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A SEMI-EMPIRICAL APPROXIMATE METHOD FOR STUDYING SOME ISSUES OF AERONOMY OF THE IONOSPHERIC D-REGION.

III. DETAILED ANALYSIS OF THE PHOTOCHEMISTRY OF THE ENVIRONMENT UNDER CONDITIONS OF INCREASED IONIZATION

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Abstract. Using the previously proposed semi-empirical method (Kozlov et al., 2022; Kozlov, Nikolaishvili, 2024), which is a fairly simple mathematical model (a system of five algebraic equations for calculating the concentrations of primary and cluster positive ions, primary and complex negative ions, as well as the electron density), we have calculated the ionospheric parameters that determine the behavior of the D-region under conditions of increased ionization (Solar Proton Events (SPE) on November 2–5, 1969, and the High-altitude Nuclear Explosion (HANE) conducted in 1962).

Detailed analysis of the obtained parameter values has shown that the calculation results do not contradict the generally accepted photochemical mechanisms occurring under the SPE and HANE conditions considered. We identified the main trends in the changes of these parameters. A conclusion is made about the possibility of using the semi-empirical method in various heliogeophysical conditions and the need to develop a model for the transitional time of day (morning and evening twilight), and some possible directions for further research are outlined.

Keywords: lower ionosphere, missile launch, aeronomy, inverse problem.

INTRODUCTION

Kozlov and Nikolaishvili [2024] report the results of calibration, based on experimental data, of the semi-empirical method [Kozlov et al., 2022] for studying some issues of aeronomy of the disturbed and quiet ionospheric D-region. Of particular interest is to calibrate the method, which is a fairly simple mathematical model (a system of five algebraic equations for calculating the concentrations of primary X_1^+ and cluster X_2^+ positive ions, primary $X_1^- \equiv O_2^-$ and complex X_2^- negative ions, as well as the electron density N_e), from data obtained during November 2–5, 1969 solar proton events (SPEs) [Ulwick, 1972] and the American nighttime high-altitude nuclear explosion (HANE) in 1962 [Whitten et al., 1965] when vertical distributions of $N_e(h)$ and atmospheric ionization rates $q(h)$ were simultaneously measured. These measurements made it possible to quantify the accuracy of calculations, carry out a number of improvements to the model, and formulate proposals for using the semi-empirical method under various heliogeophysical conditions. Unfortunately, because of the volume requirements, Kozlov and Nikolaishvili [2024] do not discuss the well-known problem (see, e.g., [Swider, 1977; Kozlov, 2021]) about the possibility of changes in the concentrations of minor neutral and excited components affecting N_e during SPEs and HANE (in the model, they are H_2O, CO_2, O_3); calculations are not compared with experimental data on each missile launch for the parameter $\alpha = q/N_e^2$, although it is concluded that such a comparison is advisable; there is no complete analysis of the very informative characteristics of the medium:

$$\lambda(q,h) = \left(\left[X_1^-\right]+\left[X_2^-\right]\right)/N_e,$$

$$\varphi^+(q,h) = \left[X_2^+\right]/\left[X_1^+\right],$$

$$\varphi^-(q,h) = \left[X_2^-\right]/\left[X_1^-\right],$$

$$\alpha_{\text{eff}}(q,h) = q/\left[N_e^2(1+\lambda)\right],$$

$$A(q,h) = \left[X_1^+\right]+\left[X_2^+\right] = N_e + \left[X_1^-\right]+\left[X_2^-\right],$$

$$\alpha(q,h) = q/\left(2A^2\right);$$

the choice of unknown model parameters (the rate of photodetachment of I_2 from X_2^- and the coefficient of dissociative recombination α_{d2} of X_2^+ is insufficiently substantiated. The experimentally found effect of a drop in N_e at $q_e \approx (1.8 \div 2.0)10^2$ cm^{-3} s^{-1} at all heights calls for a separate study.

This paper addresses the aforementioned questions. The analyzed calculation results were obtained at the fourth method calibration stage (see Table 4 in [Kozlov, Nikolaishvili, 2024]).

1. POSSIBILITY OF CHANGING MINOR NEUTRAL AND EXCITED COMPONENTS OF THE D-REGION UNDER CONDITIONS OF INCREASED IONIZATION

As noted above, the method employs only three minor components of the medium: H_2O, CO_2, and O_3, whose concentrations in the height range 50–85 km are known with low accuracy [Kozlov et al., 2022] and depend on latitude, season, time of day, and solar activity. However, in the context of this paper it is most important to understand whether the distributions of $H_2O(h)$, $CO_2(h)$, and $O_3(h)$ can change under conditions of increased ionization in the D-region and how to account for this effect, if it occurs, in the semi-empirical model.

