PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 60 (1998) 1331–1342

Journal of
ATMOSPHERIC AND
SOLAR-TERRESTRIAL
PHYSICS

A generation model of small-scale geomagnetic field-aligned plasma inhomogeneities in the ionosphere

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Received 25 April 1996; received in revised form 7 July 1998; accepted 13 July 1998

Abstract

The dissipative instability of acoustic-gravity waves in the ionosphere is investigated. This instability results in formatting the horizontal periodic structure of conductivity disturbances which move with the velocities considerably less than the sound velocity. In the presence of an external DC electric field the conductivity variations in the E-layer lead to an appearance of polarization electric fields propagating into the upper ionosphere and generating the plasma density variations at these altitudes. Estimates of the space-time and amplitude characteristics of the excited ionospheric disturbances and their comparison with the experimental data show that the developed mechanism can be applied to generation model of the earthquake-related small-scale plasma inhomogeneities in the upper ionosphere.

1. Introduction

Experimental studies of the ionospheric structure by means of both ground-based radio sounding technique and of direct measurements of the ionospheric parameters onboard satellites and rockets performed during the last decades have revealed that the ionosphere displays strongly irregular structure with the spatial scales of irregularities in the range from several cms to hundreds of kms. Many papers are devoted to experimental studies of the irregular ionospheric structure as well as to generation mechanisms of ionospheric irregularities. The results of these investigations are most comprehensively systemized in the review papers by Fejer and Kelley (1980), Ossakow (1979) and Kelley (1989).

The irregular structure of the ionosphere is pronounced most of all in the high-latitude and near-equatorial regions. This fact is argued by numerous results of radar observations (Evans, 1975; Greenwald et al., 1978) and by in situ satellite and rocket measurements (Clark and Raitt, 1976; Dyson, 1969; Dyson et al., 1974).

To account for the generation mechanisms of the ionospheric plasma density irregularities, various types of plasma instabilities are considered. Formation of small-scale irregularities in the ionospheric current jets (equatorial and polar electrojets) are explained by a development of the Farley–Buneman two-stream instability (Farley, 1963; Buneman, 1963; Fejer and Providakes, 1987) or by gradient–drift ($E \times B$) instability (Farley and Balsley, 1973; Knox, 1964; Fejer and Providakes, 1987). The gradient–drift instability was considered also to account for the midlatitude sporadic E-layer (Tsuda et al., 1966), equatorial spread E_s-layer (Martyn, 1959; Simon, 1963) and the irregular structure of the high-latitude F-layer (Unwin and Knox, 1971). The other types of instabilities playing an important role in the formation of the irregular structure of the ionosphere are the Post–Rosenbluth instability (Ott and Farley, 1975; Reid, 1968) and electrostatic ion-cyclotron instability (Kindel and Kennel, 1971; Ungstrup et al., 1979).

According to COSMOS-1809 satellite data (Chmyrev et al., 1997) inhomogenites of electron density with the spatial scale $\leqslant$ 10 km arise in the upper ionosphere before an earthquake. They are localized in the geomagnetic force tube with the root on the projection of an epicentral zone onto the ionosphere E-layer. The characteristic horizontal scale of the disturbed region occupied by these inhomogenites is 300–450 km. We note in this connection that such irregularities with magnitude $dN_e/N_e > 5\%$ are

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S1364–6826/98/$—see front matter
PII: S1364-6826(98)00078-9

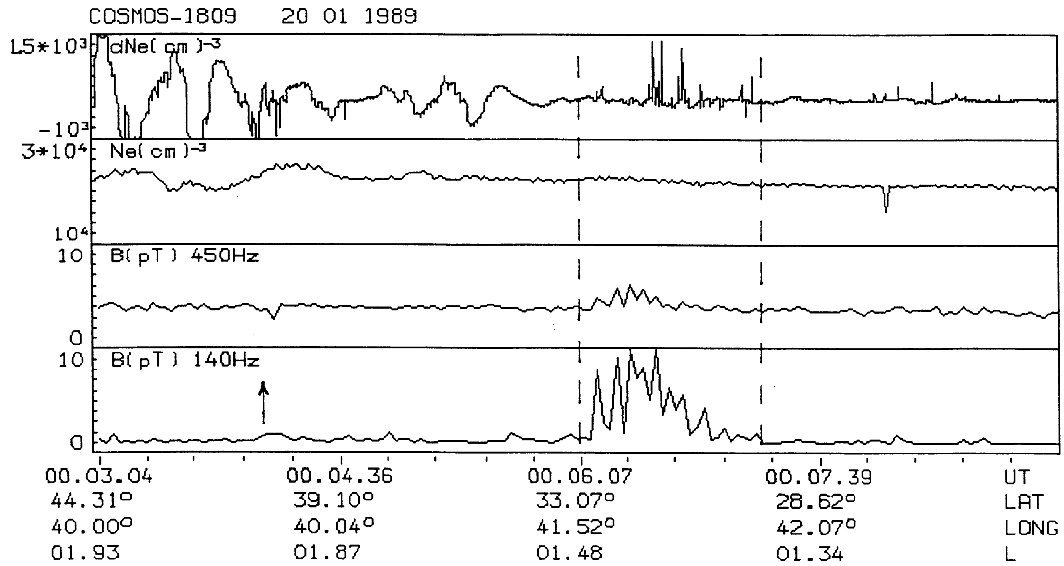


Fig. 1. An example of seismic related plasma density variations dN_e (upper panel) over the Spitak earthquake zone $\sim$ 3.3 h before the shock on 20 January 1989. Lower panels present plasma density N_e and intensities B of ELF magnetic field oscillations at the frequencies $\sim$ 140 and 450 Hz.

not typical for the midlatitude ionosphere under normal conditions (Clark and Raitt, 1976).

Figure 1 presents an example of experimental data by Chmyrev et al. (1997) on the distributions of plasma density N_e and its variations dN_e together with ELF radiation intensity at the frequencies $f \sim$ 140 and 450 Hz over the zone of seismic activity 3.4 h before an aftershock of the Spitak earthquake on 20 January 1989. The time instant 00.04.06 UT when the satellite crossed the geographic latitude of the earthquake focus is marked with the vertical arrow. The measurements were carried out in the night-time sector during the recovery phase of geomagnetic storm. As seen from Fig. 1 the small-scale fluctuations of plasma density dN_e (upper panel in Fig. 1) with characteristic spatial scales $l \approx 8$ km and the magnitude dN_e/N_e up to 8% were observed in the region where intense burst of electromagnetic emission at the frequencies $f \sim 140$ Hz (bottom panel) with the amplitude up to 10 pT was observed in the longitude range $41.6 < \lambda < 42.0^\circ$ i.e. approximately 2° to the west from the earthquake focus and in the latitude range $30 < \phi < 33.1^\circ$. A weaker increase of electromagnetic noise (up to 3 pT) in the same region was observed also at the frequencies $f \sim 450$ Hz. At higher frequencies no emissions were registered. The zone of increased values of the radiation intensity and the plasma density variations is marked by vertical dotted lines in Fig. 1. The dimension of this zone is ~ 450 km along the satellite orbit.

