and the velocity of movement of the structures U will be determine by (48).

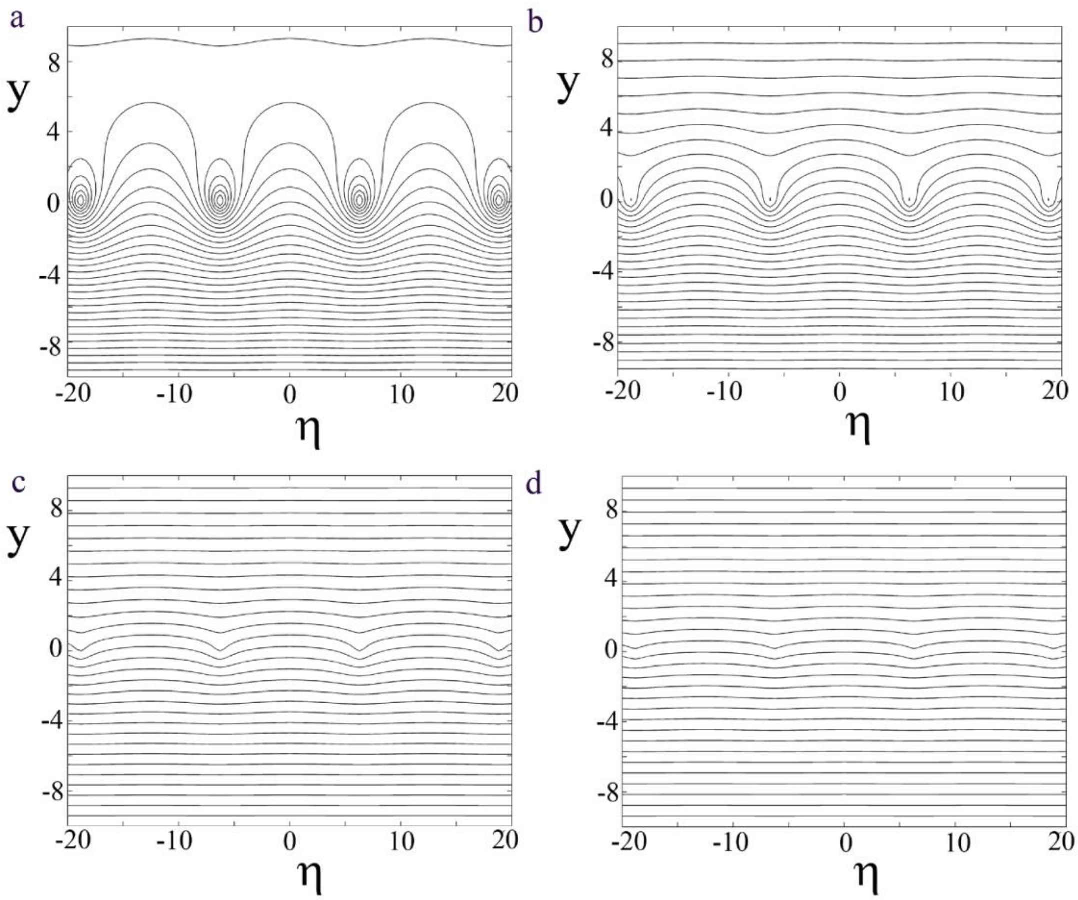

Figure 5. The level lines and relief of the stream function of vortex solution (55) in the moving system of coordinates to the parameters: a). $\psi_0^0 = 1$, $\mathrm{U} = 0.6$, $æ_0 = 0.2$, $\kappa = 0.5$; b). $\psi_0^0 = 1$, $\mathrm{U} = 1.5$, $æ_0 = 0.2$, $\kappa = 0.5$; c). $\psi_0^0 = 1$, $\mathrm{U} = 5$, $æ_0 = 0.2$, $\kappa = 0.5$; d). $\psi_0^0 = 1$, $\mathrm{U} = 10$, $æ_0 = 0.2$, $\kappa = 0.5$;