In general, the formulated problem can be solved by multicomponent models such as [Swider, 1977; Swider et al., 1978; Read, 1977; McEwen and Phillips, 1978; Kozlov, 2021]) which simultaneously calculate concentrations of ionized components and minor neutral and excited components of the ionosphere. Inclusion of complementary equations in the model will lead to an even greater increase in the number of uncertain parameters and will, in general, emasculate the semi-empirical method, which has a fundamental idea: addressing many problems of D-region photochemistry under quasi-stationary conditions requires only the experimental profile $N_e(h)$. Nonetheless, we can handle this situation if we use the research results of the above-mentioned (and other similar) works, as well as the relation indicating the need to take into account changes in the background concentration N_{i0} of one or another minor component i during the operation time t_u of the ionization source [Kozlov, 2021]:

$$W\int_0^{t_u} q(h,t)d \gtrsim \frac{3}{2}k\int_0^{t_u} T(h,t)N_{i0}(h,t)dt, \qquad (1)$$

where T is the ambient temperature; $W\approx33\div35$ eV is the well-known energy used to form one pair of ions. In a certain sense, relation (1) is universal. If it is not fulfilled due to the fact that the effect of the ionization source can be arbitrarily extended over time or its power is relatively low, it is still impossible to talk about the constant concentration N_{i0} of one or another minor component, since on its left side there is the total energy brought by ionizing radiation in the medium; and on the right side, only the energy "stored" in N_{i0} under the assumption of a Maxwellian velocity distribution of all neutral components. If t_u is much shorter than the characteristic time $t_x(N_{i0})$ of a change in the concentration of the minor component in vivo, integration in (1) can be discarded. Even at $t_u \geq t_x(N_{i0})$ there is always a time interval for a component when it is quite justified to consider the concentrations N_{i0} and certainly $T(h)$ as constant. In the described situations,

$$Wq(h)t_u \gtrsim \frac{3}{2}kT(h)N_{i0}(h), \qquad (2)$$

The values of $t_x[H_2O]$ and $t_x[CO_2]$ in the D-region at any latitudes and heights are large enough, since $[H_2O]$ and $[CO_2]$ are primarily determined by sources on the ground and in the underlying layers of the atmosphere, as well as by dynamic processes. This is confirmed by calculations by various multicomponent models (see the above references) under conditions of increased ionization: the concentrations $[H_2O](h)$ and $[CO_2](h)$ remained virtually unchanged. The same results are obtained by the multicomponent model [Gordillo Vazquez, 2008; Van Gaens, Bogaerts, 2013] (77 components, 221 reactions for ionized components, and 304 processes for neutral ones).

To estimate $t_x(O_3)$, we rely on the well-known Chapman oxygen cycle, which has been studied in detail in many works including [Perov, Khrgian, 1980]. Indeed, it is basic at the heights considered, which significantly exceed the maximum in the $[O_3](h)$ distribution. If we omit some details [Kozlov, 2021], the cycle includes four main processes

$$O_2 + h\nu \rightarrow 2O,\ J_3 \approx 6\cdot10^{-9}\ \text{s}^{-1}, \qquad (3)$$

$$O_3 + h\nu \rightarrow O + O_2,\ J_4 \approx 10^{-2}\ \text{s}^{-1}, \qquad (4)$$

$$O{+}O_2 + M \rightarrow O_3 + M,\ k_5 \approx 10^{-34}\ \text{cm}^6\ \text{s}^{-1}, \qquad (5)$$

$$O{+}O_3 \rightarrow 2O_2,\ k_6 \approx 1.5\cdot10^{-15}\ \text{cm}^3\ \text{s}^{-1}. \qquad (6)$$