Analysis of more than 50 events of such kind enable us to draw the conclusion that the seismic related plasma density irregularities in the upper ionosphere have characteristic spatial scales of $l \sim$ 4–10 km and the magnitudes $dN_e/N_e \sim$ 4–10%.

One can assume that the observed fluctuations (dN_e) result from spacecraft crossing plasma irregularities stretched parallel to geomagnetic field. These irregularities could arise due to formation of the field-aligned currents with the transverse scale $\leqslant$ 10 km excited in the lower ionosphere. One of the mechanisms generating a wave of field-aligned currents (shear Alfven wave) is a process of formation of the horizontal irregular structure of the ionosphere conductivity and its interaction with ionospheric DC electric field in the region of S_q currents. Thus the appearance of electron density fluctuations in the upper ionosphere observed from the spacecraft could originate in the lower ionosphere due to excitation of small scale conductivity variations. In a frame of such notion these conductivity variations should arise in a localized zone in the ionosphere over a zone of enhanced seismic activity. A velocity of such disturbances should be considerably less than a satellite velocity. These properties are characteristic for acoustic-gravity waves (AGW) in the lower ionosphere.

Thus the origination of the observed plasma density fluctuations can be related to the physical processes resulting in intensification of AGW above the seismic zone. The dissipative AGW instability in the ionosphere due to Joule heating in the ionospheric currents disturbed by this wave could be considered as such a process. One can expect, due to dependence of conductivity variation on AGW parameters, that the wave propagation leads to conductivity modulation and appearance of additional currents induced by the ionospheric electric field. Joule heating due to these currents will increase the AGW amplitude and, hence, the value of conductivity disturbance resulting in their exponential growth.

2. The electric field effect on stability of acoustic-gravity waves in the ionosphere

Ingard and Gentle (1965), Ingard (1966) and Ingard and Shulz (1967) have examined the instability of acoustic-gravity waves in a weakly-ionized plasma. It has been shown that the instability is developed with the condition that the electron temperature is higher than the temperature of neutral molecules. The energy source for the instability is supplied by heated electrons. Their energy is transferred to the molecules due to elastic collisions. Similar results were obtained by Rognlien and Self (1971) for the ion-acoustic instability in a two-temperature completely ionized plasma. In these papers it was assumed that the equilibrium temperature of the neutral or ion component was stationary. However Kaw (1969), Kaw and Sundaram (1972) and McBride and Chu (1972) found that due to energy transfer from more heated electrons the equilibrium temperature of neutral or ion component was increased. This effect results in damping of the acoustic instability.

Another type of instability of acoustic-gravity waves is considered. This type of instability is considered for isothermic weakly-ionized plasma in the external magnetic and electric fields by Sorokin and Chmyrev (1997). Strong heat interchange assumes that the electron temperature is equal to the temperature of ions and molecules. Such an approach is generally applied for a model of ionosphere with stabilized thermal balance. It is realised at the characteristic times $\tau \gg M/m\nu_{ei}$ and for the spatial scale $\lambda \gg aM/m\nu_{ei}$, where m, M are the electron and ion masses and a is a sound velocity. This balance determines the stationary temperature. According to Piddington (1959), in the low-frequency approximation, the ionosphere can be considered as a continuous medium with a tensor conductivity. As will be shown later, propagation of small acoustic oscillations in such a medium is accompanied by a conductivity disturbance and, hence, with a perturbation of the currents. With certain conditions these disturbances have such a character that Joule heading due to the disturbed currents results in the growth of the acoustic wave amplitude. In contrast to the results of the quoted papers, the energy source of the instability under consideration is the electromotive force of the external electric field. The electric field energy transforms to the energy of acoustic oscillations without a change in the medium thermal balance.

Let us assume that the ionosphere consists of electrons and ions with densities N and of molecules with the densities N_n. Plasma is weakly ionized $N/N_n \ll 1$ and is placed in a given uniform magnetic B and electric E fields. Let m be the mass of electron and M be the mass of ion and molecule. The mean velocity of electrons, ions and molecules and their density, pressure and temperature are v_a, ρ_a, P_a, T_a respectively (the index a may be e, i or n). Analysis of stability of acoustic-gravity waves (AGW) will be performed based on the following set of equations (Hines, 1968; Hines and Hooke, 1970; Gossard and Hooke, 1975):

$$\rho \mathrm{d}v/\mathrm{d}t = -\nabla p + \rho g + (1/c)[j \times B]$$
$$\partial\rho/\partial t + \nabla(\rho v) = 0$$
$$\rho c_p \mathrm{d}T/\mathrm{d}t = \mathrm{d}p/\mathrm{d}t + (j \cdot E)$$
$$p = \rho R T \tag{1}$$

and Ohm's law for the current density j (Alfven and Falthammar, 1963):

$$j = \sigma_{\parallel} E_{\parallel} + \sigma_p E_{\perp} + \sigma_h [B \times E_{\perp}]/B \tag{2}$$

The following quantities are introduced in these equations: mean-mass velocity

$$v = \sum_k \rho_k v_k / \sum_k \rho_k$$

characterising the motion of gas as a whole, its density $\rho = mN + MN + MN_n = \rho_e + + \rho_i + \rho_n$, and pressure $p = p_e + p_i + p_n$. The temperatures of the gas components are assumed to be equal $T_e = T_i = T_n = T$. In eqn (1) the following definitions were introduced: $\mathrm{d}/\mathrm{d}t = \partial/\partial t + v\nabla$; $R = c_p - c_v$ is the universal gas constant, c_p and c_v are the heat capacities at constant pressure and constant volume, g is acceleration due to Earth's gravity. In eqn (2) the following notations are used; $\sigma_{\parallel}$ is the field-aligned conductivity, σ_h and σ_p are Hall and Pedersen conductivities, respectively, and $E_{\parallel}$ is the magnetic field-aligned component of the electric field. The conductivities depend on the collision frequencies (Cowling, 1945):

$$\sigma_{\parallel} = e^2 N(1/\mathrm{m}\nu_e + 1/\mathrm{M}\nu_{in}),$$
$$\sigma_p = e^2 N[\nu_e/m(\omega_e^2 + \nu_e^2) + \nu_{in}/M(\omega_i^2 + \nu_{in}^2)],$$
$$\sigma_h = e^2 N[\omega_e/m(\omega_e^2 + \nu_e^2) - \omega_i/M(\omega_i^2 + \nu_{in}^2)], \tag{3}$$

where e is electron charge, $\omega_e = eB/mc$ and $\omega_i = eB/Mc$ are the gyrofrequencies of electrons and ions, ν_{ab} are collision frequencies of particles of the sort a with those of the sort b, $\nu_e = \nu_{ei} + \nu_{en}$.