Figure3a shows the $\kappa = 0.5$ case and $\Psi_0^0 = 1$, $\mathrm{U} = 0.1$, $æ_0 = 0.2$, while Figure 3c shows the $\kappa = 1$ case. Three dimensional plots for the same parameters are shown in Figure 3b and 3d. At decrease of the linear scales of the vortices (with increase of κ) the number of the vortices will increase in the given area of the medium and their amplitudes will decrease (Figure 3c, 3d).The reduction in κ causes a reduction in number of vortices, e.g., the $\kappa = 1$stream function plots six vortices (Figure 3c, 3d). We, therefore, note that the number of vortices increases with increasing κ, e.g. the formation of nonlinear structures is attributed to low frequency mode.

At decrease of the linear scale of the background wind inhomogeneity (increasing $æ_0$) the linear scales, amplitudes and steepness of peaks of the vortices decrease accordingly (Figure 4).

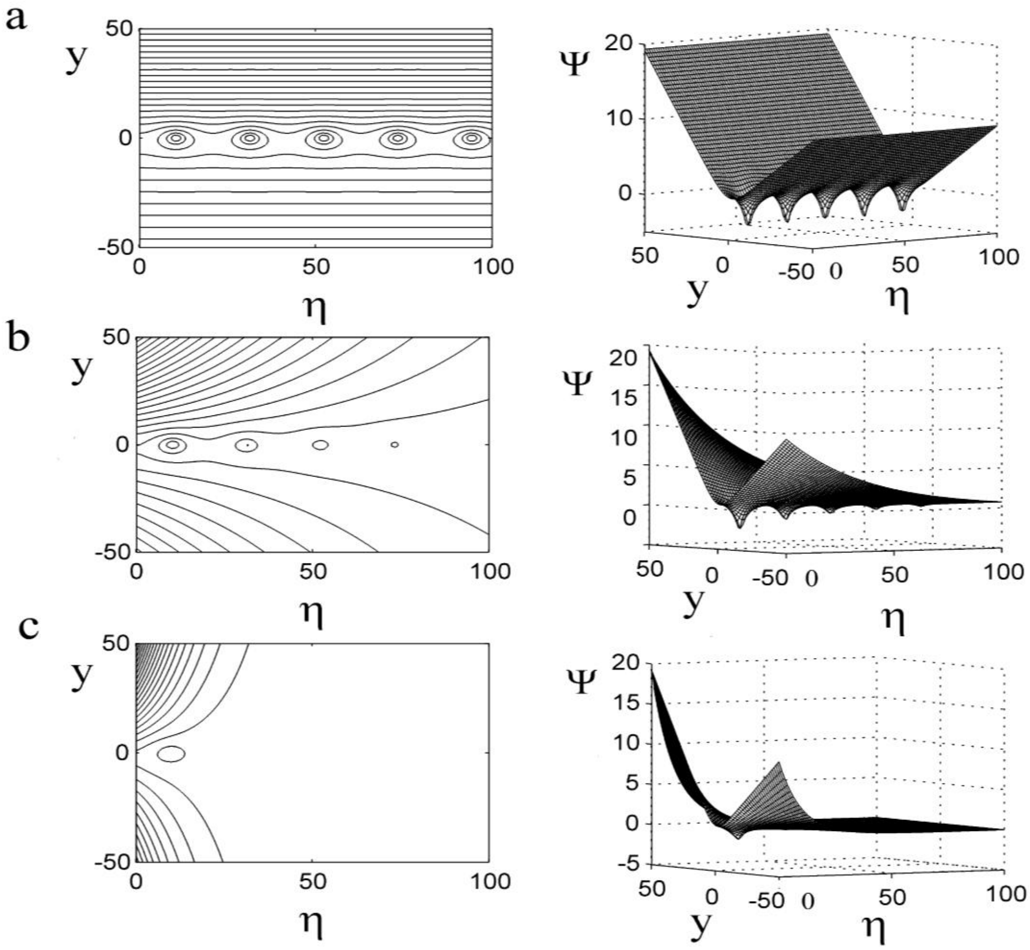

Figure 6. Spatial damping of the vortex structures (the level lines and relief of the stream function), calculated from formula (66) to the parameters: a). $\psi_0^0 = 1$, $\mathrm{U} = 0.1$, $æ_0 = 0.2$, $\kappa = 0.3$, $\Lambda = 0.0000$; b). $\psi_0^0 = 1$, $\mathrm{U} = 0.1$, $æ_0 = 0.2$, $\kappa = 0.3$, $\Lambda = 0.0025$; c). $\psi_0^0 = 1$, $\mathrm{U} = 0.1$, $æ_0 = 0.2$, $\kappa = 0.3$, $\Lambda = 0.0100$;

The street of vortices is in almost stationary frame of reference, it disappears for higher frame velocity ($\mathrm{U} > 1$), i.e. the contribution of logarithmic and hyperbolic trigonometric functions are no longer overcome by the contribution of linear term viz. Uy in (55) and, therefore, vortex formation is replaced by straight stream lines (Figure5). Due to increase of the translation velocity (U) of the structures and the background flows the scales and amplitudes of the generated vortices will decrease. In case of comparably high velocity background wind ($U > 1$) the vortex will not be generated at all and only the background flow will remain in the medium (Figure 5). Further, due to the nonlinear term, the velocity of dispersive waves must be greater than the phase velocity of a wave which resulted in a bending of the wave front and hence vortices start to form.

