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RECOMBINATION PROCESSES IN THE LOWER IONOSPHERE

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SUMMARY

The peculiarities of recombination of auroral ionization are considered. The rate of ions NO^+ recombination is evaluated. It is shown that when taking into account the reaction $N_2^+ + O_2 \rightarrow NO^+ + NO$ ($\gamma = 10^{-13} - 10^{-12}$ cm^3/sec), we are in a position to explain the rate of recombination not only in polar aurorae, but also in a quiet diurnal ionosphere.

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It is now generally accepted [1 - 4] that electrons vanish in the ionosphere as a result of dissociative recombination with molecular ions

$$O_2^+ + e \rightarrow O + O, \qquad (\alpha_1), \qquad (1)$$

$$NO^+ + e \rightarrow N + O, \qquad (\alpha_2), \qquad (2)$$

$$N_2^+ + e \rightarrow N + N, \qquad (\alpha_3). \qquad (3)$$

At the same time ions O_2^+ and NO^+ are formed as a consequence of direct ionization of the corresponding molecules, as well as in the course of ion-molecular exchange reactions, of which the basic ones are

$$O^+ + O_2 \rightarrow O_2^+ + O, \qquad (\gamma_1), \qquad (4)$$

$$O^+ + N_2 \rightarrow NO^+ + N \qquad (\gamma_2). \qquad (5)$$

The rates of processes (1) - (5) were considered at length in references [5 - 8], and it was shown that in daytime the effective recombination coefficient is determined in the E-layer and in the lower layers of the F-region mainly by the rate of dissociative recombination of ions O_2^+ and rate γ_1 of the process (4). At the same time $\alpha_1 = (1 \div 3) \cdot 10^{-8}$ and $\gamma_1 \approx 10^{-11}$. It should be noted, however, that the altitude distribution of molecules' O_2 concentration is so far known very approximately, and this is why the estimate of the quantity γ_1 is also quite rough.

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* PROTSESSY REKOMBINATSII V NIZHNEY IONOSFERE

In nighttime the ionosphere at the E-layer level consists almost entirely of ions NO^+ [9]. This allowed the authors of [6, 7] to assume that the minimum value of the effective recombination coefficient in the E-layer in nighttime, equal to 10^{-9} cm^3/sec, corresponds to the value (α_2) of ions' NO^+ dissociative recombination.

The auroral ionization is observed at the altitude of ∿ 100 km, and this is why it is natural to expect that its recombination is determined by the same processes (1) - (5), as those of the standard ionization at E-layer level. At the same time, during aurora outburst and a certain time afterward, the rate of recombination of auroral ionization must apparently be mainly determined by the rate of ions' O_2 dissociative recombination. Then, as the relative concentration of the slowly recombining ions NO^+ increases, the recombination rate must decrease, assuming after about 0.5 - 1 hours, the value of α_2. But in reality the behavior of the auroral ionization differs notably from the above expounded scheme. This means that, besides reactions (1) - (5), some additional processes play an essential role. We shall consider at further length the fundamental experimental data relative to the recombination rate in polar aurorae.

The value of the effective recombination coefficient in aurorae was estimated in ref. [10 - 12] from the comparison of electron density in the E_s -region with the brightness of aurorae observed at that time. During calculations the authors started from the following considerations. Laboratory investigations of ref. [13 - 14] have shown that the ratio of the ionization cross-section of nitrogen molecules by the flux of electrons to the excitation cross-section I of the negative system N_2^+ does not practically vary within a wide energy range. This is why it may be considered that during aurorae the rate of ions' N_2^+ formation is proportional to aurora brightness. Then it follows from the ionization balance equation that the concentration of electrons, n in the aurora is

$$n_e = \sqrt{kI/\alpha}, \tag{6}$$

where I is the intensity of 1 N G N_2^+ emission in quanta.