In the ionosphere $\sigma_{\parallel}/\sigma_P \sim \sigma_{\parallel}/\sigma_h \sim 10^4$–$10^5$, hence, one can assume $E_{\parallel} = 0$. Above 120 km in the ionosphere the following inequalities are satisfied: $\nu_e \ll \omega_e$; $\nu_{in} \ll \omega_i$; $m\nu_e/M\nu_{in} \sim (m/M)^{1/2} \ll 1$. Therefore:

$$\sigma_p = e^2 N \nu_{in}/\omega_i^2; \quad \sigma_h = (\nu_{in}/\omega_i)\sigma_P \ll \sigma_P \tag{4}$$

where

$$v_{in} = qv_i^* N_n; \quad v_i^* = (8RT/\pi)^{1/2}.$$

In eqn (4) q is the cross-section of ion scattering on molecules, v_i^* is mean thermal velocity of ions. The dependence of the conductivity σ_P on thermodynamical quantities is determined by the equation:

$$\sigma_p = \mu\rho_i\rho(T)^{1/2}, \quad \mu = 8qc^2/\pi MB^2 \tag{5}$$

Let us consider the AGW propagation in a layered irregular isothermic ionosphere in the presence of an external DC electric field. We use the right hand Cartesian coordinate system with the z-axis directed vertically upward along the magnetic field B and the x-axis along the electric field E. Let us consider the small perturbations of the velocity v_1, density ρ_1, pressure p_1 and temperature T_1 at the background of their stationary values v_0, ρ_0, p_0 and T_0. From eqns (1), (2) and (5) for the stationary state we derive:

$$\rho_0 v_{0z}\,\mathrm{d}v_{0z}/\mathrm{d}z = -\,\mathrm{d}p_0\,\mathrm{d}z - g\rho_0$$

$$\rho_0 c_p v_{0z}\,\mathrm{d}T_0/\mathrm{d}z = v_{0z}\,\mathrm{d}p_0/\mathrm{d}z + \mu\rho_{i0}\rho_0(T_0)^{1/2}E^2$$

$$p_0 = R\rho_0 T_0; \quad \mathrm{d}\rho_0 v_{0z}/\mathrm{d}z = 0. \tag{6}$$

The generally accepted model of stationary ionosphere applied for studying the AGW properties is the isothermic ($T_0 = \text{const}$) exponentially stratified medium (Gossard and Hooke, 1975):

$$p_0 \sim \rho_0 \sim \exp(-z/H); \quad H = RT_0/g. \tag{7}$$

Ion density varies with altitude substantially slower than the atmosphere density ρ_0 with the scale H, therefore it could be assumed constant. The ionosphere stationarity is provided by various processes of cooling such as thermal conductivity, radiation, convection, etc. which do not result in considerable effects on the atmosphere waves in the AGW range. The corresponding summands could be added to the second eqn (6) of the law of energy conservation. In eqn (6) the stationarity of temperature is provided by slow vertical mass transfer with the velocity v_{0z}. If $v_{0z} \ll (gH)^{1/2} \sim 3\times10^4$ cm s^{-1} ($g \approx 10^3$ cm s^{-2}, $H \approx 10^6$ cm) then we obtain from the first eqn (6) $\mathrm{d}p_0/\mathrm{d}z = -g\rho_0$. Assuming $\mathrm{d}T_0/\mathrm{d}z = 0$ in the second eqn (6) and substituting the derivating value $\mathrm{d}p_0/\mathrm{d}z$ we shall obtain an estimate of the velocity value $v_{0z} \sim \sigma_{p0}E^2/g\rho_0$. Taking, for the conducting lower ionosphere, the values $\sigma_{p0} \sim 10^6$ s^{-1}, $E \sim 3$ mV m$^{-1} = 10^{-7}$ cgse, $\rho_0 \sim 10^{-12}$ g cm^{-3}, we obtain $v_{0z} \sim 10$ cm s^{-1}. Thus, when deducing the equations for perturbations, one can assume the ionosphere to be at rest. Neglecting the Hall conductivity as compared to Pedersen conductivity and saving in eqn (1) the perturbations of the first order of smallness, we obtain:

$$\rho_0\,\partial v_1/\partial t = -\nabla p_1 + \rho_1 g$$

$$\partial\rho_1/\partial t + \rho_0\nabla v_1 + v_{1z}\,\mathrm{d}\rho_0/\mathrm{d}z = 0$$

$$\partial p_1/\partial t + v_{1z}\,\mathrm{d}p_0/\mathrm{d}z - \gamma RT_0\{\partial\rho_1/\partial t + v_{1z}\,\mathrm{d}\rho_0/\mathrm{d}z\} = (\gamma-1)\Delta\sigma_p E^2$$

$$p_0 = R\rho_0 T_0. \tag{8}$$

In eqn (8) $\Delta\sigma_p = \sigma_p - \sigma_{p0}$ is a perturbation of the ionosphere conductivity and $\gamma = c_p/c_v$. Using formula (5), the equation of state and the linear dependence between the relative variations of ion and neutral component densities $\rho_{i1}/\rho_{i0} = \alpha\,(\rho_1/\rho_0)$, we obtain:

$$\sigma_p = \mu\rho_i(P\rho/R)^{1/2} = \sigma_{p0}(1+\alpha\rho_1/\rho)(1+p_1/p_0)^{1/2}(1+\rho_1/\rho_0)^{1/2}$$

$$= \sigma_{p0}[1+p_1/2p_0+(2\alpha+1)\rho_1/2\rho_0], \quad \sigma_{p0} = \mu(T_0)^{1/2}\rho_{i0}\rho_0(z).$$

Hence:

$$\Delta\sigma_p = (\sigma_{p0}/2)p_1/p_0 + [(2\alpha+1)\sigma_{p0}/2]\rho_1/\rho_0. \tag{9}$$

The coefficient α characterises the variation of ion density relatively to variation of neutral gas density in the wave. If $\alpha = 0$ the conductivity perturbation will be determined only by a variation of the collision frequency which depends on neutral gas density and temperature. At $\alpha = 1$ the variation of ion density coincides with relative variation of gas density as a whole. At $\alpha > 1$ the conductivity perturbation is mainly determined by ion density variation. This coefficient enables one to estimate the effect of a degree of interaction between the neutral and ionized components on the wave stability. Substituting equality (9) in the third eqn (8), we obtain:

$$(\partial/\partial t - \omega_2)p_1 + v_{1z}\,\mathrm{d}p_0/\mathrm{d}z - a^2\{(\partial/\partial t + \omega_1)\rho_1 + v_{1z}\,\mathrm{d}\rho_0/\mathrm{d}z\} = 0 \tag{10}$$

In eqn (10) it is defined that:

$$\omega_1 = (2\alpha+1)(\gamma-1)\sigma_{p0}E^2/2a^2\rho_0; \quad a^2 = \gamma RT_0;$$

$$\omega_2 = \gamma(\gamma-1)\sigma_{p0}E^2/2a^2\rho_0; \quad \omega_1 = [(2\alpha+1)/\gamma]\omega_2. \tag{11}$$

Since $\sigma_{p0}(z) \sim \rho_0(z)$, the quantities ω_1, ω_2 and a^2 are independent of the altitude z. The first two eqns (8) and (10) describe the AGW propagation in isothermic conducting ionosphere with the horizontal external electric field. Taking $\omega_1 = 0$, we obtain the well known equations for the AGW in exponentially stratified atmosphere (Gossard and Hooke, 1975). The quantity ω_1 has the meaning of the ratio of specific power released by the currents due to perturbation of the ionosphere conductivity in the electric field to the energy density of the acoustic wave. It determines the characteristic time during which the energy of external DC electric field is transformed to the wave energy.