The street of vortex disappears in the space for high dissipation rate Λ (or collision frequency) (Figure 6). We credence that the dissipation effect has not permitted the vortex formation, but the topography of stream line function has been modified (Figure 6).

5.3. Relaxation of the vortex structures in the ionosphere

The real mechanism of dissipation in the atmosphere against the background of baroclinic, nonlinear and dispersive effects generates in the ionosphere moving spatial structures representing the equilibrium stationary solutions (54) and (55) of the governing magneto-hydrodynamic equations (1) and (2). For qualitative estimation of the evolution and the temporal relaxation of stationary vortex structures in the ionosphere, built in previous paragraphs, the dynamic equations (1) and (2) can be approximately written as the following Helmholtz's vortex transfer equation:

$$\frac{\partial}{\partial \boldsymbol{t}}\nabla\times\boldsymbol{V} = \boldsymbol{P} - \Lambda(\nabla\times\boldsymbol{V}), \tag{67}$$

which describes the generation of nonzero vorticity $\nabla\times\boldsymbol{V}$ ($(\nabla\times\boldsymbol{V})_{\boldsymbol{z}} = \Delta\Psi$) in the ionosphere under the action baroclinic vector $\boldsymbol{P}$ (source function) taking in to account the temperature contrasts in the form of advection of warm and cold, medium dispersion and influence of small nonlinearity. According to the observations (Gill, 1982; Pedlosky, 1982), vector $\boldsymbol{P}$ for low-frequency disturbances is a slowly varying function of time. In this case the vortex Eq. (67), with the initial conditions of Cauchy $\nabla\times\boldsymbol{V}\big|_{\boldsymbol{t}=0} = 0$ (at the initial moment in the atmosphere there no vortices) has the bounded solution:

$$\nabla\times\boldsymbol{V} = \frac{\boldsymbol{P}}{\Lambda}\left(1-\boldsymbol{e}^{-\Lambda\boldsymbol{t}}\right). \tag{68}$$

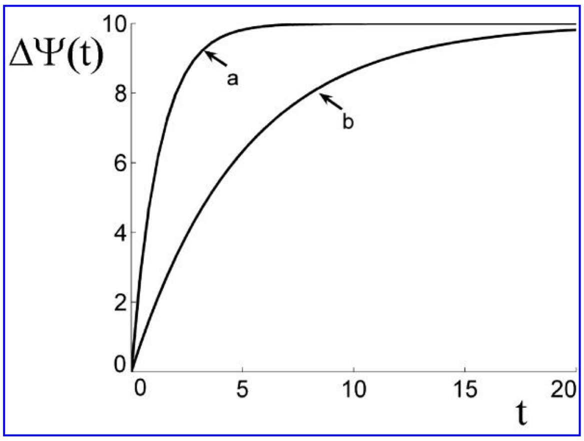

Figure 7. Relaxation of the vorticity of perturbations, calculated from formula (68) to the parameters: a). $\Lambda = 0.8$, $P/\Lambda=10$; b). $\Lambda = 0.2$, $P/\Lambda=10$.

