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ESTIMATE OF THE RATE OF CHARGED PARTICLE VERTICAL TRANSFER IN THE OUTER PART OF THE IONOSPHERE F2-REGION

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SUMMARY

A method is presented here for the determination of effective rate of charged particle vertical transfer in the ionosphere, taking into account the velocities' vertical gradients. Analytical expressions are obtained for the rate of vertical ionization transfer for various forms of distribution N(h). Numerical estimates are made of the rate of vertical ionization transfer w in the upper part of ionosphere's F2-region for the conditions near the settled ones ($\partial N/\partial t = 0$).

It is shown, that at altitudes < 350 km, the ambipolar diffusion with velocity of the order of several m/sec, cannot ensure the rate of vertical transfer necessary for the agreement of experimental N(h)-curves with the presently available data on the structural parameters of the upper atmosphere, on solar short-wave radiation and on ionization-recombination processes. The joint examination of ambipolar diffusion and of plasma flows arising from the upper atmosphere's wind motions, allows us to obtain values of w agreeing with those estimated according to N(h)-profiles.

* * *

When considering the behaviour of the F2-region of the ionosphere one often has recourse to such ionization transfer processes as diffusion, drift on account of electrostatistic fields, contributed to the F2-region from without, and motions arising in neutral atmosphere on account of the wind. It is known, in general, that the diffusion leads to the formation of the F2-layer at altitudes much lower than would be the case if one considered only the ionization-recombination processes. The role of the remaining forms of plasma motion in the behavior of the F2-region is not yet clear. In connection with this, it is interesting to attempt the estimate of the effective motion velocities of electronic gas without specific assumptions regarding the causes of the motions. Such estimates are based on the presently available data on the distribution of electron concentration N and of structural atmospheric parameters, and on the basic elementary processes and their velocity ratios. Some attempts were made [1-4], for the lower part of the F2-region, applicably to night conditions, in estimating the vertical component of the directed motion of electrons. However, the presently available methods do not permit to take into account the vertical gradients of motion velocity. Attempt was made in [3] to take these gradients into account for some particular cases.

Attempts to estimate the velocities of plasma motion, according to ionospheric data, are based on the continuity equation for the electron gas

$$\frac{\partial N}{\partial t} = Q - L - \mathrm{div}\ (N\vec{v}) \tag{1}$$

where Q is the rate of ion formation in the atmosphere under the action of Sun's shortwave radiation; L is a term which takes into account the recombination processes.

In the equation (1), we shall take into account only the vertical velocity component $\vec{v}$, i.e. $\vec{v}(0,0,w)$, as from general considerations it follows that the influence of horizontal components of velocity $\vec{v}$ on the distribution of N, is much smaller. The only exception are the morning hours' conditions, when the longitudinal gradients of N are great.

Not yet refining the concrete form of functions Q and L, we shall represent Eq. (1) in the form

$$\frac{\partial w}{\partial h} + \frac{1}{N}\frac{\partial N}{\partial h} w = \frac{1}{N}\left(Q - L - \frac{\partial N}{\partial t}\right), \tag{2}$$

