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THEORETICAL MODEL OF POSSIBLE DISTURBANCES IN THE NIGHTTIME MID-LATITUDE IONOSPHERIC *D* REGION OVER AN AREA OF STRONG-EARTHQUAKE PREPARATION

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We present a theoretical model of possible electron-density disturbances in the nighttime mid-latitude ionospheric D region, preceding strong earthquakes. It is found that the electron density in the nighttime D region over an earthquake epicentral zone can considerably increase before severe earthquakes. The horizontal size of the area of disturbed electron density is about 300 *km. The disturbance effect is expected to be more pronounced if a powerful VLF transmitter operates in the vicinity of an imminent earthquake epicentral zone. In this case, a very dense ionization layer of daytime D-layer type can be formed at the altitudes of the upper nighttime mesosphere and can give rise to the effect of strong absorption of HF radio waves propagating over the earthquake preparation area.*

1. INTRODUCTION

Based on measurements of the propagation characteristics of VLF radio waves of the “Omega” phase navigation system along paths crossing seismo-active areas, bay-shaped phase perturbations of the radio signals, not related to solar–magnetospheric activity, were discovered in [1]. The statistical analysis of 1300 earthquakes with magnitudes $M = 4.0-7.0$ showed that such phase perturbations began to appear in the nighttime $10-20$ days before earthquakes. The confidence probability of the relationship between the observed signal-phase perturbations and the earthquakes was about 90%. Phase perturbations of the radio signals of the “Omega” system were most prominent before very severe earthquakes in Spitak (Armenia, $M = 7.1$, 1988) [2], Rudbar (Iran, $M = 7.5$, 1990) [3], and Kobe (Japan, $M = 7.1$, 1995) [4]. Such signal-phase perturbations can be caused by a noticeable increase in the electron number density at the altitudes of the nighttime ionospheric *D* region above earthquake-preparation areas.

In this respect, it is interesting to clarify how the processes in the source of an imminent earthquake at the final stage of its preparation can influence the electron density in the nighttime ionospheric *D* region. The authors of [4] suggested that such an influence can probably be explained by the generation of long-period gravity waves similar to planetary Rossby waves as a result of resonance interaction between the seismic processes and the neutral atmosphere. However, such an explanation seems unreal, since no significant changes in the near-surface atmospheric layer above the epicentral zone of an imminent earthquake have been observed so far. Meanwhile, excitation of planetary Rossby waves, even by various resonance mechanisms, requires significant amounts of energy and momentum to be transferred to the atmosphere. Moreover, since Rossby waves have planetary scales, phase perturbations of the “Omega” signals should also be observed on paths passing thousands of kilometers away from the earthquake epicenter.

Evolution of charged components in the ionospheric *D* region is determined quite strictly by the conditions of ionization-recombination equilibrium, so that the observed disturbances of the electron density

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N_e can hardly be explained by a simple redistribution of the plasma due to the drift of charged particles induced by an electric field unless such a field is extremely strong. In this respect, a hybrid mechanism was proposed in [5] to explain the seismic nature of the electron-density disturbances in the D region. According to this mechanism, the above-mentioned disturbances of the number density N_e are caused by the vertical transport of charged particles into the D region from the upper sporadic E_s layer and variation in the density of nitric oxide under the combined effect of electric fields and infrasonic waves generated in the earthquake-preparation source and propagated up to ionospheric altitudes. However, such a hypothesis was not corroborated in [5] by any quantitative calculations of variations in N_e.

In this paper, we present a theoretical model that explains and allows for calculating the possible electron-density disturbances in the nighttime ionospheric D region over epicentral zones of earthquakes under preparation. Our model is a natural development of our multi-year theoretical studies of the possible ionospheric precursors of strong earthquakes, which were performed within the framework of a unified approach based on the assumption that the primary source of ionospheric disturbances preceding severe earthquakes is a disturbance of the vertical electric field on the ground initiated by physico-chemical processes in an earthquake source. Indeed, such disturbances of the vertical electric field were observed repeatedly in epicentral zones before earthquakes [6–8]. Penetration of an electrostatic field of seismogenic origin into the ionosphere was calculated quantitatively in [9], in which the electric field in the ionosphere was shown to be fairly strong. Using the results of [9] and allowing for the recent level of theoretical modelling of the ionosphere, we elaborated step-by-step quantitative models of strong-earthquake precursors at the altitudes of the E and F regions [10, 11] and also in the upper ionosphere [12]. Note that the immediate factor determining the ionospheric disturbances in these models was the drift of charged particles of the ionospheric plasma under the action of the electric field of a seismic source. However, as was pointed out above, the electric drift of charged particles in the ionospheric D region does not have a significant effect on their number-density distribution. Hence, in this case, the electron-density disturbance before an earthquake is determined by a physical mechanism of a different origin, which is considered in detail below.