Dissipative effects have an accumulative nature and its action becomes perceptible only after a certain interval. From Eq. (68) it follow that vorticity will increase linearly with time only at small time intervals ($t \ll 1/\Lambda$) under the action of baroclinicity and some other effects. After a certain time, when the dissipation effect reaches a specific value, vortex growth speed decreases (the vorticity growth rate decreases) and for the large intervals of time ($t \gg 1/\Lambda$) it tends to constant (equilibrium) value $\boldsymbol{P}/\Lambda$ (Figure 7).The value of dimensional time $T = 1/\Lambda \approx 10^5 s \geq 24$ hour can be called a relaxation time of non-stationary vortex street. Indeed, for the lower atmosphere relaxation time is of the order of twenty-four hours (Gossard and Hooke, 1975; Pedlosky, 1982) and consequently here large scale vortices must be long-lived. Stationary solution describes the equilibrium between baroclinicity and the dissipation effects ($\boldsymbol{P} = \Lambda(\nabla\times\boldsymbol{V})$). As a result, the dissipative structure is generated in the ionosphere in the form of stationary street of cyclones and anticyclones.

6. Conclusions

Thus, in the present article we have obtained the simplified system of nonlinear dynamical equations describing linear and nonlinear interaction of planetary electromagnetic ultra-low-frequency fast and slow wavy structures with zonal shear flow in the Earth's dissipative ionosphere. Along with the prevalent effect of Hall conductivity for such waves, the latitudinal inhomogeneity of both the angular velocity of the Earth's rotation and the geomagnetic field becomes essential. Due to spatial inhomogeneity of the Earth's rotation velocity fast and slow waves can be coupled. Such coupling results in an appearance of strong dispersion of these waves. Note that, without this coupling the fast branches in the both ionospheric E and F-regions lose the dispersion property for both large and short wave-length perturbations.

Effective linear mechanisms are revealed, which account the transient pumping of shear flow energy into wave disturbance energy, an extreme intensification (by several orders) of wavy processes, self-organization of generated wavy disturbances into the nonlinear solitary vortex structures, dissipation relaxation of vortices and finally the conversion of perturbation energy to heat. A remarkable feature of the sheared flow is a reduction in the scales of wave perturbations in the linear regime due to the variation of the wave vector of the perturbations with time $k = k(\tau)$ and also due to the linear drift of the SFHs of the perturbations in wave number space and, accordingly, the energy transfer into small scales, i.e., into the dissipative region. The Linear intensification of EM ULF wave may take place temporarily, for certain values of the parameters of the medium, shear and waves. This makes an unusual way of shear flow heating in the ionosphere: waves draw up the shear flow energy and pump it through the linear drift of spatial Fourier-harmonics (SFH) in the space of wave numbers (subdivision of disturbance scales) to the damping domain. Finally, the friction, viscosity and inductive damping may convert this pumped energy to heat. The process is permanent and may lead to a strong heating of the medium. The heating intensity depends on the initial disturbance level and shear flow parameters.