On the right side are average photodissociation rates and reaction rate constants at h=55–90 km, derived by generalizing the detailed calculations [Perov, Khrgian, 1980] made for midlatitudes and approximately midday conditions (secχ=2 or the solar zenith angle χ=60°). Launches No. 1–6 (see Table 1 in [Kozlov, Nikolaishvili, 2024]) were carried out at 59° N, i.e. at the boundary of the transition from the mid-latitude to polar ionosphere, and at $\chi \gtrsim 75°$. Taking these factors into account will lead to a significant decrease in J_3 and J_4 and hence to an increase in the time of change (life) of O_3 according to reaction (4). Estimating $t_x(O_3)$ from (5) and (6) requires knowledge of $[O](h)$, $[O_2](h)$, $[M](h)$. The characteristic time of change of O_3 according to (5) is $(0.21\ k_5[M]^2)^{-1}$, but more correctly $(0.21\ k_5[O][M])^{-1}$. In the lower part of the D-region (h<60 km) due to the very low atomic oxygen concentration, $t_x(O_3)$ is very high. A similar situation occurs at h>60 km, where [O] increases and [M] decreases, but always $[O]<0.21[M]$. Time variations in O_3 as a result of process (6) are determined by the expression $(k_6[O])^{-1}$ and even for $[O]\approx10^9\div10^{10}$ cm^{-3} at h>70 km yield $t_x(O_3)\approx6.7\cdot10^4\div6.7\cdot10^5$ s. The values are quite large. The findings allow us to use expression (2) in the future.

Let us return to the SPEs of interest. First, we found the energy $E_0(h)$, contained in ozone, for the daily distribution of $[O]_0(h)$, identified from Aura experimental data. Then, using the experimental data presented in Table 2 from [Kozlov, Nikolaishvili, 2024], we found the average rates of $\bar{q}_{\text{exp}}$ at each height h and further from equation

$$t_u(h) = E_0(h)/W\,\bar{q}_{\text{exp}}(h) \qquad (7)$$

we estimated times when the input energy during SPE was equal to $E_0(h)$. $[O_3]_0$, T, E_0, $\bar{q}_{\rm exp}$, and $t_{\rm u}$ are listed in Table 1. Note that $\bar{q}_{\rm exp}(h)$ differ at most only by a factor of ~1.8. In fact, $t_{\rm u}$ values should be larger, since the coefficient W includes the energy expended not only in air ionization, but also in dissociation of molecules and in various types of excitation of neutral and ionized components. Accordingly, the energy causing changes in O_3 should be lower. This is supported by calculations [Smirnova et al., 1984] by the 30-component model: at $h=70$ km with an energy input of $1.2\cdot10^8$ eV·cm^{-3} (W=33 eV, $q=10^3$ cm^3 s^{-1}, $t_{\rm u}=3.6\cdot10^3$ s), it has been found that it corresponds to the beginning of changes in the minor oxygen components at initial $T\approx220$ K and $[O_3]_0\approx10^{10}$ cm^{-3}. For T and $[O_3]_0$, the energy stored in ozone according to (1) $E_0=2.6\cdot10^8$ eV·cm^{-3}, whence $W(O_3)$ leading to variations in O_3 turned out to be $W(O_3)=33\cdot1.2\cdot10^8/E_0\approx14.1$ eV. This estimate is qualitatively confirmed by calculations made by the above 77-component model for the same values of T, $[O_3]_0$, and $\bar{q}_{\rm exp}$ (see Table 1), and at $h>70$ km the $t_{\rm u}$ values are almost identical. At all heights, $[O_3]$ decreases relative to $[O_3]_0$, $W(O_3)<33$ eV; in the lower part of the D-region ($h<65$ km), the decrease in $[O_3]$ does not exceed ~5–7 %; in the upper part, it can run to ~25 %. In general, the calculations are consistent with the previously performed ones (see [Kozlov, 2021]).

The analysis allows us to recommend using $[O_3]_0\approx const$ at $h<65$ km and $[O_3]\approx(0.75\div0.8)[O_3]_0$ at $h>65$ km for the SPEs considered. In both cases, it is necessary to take into account changes in $[O_3]_0(h)$ depending on time of day. Note that the role of negative ions related to O_3 decreases markedly at high altitudes. The calculations

$$\Delta q=(q_{\rm exp}-q_{\rm m})/q_{\rm m},\quad \Delta N_{\rm e}=(N_{\rm e\,exp}-N_{\rm em})/N_{\rm em}, \qquad (8)$$

where the index “exp” refers to experimental values, and “m” refers to model values, "did not feel" the recommended changes in $[O_3]$ at $h>65$ km.