3. Formation of the horizontal irregularities of the ionosphere conductivity

Let us consider the horizontal propagation of the planar wave along the x-axis. First of all we analyze the case when the terms with acceleration due to gravity in eqns (8) and (10) can be neglected. Assuming $g = 0$ we obtain:

$$\rho_0\,\partial v_{1x}/\partial t = -\,\partial p_1/\partial x, \quad \partial\rho_1/\partial t + \rho_0\,\partial v_{1x}/\partial x = 0,$$

$$(\partial/\partial t - \omega_2)p_1 - a^2(\partial/\partial t + \omega_1)\rho_1 = 0.$$

Assuming the dependance on coordinates and time as $\exp(-i\omega t + ikx)$ we derive the dispersion equation:

$$k^2 = \omega^2(\omega - i\omega_2)/a^2(\omega + i\omega_1) \tag{12}$$

For $\omega_1 = \omega_2 = 0$ we obtain the equation $k = \omega/a$ describing the acoustic wave propagation in a uniform medium with the velocity a without dispersion. Let us introduce the complex refraction index from the formula:

$$k = (n + i\kappa)\omega/a \tag{13}$$

where n is the refraction index and κ is the absorption coefficient. Substituting eqn (13) into eqn (12) and separating the real and imaginary parts, we obtain:

$$n(\omega) = \{[(\omega^2+\omega_1^2)^{1/2}(\omega^2+\omega_2^2)^{1/2} + \omega^2 - \omega_1\omega_2]/2(\omega^2+\omega_1^2)\}^{1/2}/\kappa(\omega) = -\{[(\omega^2+\omega_1^2)^{1/2}(\omega^2+\omega_2^2)^{1/2} - \omega^2 + \omega_1\omega_2]/2(\omega^2+\omega_1^2)\}^{1/2} \tag{14}$$

The character of $n(\omega)$ and $\kappa(\omega)$ dependencies in eqn (14) practically will be not changed if we take formally $\omega_1 = \omega_2$ that is satisfied when $2\alpha + 1 = \gamma$, see eqn (11). Assuming the perfect gas approximation we put $\gamma = 1.4$ and accordingly $\alpha = 0.2$. In this case eqn (14) is simplified:

$$n(\omega) = \omega/(\omega^2+\omega_1^2)^{1/2},$$

$$\kappa(\omega) = -\omega_1/(\omega^2+\omega_1^2)^{1/2}. \tag{15}$$

These equations give a negative absorption coefficient $\kappa < 0$ that means the instability development and exponential growth of the wave amplitude. Since the refraction index $n < 1$, the phase velocity $v_{ph} = a/n$ of a wave propagating with a dispersion exceeds the acoustic velocity a. This case gives evidence to possible instability of the AGW because the limit $g = 0$ describes the high-frequency range of the spectrum of these waves. To analyze the AGW instability let us write the components of eqns (8) and (10):

$$\rho_0\,\partial v_{1x}/\partial t = -\,\partial p_1/\partial x,$$

$$\rho_0\,\partial v_{1z}/\partial t = -\,\partial p_1/\partial z - g\rho_1,$$

$$\partial\rho_1/\partial t + \rho_0(\partial v_{1x}/\partial x + \partial v_{1z}/\partial z) - (\rho_0/H)v_{1z} = 0,$$

$$(\partial/\partial t - \omega_2)p_1 - (p_0/H)v_{1z} - a^2\{[(\partial/\partial t + \omega_1)\rho_1 - (\rho_0/H)v_{1z}\} = 0. \tag{16}$$

Let us pass to the field variables through the formulas (Gossard and Hooke, 1975):

$$U = (\rho_0/\rho_s)^{1/2}v_{1x}, \quad W = (\rho_0/\rho_s)^{1/2}v_{1z},$$

$$P = (\rho_0/\rho_s)^{-1/2}p_1, \quad R = (\rho_0/\rho_s)^{-1/2}\rho_1,$$

$$\rho_0 = \rho_s \quad \exp(-z/H), \tag{17}$$

where ρ_s is the density value at the level corresponding to $z = 0$. For the field variables we derive the system of uniform equations with constant coefficients:

$$\rho_s\partial U/\partial t = -\,\partial P/\partial x; \quad \rho_s\partial W/\partial t = -\,\partial P/\partial z + P/2H - gR;$$

$$\partial R/\partial t + \rho_s(\partial U/\partial x + \partial W/\partial z - W/2H) = 0;$$

$$(\partial/\partial t - \omega_2)P - a^2(\partial/\partial t + \omega_1)R + (\gamma-1)g\rho_s W = 0. \tag{18}$$

Let us consider the horizontal AGW propagation along the x-axis assuming $\partial/\partial z = 0$. Using again the coordinate and time dependence of all functions according to $\exp(-i\omega t + ikx)$ we derive the dispersion equation:

$$k^2a^2[\omega(\omega + i\omega_1) - \omega_g^2] = \omega^2[\omega(\omega - i\omega_2) - \omega_a^2] + i\omega\omega_2\omega_3^2 \tag{19}$$

where $\omega_a^2 = \gamma g/4H$ is the boundary acoustic frequency, $\omega_g^2 = (\gamma-1)g/\gamma H$ is the Brunt–Vaisala frequency and $\omega_3^2 = \omega_a^2(2\alpha+3)/\gamma$. Taking, in (19), $\omega_a = \omega_g = 0$, we obtain formula (12) describing the acoustic wave dispersion in a uniform medium. The case of electric field vanishing corresponds to the transition to $\omega_1 = \omega_2 = 0$ in (19):

$$k^2 = \omega^2(\omega^2 - \omega_a^2)/a^2(\omega^2 - \omega_g^2)$$

This dispersion equation is satisfied for the AGW propagating in the horizontal direction (Gossard and Hooke, 1975). Using in (19) the complex refraction index (13) and separating the real and imaginary parts, we obtain:

$$n(\omega) = \{[A^2(\omega) + B^2(\omega)]^{1/2} + A(\omega)\}^{1/2}/\Omega(\omega)$$

$$\kappa(\omega) = -\{[A^2(\omega) + B^2(\omega)]^{1/2} - A(\omega)\}^{1/2}/\Omega(\omega) \tag{20}$$

In eqn (20) it is defined that:

$$A(\omega) = (\omega^2 - \omega_a^2)(\omega^2 - \omega_g^2) - (\omega^2 - \omega_3^2)\omega_1\omega_2,$$

$$B(\omega) = (\omega^2 - \omega_a^2)\omega\omega_1 + (\omega^2 - \omega_g^2)(\omega^2 - \omega_3^2)\omega_2/\omega,$$

$$\Omega(\omega) = \{2[(\omega^2 - \omega_g^2)^2 + \omega^2\omega_1^2]\}^{1/2}. \tag{21}$$

