Self-organization of ULF electromagnetic wave structures in the shear flow driven dissipative ionosphere

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The authors thank the reviewer to spend a time to read our article. This work is based on our previous works, published in the leading impact factor international journals (Aburjania et al, 2002-2008). The wave structures considered in this paper are not compressible MHD waves. In the upper atmosphere, all wavy varieties can be divided into a relatively small, mesoscale (with wavelengths < 10^3km) and large, synoptic-scale (with wavelengths in the region of $10^3 - 10^4$km) perturbations. In the first class of waves belong the acoustic, inertio-gravitational and MHD (Alfven and magnetoacoustic) waves, while the second class of waves contains planetary Rossby waves and magnetogradient waves, which are caused by the latitudinal inhomogeneity of both the angular velocity of the Earth's rotation and the geomagnetic field (Khantadze et al, 1973, 2010; Kaladze et al, 2013). The large-scale undulations in the westerly winds are related to an ideal form of motion known as 'planetary'wave. These waves owe their existence to the rotation and spherical shape of the Earth. Wave patterns and the general circulation are mostly much wider than the depth of the ionophere: viewed from the side, the wave system is 100 to 1000 times thinner (vertically) than its width. This extreme thinness, beyond reminding us of the fragile nature of the ionophere, causes horizontal winds to be stronger than vertical winds in such weather systems. Exactly such large scale (10^3km - 10^4km) ULF electromagnetic waves, which are zonal ones, propagating along the parallels and having definite features are subject of our investigation. The waves propagate along the parallels to the east as well as to the west. In E-region the fast waves have phase velocities (2÷20) km·$\text{s}^{-1}$and frequencies (10^{-1}÷10^{-4}) s^{-1}; the slow waves propagate with local winds velocities and have frequencies (10^{-4}÷10^{-6}) s^{-1}. In F-region the fast ULF electromagnetic waves propagate with phase velocities tens-hundreds km·s^{-1} and their frequencies are in the range of (10÷10^{-3}) s^{-1}. The slow mode is produced by the dynamo electric field, it represents a generalization of the ordinary Rossby waves in the rotating ionosphere and is caused by the Hall effect in the E-layer. The fast disturbances are the new modes, which are associated with oscillations of the ionospheric electrons frozen in the geomagnetic field and are connected with the large –scale internal vortical electric field generation in the ionosphere. The large-scale waves are weakly damped. The features and the parameters of the theoretically investigated electromagnetic wave structures agree with those of large-scale ULF midlatitude long-period oscillations (MLO) and magnetoionospheric wave perturbations (MIWP), observed experimentally in the ionosphere (more detailed description see in Aburjania G. et al, 2005, Khantadze et al, 1973, 2010; Kaladze et al, 2004, 2013). Pressure, temperature and density gradients are assumed to be not sufficient for the considered planetary waves (like for ordinary Rossby waves in a barotropic, divergence free approximation) waves (Khantadze et al, 1973, 2010; Kaladze et al,2004, 2013; Gossard and Hook, 1975). So, the medium can be considered incompressible for such motions ($\nabla V = 0$). This assumption gives us possibility to represent the flow velocity ($V(V_x, V_y, 0)$) via stream function ψ, $\mathrm{V}_x = \partial\psi / \partial y$, $\mathrm{V}_y = -\partial\psi / \partial x$ and the condition $\nabla V = 0$ is fulfilled. For the description of the problem we use quasi-hydrodynamic equations, which describe the flows, electromagnetic currents and diffusive processes in the ionospheric plasma and which differ from hydrodynamic equations by the presence of "friction force", caused by collision of different particles (Cowling, 1975; Kamide, 1988; Kelley, 1989).. However, the diffusive processes, compressibility and inhomogeneity of the atmosphere play secondary role for considered large-scale ionospheric perturbations (wavelength $\lambda \geq 10^3$km (Cowling, 1975; Kamide, 1988; Kelley, 1989;

Gershman, 1974; Khantadze, 1973, Rapoport et al, 2014, Saliuk et al, 2012). For planetary scale waves it can not be neglected the latitude variations of angular velocity of the Earth rotation $\mathbf{\Omega}_0(\theta)$ and the geomagnetic field $\mathbf{B}_0(\theta)$. Naturally, for such waves a solution of obtained initial dynamic equations can be sought in the plane wave form $\exp\{i[k_x x-\omega t]\}$, at which $(\mathbf{k}\cdot\mathbf{B}_0)\equiv 0$ (in a linear approximation) and accordingly, after this the slow MHD waves, helicon and Alfven type waves will be filtered out. This is equal to an assumption $k_y R \operatorname{tg}\theta_0 \ll 1$ or $k_y \to 0$ in the general dispersion equation. The last condition means, that along y-axis the oscillations don't propagate, i.e. the waves don't propagate along y-axis and in this direction only the particles will oscillate and the waves will spread in x direction (for the detail analysis see Aburjania G. et al, 2005).

