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MAGNETOSPHERIC-IONOSPHERIC CHANGES CAUSED BY FLIGHTS OF SPACE VEHICLES

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The process of formation and disappearance of an ionospheric "hole" in the F2 layer caused by the ejection of water molecules during the flight of a space vehicle has been considered using the method of computational experiment based on the mathematical ionospheric-magnetospheric model in a coordinate system fixed on the magnetic force line of the Earth.

Introduction. An active exploration of circumterrestrial space requires ever more precise ideas of the atmospheric changes caused by various anthropogenic influences. Significant is the problem of pollution of upper atmosphere by products of combustion of the fuel of space vehicles (H_2O, CO_2, and H_2), which, while entering into interaction with an ionospheric plasma, markedly change its parameters. Among the principal effects of this change is a decrease in the electron concentration of the F2 region of the ionosphere and the formation of an ionospheric "hole," which results in disruptions of radio communications that can be observed at fairly long distances (of up to 2000 km) from the place of launching of a rocket for a fairly long time (of the order of 3–4 h).

A theoretical investigation of this phenomenon was carried out repeatedly and has been most completely described in [1] in a coordinate system for a limited range of heights. In [2], it was considered with account for the ionospheric-magnetospheric interaction in a coordinate system fixed on the magnetic force line. In this work, the formation and closing of an ionospheric "hole" is studied using a mathematical model with account for the ionospheric-magnetospheric interaction.

Brief Description of the Model. Mathematical modeling of the behavior of charged particles along the magnetic force line of the Earth is based on the numerical solution of the system of equations:

of continuity

$$\frac{\partial n_i}{\partial t} + B \frac{\partial}{\partial s}\left(\frac{1}{B} n_i V_i\right) = F_i - \alpha_i n_i \,, \tag{1}$$

of motion

$$n_i m_i \left(\frac{\partial V_i}{\partial t} + V_i \frac{\partial V_i}{\partial s}\right) + \frac{\partial P_i}{\partial s} = - n_i m_i g \sin I + n_i \sum_j S_{ij} (V_j - V_i) + n_i R_i (V_{nx} \cos I - V_i) - \frac{n_i}{N_e} \frac{\partial P_e}{\partial s} \,, \tag{2}$$

and of energy

$$\frac{3}{2} k N_e \frac{\partial T_e}{\partial t} = B \frac{\partial}{\partial s}\left(\frac{1}{B} \lambda_e \frac{\partial T_e}{\partial s}\right) + \sum_i \frac{3 m_e N_e}{m_i} \nu_{ei} k (T_i - T_e) + Q_e - L_{e\,n}, \tag{3}$$

$$\frac{3}{2} k n_i \frac{\partial T_i}{\partial t} = B \frac{\partial}{\partial s}\left(\frac{1}{B} \lambda_i \frac{\partial T_i}{\partial s}\right) + 3 n_i \nu_{ie} k (T_e - T_i) + \sum_n \frac{3 m_i n_i}{m_i + m_n} \nu_{in} k (T_n - T_i) + Q_i - L_i \,. \tag{4}$$

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TABLE 1. Reactions of Positive Ions

Nos.	Reaction	Rate coefficients of reactions
1	$O^+ + O_2 \to O_2^+ + O$	$\gamma = \begin{cases} 2.0\cdot10^{-17}(300/T_{1n})^{0.4}, T_{1n} \le 1800 \\ 1.3\cdot10^{-18}(T_{1n}/300)^{1.2}, T_{1n} > 1800 \end{cases}$
2	$O^+ + H_2O \to H_2O^+ + O$	$\gamma = 2.3\cdot10^{-15}$
3	$O^+ + N_2 \to NO^+ + N$	$\gamma = \begin{cases} 1.2\cdot10^{-18}(300/T_{1n}), T_{1n} \le 750 \\ 8.0\cdot10^{-20}(T_{1n}/300)^2, T_{1n} > 750 \end{cases}$
4	$O^+ + H \to H^+ + O$	$\gamma = 4.0\cdot10^{-16}(T_{1n}/300)^{0.5}$
5	$H^+ + O \to O^+ + H$	$\gamma = 3.5\cdot10^{-16}(T_{2n}/300)^{0.5}$
6	$N_2^+ + O \to NO^+ + N$	$\gamma = 1.4\cdot10^{-16}(T_n/300)^{-0.44}$
7	$N_2^+ + O_2 \to O_2^+ + N_2$	$\gamma = 4.5\cdot10^{-17}(T_n/300)^{-0.6}$
8	$O_2^+ + NO \to NO^+ + O_2$	$\gamma = 4.5\cdot10^{-16}$
9	$O_2^+ + e \to O + O$	$\gamma = 1.6\cdot10^{-13}(T_e/300)^{-0.55}$
10	$NO^+ + e \to N + O$	$\gamma = 4.2\cdot10^{-13}(T_e/300)^{-0.85}$
11	$N_2^+ + e \to N + N$	$\gamma = 1.8\cdot10^{-13}(T_n/300)^{0.4}(T_e/300)^{-0.38}$
12	$H_2O^+ + e \to H + OH$	$\gamma = 1.7\cdot10^{-13}$
13	$H_2O + \hbar\nu \to OH + H$	$\gamma = 10^{-11}$
14	$O + \hbar\nu \to O^+ + e$	$10^{-10} \le \lambda \le 91.1\cdot10^{-9}$
15	$O_2 + \hbar\nu \to O_2^+ + e$	$10^{-10} \le \lambda \le 80\cdot10^{-9}$
16	$N_2 + \hbar\nu \to N_2^+ + e$	$10^{-10} \le \lambda \le 103.7\cdot10^{-9}$