The dependencies $n = n(\omega)$ and $\kappa = \kappa(\omega)$ calculated from eqns (20) are presented in Fig. 2 for the following set of

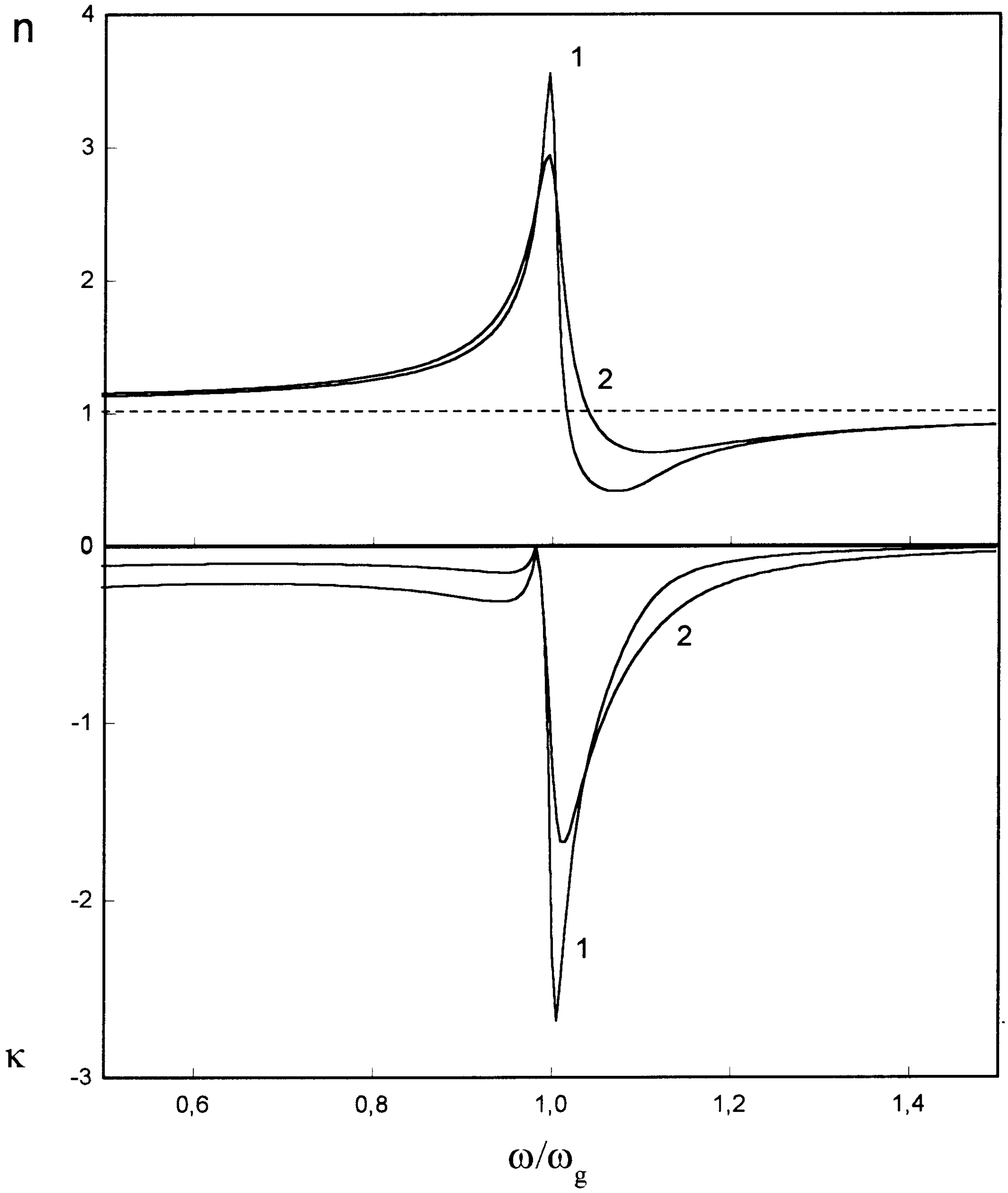


Fig. 2. The frequency dependence of the refractive index (n) and the absorption coefficient (κ) of acoustic-gravity wave in the ionosphere in the presence of an external electric field.

parameters: $\gamma = 1.4$; $g = 10^3$ cm s^{-1}; $H = 10^6$ cm; $\sigma_{p0} = 5 \times 10^6$ s^{-1}; $\rho_0 = 5 \times 10^{-13}$ g cm^{-3}; $E = 3 \times 10^{-7}$ cgse; $\omega_g = 2 \times 10^{-2}$ s^{-1}. The curve 1 corresponds to the case of $\alpha = 0{,}2$ ($\omega_1/\omega_g = 1.4 \times 10^{-2}$; $\omega_3/\omega_g = 2.7$), and the curve 2 corresponds to the case of $\alpha = 1$ ($\omega_1/\omega_g = 3 \times 10^{-2}$; $\omega_3/\omega_g = 3.9$). As seen from these curves the absorption coefficient is negative and has the maximum value at the frequencies $\omega \sim \omega_g$. Thus the instability and the wave growth occur in the relatively narrow region around the Brunt–Vaisala frequency. This process results in creation of the periodic structure of ionospheric perturbation. Parallel with the variations of plasma density and pressure in the wave the oscillations of conductivity take place according to formula (9). The horizontal periodic structure of the ionospheric conductivity is formed with the scale $l \sim \lambda/2$ where λ is wavelength of AGW at the frequencies $\omega \sim \omega_g$ corresponding to the maximum κ value. At these frequencies the waves have maximum values of refraction index $n(\omega_g)$ or minimum phase velocities $v_g = a/n/(\omega_g) < a$. The horizontal scale of the conductivity variations is:

$$1 = \lambda/2 = \pi v_g/\omega_g = \pi a/\omega_g n(\omega_g) \quad (22)$$

Thus the dissipative instability of AGW in the presence of an external electric field in the ionosphere results in excitation of plasma density variations and formation of periodic horizontal structure of conductivity with characteristic scale, eqn (22).

4. Formation of field-aligned currents and plasma inhomogeneities in the upper ionosphere as a result of AGW instability in the lower ionosphere

One can expect that the AGW related wave of conductivity in the ionosphere in the presence of an external electric field will excite an obliquely propagating hydromagnetic wave into the upper ionosphere and the magnetosphere. The field-aligned current in this wave is carried by electrons while the closing current is carried by ions. It is shown below that transferring such disturbances from the E-layer to the upper ionosphere induces there the variations of plasma density.