where h is the altitude. The solution of Eq.(2) has the form

$$w = \exp\left(-I_1\right)\left[C + I_2 - I_3 - I_4\right], \tag{3}$$

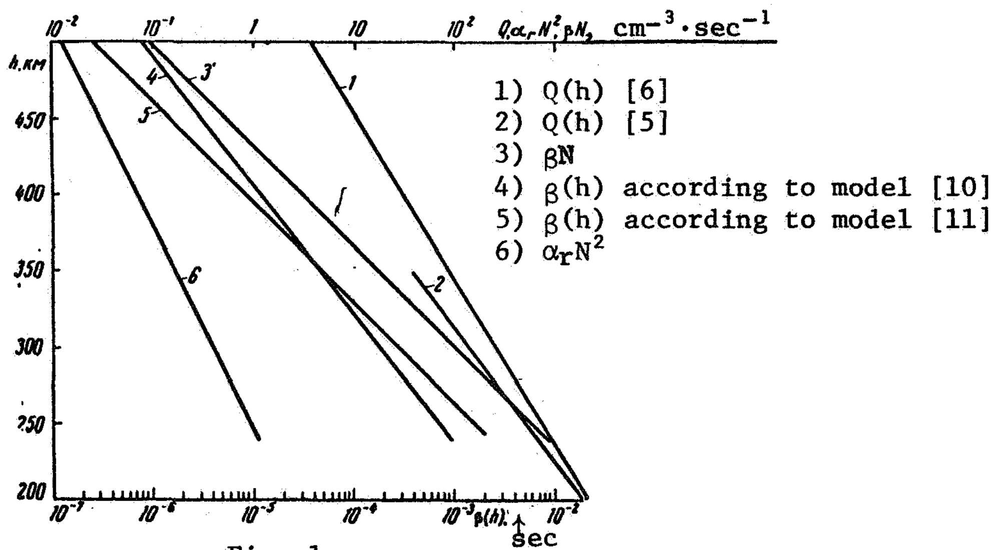

Fig. 1.

where C is an integration constant

$$I_1 = \int \frac{1}{N}\frac{\partial N}{\partial h}\,dh = \ln N, \quad I_2 = \int \frac{Q}{N}[\exp I_1]\,dh,$$
$$I_3 = \int \frac{L}{N}[\exp I_1]\,dh, \quad I_4 = \int \frac{1}{N}\frac{\partial N}{\partial t}[\exp I_1]\,dh.$$

Thus, with N(h,t), Q(h,t) and L(h,t), available, one may compute from (3) the rate of vertical ionization transfer at any altitudes and for any moment of time. The night conditions stem from (3) as a particular case at $I_2 = 0$, while the equilibrium conditions do so at $I_4 = 0$.

It should be noted, that uncertainties in w(h) are conditioned by the uncertainties in N, Q and L. Therefore, the aim of such estimates of w is the clarification of the question: what rates are required for the ionization's vertical transfer, in order to coordinate the available distribution N(h,t), with the presently available data on Q(h,t) and L(h,t).

Our estimates of w will be related to the outer part of the F2-region, where for h > 250 km mainly atomic oxygen is ionized. The altitude distribution of Q is approximated by the function

$$Q = Q_0 \exp(-h/H_Q) \qquad (4)$$

The distributions $Q = Q(O) + Q(N_2)$ for the conditions close to solar activity minimum according to [5,6], are shown in Fig.1, for the Sun's $Z_{\odot} = 30°$ zenithal angle.

Atomic oxygen ions predominate at the exmanied altitudes ($h \approx 250$–500 km) [7]. There are two ways of ion vanishing. One is the radiative recombination with electrons with velocity ratio $\alpha_r(O+) \approx 1.5 \cdot 10^{-12}$ $cm^3 \cdot sec^{-1}$ for a $\sim$ 1000°K temperature [8], the other is reduced to ion-molecular reactions with N_2 and O_2 which lead respectively to the formation of $NO+$ and O_2+ ions. In their turn, these molecular ions vanish by way of dissociative recombination with electrons. With the accounting

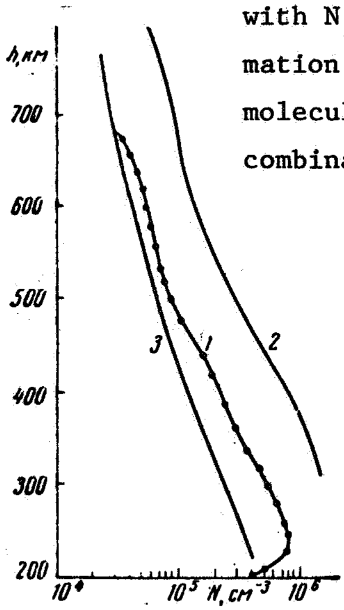

Fig. 2

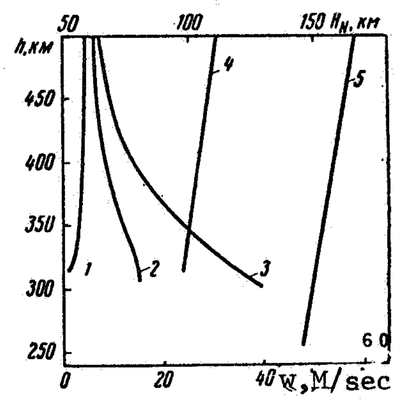

Fig. 3

of these two ways of O+ ion vanishing, the recombination term in (2) has the form [9]

$$L = \alpha_r N^2 + \beta N = \alpha_r N^2 + \{\lambda(N_2)[N_2] + \lambda(O_2)[N_2]\}N. \tag{5}$$