The generation of the slow electromagnetic linear waves in the ionospheric E-region by the gradient of both geomagnetic field's, angular velocities of the Earth's rotation and inhomogeneous zonal wind was shown. Slow wave propagate in E-region along the latitudinal circles westward and eastward against a background of mean zonal wind and are the waves of Rossby type. The frequency of the slow waves vary in the diapason of $(10^{-4} \div 10^{-6})\,\mathrm{s}^{-1}$; period of these waves vary in the range from 2 hour to 14 day; wavelength is about 10^3 km and longer, the phase velocity has the same order as the local winds' do from a few to hundred of $\mathrm{m \cdot s^{-1}}$ ($V_p^s \approx (1 \div 100)\ \mathrm{m \cdot s^{-1}}$). The slow waves experience the strong attenuate by Rayleigh friction between the layers of the local atmosphere and the damping factor is $|\gamma^s| = \Lambda \sim 10^{-5}\, s^{-1}$. Though the attenuation would be weaker for longer large-scale waves with wavelength of about 10^4 km and the timescale of a week or longer. The linear slow waves perturb the magnetic field, which has the order of $h^s \approx \left|4\pi e N V_p^s \xi\right| / c$ (ξ - transversal shift of the charged particles). For the value of the phase velocity $V_p^s = 50\ m \cdot s^{-1}$ and $\xi = 1$ km, we have $h^s \approx 1$ nT. Perturbed magnetic field strength increases up to 20 nT, if transversal displacement of the system ξ =10 km and the phase velocity $V_p^s \sim 10^2\ \mathrm{m \cdot s^{-1}}$. Thus, the linear slow electromagnetic waves in the dynamo-region are accompanied by the noticeable micro-pulses of the geomagnetic field and have the same order as the micro-pulses caused by S_q currents in the same region. The slow waves are generated by the dynamo electric field $\boldsymbol{E_d} = \boldsymbol{V} \times \boldsymbol{H}_0 / c$. These waves, on seen, were observed in the experiments (Cavalieri et al. 1974; Manson et al. 1981; Sharadze et al. 1989; Zhou et al. 1997).

Generation of the linear fast planetary electromagnetic waves in the ionospheric E-region by the gradient of geomagnetic field, the Hall's effect and inhomogeneous zonal wind was established. These waves propagate along the latitude against a background of the zonal-mean flow westward and eastward at the speed of a few $\mathrm{km \cdot s^{-1}}$ ($V_p^f \approx (1 \div 7)\, km \cdot s^{-1}$) in the dynamo-region. The waves have the frequency of order of $(10^{-1} \div 10^{-4})s^{-1}$; the periods are in the interval from 4 minutes to 6 hours; wavelength of about 10^3 km and longer. They attenuate weakly and $|\gamma^f| \sim 0.01\Lambda \sim 10^{-7} s^{-1}$. The essential micro-pulses of the geomagnetic field caused by the fast waves equal to $h^f \approx \left|2eNC_H \lambda^f\right| / c \sim 10^3$nT. They could be assumed as a new mode of the own oscillations in E-region of ionosphere. Frequencies and phase speeds of fast waves depend on density of the charged particles. Therefore, the phase velocities of fast disturbances in E-region of the ionosphere differ almost by one order of magnitude for daytime and nighttime conditions. High phase velocities, as well as their strong change between day and night preclude the identification of these disturbances with MHD waves. The fast waves are caused by oscillations of the electrons, completely frozen-in the geomagnetic field and are generated by the vortex electric field $\boldsymbol{E_v} = \boldsymbol{V_D} \times \boldsymbol{H}_0 / c$. These waves were observed in the experiments (Al'perovich et al. 1982; Sharadze et al, 1988; Burmaka et al, 2004; Georgieva et al, 2005).

It is established, that in the ionospheric F-region inhomogeneity of the geomagnetic field and inhomogeneous zonal wind generates fast planetary electromagnetic wave, propagating along the latitude circles to the east or to the west with phase velocity $V_p^f \approx (5 \div 50)$ km s^{-1}. Frequency of waves is in limits

$(10 \div 10^{-3})s^{-1}$ and the waves are weakly damped with decrement $\left|\gamma^f\right| \approx 10^{-6} s^{-1}$. The period of perturbations varies in a range (1 ÷ 110) s. Amplitude of geomagnetic micro pulsations, generated by these waves, is about $h^f \approx 10^3$ nT. These waves are new modes of eigen oscillations of F-region of the ionosphere. Such waves as magneto-ionospheric wave perturbations have been found out in experiments (Sharadze *et al* 1988, Sorokin 1988, Bauer *et al* 1995, Burmaka *et al* 2004, Georgieva *et al* 2005, Fagundas *et al* 2005).