According to Section 3 we consider the AGW propagation along the x-axis. Therefore, the irregularities of conductivity are stretched along the y-axis. Let the electric field E_0 be located in the x-y plane and the magnetic field B directed along the z-axis. Let us consider the simplified model of formation of plasma irregularity in the upper ionosphere caused by a motion of the conductivity irregularity $\Delta\sigma_{P,h}$ in a form of isolated band with the width $l = \lambda/2$ stretched along the y-axis in the ionospheric E-layer (Lyatsky and Maltsev, 1983). The horizontal velocity of the band motion along the x-axis is v_g. The wave propagation in the magnetosphere is characterized by the Alfven velocity u or by the integral wave conductivity $\Sigma_w = c^2/4\pi u$. The conducting band in the ionospheric E-layer causes the appearance of polarization electric field ΔE which is transferred along the magnetic field lines to the upper ionosphere and results in a change of plasma density in this region. Since ions can move in the electric field in horizontal direction, integrating along the x-axis the stationary equation of continuity for ions on the band boundary gives:

$$N(v_i - v_g) = N_0(v_{i0} - v_{g0}), \quad (23)$$

where N, v_i; N_0, v_{i0} are the balanced densities and velocities along the x-axis of ions inside and outside the band. To determine the ion velocities we use the equations of motion for ions and electrons (Sorokin and Fedorovich, 1982). In quasi-static approximation ($d/dt = 0$) when $/u/ \gg /v_g/$, we obtain:

$$v_{ix} = v_{ex}(1 - \nu_i E_x/\omega_i E_{y0})/(1 + \nu_i^2/\omega_i^2), \quad (24)$$

where ν_i is the collision frequency of ions, $v_{ex} = -cE_{y0}/B$ is the velocity of electron drift and $E_x = E_{x0} + \Delta E_x$ is the electric field within the band. Substituting eqn (24) into eqn (23) we obtain the density ratio in the following form:

$$N/N_0 = \{(1 - \nu_i E_{x0}/\omega_i E_{y0}) - (1 + \nu_i^2/\omega_i^2)v_g/v_{ex}\}/$$
$$\{[1 - \nu_i(E_{x0} + \Delta E_x)/\omega_i E_{y0}] - (1 + \nu_i^2/\omega_i^2)v_g/v_{ex}\} \quad (25)$$

It is seen from eqn (25) that the plasma density N is determined by the electric field change ΔE and the velocity of the band motion v_g. The quantity N depends on the altitude of the layer determined by the altitudinal variation of ν_i/ω_i. Thus, electric field variations at certain altitudes in the ionosphere are accompanied by the variations of plasma density.

The polarization electric field in the band is determined by the condition of current continuity in each of the ionospheric layers:

$$J_x - J_x^0 = J_z, \quad (26)$$

where J_x, J_x^0 and J_z, are the surface densities of ionospheric and field-aligned currents. The field-aligned current J_z is considered as positive when it flows up of the layer. Equation (26) determines J_z on the frontal (when moving along the x-axis) boundary of the band. On the back boundary the sign of J_z should be inverse. According to the Ohm's law the surface density of transverse ionospheric current J_x in each layer is determined by the integral (over the layer) Pedersen (Σ_p) and Hall (Σ_h) conductivities:

$$J_x = \Sigma_p E_x + \Sigma_h E_y \quad (27)$$

Taking into account that the Hall conductivity in the upper ionosphere is close to zero and applying eqns (26) and (27) to the E-layer, we obtain:

$$\Sigma_p E_x - \Sigma_{p0} E_{x0} + (\Sigma_h - \Sigma_{h0})E_{y0} = J_z^E$$
$$\Sigma_F E_x - \Sigma_{F0} E_{x0} = J_z^F \quad (28)$$

where Σ_p and Σ_h are the integral Pedersen and Hall conductivities of the E-layer, Σ_F is the integral Pedersen conductivity of the upper ionosphere, index *0* corresponds to undisturbed values, J_z^E and J_z^F are the field-aligned currents in the E-layer and in the upper ionosphere. The resulting field-aligned current flowing out from the ionosphere to the magnetosphere is:

$$J_z = J_z^E + J_z^F \quad (29)$$

Let us determine the connection between J_z and the horizontal electric field. Current densities and fields in the magnetosphere satisfy the Maxwell's equations:

$$[\nabla \times b] = 4\pi j/c + \partial E/c\,\partial t$$
$$[\nabla \times E] = -\,\partial b/c\,\partial t \quad (30)$$

From the equations of electron and ion motion we obtain the Ohm's law:

$$j_{\perp} = (c^2MN/B^2)(\partial E/\partial t) \quad (31)$$

where MN is magnetospheric plasma density and $j_{\perp}$ is the transverse component of current density. When deducing the Ohm's law, the conditions $\partial/\partial t \ll \omega_i$ and $E_{\parallel} = 0$ have been used. The polarization electric field arising within the band is transferred along the magnetic field lines into the magnetosphere. The polarization currents in the magnetosphere corresponding to eqn (31) is:

$$j_x = (c^2/4\pi u^2)\,\partial E_x/\partial t = (c^2/4\pi u^2)v_g\,\partial E_x/\partial x. \quad (32)$$

In the case of a uniform band these currents arise only on the band boundaries where $\partial E/\partial x \neq 0$.

To provide the coupling of the Alfven wave with AGW and related disturbances of conductivity the transverse velocity of Alfven wave should be equal to the AGW velocity:

$$v_g = u \quad \tan \quad \varphi, \quad (33)$$

where φ is wave front inclination angle of the hydromagnetic disturbance relatively to external magnetic field. The transverse and the field-aligned currents are determined by the equations:

$$j_x = (c^2v_g/4\pi u^2)\,\partial E_x/\partial x = \Sigma_w(v_g/u)\,\partial E_x/\partial x.$$

$$j_z = J_x \quad \tan \quad \varphi = \Sigma_w\,\partial E_x/\partial x, \quad (34)$$

where $\Sigma_w = c^2/4\pi u$ is the magnetospheric integral conductivity for the Alfven wave. Integrating the expression for current j_z over the thickness of the layer boundary and introducing the surface density of field-aligned currents J_z, we obtain:

$$J_z = \Sigma_w(E_{x0} - E_x) \quad (35)$$

Equations (28) and (35) result in the equation for the electric field within the band:

$$E_x = [\Sigma_{F0}E_{y0}/(\Sigma_p + \Sigma_w)]\{[1 + (\Sigma_{p0} + \Sigma_w)/\Sigma_{F0}]E_{x0}/E_{y0} + (\Sigma_h - \Sigma_{h0})/\Sigma_{F0}\}. \quad (36)$$

When deducing eqn (36), we used the fact that the conductivity of the upper ionosphere is much less than the E-layer conductivity $[\Sigma_F \ll (\Sigma_p + \Sigma_w)]$.