2. ADDITIONAL CONSIDERATIONS CONCERNING SELECTION OF UNKNOWN RATES OF ELECTRON PHOTODETACHMENT FROM X_2^- AND THE COEFFICIENT OF DISSOCIATIVE RECOMBINATION OF X_2^+ WITH ELECTRONS

In comparing the experimental median values $\alpha_{\rm exp}(h)=q_{\rm exp}(h)/N^2_{\rm e\,exp}(h)$ with similar theoretical calculations when temperature dependences of reaction rate constants were included in the model, the new value of the rate of electron photodetachment from O_2^- $I_1=2.44$ s^{-1} [Kozlov, Lyakhov, 2023], and the distribution $T(h)$ was taken from the MSIS-90 model, an almost perfect agreement was reached between $\alpha_{\rm exp}$ and $\alpha_{\rm m}$ (see Figure 6 in [Kozlov, Nikolaishvili, 2024]) with I_2 and $\alpha_{\rm d2}$ given in Table 2. $\alpha_{\rm d2}$ was calculated from the hypothetical equation proposed in [Kozlov, Nikolaishvili, 2024],

$$\alpha_{\rm d2}=2\cdot10^{-6}(300/T)^{0.5} \qquad (9)$$

with coefficients 0.2 for $h<65$ km and 0.33 for $h>65$ km. The values in Table 2, which were estimated partly intuitively, require additional explanation. The $\alpha_{\rm d2}(h)$ values vary slightly in the height range considered. Average $\alpha_{\rm d2}=6.1\cdot10^{-7}$ cm^3 s^{-1}.

It is more difficult to explain the high values of I_2. Kozlov and Nikolaishvili [2024] suggested taking into account in I_2 the processes of electron detachment from X_2^- in collisions with ground- and excited-state neutral components. In this case,

$$I_2=I_\Phi+\alpha_i[M_j], \qquad (10)$$

where the first term refers to photodetachment; and the second, to detachment in collisions i involving the neutral component j. Unfortunately, our knowledge of the

Table 1

Dependence of $[O_3]_0$, T, E_0, $\bar{q}_{\rm exp}$ and $t_{\rm u}$ on height h

h, km	$[O_3]_0$, cm^{-3}	T, °K	E_0, eV·cm^{-3}	$\bar{q}_{э}$, cm^{-3} s^{-1}	t_u, s
50	2.9319 E+10	262.5	1.000 E+09	2.10 E+02	1.443 E+05
55	9.3131 E+09	247.8	2.980 E+08	2.52 E+02	3.583 E+04
60	4.0335 E+09	237	1.220 E+08	2.01 E+02	1.839 E+04
65	1.6642 E+09	218.6	4.700 E+07	1.92 E+02	7.418 E+03
70	7.4945 E+08	203.7	2.000 E+07	1.58 E+02	3.836 E+03
75	3.7029 E+08	196.1	9.400 E+06	1.41 E+02	2.020 E+03
80	4.7035 E+08	193.1	1.200 E+06	1.25 E+02	2.909 E+02
85	1.7259 E+08	183.4	4.100 E+06	1.41 E+02	8.812 E+02

Table 2

Values of I_2 and α_2 providing the best fit between $\alpha_{\rm m}$ and $\alpha_{\rm exp}$

H, km	50	55	60	65	70	75	80	85
I_2, s^{-1}	1	1	0.5	0.2	0.8	0.8	0.8	0.8
α_{d2} cm^{-3} s^{-1}	$4.4\cdot10^{-7}$	$4.4\cdot10^{-7}$	$4.4\cdot10^{-7}$	$4.5\cdot10^{-7}$	$7.7\cdot10^{-7}$	$7.7\cdot10^{-7}$	$7.8\cdot10^{-7}$	$7.8\cdot10^{-7}$

rate constants α_i of these processes is very limited and rather doubtful [Boyarchuk et al., 2006; Swider, 1977; Massey, 1950; Smirnov, 1978, 1983; Saidia et al., 2019]. Analysis of these and many other reference and scientific works has shown that only a few reactions can be considered

$$O_3^- + O_3 \rightarrow 3O_2 + e,\ \alpha_{11} \approx 3\cdot 10^{-10},\ \alpha_{11} \approx 10^{-12}, \quad (11)$$

$$O_3^- + O_2 \rightarrow O_3 + O_2 + e,\ \alpha_{12} \approx 2.3\cdot 10^{-11},\ \alpha_{12} \approx 10^{-12}, \quad (12)$$