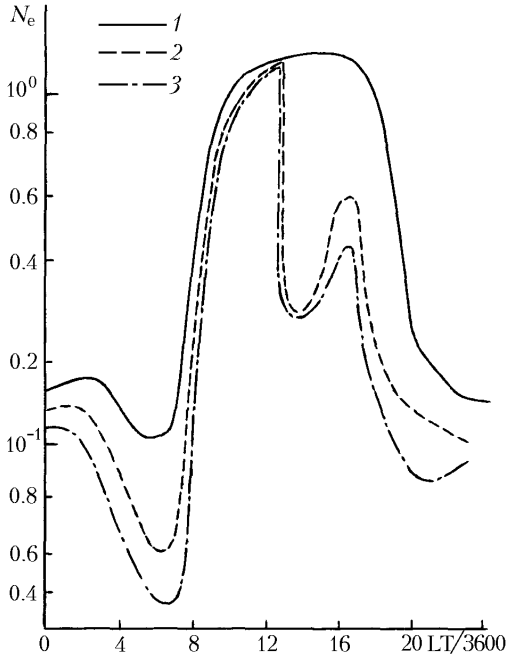
The system of equations for the meridional V_{nx} and zonal V_{ny} components of neutral wind along the geomagnetic force line is written in the form

$$\frac{\partial V_{nx}}{\partial t} = \frac{\xi}{\sin^2 I}\frac{\partial^2 V_{nx}}{\partial s^2} - \frac{1}{\rho_n}\sum_j n_j R_j\,(V_{nx} - V_j \cos I) + 2\Omega \sin\varphi V_{ny} - \frac{1}{\rho_n}\frac{\partial P_n}{\partial x}\,, \quad (5)$$

$$\frac{\partial V_{ny}}{\partial t} = \frac{\xi}{\sin^2 I}\frac{\partial^2 V_{ny}}{\partial s^2} - \frac{1}{\rho_n}\sum_j n_j R_j V_{ny} - 2\Omega \sin\varphi V_{ny} - \frac{1}{\rho_n}\frac{\partial P_n}{\partial y}\,. \quad (6)$$

The system of equations (1)–(6) and the numerical methods for their solution have been described in detail in [3]. The concentrations of molecular ions were calculated on the basis of the numerical solution of continuity equations (1) in the absence of transfer processes. Since molecular ions are only present at small heights (of 100–200 km), the coordinate s for them can be replaced by the height z.

The height-time distribution of neutral components H and H_2O in a unidimensional approximation with allowance for transfer processes was calculated using continuity equation (1). Here, the height z can also be employed in lieu of the coordinate s. As transfer processes, we considered only molecular diffusion, whose rate is determined from the equation



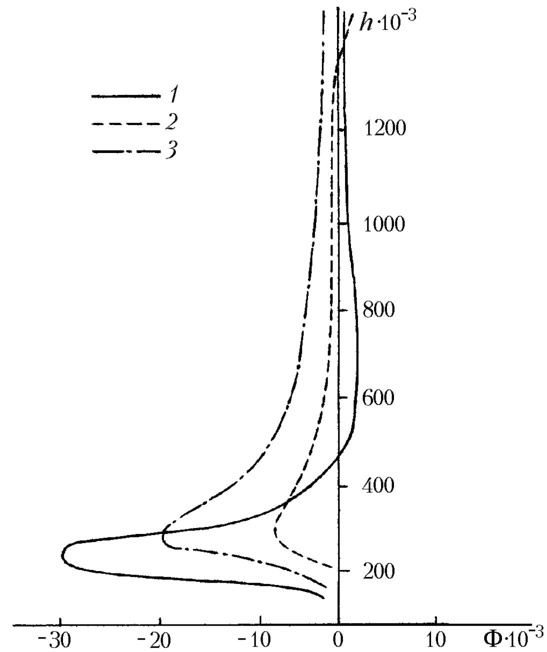


Fig. 1. Numerical results for diurnal variations in [N_mF2]: background values of [N_mF2] (1), values of [N_mF2] without regard for H (2) and with account for the H formation (3) at [H_2O] = 20 m^{-3}. N_e, m^{-3}.