2. THE PHYSICAL MECHANISM

It was shown in [12] that a plasma irregularity extending from one hemisphere to another along the geomagnetic field is formed in the plasmasphere before a strong earthquake under the action of the electric field of a seismic source in the vicinity of the geomagnetic field line passing through the epicenter of an imminent earthquake. The typical size of the irregularity across the geomagnetic field is about 300 km at altitudes about 2000 km. Such a plasma irregularity is a duct for low-frequency electromagnetic waves of natural and artificial origin. We should note that similar plasma irregularities elongated along the geomagnetic field lines can also occur under the action of the electric fields of large thunderclouds [13]. Coherent VLF radio waves emitted by powerful ground-based radio stations, including the transmitters of the “Omega” navigation system, should be efficiently channeled in such ducts and should propagate along them in the plasmasphere penetrating in the region of trapped high-energy particles of the Earth’s radiation belt. The resonance cyclotron interaction of the propagating VLF wave and the energetic-electron population can take place in the radiation belt, which leads to the pitch-angle scattering of the trapped particles. As a result, some energetic electrons will be scattered into the loss cone and precipitate in the lower atmosphere. The resonance cyclotron interaction of VLF waves with energetic charged particles is the subject of many publications (see, e.g., the reviews [14, 15]).

Natural incoherent wideband VLF radiation trapped in a duct should lead to chaotic variations in the pitch angles of energetic electrons. Mathematically, such a pitch-angle scattering can be described as diffusion in the pitch-angle space [15]. In this case, natural VLF waves can be efficiently amplified in a duct, which, in turn, should result in intense pitch-angle scattering of the energetic electrons and in their enhanced precipitation [16–18]. Coherent VLF radio waves have a much stronger effect on the pitch-angle distribution of energetic charged particles and on their precipitation from the radiation belt since, in this case, variations in the pitch-angle during the bounce period are no longer chaotic, but regular. The pitch-angle scattering of energetic electrons interacting with coherent VLF radio waves were calculated in [19–21] under various conditions.

Energetic-electron precipitation from the radiation belt was observed at the middle and lower latitudes using different methods [22–26]. In view of our analysis, we specially mention the paper [24] in which the results of observations of a localized precipitation of energetic electrons, initiated by the radiation of a ground-based VLF radio station, were reported.

Thus, the formation of a plasma duct under the action of a seismic electric field should lead to energetic-electron precipitation from the radiation belt. It is exactly the collisional ionization by these electrons that should give rise to an increase in the electron density in the nighttime mid-latitude ionospheric D region. For clarity, we present in Fig. 1 a general sketch of the physical mechanism for increasing the electron density in the nighttime mid-latitude ionospheric D region before a strong earthquake.

Now we proceed to calculating the rate of collisional ionization of the neutral component of the D region by flows of precipitating energetic electrons.

3. CALCULATION OF THE IONIZATION RATE

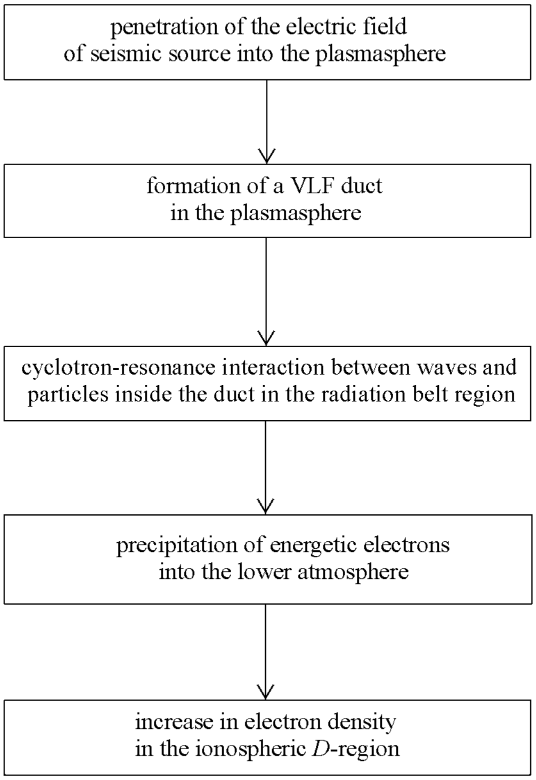

Fig. 1.

