# Generation Mechanism and Propagation Features of the Ionospheric Weather Forming ULF Electromagnetic Wave Structures

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Results of theoretical investigation of the dynamics of generation and propagation of planetary (with wavelengths $10^3$ km and more) weather-forming Ultra-Low Frequency (ULF) electromagnetic wave structures in the dissipative ionosphere are given in this paper. It is established that the global factor, acting permanently in the ionosphere – spatial inhomogeneity and curvature of the geomagnetic field and inhomogeneity of angular velocity of the Earth's rotation – generates the fast and slow planetary ULF electromagnetic waves. The waves propagate along the parallels to the east as well as to the west. In the E-region the fast waves have phase velocities of (2÷20) km·s$^{-1}$ and frequencies of ($10^{-1} \div 10^{-4}$) Hz; the slow waves propagate with local wind velocities and have frequencies ($10^{-4} \div 10^{-6}$) Hz. In the F-region the fast ULF electromagnetic waves propagate with phase velocities of tens-hundreds km·s$^{-1}$ and their frequencies are in the range of ($10 \div 10^{-3}$) Hz. The large-scale waves are weakly damped. The waves generate the geomagnetic field perturbations from several tens to several hundreds nT and more. It is established that planetary ULF electromagnetic waves, at their interaction with the local shear winds, can self-localize in the form of nonlinear solitary vortices, moving along the latitude circles westward as well as eastward.

## Introduction

This paper presents a theoretical analysis of planetary-scale Ultra-Low-Frequency (ULF) weather forming waves in the E- and F- ionospheric layers. These waves are stipulated by permanently acting in the ionosphere factor – the spatial inhomogeneity and curvature of the geomagnetic field and the Earth's rotation velocity. It was assumed before that such perturbations are produced in the troposphere and stratosphere and then penetrate upward to the ionospheric levels. However, theoretical studies demonstrated that the system of zonal winds shields the upper atmosphere from the large-scale tropospheric perturbations, especially in the summer. But the results of many years' observations show that in the ionosphere at any period of season and day the large-scale ULF wave perturbations permanently exist. Thus, in E-region there are observed the low-speed long-period planetary waves propagating along parallel with phase velocity of 100-300 m/s, with period of a few days and with wavelengths $10^3$ km and more [1]. In contrast to regular Rossby waves, they produce essential magnetic perturbations of the order of tens of nT. It denotes an electromagnetic nature of these waves. Observations demonstrate also existence in the E-layer of short period (1-30 min) fast electromagnetic waves which propagate along ground surface (along parallel) with speeds of 2-20 km/s and with wavelengths $10^3$ km and more [2]. Their phase velocities are different by one order at daily and nightly conditions in the ionosphere.

In the F-region of ionosphere in mid-latitude the fast planetary electromagnetic wave perturbations are experimentally observed [3-5]. They propagate along the latitude circles with phase velocities from tens to several hundreds of km/s$^1$, with periods from a second to several minutes and with wavelengths of $10^3$ km and more.

For the theoretical modeling of such ULF electromagnetic waves we use closed system of magneto-hydro-dynamic (MHD) equations describing the rotated magnetized ionosphere [6, 7], taking into account the curvature of the geomagnetic force lines. Solving these equations in the linear approach, we found that the permanent fundamental parameters for the global processes like latitudinal inhomogeneity and curvature of the force lines lead to the additional elasticity force and to appearance of new, above-mentioned wave oscillations in the upper atmosphere.

## Planetary electromagnetic waves in the F-layer

*Fast* $C_n$ *-waves.* The phase velocity of the fast planetary electromagnetic waves $C_n$ taking into account at the same time curvature and latitude gradients of the magnetic field is:

$$C_n = \frac{\omega_n}{k} = \frac{1}{2} \frac{H_e}{\sqrt{4\pi N_m M}} \frac{\left(-\sin\theta \pm \sqrt{24 + \sin^2\theta}\right)}{kR}. \quad (1)$$

Here, $\omega_n$, $H_e$, $N_m$, $M$, $R$, $k$, and $\theta$ are wave frequency, value of geomagnetic field strength in the equator, neutral concentration and mass, radial

distance (Earth radius), longitudinal wave-number, and co-latitude, accordingly. A large–scale electromagnetic perturbation with frequency (1) is a new eigen mode for the F-region of the ionosphere. We can see that eastward and westward propagation speeds of electromagnetic perturbations in this region are different. For example, at the equator ($\theta = \pi/2$), where the phase velocity reaches its maximal value, the phase velocity of the eastward propagation ($C_n > 0$) is: $C_{n+} = 2C_0$, $C_0 = H_e /(kR\sqrt{4\pi MN_m})$, and for the westward propagation ($C_n < 0$) the velocity is: $C_{n-} = -3C_0$. Significant result is that the geomagnetic field stratifies the ionospheric plasma along meridian, like the gravity field stratifies the ionosphere throughout the height. The waves move westward faster than eastward. It means that the curvature of the geomagnetic field select preferred directions for the planetary electromagnetic waves. Non-linear stage of such waves in the F-region has been studied in [8]. In this paper it is shown, that the planetary ULF electromagnetic waves, at their interaction with the local shear winds, can self-localize in the form of nonlinear solitary vortices, moving along latitude circles westward as well as eastward.