Equations (25) and (36) make it possible to derive a change of plasma density in the upper ionosphere above the band of increased conductivity in the E-layer:

$$N/N_0 = (1 + D_1 - v_g/v_{ex})/(1 + D_2 - v_g/V_{ex}), \quad (37)$$

where:

$$D_1 = v_iE_{x0}/\omega_iE_{y0},$$

$$D_2 = (v_i/\omega_i)[(\Sigma_{p0} + \Sigma_w)E_{x0}/(\Sigma_p + \Sigma_w)E_{y0} + (\Sigma_h - \Sigma_{h0})/(\Sigma_p + \Sigma_w)],$$

$$v_{ex} = -cE_{y0}/B, \quad v_g = a/n(\omega_g). \quad (38)$$

The density variation $\Delta N = N - N_0$ as follows from eqn (37) is determined by the equation:

$$\Delta N/N_0 = (D_1 - D_2)/(1 + D_2 - v_g/v_{ex}). \quad (39)$$

Let the electric field be directed along the x-axis ($E_{y0} = 0$). In the ionosphere the equality $\Sigma_w = \Sigma_{P0}$ is satisfied with the sufficient degree of accuracy. For example, at the $u \sim 5\times10^7$–8×10^7 cm s^{-1} and $\sigma_{p0}(z_{max}) \sim 3\times10^5$–$3\times10^6$ s^{-1}, we obtain $\Sigma_{p0} = \int dz\sigma_{p0}(z) \sim \sigma_{p0}(z_{max})\cdot\Delta z \sim 10^{12}$–$10^{13}$ cm s^{-1} for $\Delta z \sim 3\times10^6$ cm and $\Sigma_w = c^2/4\pi u \sim 10^{12}$–$2\times10^{12}$ cm s^{-1}. If we assume $\Delta\Sigma_p/\Sigma_{p0} = \Delta\sigma_p/\sigma_{p0}$ and $v_icE_{x0}/\omega_iv_gB \ll 1$ then, for estimating the value of the plasma density change, we obtain the formula:

$$\Delta N/N_0 = (v_icE_{x0}/\omega_iv_gB)(\Delta\sigma_p/\sigma_{p0})/(2 + \Delta\sigma_p/\sigma_{p0}). \quad (40)$$

With growing the relative conductivity disturbance $\Delta\sigma_p/\sigma_{p0}$ eqn (40) tends to the limiting value:

$$\Delta N/N_0 = v_icE_{x0}/\omega_iv_gB = v_icE_{x0}n(\omega_g)/\omega_iaB \quad (41)$$

When a satellite moving with the velocity v_s crosses the plasma irregularities of the scale l (see Fig. 3), plasma density fluctuations are registered with the period:

$$\Delta t = 1/v_s = \pi a/v_s\omega_gn(\omega_g) \quad (42)$$

Equations (41) and (42) enable us to estimate the magnitude and the characteristic period of plasma density variations due to disturbances of conductivity in the ionospheric E-layer that should be observed onboard the satellite in the upper ionosphere. These values depend on the altitude as $v_i = v_i(z)$. Thus, the excitation of horizontal spatial structure of the ionosphere conductivity results in forming the plasma layers stretched along the geomagnetic field.

The argument for formation of the field-aligned currents in the ionosphere resulting in formation of plasma irregularity can be found in the satellite data presented by Chmyrev et al. (1989). Figure 4 from this paper shows the variations of two horizontal magnetic field components B_x and B_y in the frequency range 0.1–8 Hz along with the vertical component of quasistatic electric field E_z which were observed onboard the 'Intercosmos-Bulgaria 1300' satellite within the 15 min interval before the earthquake occurred on 12 January 1982 at 17.50.26 UT. The quasistatic electric field 3–7 mV m^{-1} was observed in two zones: above the focus and in the magnetically conjugated region. The size of the zones was 1–1.5° in latitude. The amplitude of geomagnetic pulsations at the frequency about 1 Hz observed in these regions was ~ 3 nT. According to the physical model presented above a growth of the electric field in the ionosphere observed above the zone of developing earthquake leads to the AGW dissipative instability. As a result the horizontal irregularities of the ionospheric conductivity are formed

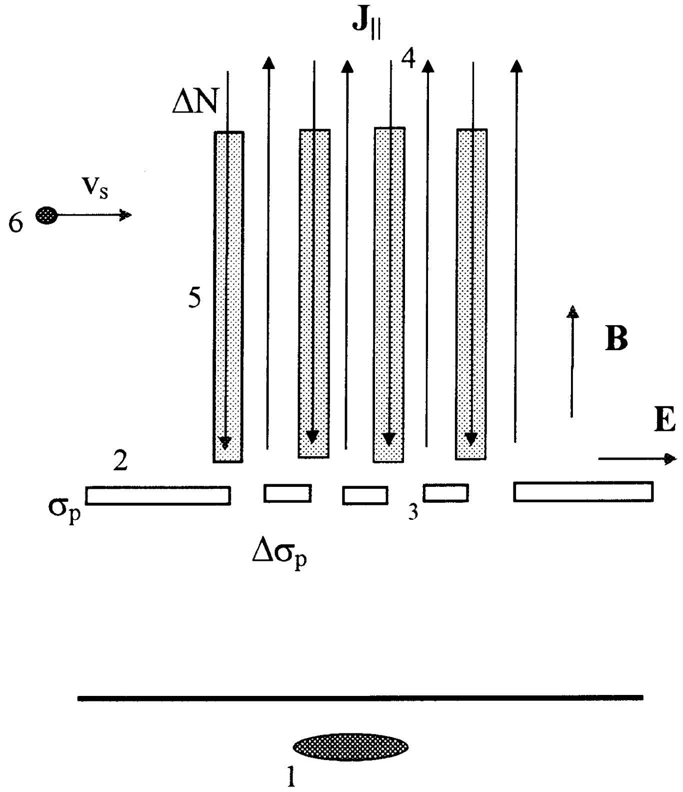


Fig. 3. The scheme of satellite observations of plasma density inhomogeneities and ULF magnetic field oscillations: 1. Earthquake zone; 2. Lower ionosphere; 3. Horizontal inhomogenities of ionospheric conductivity: 4. Field-aligned electric currents; 5. Field-aligned plasma density inhomogenities; 6. Satellite.

and the field-aligned currents arise. The satellite moving through the periodic current sheets will observe the related magnetic field oscillations with the period $\Delta t = l/\mathrm{v}_s$ and the amplitude:

$$b = (2\pi/c)J_z \tag{43}$$

where J_z is the surface density of the field-aligned current sheet. Substituting eqns (35) and (36) into eqn (43), we obtain:

$$b = (2\pi/c)E_x\Sigma_w\{\Delta\Sigma_p/[\Sigma_{p0}+\Sigma_w+\Delta\Sigma_p]\} \tag{44}$$

In eqn (44) it is assumed $E_y = 0$. Taking $\Sigma_w = \Sigma_{p0}$, $\Delta\Sigma_p/\Sigma_{p0} = \Delta\sigma_p/\sigma_{p0}$, we obtain from eqn (44) the formula for estimating the amplitude of geomagnetic pulsations:

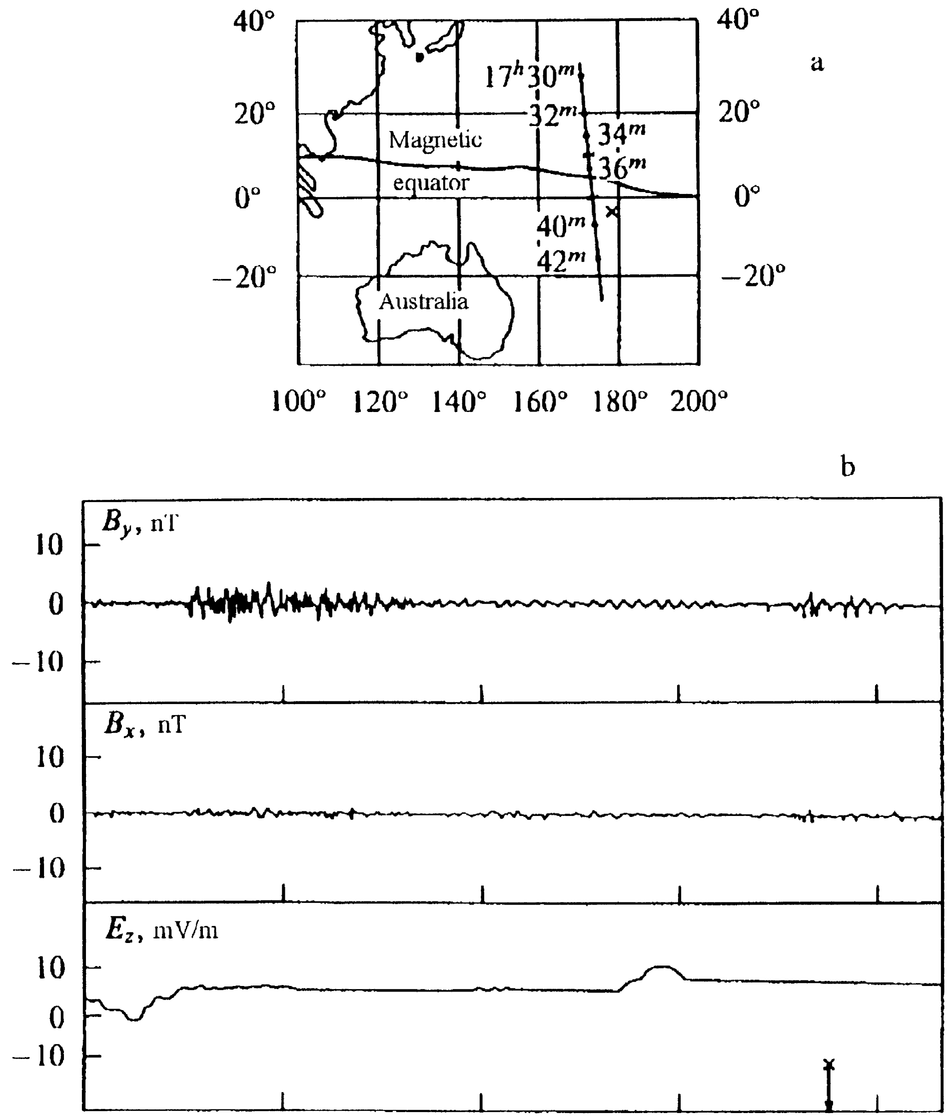
$$b = (\pi/c)E_x\Sigma_{p0}[\Delta\sigma_p/(2\sigma_{p0}+\Delta\sigma_p)] \tag{45}$$

Thus, the satellite passing through the considered structure of field-aligned currents will observe the plasma density fluctuations, eqn (41) and the ULF-oscillations of the geomagnetic field, eqn (45) with the characteristic period eqn (42).

5. Conclusion

In the ionosphere with magnetic and electric fields the dissipative instability of acoustic-gravity waves can arise. In case $(\partial\sigma_p/\partial\rho) > 0$ the plasma density variations in the wave result in growth of the conductivity disturbances and the Joule heating connected with the disturbed currents. The instability increment is proportional to the square of external electric field and to the value of derivative $(\partial\sigma_p/\partial\rho)$. The dissipative instability leads to growth of waves with the frequencies of the order of Brunt–Vaisala frequency. As a result the conductivity irregularities with the horizontal spatial scale l determined by eqn (22) are excited in the lower ionosphere.

The wave related irregularities of conductivity change the ionospheric electric fields. High conductivity along magnetic field lines results in the electric field propagation to the upper ionosphere and the magnetosphere. The fields are transferred by the field-aligned currents which are closed by the transverse currents in the ionosphere due to Pedersen conductivity. Since the field-aligned cur-



UT	17.35	17.36	17.37	17.38	17.39
h, km	799,5	800,1	800,8	802,1	803,6
φ	9,9°	6,3	3,3	−0,4	−4,0°
λ	173,5°	173,9	174,1	174,4	174,7°
L	1,104	1,096	1,096	1,104	1,122

Fig. 4. An example of DC electric field (vertical component) and ULF magnetic field (horizontal components) observations over the earthquake zone and in the magnetically conjugate region ∼ 15 minutes before an earthquake.

rents are carried by electrons, while the transverse currents are carried by ions, the upward propagation of the transverse electric field is followed by the local variations of plasma density. This means that the excitation of horizontal spatial structure of conductivity in the lower ionosphere results in the formation of plasma layers stretched along the geomagnetic field. Transverse spatial scale of the layers coincides with the scale of conductivity irregularities. When a satellite crosses the field-aligned currents and related field-aligned plasma inhomogeneities the oscillations of plasma density and ULF-oscillations of geomagnetic field are registered with amplitude whose order of value is determined by eqns (41) and (45). The oscillation period Δt is determined by eqn (42). Let us estimate these quantities. At the altitude of the order of 1000 km the total number of ions collisions is $v_i = v_{i(n+i)} \sim 0.5\ s^{-1}$ (Schunk and Nagy, 1980) and the ion gyrofrequency $\omega_i \sim 30\ s^{-1}$. Let us assume $a = 3 \times 10^4$ cm s^{-1}; $E = 9$ mV $m^{-1} = 3 \times 10^{-7}$ cgse; $B = 3 \times 10^4$ nT $= 0.3$ cgsm; refractive index $n = 1$–10, from eqn (41) we obtain:

$$\Delta N/N_0 \approx v_i cnE/\omega_i aB = (1.6\text{–}16)\%. \tag{46}$$

Assuming $\Sigma_{P0} = 2 \times 10^{12}$ cm s^{-1} in eqn (45) we obtain:

$$b \approx (\pi/c)E\Sigma_{P0} = 5n\mathrm{T}.$$

Equation (42) gives the estimate for the oscillation period Δt at $\omega_g = 2 \times 10^{-2}\ s^{-1}$ and $v_s \sim 10^6$ cm s^{-1}:

$$\Delta t \approx \pi a/v_s\omega_g n(\omega_g) = (0.3\text{–}3)s.$$

These values in their order of magnitude are in agreement with the satellite data presented in Figs. 1 and 4. These values correspond to seismic related ionospheric disturbances observed onboard the COSMOS-1809 satellite over the zone of Spitak earthquake (Chmyrev et al., 1997). We believe that the mechanism of dissipative instability of acoustic-gravity waves in the ionosphere developed in this paper can be used as a basis for the theory of electromagnetic and plasma response of the ionosphere to the earthquake preparation processes.

Acknowledgements

This work was partly supported by NASA through NASA-RSA contract NAS15–10110 and by RFFI under contracts 96–05–65304 and 97–05–64359.

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