The distribution of the loss factor is also approximated by the exponential function

$$\beta = \beta_0 \exp(-h/H_\beta) \tag{6}$$

For the computation of $\beta(h)$ model neutral atmospheres of [10,11] were used. The velocity ratios of $\lambda(N_2)$ and $\lambda(O_2)$ ion-molecular reactions in laboratory conditions ($T = 300°K$) were measured repeatedly. The $\lambda(N_2)$ and $\lambda(O_2)$ temperature dependence is still unclear. We have used the data of two independent measurements: $\lambda(N_2) = 2.25 \cdot 10^{-12}$, $\lambda(O_2) = 2.0 \cdot 10^{-11}$ $cm^3 \cdot sec^{-1}$ according to [12] and $\lambda(N_2) = 1.80 \cdot 10^{-12}$, $\lambda(O_2) = 4.0 \cdot 10^{-11}$ $cm^3 \cdot sec^{-1}$ according to [13]. During computations of $\beta(h)$ the quantities $\lambda(N_2) = 1.80 \cdot 10^{-12}$, $\lambda(O_2) = 2.0 \cdot 10^{-11}$ $cm^3 \cdot sec^{-1}$ were taken for the model atmosphere of [11] and $\lambda(N_2) = 2.25 \cdot 10^{-12}$, $\lambda(O_2) = 4.0 \cdot 10^{-11}$ $cm^3 \cdot sec^{-1}$ for the model of [10].

The $\beta(h)$ distribution is shown in Fig.1. For models of upper atmosphere [10] and [11], the distribution parameters (6) are respectively equal to $\beta_0 = 0.5$ sec^{-1}, $H_\beta = 37.3$ km and $\beta_0 = 12.0$ sec^{-1}, $H_\beta = 28.2$ km.

Estimates of $\alpha_r N^2$ and βN contributions to L show (see Fig.1) that at altitudes below ~ 500 km $\alpha_1 N \ll \beta$. Therefore the recombination term (5) was taken in the form

$$L = \beta N \tag{7}$$

The distributions of N(h) in the outer part of the F2-region, obtained from rocket sounding measurements [14] and from outer ionosphere sounding [15], are shown in Fig.2. More detailed information on these date is compiled in the table I below (the curve numeration shown in Fig.2 corresponds to that of the Table). Examination of the indicated and other distributions of N(h), has

T A B L E I

by Or-der	Date	Coordinates			L. T.	$Z_\odot$	K_p	Annotation
		ϕ	λ					
1	31.1 1965	31°15'N	131°04'E	43	14 hrs. 0.1 m	57	0	Rocket Sounding [14]
2	1.VI 1963	13,62°N	84,7°W	43	14 10	33	1+	"Alouette-1"[15]
3	21.IX 1963	62,39°N	177,9°E	72	12 55	63	3_	" "

shown that at separate altitude intervals, they could be approximated by dependences of the type

$$N = N_0 \exp(-h/H_N) \tag{8}$$

$$N = N_0 \exp\{a \exp(-h/b)\}. \tag{9}$$

In particular, for the curve 1 in Fig.2, with h = 250-500 km, the distribution parameters (8) are $N_0 = 7.61 \cdot 10^6$ cm^{-3}, H_N = 112 km. The parameters of curves 2 and 3 in Fig.2, presented in the form (9), are respectively $N_0 = 1$ cm^{-3}, a = 18, b = 1414 km (h = 300-500 km) and $N_0 = 1$ cm^{-3}, a = 14.60, b = 1848 km (h = 250-500 km).

Using (4), (7), (8), Eq.(3) may be represented in the form

$$w = \exp\left(\frac{h}{H_N}\right)\left[C - \frac{Q_0}{N_0} H_Q \exp\left(-\frac{h}{H_Q}\right) + \right.$$
$$\left. + \beta_0 H_{\beta N} \exp\left(-\frac{h}{H_{\beta N}}\right) - \frac{1}{N_0}\int \frac{\partial N}{\partial t}\, dh\right], \tag{10}$$