The rates of collisional ionization of the neutral atmospheric components by precipitating energetic electrons have been calculated in a number of papers [27–29]. We apply the calculation technique developed in [28]. According to this paper, the rate q of creation of ion pairs in a unit volume, normalized to the monoenergetic flux F of electrons with energy E_0 is given by the formula

$$q/F = q_{\mathrm{e}}(E_0) = \frac{E_0}{r_0\,\Delta E_{\mathrm{ion}}}\lambda\,(z/R)\,\frac{n(\mathrm{M})_z}{n(\mathrm{M})_R}\,, \qquad (1)$$

where $\Delta E_{\mathrm{ion}} = 0.035$ keV is the ionization energy per ion pair, $r_0 = R/\rho$, ρ is the air density at the maximum depth R to which electrons with a given energy can penetrate, $\lambda(z/R)$ is the dimensionless distribution function of energy loss, $z = \int_h^{h_{\mathrm{top}}} \rho\,\mathrm{d}h'$, h is the height in the atmosphere at which the ionization rate is calculated, $h_{\mathrm{top}} = 1000$ km is the adopted altitude of the upper boundary of the atmosphere, and $n(\mathrm{M})_z$ and $n(\mathrm{M})_R$ are the number densities of atoms and molecules being ionized at depths z and R, respectively. In this case, the maximum depth of penetration into the atmosphere and the initial electron energy $0.4\,\mathrm{keV} \le E_0 \le 500\,\mathrm{keV}$ at the upper boundary of the atmosphere are related as follows: $R[\mathrm{g/cm^2}] = 4.57 \cdot 10^{-6}\,(E_0[\mathrm{keV}])^{1.75}$.

If the flux of precipitating electrons having an arbitrary differential energy spectrum $g(E_0)$ in the energy range from $E_0^{\min}$ to $E_0^{\max}$ is isotropic over the upper hemisphere, then the ionization rate Q per unit volume can be presented in the following way with allowance for Eq. (1):

$$Q = \pi \int\limits_{E_0^{\min}}^{E_0^{\max}} g(E_0)q_{\mathrm{e}}(E_0)\,\mathrm{d}E_0. \qquad (2)$$

According to [23, 25], two global zones exist in the northern hemisphere at the middle and low latitudes, in which nighttime precipitation of energetic electrons is regularly observed. One of these zones corresponds to the L shell with an index of about 2.6, and another, to the shell with $L \approx 1.4$. In the southern hemisphere, in addition to the above-mentioned zones, there is also the region of South-Atlantic Anomaly in which electron precipitation is most intense. Narrow localized precipitation of electrons over an operating high-power VLF radio station was observed in [24] in the vicinity of the magnetic shell with $L = 1.67$ in the northern hemisphere.

In our calculations, we used the spectra of precipitating energetic electrons similar to those observed by the "S3-2" satellite [25] near the global mid-latitude zone of nighttime precipitation in the vicinity of the shell with index $L = 2.6$ and by the "OVI-14" satellite [24] in the region of narrowly localized precipitation over a powerful VLF radio station in the vicinity of the shell with $L = 1.67$. The approximations of the chosen differential energy spectra are shown in Fig. 2 in which the particle spectrum corresponding to the global background precipitation at the middle latitudes (*a*) and the spectrum of electrons precipitating over a VLF radio station (*b*) are presented. The results of calculation of the ionization rate Q for the neutral-atmosphere model MSIS-E-90 are given in Sec. 5.

4. CALCULATION OF THE ELECTRON DENSITY

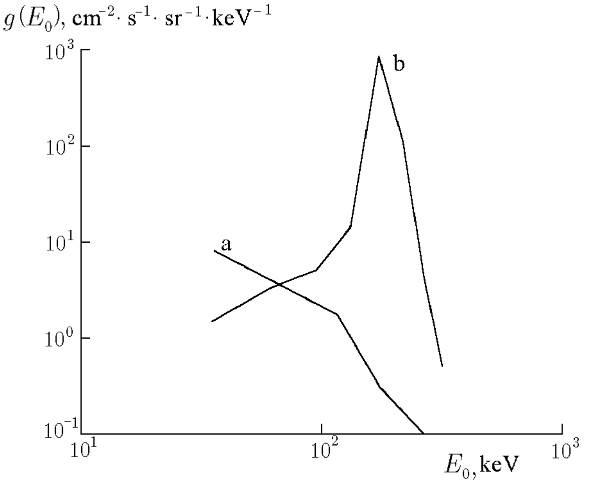

Fig. 2.