It was found from the measurement of n_e and I that $\alpha = 10^{-8} - 10^{-7}$. However, the authors of [10 - 12] failed to account for a series of circumstances.

1. Since the intensity of 1 N G N_2^+ emission is measured, so consequently is the rate of ions' N_2^+ formation. At the same time, the concentration of electrons is determined by the rate of ions' NO^+ recombination, of which the rate of formation is not necessarily equal to that of N_2^+. For that reason such a comparison is not quite lawful.

2. Formula (6) is valid only in the case when the regions of luminescence and anomalous ionization coincide spatially. But in reality the region of auroral ionization is found to be substantially wider (200 - 300 km according to [15]), than the luminescence region (20 to 100 km for the standard arc). If we consider that the anomalous ionization and the aurora are induced by intrusion into the atmosphere of various corpuscular streams, the calculations of ref. [10 - 12] are generally devoid of any sense. But if we consider that the noncoincidence of the region of enhanced ionization and of the aurora

glow region is explained by the carrying of the ionization out of the region of corpuscular stream intrusion (by ionospheric wind, for example, [16]), one must take into account that the mean density of ionization is found to be $\sim (l/L)\sqrt{kI/\alpha}$, where l and L are the widths of the glowing arc and of the region of anomalous ionization, i. e. five times less than the value given by formula (6). Thus, the quantity α (or its value) obtained in [10 - 12], is apparently overrated by $(L/l)^2$ times, that is, by 1 to 2 orders.

3. If the value of α is determined in the course of short-lived flashes of aurora (for example of radial shapes), when the carrying of the ionization out of the intrusion region of the corpuscular stream can be neglected, one must take into account that expression (6) gives the equilibrium, i. e., the limit value of ionization density.

As to the general case, we have $n_e = f(T)\sqrt{q/\alpha}$, T being the duration of the aurora and f(T) is significantly less than the unity when T = 10 - 15 min. [17]. Let us consider this question at further length.

The effective recombination coefficient of auroral ionization may be determined by several methods:

a) by lag of geomagnetic disturbance's peaks relative to peaks of integral luminance of polar aurorae [18, 19];

b) by the rapidity of geomagnetic field's restoration to standard level [20 - 22];

c) by ratio's $\delta H/\delta I$ dependence on aurora duration.

The results of these independent measurements of the quantity α were found to be identical and gave $\alpha = (1-5) \cdot 10^{-9}$, which is rather close to the above indicated value α_2 for the dissociative recombination of ions NO^+.

Nevertheless, the idea of dissociative recombination of auroral ionization is apparently unacceptable. As a matter of fact the recombinations of electrons and ions NO^+ at E-layer level must proceed according to the law $\alpha n_e{}^2$ for any admissible values α_2, while according to the data of the above referred to works it must take place according to the law βn_e $(\beta = (5 \div 10) \cdot 10^{-4} \mathrm{sec}^{-1})$.

This result seems to be in contradiction with the experimental data of ref. [11, 23, 24], where it is shown that the brightness of aurorae is proportional to the square of ionization density in the E_s clouds, or to the square of the intensity of simultaneously observed geomagnetic disturbances. It should be borne in mind that the intensity of the geomagnetic disturbance and the density of electrons are determined not only by aurora brightness, but also by the area occupied by them [16, 17]. Therefore, the quantity δH must be compared not with the brightness of aurorae, but with their integral luminance [17]. Besides, the quantities n_e and δH depend also on the duration of the aurora which must be taken into account during the comparison of either δH or n_e with δI.

Taking this into account, the link of aurora intensity with the amplitude of geomagnetic disturbances was investigated in ref. [25], where it is shown that there is observed between the quantities δH and $(\delta I \times T)$, where T is the duration of the aurora, a clearly linear and not quadratic dependence in the range $\delta H = 50 - 600\gamma$, i. e., the recombination of auroral ionization does indeed take place according to the law βn_e, and not αn_e^2.