The frequencies of the investigated waves vary in the band ω~ (10- 10^{-6}) s^{-1} and occupy both infrasound and ULF bands. Wavelength is λ~ (10^3 -10^4) km, period of oscillation is $T \sim 1$ s -14 days. The electromagnetic perturbations from this band are biological active (Kopitenko et al. 1995). Namely, they can play an important role as a trigger mechanism of the pathological complications in people having the tendency to hyper tensional and other diseases. Thus, these waves deserve great attention, as they are to be the significant source of the electromagnetic pollution of environment.

It is show, that at interaction with the inhomogeneous local wind the EM ULF wave perturbations can sufficiently increase own amplitude and energy and in their dynamics the nonlinear effects will be appeared. Dynamical competition of the nonlinear and the dispersion effects at the different layers of the ionosphere creates a favorable condition for self-organization of the EM ULF disturbances into nonlinear vortex structures. The self-localization of the planetary ULF waves into the long-lived solitary vortex streets in the non-dissipative ionosphere is proved in the basis of the analytical solution of the governed nonlinear dynamic equations. The exact stationary solution of these nonlinear equations has an asymptote $\psi \sim exp(-\kappa r)$ at $r \to \infty$, so the wave is strongly localized along the Earth surface. The translation velocity U of ULF EM vortices is very crucial which in turn depends on parameters β and β_{H}. From analytical calculation and plots we note that the formation of stationary nonlinear vortex street require some threshold value of translation velocity U (48) for both nondissipation and dissipation complex ionospheric plasma. For some large value of the background wind's spreading velocity ($U \geq 10$) the vortex structures may not be raised at all and only the background wind will be preserved in the medium (Figure 5). Number of vortices in generated nonlinear structures and a value of amplitudes of these vortices essentially depend on the size of the background wind's inhomogeneity – decreasing the latter – generated vortex's size and amplitude will automatically decrease (Figure 4). It's shown that the space and time attenuation can't resist the formation of the vortex structures, but affect the topographic features of the structures (Figure 6, Figure 7). The generated nonlinear vortex structures are enough long-live (> 24 hour) in dissipative ionosphere.

Depending on the type of velocity profile of the zonal shear flow (wind), the generated nonlinear long-lived vortex structures maybe represent monopole solitary anticyclone or cyclone, the cyclone – anticyclone pair, connected in a certain manner and/or the pure dipole cyclone – anticyclone structure of equal intensity, and/or the vortex street, or the vortex chains, rotating in the opposite direction and moving along the latitudinal circles (along the parallels) against a background of the mean zonal wind (see also - (Jovanovich et al. 2002, Aburjania et al. 2003; 2006; 2007)).

The nonlinear large-scale vortices generate the stronger pulses of the geomagnetic field than the corresponding linear waves. Thus, the fast vortices generate the magnetic field $h^f \approx 10^5\ nT$, and the slow vortices form magnetic field $h^s \approx 10^4\ nT$. The formation of such intensive perturbations could be related to the specific properties of the considering low frequency planetary structures. Indeed, they trap the environmental particles, and the charged particles in E- and F-regions of the ionosphere are completely or partially frozen into the geomagnetic field. That's why, the formation of these structures indicates at the significant densification of the magnetic force lines and, respectively, the intensification of the disturbances of the geomagnetic field in their location. Since, the number of the capture parcels is the order of the passed-by (transient), the perturbation of the magnetic field in the stronger faster vortices would be the same order as of the background field. On the earth surface located R_0 (($\sim (1 \div 3) \cdot 10^2$ km) below the region of the researching wave structure, the level of the geomagnetic pulses would be less by $exp(-R_0/\lambda_0)$ factor. λ_0 is the characteristic length of the electromagnetic perturbations. Since $\lambda_0 \sim (10 \div 10^2)R_0 >> R_0$ the magnetic effect on the earth would be less then in E- and F-regions, but in spite of this they are easily registered too.