Fig. 2. Ionospheric plasma flux for LT = 13^{00}. Designations 1–3 are the same as in Fig. 1. h, m; Φ, $m^{-2}\cdot sec^{-1}$.

$$V = -D\left(\frac{1}{n}\frac{\partial n}{\partial z} + \frac{1}{H} + \frac{1}{T_n}\frac{\partial T_n}{\partial z}\right),$$

where $D = kT_n/(m\nu)$ is the coefficient of molecular diffusion, ν is the frequency of collisions with particles of the surrounding gas, and $H = kT_n/(mg)$ is the height scale of a neutral component. The terms of formation and losses F_i and α_i were calculated by the photochemical scheme (see Table 1).

As the initial conditions for H_2O, we assumed the barometric distribution at the maximum of the F2 layer of the ionosphere, [H_2O] = 20 m^{-3}. The system of equations for H_2O and H was solved in the limited region 125 km $\leq s \leq$ 800 km. At the upper bound, a zero flux was specified for H_2O, and the magnitude of the flux for H was determined by the runaway velocity, equal to its thermal velocity.

Results of the Computational Experiment. Figure 1 presents time variations of N_mF2 calculated for three cases, viz., for calm conditions, for water ejection with [H_2O] = 20 m^{-3} in the F2 region without regard for the formation of H and with account for it; the electron concentration decreases to [N_mF2] = 0.1 m^{-3} at evening hours and to [N_mF2] = 10^{-2} m^{-3} at morning hours. Evidently, the amplitude of decrease in N_mF2 is dependent on the amount of injected water.

In the current study, account is taken of the formation of atomic hydrogen in photodissociation of water molecules:

$$H_2O + \hbar\nu \rightarrow OH + H\,.$$

Allowing for this reaction as an additional source of H gives rise to the second ionospheric "hole" at sunset (LT $\approx 20^{00}$ h). Subsequently, in the time interval $13^{00} \leq$ LT $\leq 16^{00}$, a closing of an ionospheric "hole" (an increase in N_e, Fig. 1) occurs, which may be attributed to the photoionization processes (see Table 1, reactions No. 14–16) and decrease in [H_2O] (by reactions No. 2, 4, and 13). However, an essential factor is the change in the flux of ionized particles (Fig. 2). As is known, for normal conditions the flux of charged particles is in the daytime directed from the F2 region to the magnetosphere at heights over 400 km (Fig. 2, curve 1). The formation of an ionospheric "hole" caused

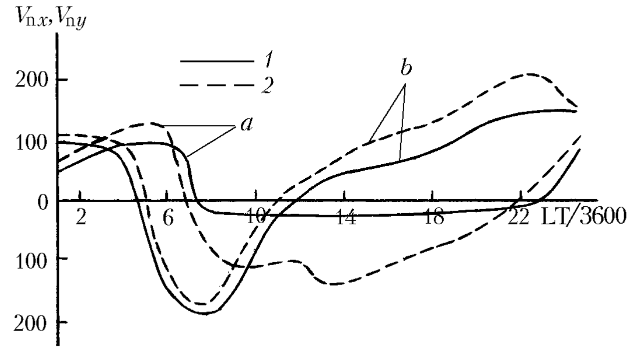


Fig. 3. Results for V_{nx} (a) and V_{ny} (b) calculated according to the model. Designations 1 and 2 are the same as in Fig. 1. V_{nx}, V_{ny}, m·sec^{-1}.

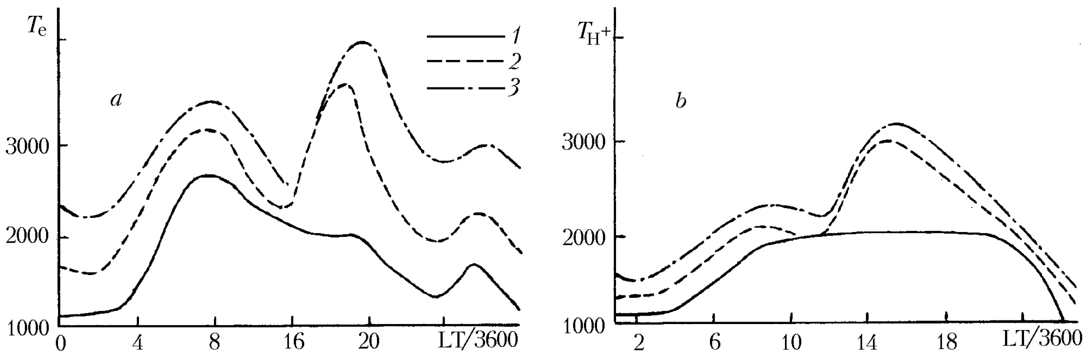


Fig. 4. Results for T_e (a) and T_{H^+} (b) calculated according to the model. Designations 1–3 are the same as in Fig. 1. T_e, T_{H^+}, K.

a reversal of the flux direction, the flux then being directed from the magnetosphere to the ionosphere (Fig. 2, curves 2 and 3).