The result obtained can be understood, for electron adherence to neutral molecules and oxygen atoms plays an essential role in the lower ionosphere layers [5, 21]. At the same time, in order to explain the linear dependence of the rate of recombination on the density of ionization, it is sufficient to admit that the rate of dissociative recombination of ions NO^+ is lower than the rate of electron adherence to oxygen atoms, i. e. $\alpha_2[NO^+]n_e \leqslant \beta n_e$. Inasmuch as the linear dependence between δH and (δIT) is preserved at least through $\delta H = 600\gamma$, which corresponds to $n_e \approx 5 \cdot 10^5$ cm^{-3}, we find $\alpha_2 \lesssim 10^{-9}$cm^3/s at $\beta = 5 \cdot 10^{-4}$ and $[NO^+] \approx n_e$.

The obtained value of the coefficient α_2 was found to be of the same order as according to data of ref. [1, 6, 7], though somewhat less. This is why it is apparently appropriate to assume $\alpha_2 \approx 10^{-9}$ cm^3/sec.

Having estimated the value of α_2, the rate γ_2 of reaction (5), is found in the usual way [26, 27]: it follows from the ions' NO^+ and O^+ concentrations ratio in the F_2-layer that $\gamma_2/\alpha_2 \approx 10^{-4}$, thus $\gamma_2 \approx 10^{-13}$. During calculation the dependence of the values of α_2 and γ_2 on temperature is not taken into account, since we are concerned only with the order of the considered quantities.

The above obtained values of α_2 and γ_2 are close to the generally assumed values [1, 6]. At the same time, if reaction (5) determines the rate of molecular ion formation in the F_2-region, and consequently the rate of recombination in the same region, the sticking coefficient here is $\beta = \gamma\ [N_2]$. If we accept the distribution of nitrogen molecules with altitude, as indicated in [28], we shall have $\beta = 10^{-13}\ [N_2] \exp\ [(300 - h)/50] = 0.8 \cdot 10^{-4} \exp\ [300 - h)/50]$, which does not depart too much either from the true value $\beta = (0.8 \div 3) \cdot 10^{-4} \exp\ [(300 - h)\ /\ 50]$ [6, 8, 29, 30]. But, as to how a somewhat noticeable number of ions NO^+ have time to accumulate in the course of some 15 to 30 min. aurora flare time at such a low rate of process (5), it is not understandable. In reality, since $\gamma_1/\gamma_2 = 100$, the rate of ions' NO^+ formation constitutes only a small fraction of the total rate of ion formation in the aurora region. At the same time, the above data and the results of rocket observations [31] show that the concentration of ions NO^+ is sufficiently high almost outright after aurora commencement. This circumstance compels us to search for an additional source of ions' NO^+ formation.

An important peculiarity of aurora resides in the extremely high rate of formation in the region of ions' N_2^+ glow, to which the aurora spectrum attests. It is thus natural to expect that the ions N_2^+ constitute precisely the source of ions' NO^+ formation searched for. In reality, if in the higher ionosphere layers (> 150 km) the very rapidly recombining ions N_2^+ vanish without contributing substantially to ionosphere formation [32, 33], the pattern changes essentially. As is shown in [34], the dissociative recombination of ions N_2^+ can not take place in the ionosphere layers where the concentration of neutral particles is by several orders higher than the concentration of ions. In this case the following reactions must take place [26, 35, 36]

$$N_2^+ + O \rightarrow N_2 + O^+ + 2{,}0 \quad (7)$$
$$N_2^+ + O_2 \rightarrow NO^+ + NO + [4{,}5 - E(^3\Pi) \quad (8)$$
$$N_2^+ + O \rightarrow NO^+ + N + [3{,}1 - E(^3\Pi)] \quad (9)$$

It was shown in [26] that reaction (7) may play an important role in the lower ionosphere, transforming the ions N_2^+ into O^+, that participate in the basic processes (5) and (4). However, even a rapid course of this process may explain neither the singularities of behavior of auroral ionization, nor the observed concentration of ions NO^+ in a quiet diurnal ionosphere.