The D region is the most poorly studied part of the Earth's ionosphere, which is explained by both the plethora of various complicated chemical processes taking place in this region and the fact that it is relatively inaccessible for regular observations, especially in the nighttime when the typical number density of charged particles falls below 10^3 cm^{-3}. Various aspects of studying the ionospheric D region are discussed in the comprehensive review [30]. Recent theoretical models of the D region include a variety of chemical reactions and are mainly based on solving the system of chemical-kinetics equations (see, e.g., [31, 32]). Analysis of specific issues of modelling the ionospheric D region is beyond the scope of this paper and, thus, are not touched upon below. Our consideration is aimed at demonstrating the principal possibility of formation of localized electron-density disturbances at the altitudes of the nighttime ionospheric D region before strong earthquakes, but we do not intend to calculate the detailed distribution of N_e in any specific case. Let us use the stationary continuity equation for the electron density N_e, which can be written as [33, 34]

$$\alpha N_\mathrm{e}^2 + \ell N_\mathrm{e} - q = 0. \tag{3}$$

Here, $\alpha = 6 \cdot 10^{-7}$ cm$^3 \cdot$ s^{-1} is the recombination rate, $\ell = k_1 N^2(\mathrm{O}_2) + k_2 N(\mathrm{O}_2) N(\mathrm{N}_2)$ is the electron-attachment rate, $N(\mathrm{O}_2)$ and $N(\mathrm{N}_2)$ are the number densities of O_2 and N_2 molecules, respectively, $k_1 = 1.4 \cdot 10^{-29}\,[300/T_\mathrm{n}[\mathrm{K}]]\exp[-600/T_\mathrm{n}[\mathrm{K}]]$ cm$^6 \cdot$ s^{-1}, $k_2 = 10^{-31}$ cm$^6 \cdot$ s^{-1}, T_n is the temperature of the neutral atmosphere, and $q = Q + q_1$ is the sum of the rate Q of collisional ionization by the precipitating energetic electrons and the rate q_1 of photoionization by the scattered solar radiation in the hydrogen L_α line at wavelength 1216 Å. The photoionization rate q_1 is taken from [35]. As in the above calculations of Q, we used the neutral-atmosphere model MSIS-E-90.

5. RESULTS OF CALCULATIONS

The calculated altitude distribution of the rate of collisional ionization by precipitating energetic electrons at the altitudes of the upper mesosphere is shown in Fig. 3 for two cases. Curve *1* corresponds to

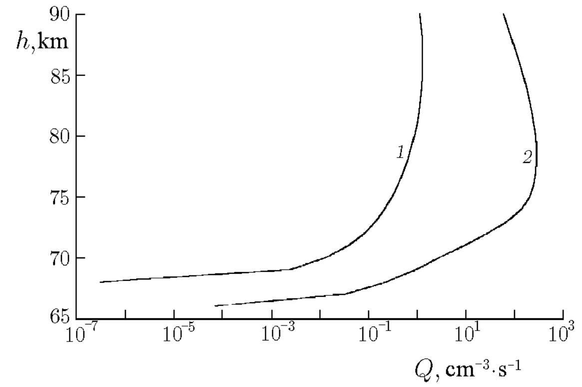

Fig. 3

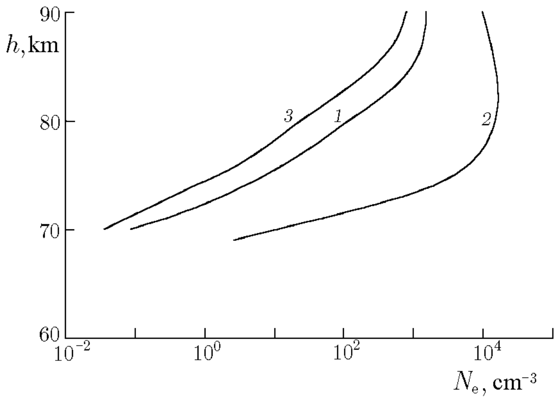

Fig. 4

the case that can be realized in the final stage of preparation of a strong earthquake whose source is located far away from the operating artificial sources of VLF radio waves. Curve *2* shows the possible ionization rate over the epicentral area of an imminent earthquake in the case where a powerful VLF radio station operates nearby. It follows from Fig. 3 that the ionization rate in the D region is much higher in the second case compared with the first one, and this difference increases with decreasing altitude.