Figure 3 presents diurnal variations in the meridional velocity of neutral wind V_{nx}, which is positive in the direction to the south, and in the zonal velocity V_{ny}. Clearly, the water ejection $[H_2O] = 20$ m^{-3} is accompanied by a marked variation in V_{nx}. An increase in the meridional velocity V_{nx} of neutral wind is linked with a reduction in the ion slowdown and leads to a decrease in the height of the layer maximum h_mF2.

Figure 4 shows diurnal variations in the electron T_e and ion T_{H^+} temperatures at the height h_mF2 with the H_2O ejections. Clearly, the formation of an ionospheric "hole" causes a substantial increase in the electron temperature. With ejections $[H_2O] = 10$ m^{-3} at the maximum of the F2 layer, the decrease in $[N_m$F2$]$ is about 50% for the chosen conditions, which leads to a noticeable variation in the electron temperature. The computational experiment indicated that the formation of an ionospheric "hole" does not noticeably change the ion temperature T_{O^+}.

Conclusions. The mathematical model presented allows the investigation of modification of the F2 ionospheric region under anthropogenic influences based on the numerical solution of equations of continuity, motion, and heat balance for a multicomponent plasma written for geomagnetic field tubes. With the specific example of water injection in a field tube, quantitative characteristics have been obtained for the conditions of formation and evolution of an ionospheric "hole." It has been shown that the basic reason for a decrease in the electron concentration of the F2 region is the reaction of destruction of O^+ ions on water molecules. During the formation of an ionospheric "hole," the direction of the plasma flux changes. A flux from the plasmasphere to the ionosphere forms, which, alongside the decrease in the H_2O concentration during chemical interactions, promotes the closing of the ionospheric "hole." The time of relaxation of the electron concentration to unperturbed values is characterized by two periods, viz., a short period (of about 4 h) of recovery of up to 80% of the unperturbed value of N_mF2 and an approximately 24-hour period of complete recovery of N_mF2.

In this work, the mechanism of formation of the second ionospheric "hole" in the h_mF2 region at sunset has been explained in detail. The effect of horizontal velocities of neutral wind on a decrease in N_mF2 and h_mF2 has been shown. A need for taking them into account in the case of anthropogenic influences on the ionosphere has been noted.

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NOTATION

B, magnetic induction, T; *D*, diffusion coefficient, $m^2 \cdot sec^{-1}$; *F*, rate of particle formation, $m^{-3} \cdot sec^{-1}$; *g*, acceleration due to gravity, $m \cdot sec^{-2}$; *H*, height scale, m; *h*, height, m; $\hbar\nu$, light quantum energy, J; h_mF2, height of the maximum of the F2 layer of the Earth's ionosphere, m; *I*, magnetic inclination, deg; *k*, Boltzmann constant, $J \cdot K^{-1}$; *L*, coefficient of gas cooling, $W \cdot sec^{-1}$; LT, local time, h; *m*, mass, kg; N_e, electron concentration m^{-3}; N_mF2, concentration of the maximum of the F2 layer of the Earth's ionosphere, m^{-3}; n_i, ion concentration, m^{-3}; *P*, gas pressure, Pa; *Q*, coefficient of gas heating, $W \cdot sec^{-1}$; *R*, coefficient of ion–neutral friction force, sec^{-1}; *S*, coefficient of ion–ion friction force, sec^{-1}; *s*, length of the force line, m; *T*, particle temperature, K; *t*, time, sec; *V*, particle velocity, $m \cdot sec^{-1}$; *z*, height, m; α, coefficient of particle recombination, sec^{-1}; γ, reaction coefficient, $m^{-3} \cdot sec^{-1}$; λ, wavelength, m; λ_i and λ_e, thermal conductivities of ions and electrons, $W \cdot m^{-2} \cdot K^{-1}$; ν, collision frequency, sec^{-1}; ξ, kinematic viscosity, $m^2 \cdot sec^{-1}$; ρ, gas density, $kg \cdot m^{-3}$; Φ, particle flux, $m^{-2} \cdot sec^{-1}$; φ, latitude, deg; Ω, rate of rotation of the Earth, $rad \cdot sec^{-1}$. Subscripts: i = 1, 2; j = 1, 2, ions (1, O^+; 2, H^+ ($i \neq j$)); e, electron; m, maximum; n, neutral; *x*, *y*, and *z*, meridional, zonal, and vertical directions.

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