Reactions (8) and (9) are considered in detail in ref. [36], where it is shown that inasmuch as ions NO^+ may be forming in these reactions only in an excited state ($^3\Pi$) and $E(^3\Pi) = 4.6$ ev, process (9) is endothermic and it cannot play a noticeable role in the ionosphere. The authors of [36] consider process (8) as also little probable. However, the energy deficit in this reaction is quite insignificant, and its rate may apparently be not too low.

The ionic composition of auroral ionization has been extremely little investigated, so that the rate of reaction (8) cannot be determined at present. Let us thus estimate if only its order. For the ionization density to attain the observed magnitude in the aurora zone it is necessary that the rate of ions' NO^+ formation in reaction (8) be if only of same order as that of the dissociative recombination of ions N_2^+; in any case, no less than one tenth of the fraction of ions N_2^+ must pass into ions NO^+. Thus,

$$\gamma_3[N_2^+][n_e] > 0{,}1\,\alpha_3\,[N_2^+]n_e,$$

whence for an altitude from 100 to 120 km at $n_e = 5 \cdot 10^5$ and $\alpha_3 = 5 \cdot 10^{-7}$ it follows that $\gamma_3 > 5 \cdot 10^{-14}$ cm³/sec.

If ions N_2^+ vanish only in the course of dissociative recombination and of process (8), while ions O_2^+ and NO^+ vanish only as a result of dissociative recombination processes (1) and (2), the concentration of basic ions is

$$[O^+] = \frac{q_{O^+}}{\gamma_1[O_2] + \gamma_2[N_2]}, \qquad [N_2^+] = \frac{q_{N_2^+}}{\gamma_3[O_2] + \alpha_3 n_e},$$
$$[NO^+] = \frac{1}{\alpha_2 n_e}\left\{\gamma_3\frac{q_{N_2^+}[O_2]}{\gamma_3[O_2] + \alpha_3 n_e} + \gamma_2\frac{q_{O^+}[N_2]}{\gamma_1[O_2] + \gamma_2[N_2]}\right\}, \quad (10)$$
$$[O_2^+] = \frac{1}{\alpha_1 n_e}\left\{q_{O_2^+} + \gamma_1\frac{q_{O^+}[O_2]}{\gamma_1[O_2] + \gamma_2[N_2]}\right\}$$

where q_{O^+}, $q_{O_2^+}$ and $q_{N_2^+}$ are ionization rates of molecules O, O_2 and N_2. Analysis of these expressions shows that at the level of E_s -layer, even for $\gamma_3 = 10^{-14}$ the rate of ions' NO^+ formation in reaction (5) is by about one order lower than in reaction (8). As the altitude increases, the ratio v_8 / v_5 of these reactions decreases and process (5) becomes predominating already at 120 km for $\gamma = 10^{-13}$, and about 180 km at $\gamma_3 = 10^{-11}$.

Moreover, from relations (10) it may be seen that at E-layer level and in equilibrium conditions the concentration ratio $[NO^+] / [O_2^+]$ is

$$\frac{[NO^+]}{[O_2^+]} \approx \frac{\alpha_1}{\alpha_2} \frac{q_{N_2^+}}{q_{O_2^+}} \frac{1}{1+(\alpha_3 n_e/\gamma_3 [O_2])} = \frac{\alpha_1}{\alpha_2} \frac{q_{N_2^+}}{q_{O_2^+}} \frac{1}{1+a}\,. \qquad (11)$$

where

$$a \equiv \frac{\alpha_3 n_e}{\gamma_3 [O_2]} = \begin{cases} 1 \div 2 & \text{at} \quad \gamma_3 = 10^{-13}, \quad n_e = (2 \div 5) \cdot 10^5, \\ 0{,}1 \div 0{,}2 & \text{at} \quad \gamma_3 = 10^{-12}, \quad n_e = (2 \div 5) \cdot 10^5. \end{cases}$$