$$O_3^- + O \rightarrow O_3 + O + e,\ \alpha_{13} \approx 3\cdot 10^{-10}, \quad (13)$$

$$NO_2^- + O \rightarrow NO_3 + e,\ \alpha_{14} \approx 10^{-12}, \quad (14)$$

Different publications give different values of α_i for the same process, for example, for (11) and (12). It is apparent from (11)–(14) that reaction (12) even at $\alpha_{12}\approx 10^{-12}$ cm^3 s^{-1} at all heights yields $10^{-12}[O_2]=J_2$, shown in Table 2. But O_3^- according to any multicomponent models is considered intermediate between primary O_2^- and unknown final X_2^- [Kozlov, 2021; Swider, 1977; Mitra, 1977]. In terms of the results obtained in the aforementioned studies, it is often assumed that CO_3^-, NO_2^-, NO_3^-, hydrate ions can be X_2^-. Therefore, for further estimates, which will certainly be approximate, it is advisable to rely only on reaction (14) that depends on [O](h). The [O](h) values increase with height, yet at $h \geq 50$ km they are very variable and depend on solar activity, time of day, season, and latitude. Satisfying I_2 in Table 2 requires $[O]=(I_2-I_\Phi)/\alpha_{14}$. Assuming $I_\Phi=0.04$ s^{-1}, as in the first stages of calibration of the semi-empirical method [Kozlov, Nikolaishvili, 2024], for $I_2=0.2\div 1$ s^{-1} we get $[O]=(2\div 9.6)\cdot 10^{11}$ cm^{-3}. Analysis of experimental and theoretical works [Zuev, Komarov, 1986; Zhuravleva, Kudryavtsev, 1994; Shimazaki, Laird, 1972], where the distribution of [O](h) was examined to different extents, shows that the [O] values found are quite possible, especially under conditions of long-term increased ionization characteristic of SPEs, due to dissociation primarily of O_2 and O_3 [Swider, 1977; Smirnova et al., 1984].

In addition, we should once again point to our lack of knowledge of I_Φ and α_{14}, as mentioned above (see also [Kozlov et al., 2022; Kozlov, Nikolaishvili, 2024]), and the possibility of reducing I_2 in Table 2, remaining within the basic argument — calculations and experiment are in good agreement if the former fall within the range of instrumental precision of measurands.

1. ANALYZING THE BEHAVIOR OF OTHER AERONOMIC PARAMETERS DEPENDING ON HEIGHT AND RATE OF ATMOSPHERIC IONIZATION

The experience of studying the D-region with increased ionization suggests [Kozlov, 2021] that the most important and interesting is to examine the q dependences of the parameters λ, φ^-, α_{ef}, α_i, φ^+, $A(h)$ discussed in Introduction. The results of calculation of these parameters are presented in Figures 1–6. Numbers near dots indicate the conventional numbers of missile launches during SPEs and HANE. Minimum information on these launches compared to [Kozlov, Nikolaishvili, 2024] is given in Table 3.

Analysis of the obtained results allows us to draw the following main conclusions.

1. As expected, the parameters discussed, except for A, strongly depend on height. In this case, the h range can be divided into two: $h<65$ km and $h>65$ km.

2. The aeronomy of the D-region with increased ionization at night seems to differ markedly from daytime conditions. It is impossible to draw a more detailed and valid conclusion because it is based on the only available nighttime experimental data acquired during HANE (q_{exp} and $N_{\text{e exp}}$ appeared to be significantly higher than daytime ones).

3. The behavior of the parameter $\lambda(q, h)$ is primarily determined by h (see Figure 1). Naturally, $\lambda(q, h)$ decreases with increasing height. The range of changes in λ in the lower part of the D-region ($h \leq 65$ km) $1<\lambda<10^2$ is about ten times less than at $h>65$ km. The most interesting result is that daytime λ is independent of q at all heights, at least within $q \leq 2\cdot 10^3$ cm^{-3} s^{-1}.