where

$$H_{\beta N} = H_\beta H_N/(H_\beta + H_N).$$

For the determination of C we shall make use of the equation

$$\frac{\partial N}{\partial t} = -\frac{\partial (Nw)}{\partial h}, \tag{11}$$

determining the N(h,t) distribution at sufficiently great altitudes, where Q and L << $|\mathrm{div}\,(N\vec{v})|$. For settled conditions ($\partial N/\partial t = 0$), using (11) as a boundary condition at the altitude h_0, from (10) and (11) we shall obtain*

$$C = H_1 \exp\left(-\frac{h_0}{H_Q}\right) + H_2 \exp\left(-\frac{h_0}{H_{\beta N}}\right),$$

where

$$H_1 = \frac{Q_0}{N_0}\left[H_Q - \frac{1}{\frac{1}{H_N} + \left(\frac{1}{N}\frac{\partial N}{\partial h}\right)_{h=h_0}}\right], \quad H_2 = \beta_0\left[\frac{1}{\frac{1}{H_N} + \left(\frac{1}{N}\frac{\partial N}{\partial h}\right)_{h=h_0}} - H_{\beta N}\right]$$

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* With $\partial N/\partial t = 0$ and the absence of plasma drift motions, an also of ionization transfer on account of diffusion, Eq.(11) passes into diffusive-equilibrium condition.

Application of boundary condition to various altitudes ($h_0 \approx 600$-700 km) has shown that the constant C is small ($|C| \leqslant 0.1$ m/sec) and stable with respect to h_0 variations. For the N(h) distribution represented by the curve 1 in Fig.2 (for the present case in (4) $Q_0 = 7.47 \cdot 10^4$ $cm^{-3} \cdot sec^{-1}$, $H_Q = 51$ km), the w(h) distribution, shown by the curve 2, in Fig.3, is obtained, whereupon velocities are directed downward everywhere. It is observed that at h ≈ 300-350 km, $|w| \simeq 15$ m/sec. At conversion to motion along the Earth's magnetic field lines $\nu_{\parallel} \approx 20$-$30$ m/sec.

But if the N(h) distribution is given in the form (9), then the general expression for w(h) has a cumbersome form and is not presented here. The results of computation of w(h), for two other N(h) distributions, shown in Fig.2, are presented in Fig.3 (curve 1 is the w for the curve 2 in Fig.2, curve 3 is the w for the curve 3 in Fig.2). Curve 1 in Fig.3, is related to the low latitudes; it is seen, that the values of w are small and almost independent of the altitude. For middle latitude (Fig.3 curve 3) a sharply outlined dependence of w on h is observed. Estimates for various upper atmosphere models [10,11] give mutually consistent w velocities.

Attempt was made to compare the rates estimated by us, of vertical plasma transfer with that of charged particles' ambipolar diffusion. From the estimates for middle latitudes it follows that at altitudes h < 350 km, the ambipolar diffusion with a velocity of the order of several m/sec, cannot assure the vertical transfer rates, required for matching the experimental distribution of electron concentration with the presently available data on the upper atmosphere's structural parameters, on solar shortwave radiation and on the ion-recombination processes, for the rate of ambipolar diffusion is smaller than the required values of w. In order to match the required values of transfer rates, it is necessary to examine besides the diffusion, other forms of plasma motion, and in particular those excited by the wind in the neutral atmosphere at the altitudes of the F-region. It was shown in [16], that the vertical component of plasma motion velocity, arising on account of winds, is directed downward at middle latitudes in daytime, and the values of velocity are ∿ 20-50 m/sec. depending upon the season.

The combined examination of the diffusive ionization transfer and plasma motions due to the indicated cause, allows us to obtain values of w at h < 310 km altitudes, agreeing with those estimated by the N(h)-profiles. Thus it follows outright from our estimates of w(h), that the real N(h) distribution of the F-region is impossible to understand, while remaining only within the framework of the diffusion model.

We shall present some estimates of plasma scale heights. According to [17] the scale height is determined by

$$H_N = -\frac{1}{d(\ln N)/dh}. \tag{12}$$

From (9) and (12) we have

$$H_N = \frac{b}{a}\exp\left(\frac{h}{b}\right). \tag{13}$$

The values of $H_N(h)$ computed according to (13) for N(h) distributions of Fig.2 (curves 2 and 3) are plotted in Fig.3 (curves 4 and 5 respectively). The difference in the computed H_N is apparently due to the difference in the latitudes, conditions of magnetic activity, etc.,

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