Assuming that the relative formation rate of ions N_2^+ and O_2^+ in the aurora is proportional to the concentration of the corresponding molecules, i. e., $q_{N_2^+} / q_{O_2^+} = 5$ at $\alpha_1 / \alpha_2 = 10$, we find

$$\frac{[NO^+]}{[O_2^+]} = \begin{matrix} 15 & \text{at} & \gamma_3 = 10^{-13}, \\ 50 & \text{at} & \gamma_3 = 10^{-12}, \end{matrix}$$

and the recombination rate of auroral ionization is mainly determined by the rate of recombination of ions NO^+, or, as already indicated — by the rate of electron adhesion to oxygen atoms.

The atmosphere ionization in daytime is qualitatively realized by another agent — the Sun's ultraviolet radiation. Then, despite the fact that in this case too nitrogen molecules are the basic atmosphere component at E-layer level, the rate of ions' N_2^+ formation is found to be 4 to 5 times lower than that of ions O_2 [1.37], Then

$$\frac{[NO^+]}{[O_2^+]} = \begin{matrix} 0{,}6 & \text{at} & \gamma_3 = 10^{-13}, \\ 2 & \text{at} & \gamma_3 = 10^{-12} \end{matrix}$$

and the rate of recombination of diurnal ionization is already determined by the rate of recombination of ions O_2^+, and not NO^+.

Rocket measurements show that at the E-layer level in daytime the ratio $[NO^+] / [O_2^+] = 1 \div 2$ [18]. This is close to the above obtained value, corroborating the validity of the chosen reaction cycle.

It should underscored that when explaining the different rate of recombination in the E-layer during aurorae and in conditions of quiescent diurnal ionosphere, we assumed in accord with the data [1, 37] that the relative rate of ions' N_2^+ and O_2^+ formation is in these cases different. This is explained by the fact that nearly the entire ultraviolet with $\lambda < 796$ A is absorbed above 120 km. and in the 100 - 120 km altitude range the ionization of molecules N_2 takes place mainly by the soft X-ray radiation ($\lambda = 10 - 170$ A); the molecules O_2 are also ionized by this radiation ($\lambda = 800 - 1027$ A), whose intensity is relatively great. This is why the assumption that the relative rate of ions' N_2^+ and O_2^+ formation is proportional to the concentration of the corresponding molecules in the entire altitude range 100 — 500 km is apparently not valid, particularly at the considered level of 100 to 120 km. At the same time, aurorae observed at ∿ 100 km, are induced by intrusion into the atmosphere of corpuscles having sufficient energies to ionize the molecules O_2 and N_2.

But if our assumption is correct, and if the singularities of auroral ionization are explained by the peculiarities of its formation (relatively high rate of molecules' N_2 ionization), then the anomalous ionization, conditioned by the intrusion of corpuscular fluxes into the lower ionosphere, must recombine just as slowly in daytime too (probably even slower because of electron photodetachment) and according to the same law βn_e. In order to verify this assumption, we investigated the daily course of the quantity β by the rate of decrease (or attenuation) of geomagnetic disturbances [22], according to data of 200 geomagnetic bays for the winter and summer seasons of 1963. From Fig.1 we may see indeed that the rate of recombination of auroral ionization is little dependent on the time of the day or on the season. The notable variation of the quantity β is observed only at 1900 or 0500 - 0600 hours UT, that is, at the moments of time when the emf (electro-motive force) responsible for the emergence of electric currents in the ionosphere varies rapidly. This is why the data relative to the quantity β at these hours are doubtful.

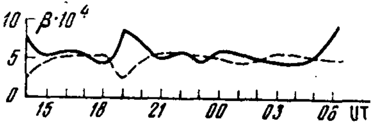

Fig.1

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