Table 3

General characteristic of missile launches (Fort Churchill, 58°44′ N, 93°49′ W)

Conditional launch number	Date, local time	Solar zenith angle	Measurement heights H (km)	Time of day at heights H
1	Nov. 02, 1969, 15:10	83°	44–105	day
2	Nov. 03, 1969, 06:57	96°	64–105	day
3	Nov. 03, 1969, 07:30	92°	60–112	day
4	Nov. 03, 1969, 12:54	75°	56–108	day
5	Nov. 04, 1969, 15:30	85°	54–103	day
6	Nov. 04, 1969, 16:38	93°	57–108	day
7	1962 no data	no data	50–80	night

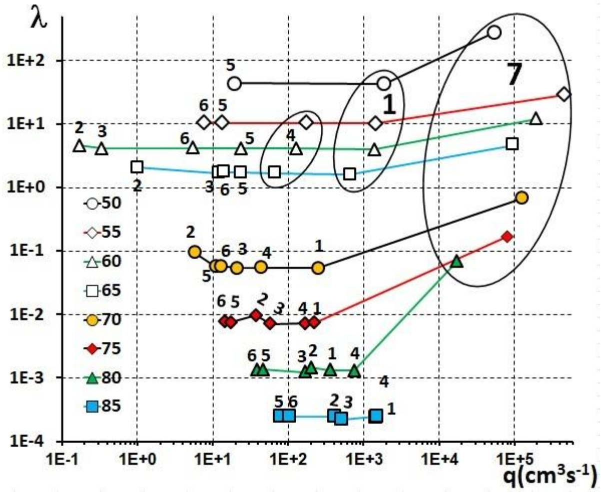

Figure 1. Behavior of the parameter λ as a function of ionization rate q and height h. Numbers near curves are launch numbers. Each line corresponds to the parameter values at 50–85 km. In legends are colors and markers of the lines, as well as the corresponding heights in kilometers

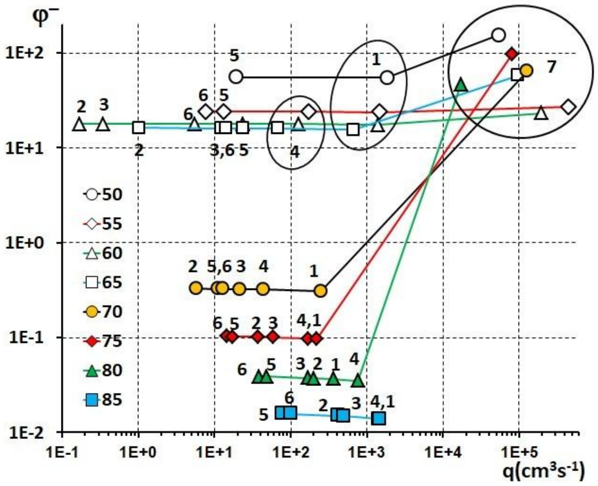

Figure 2. Behavior of the parameter φ^- as a function of ionization rate q and height h

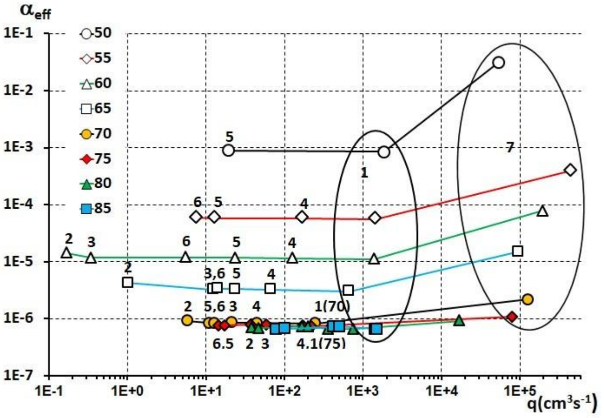

Figure 3. Behavior of the coefficient $\alpha_{\rm eff}$ as a function of ionization rate q and height h

4. Figures 2 and 3 illustrate variations in φ^- and $\alpha_{\rm ef}$ respectively depending on q and h. The behavior of these parameters is very similar to $\lambda(q, h)$: there is no dependence on q at all heights h. The main difference exists only for $\alpha_{\rm ef}$ at h>65 km: during the day it can be considered constant and equal to ~10^{-6} cm^{-3} s^{-1} (a somewhat unexpected result that will become clear when considering $N_{\rm e}(q, h)$ in Subsection 4).