We have defined the velocity diapason of propagation for vortical structures and show that vortices move faster than the corresponding linear waves. This means that if the source (for example, the above mentioned nonlinear vortex structure) moves along parallels at a velocity greater than V_p^{max}, the source does not come in resonance with the corresponding linear waves. Nonlinear vortices moving faster than the corresponding linear waves can retain their non-linear amplitude, as far as they do not lose energy by radiation of linear waves. It means, that these sources can not excite a linear wave due to Cherenkov mechanism, and can retain its initial energy (Stepanyants and Fabrikant, 1992). Thus, these vortex structures can be generated, self-sustained and propagated with velocity $|U| > V_p^{max}$ along the horizontal in any direction.

The motion of medium particles in studied nonlinear vortex structures is characterized by nonzero vorticity $\nabla \times \boldsymbol{V} \neq 0$, i.e. the particle rotate in vortices. The characteristic velocity of this rotation U_c is of order of the vortex velocity U, $U_c \geq U$. In this case the vortex contains the group of trapped particles (the number of these particles is approximately the same as the number of transit particles); rotating, these particles move simultaneously with the vortex structure. Therefore, being long-lived objects, non-linear planetary-scale electromagnetic vortex structures may play an important role in transporting matter, heat, and energy, and also in driving the macroturbulence of the ionosphere (Aburjania, 1990; 2011). In particular, the vortex structures that play the role of "turbulent agents" can be treated as elements of the horizontal macroscopic turbulent exchanges in global circulation processes in the ionospheric E and F-layers. The coefficient of the horizontal turbulent exchange can be estimated from the Obukhov-Richardson formula (Monin and Yaglom, 1967): $K_T \approx 10^{-2} d^{4/3} m^2 s^{-1}$. Thus, for vortices with dimensions of about $d \sim 10^3 km$ at latitudes of about $\varphi = 50^{\circ}$-55º, we obtain $K_T \approx 3 \times 10^6 m^2 s^{-1}$. This estimate (which can be regarded as an upper one) shows that, in the global exchange processes between high and low latitudes, the meridional heat transport from north to south in the ionospheric E and F-layers should be of macro turbulence nature (recall that, in the ionosphere, the polar regions are warmer than the equatorial region).

The fast and slow electromagnetic planetary waves are own degree of freedom of the E and F-regions of the ionosphere. Thus, first of all, the impact on the ionosphere from top or the bottom (magnetic storm, earthquake, artificial explosions and so on) induces (or intensify) the wave structures of these modes (Aburjania and Machabeli, 1998). At the certain strength of the source, the nonlinear solitary vortices would be generated (Aburjania, 1996), which is proved by the observations (Bengtsson and Lighthill, 1982; Chmyrev et al. 1991, Nezlin, 1999; Shaefer et al. 1999).

Hence, inhomogeneity of the Earth's rotation along the meridian, geomagnetic field and zonal prevailing flow (wind) can be considered among the real sources generating planetary ULF waves and vortex structures of an electromagnetic nature in the ionosphere. Such nonlinear structures can arise permanently and finally may constitute the strong vortical (or structural) turbulence in the medium (Aburjania, 1990; 2011; Aburjania et al . 2009).

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ოლეგ ხარშილაძე, ხათუნა ჩარგაზია