The altitude distributions *1* and *2* of the ionization rate (see Fig. 3) were used to calculate the electron-density disturbance in the nighttime ionospheric D region before a strong earthquake. The corresponding altitude profiles of N_e are shown by curves *1* and *2* in Fig. 4. For comparison, we also plotted in this figure the background altitude profile (curve *3*) of the electron density in the case where the energetic-electron precipitation is absent and the ionization is due only to scattered radiation in the hydrogen L_α line. It is seen that the electron density in the nighttime ionospheric D region before a severe earthquake can significantly increase. The effect of an increase in N_e is most pronounced if a powerful VLF radio station operates in the vicinity of the epicentral zone of an earthquake under preparation. In this case, a fairly pronounced, dense ionized layer with maximum electron density about $2 \cdot 10^4$ cm^{-3} is formed in the nighttime upper mesosphere at an altitude of about 85 km. Thus, the parameters of such a layer are close to the parameters of the N_e distribution in the daytime D region for the middle and low latitudes. The disturbed electron density exceeds the background values of N_e by more than one order of magnitude at altitudes 85–90 km and by 2 and 3 orders of magnitude at altitudes of 75 and 85 km, respectively. At the same time, it is noteworthy that the electron density is higher than 10^3 cm^{-3} for $h > 73$ km. In regions far away from the operating VLF radio stations, the earthquake precursors in the nighttime D region are less pronounced. However, variations in N_e are fairly significant in these regions, too. The electron density at altitudes $80-85$ km increases by about a factor of 8 compared with the background level, and the relative increase in N_e below 80 km exceeds one order of magnitude. Although the electron density reaches its maximum at the upper boundary of the D region, at an altitude of 87 km, where $N_e \sim 2.5 \cdot 10^3$ cm^{-3}, the value of N_e is nevertheless more than 10^3 cm^{-3} down to altitudes $h \approx 82$ km .

Thus, a significant enhancement of the electron density in the nighttime mid-latitude ionospheric D region can occur before severe earthquakes over their epicentral zones. This effect should be most pronounced in regions where powerful sources of VLF radio waves are located.

6. CONCLUSIONS

We present a theoretical model describing electron-density disturbances in the nighttime mid-latitude ionospheric D region, which can be the precursors of a strong earthquake. According to the above analysis, the electron number density in the nighttime ionospheric D region can significantly increase before a strong earthquake over its epicentral zone. The immediate cause of the electron-density disturbance is the collisional ionization by energetic electrons precipitating from the Earth's radiation belt. In turn, the precipitation occurs as a result of resonance cyclotron interaction between the electrons and the coherent and incoherent VLF electromagnetic waves trapped in a plasmaspheric VLF duct extending from one hemisphere to another along the geomagnetic field. Such a duct is formed under the action of a seismogenic electric field in the vicinity of the geomagnetic field line crossing the epicenter of an imminent earthquake.

The typical horizontal size of the disturbed region is about 300 km. The excess of the electron density over its background values increases with decreasing altitude and can rise to about 2–3 orders of magnitude at altitudes $75-85$ km. If a powerful VLF radio station operates in the vicinity of the epicentral zone of an earthquake under preparation, then a dense ionization region of daytime D-layer type can be formed at the altitude of the nighttime upper mesosphere. The electron density in the maximum of such a layer can be about $2 \cdot 10^4$ cm^{-3}. HF radio waves propagated over an earthquake-preparation area should be strongly absorbed due to the formation of this layer.

The effect of an electron-density increase in the D region over the source of an imminent earthquake is less pronounced in regions located far away from the operating VLF radio stations. However, the magnitude of this effect is still fairy large.

The naturally arising question concerning unambiguous identification of seismogenic disturbances of the electron density in the nighttime ionospheric D region among disturbances related to other reasons poses a complicated but solvable problem that should be analyzed separately. Here, we should only note that practical solution of this problem requires account of the meteorological environment and the level of geomagnetic and solar activity, as well as knowledge of the rate of appearance of strongly localized electron-density enhancements in the regional nighttime D region.

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