## Planetary waves in the E-region

In the E-layer, where the Hall effect plays an essential role, the fast and slow planetary electromagnetic waves should be generated.

***Fast*** $C_H$ ***-waves.*** The $C_H$ - oscillations occur in the E-region only in electrons together with the geomagnetic field frozen into them while the ions and neutrals are almost at rest state. We found that the phase velocity of the fast planetary electromagnetic wave is:

$$C_H = \frac{\omega_H}{k} = \frac{1}{2}\frac{cH_e}{4\pi eN}\frac{\left(\sin\theta \pm \sqrt{24+\sin^2\theta}\right)}{R}. \quad (2)$$

Here $\omega_H$ is the wave frequency, $N$ – concentration of electrons (ions), c is the light speed. The $C_H$-waves are a new branch of the eigen oscillations of the conductive ionosphere. These oscillations are produced also under a strong pulse action in the ionosphere either from above during magnetic storms or below as a result of earthquake and ground explosions.

***Slow waves of the Rossby type.*** We derived a general dispersion equation of the slow planetary waves taking into consideration the vector of the Earth's angular velocity. As a partial case of the zero magnetic fields, the equation transforms into the equation for the regular Rossby waves. Inclusion of the magnetic field leads to a new branch of the slow waves which we call the waves of the Rossby type. If the Coriolis force is null and geomagnetic force lines are curved, we have:

$$C_R = \frac{\omega_R}{k} = \frac{1}{2}\frac{N}{N_m}\frac{eH_e}{Mc}\frac{\left(-\sin\theta \pm \sqrt{24+\sin^2\theta}\right)}{k^2 R}. \quad (3)$$

Here $\omega_R$ is the wave frequency. This is a new wave mode in the E-layer. The slow planetary waves in the E-region have pure hydrodynamic nature. The latitudinal gradients of the Earth's angular velocity, magnetic field and curvature of the field play an essential role in the dispersion of the slow planetary waves.

We proved that the 'fast' large-scale planetary $C_H$ and $C_n$ waves were the most sensitive to the earthquake actions. Non-linear dynamics of such waves in the E-region has been studied in [9].

## Conclusions

The analysis carried out shows that the following branches of the eigen oscillations should exist:

A. In the E-layer:
   (1) small-scale inertial waves,
   (2) atmospheric whistlers (helicons),
   (3)'fast' large-scale electromagnetic planetary waves,
   (4) slow Alfven waves,
   (5) 'slow' modified Rossby waves;

B. In the F-layer:
   (1) small-scale modified slow Alfven waves,
   (2) fast large-scale electromagnetic planetary waves,
   (3) regular 'slow' Rossby waves.

Magnetic variations induced by the slow waves (i.e. existence of the local currents caused by the local winds) are of order of $S_q$-variation in the E-layer ($1-20nT$). Amplitudes of the geomagnetic variations produced by the fast waves are quite large ($10 \div 100nT$) and can be detected at the global magnetic networks.

The fast planetary modes in the F- and E-layers discovered here theoretically, are not adequately studied experimentally for the time being. To reveal and trace the fast and slow planetary waves at the ionospheric levels, we recommend using their specific features:

1. Dependencies of speed and frequency ranges on latitude: phase velocities and frequencies increase from the pole to equator;

2. The fast planetary modes in the F- layer $C_n$ and slow modes in the E-layer $C_R$ propagate in the westward direction faster than in the eastward direction. For example, the waves propagating from a definite point westward along the equator reach the antipode point 1.5 times faster than the same wave propagating eastward. But the fast modes in E-region $C_H$ are propagating faster to the east than to the west. Strong daily variations of the electron concentration cause an essential decrease of the phase speed of the $C_H$ – waves at night. Estimations show that the phase speed changes from $\sim 100 m/s$ at day to $\sim 10\,km/s$ at night.

3. Height dependency of the neutral concentration $N_n(z)$ in the F-layer leads to the strong increase of the $C_n$ - phase speed within $200 \div 500 km$ from $\sim 1\,km/s$ to $1000 km/s$.

4. The largest response in $C_H$ and $C_n$ -waves is to be during earthquakes, magnetic storms and strong man-made actions like explosions.

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