აბსტრაქტი

ნაშრომი ეძღვნება ულტრადაბალი სიხშირის ელექტრომაგნიტური ტალღური სტრუქტურების ტრანზიენტულ ზრდას და შემდგომ წრფივ და არაწრფივ დინამიკას მბრუნავ დისიპაციურ იონოსფეროში, რომელიც განპირობებულია არაერთგვაროვანი ზონალური ქარების (წანაცვლებითი დინება) არსებობით. პლანეტარული უდს ელექტრომაგნიტური ტალღები გენერირდებიან იონოსფერულ გარემოსა და სივრცით არაერთგვაროვანი გეომაგნიტური ველის ურთიერთქმედებით. ნაპოვნია დიდმასშტაბიანი უდს ელექტრომაგნიტური ტალღების გენერაციის და შემდგომი გაძლიერების ეფექტური წრფივი მექანიზმი წანაცვლებით დინებებში. ნაჩვენებია, რომ ეს ტალღური შეშფოთებები ეფექტურად ქაჩავენ ენერგიას წანაცვლებითი დინებებისგან და ზრდიან საკუთარ ენერგიას და ამპლიტუდას (რამდენიმე რიგით) დროის მიხედვით ალგებრული წესით. ამპლიტუდის ზრდასთან ერთად ირთვება თვითლოკალიზების მექანიზმი და ეს შეშფოთებები თვითორგანიზდებიან არაწრფივი განმხოლოებული, ძლიერად ლოკალიზებული უდს ელექტრომაგნიტური გრიგალური სტრუქტურების სახით, განპირობებული შეშფოთებათა პროფილის არაწრფივი გრეხით. წანაცვლებითი ქარის სიჩქარის პროფილზე დამოკიდებულებით არაწრფივი უდს ელექტრომაგნიტური სტრუქტურები შეიძლება იყოს მონოპოლური, გრიგალური ჯაჭვი ან გრიგალური ბილიკი არაერთგვაროვანი ზონალური ქარის ფონზე.

ანალიზური და რიცხვითი გამოთვლებიდან ნათელი ხდება, რომ სტაციონარული გრიგალური სტრუქტურების წარმოსაქმნელად საჭიროა სიჩქარის გადატანის რაიმე ზღვრული მნიშვნელობა ორივე დისიპაციური და არადისიპაციური იონოსფერული პლაზმისათვის. შესწავლილია გრიგალების ჩაქრობის დროითი და სივრცითი მახასიათებლები. შეფასებულია გრიგალის არსებობის მახასიათებელი დრო დისიპაციური იონოსფეროში. ხანგრძლივ გრიგალურ სტრუქტურებს გადააქვთ ჩაჭერილი ნაწილაკები, სითბო და ენერგია. ამრიგად, განსახილველი სტრუქტურები შეიძლება წარმოადგენდნენ უდს ელექტრომაგნიტურ ტალღურ მაკროტურბულენტობის სტრუქტურულ ელემენტებს იონოსფეროში.

Ултранизкочастотные электромагнитные погодаобразующие структуры в ионосфере со сдвиговым течением

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Абстракт

Работа посвяшена изучению транзиентного нарастания и дальнейшей линейной и нелинейной динамике ультранизкочастотных (УНЧ) планетарных электромагнитных (ЭМ) волн в диссипативной врашающейся ионосфере в присутствии неоднородного зонального ветра (сдвигового течения). Планетарные ЭМ УНЧ волны генерируются при взаймодействии ионосферной среды с прастранственно неоднородным геомагнитным полем. Анализируется эффективный линейный механизм генерации и усиления планетарных ЭМ волн в сдвиговых течениях. Показано, что эти волны эффективно черпают энергию сдвигового течения и существенно увеличивают свою амплитуду и энергию по алгебрайческому закону. С увеличением амплитуды возмущений включается нелинейный механизм самолокализации и эти возмущения самоорганизуются в виде сильнолокализованных УНЧ ЭМ нелинейных уединенных вихревых структур, обусловленных нелинеыным укручением профиля возмущения. В зависимости от вида профиля скорости сдвигового течения нелинейные структуры могут быть как чисто монопольным вихрем, так и вихревой дорожкой и вихревой цепочкой на фоне неоднородного зонального ветра. Как показывают аналитические и численные исследования, для формирования стационарных нелинейных вихревых структур необходима опредиленное значение скорости переноса как в диссипативной так и в недисипативной ионосферной плазме. Изучена временные и пространственные характеристики затухания вихрей. Дана оценка характерного времени затухания вихря в диссипативной ионосфере. Долгоживущие вичревые структуры переносят захваченные частици, тепло и энергию в среде. Таким образом рассмотренные структуры могут быть структурными элементами УНЧ ЭМ макротурбулунтности в ионосфере.