In some of our works, elaborated by Aburjania in his previous works, three components of the magnetic is used: h_z, $A_z=\partial h_y/\partial x-\partial h_x/\partial y$. Analysis of many works (Aburjania et al, 2002; Khantadze et al, 2010, Kaladze et al, 2004, 2011, 2013) shows that only the z-component of the magnetic induction perturbation is significant for the planetary waves. Thus, for simplicity, in our model, which describes linear and nonlinear dynamics of the planetary low-frequency electromagnetic wave perturbations in the ionospheric medium, we use only vertical component of the perturbed magnetic field.

Investigation of these waves has a long history. It begun in the last century by prof. A. Khantadze, who has revealed magnetized Rossby type electromagnetic waves in 1967 in the ionosphere, so-colled Rossby parameter of which consists from ordinary Rossby parameter and its magnetic analogue: $\overline{\beta}=\beta+\beta_{B0}$, where β - is the well known Rossby parameter (related to inhomogeneity of angular velocity of the Earth rotation) and β_{B0} - its magnetic analogue – related to inhomogeneity of the geomagnetic field. Prof. Khantadze showed that slow planetary magnetized Rossby type electromagnetic waves (SPEW) in the ionosphere can arise from the spatial nonuniformity of the geomagnetic field, in analogy with conventional atmospheric planetary Rossby waves, which are generated by the nonuniformity of the normal component of the angular velocity of the Earth's rotation. Theoretical investigationn of SPEWs was continued in Tbilisi State University by our group under leadership of Prof. George Aburjania with collaboration of Prof. Archil Khantadze in papers (Aburjania et al, 2003-2008), where existence of planetary scale ULF electromagnetic waves in the E and F ionospheric regions was theoretically revealed and justified, fast and slow PEWs in different ionospheric layers were classified and the hydrodynamic nature of slow waves and the electromagnetic nature of fast waves were analyzed (Aburjania et al, 2003-2008, Khantadze et al, 2010, Rapoport et al, 2014, Saliuk et al, 2012). In particular, it was shown that the electromagnetic force component associated with the flow velocity of the medium (the dynamo field) excites a Rossby type electromagnetic wave, while the electromagnetic force component associated with the vortex electric field produces a fast electromagnetic wave papers (Aburjania et al, 2003-2008, Khantadze et al, 2010, Rapoport et al, 2014, Saliuk et al, 2012). The distinctive features of the linear and nonlinear stages of the wave evolution due to such factors as the nonuniformity of the angular velocity of the Earth's rotation and the nonuniformity and curvature of the geomagnetic field were revealed, as well as the related anisotropic character of their propagation along the parallels of latitude.

Object oriented observations show that forced oscillations of the considered type occur in the ionosphere under the pulsed action from above (geomagnetic storms (Haykowicz, 1991)) or from below (earthquakes, volcanic eruptions, and artificial explosions (Liperovskii et al, 1992; Cheng, 1992; Drobzhev et al, 1986)). In the latter case, the perturbations exist in the form of localized solitary wave structures. In the ionosphere, external actions generate and/or amplify first of all precisely these perturbations, because they are eigenmodes of the ionospheric medium. Accordingly, they can be considered as ionospheric responses to natural and artificial activities above and on the Earth and under its surface. The large scale ULF wave motions under consideration can play an important role in the energy balance processes, as well as in atmospheric and oceanic circulations. Increased interest in ULF wave perturbations is also motivated by the fact that many ionospheric phenomena (such as superrotations of the Earth's atmosphere, ionospheric precursors of natural processes, and ionospheric responses to anthropogenic activities) occur just in their frequency range.

Planetary ULF electromagnetic zonal flows with nonuniform velocities can esquire an additional dispersion and in their dynamics the nonlinear effects will appear. Thus, the ionospheric medium creates a favorable condition for formation of the nonlinear stationary solitary wave structures with dimensions of about $d \sim 10^3\,\mathrm{km}$. The nonlinear analysis of the initial nonlinear dynamical equations shows that the disturbances with significant amplitudes propagate as coherent vortex structures in the medium. Thus, planetary ULF electromagnetic waves, at their interaction with the local shear winds, can self-organize in the form of nonlinear solitary vortices, moving along the latitude circles westward as well as eastward with velocity, different from phase velocity of corresponding linear waves (Aburjania G. et al, 2005, Khantadze et al, 1973, 2010; Kaladze et al, 2004, 2013).

Hope, we answer all the remarks of the reviewer. We clearly distinguish the class of linear and nonlinear wave structures of the subject of investigation and the reviewer will be satisfied.

Sincerely, the authors.

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