5. The effect of q and h on the ion-ion recombination coefficient α_i is illustrated in Figure 4. The nighttime values of α_i are seen to be well matched by daytime values (launches No. 1–6). Recall [Kozlov et al., 2022] that the system of five differential equations could be solved under the assumption that $\alpha_i = \alpha_{\rm d1}\left(X_1^+\right)$ and $\alpha_i = \alpha_{\rm d2}\left(X_2^+\right)$, and hence:

$$\alpha_i = \frac{\alpha_{\rm d1}\left(X_1^+\right)+\alpha_{\rm d2}\left(X_2^+\right)}{2\left[X_1^+\right]+\left[X_2^+\right]} = \frac{\alpha_{\rm d1}+\alpha_{\rm d2}f^+}{2\left(1+f^+\right)} = \frac{q}{2A^2}. \quad (15)$$

This equation, in fact, defines the behavior of $\alpha_i\,(q, h)$. At h<65 km, average $\alpha_i \approx 2.1\cdot10^{-7}$cm^{-3} s^{-1} does not depend on h and, presumably, on time of day, and indeed refers to the recombination reactions of negative and positive ions. At h>65 km, despite some spread, average $\alpha_i \approx 3.5\cdot10^{-7}$ cm^{-3} s^{-1} and relates to the reactions of dissociative recombination of positive ions with electrons. The conclusion that α_i is independent of the time of day is certainly preliminary. Comparison of the found averages of α_i with $\alpha_{\rm d2}$ from Table 2 shows that the general behavioral tendencies of α_i and $\alpha_{\rm d2}$ — independence from q and an increase with increasing h — are the same. However, in absolute values, α_i is about twice as small as $\alpha_{\rm d2}$.

6. Variations in $\varphi^+(q, h)$ are shown in Figure 5. They depend greatly on q and h. Nighttime values of HANE are

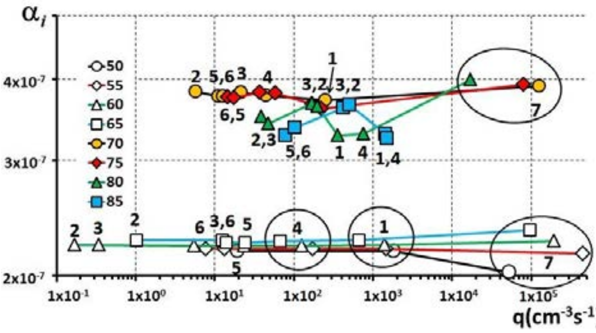

Figure 4. Behavior of the coefficient $\alpha_{\rm i}$ as a function of ionization rate q and height h

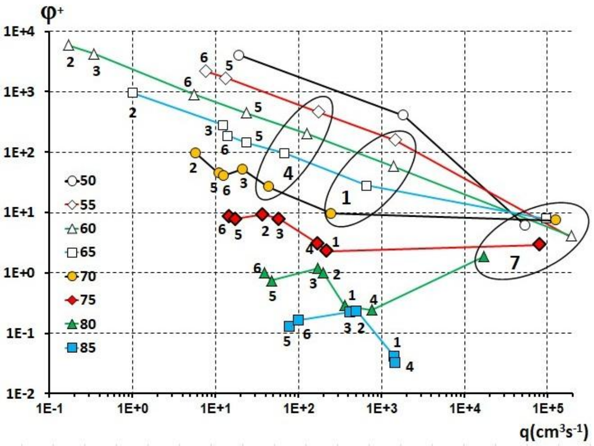

Figure 5. Behavior of the parameter φ^+ as a function of ionization rate q and height h

not matched by the daytime values and are therefore not discussed further here. With increasing q and h, φ^+ decreases as expected. During the day at h<65 km, the decrease in φ^+ is inversely proportional to q; at h>65 km, this dependence disappears (the results for launches No. 2 and 3 stand out against the rest). The inequality $\left[X_1^+\right] \geq \left[X_2^+\right]$ begins to be fulfilled only at h≥80 km.

7. Figure 6 demonstrates the dependence of the electron neutrality condition of the medium (parameter A) on ionization rate q and height h. The values of A are seen to be practically independent of height, and depend only on q. An increase in q leads to an increase in $\left[X_1^+\right]$ and N_e. In turn, a rise in N_e causes an increase in $\left[X_1^-\right]$, and an increase in $\left[X_1^+\right]$ brings about an increase in $\left[X_2^+\right]$.

2. ANALYZING THE BEHAVIOR OF MODEL VALUES $N_{em}(q_{exp}, h)$ AND $q_m(N_e, h)$

Recall [Kozlov, Nikolaishvili, 2024] that the model (calculated) values N_{em} and q_m are obtained by substituting the experimental values q_{exp} and $N_{e\ exp}$ into the corresponding equations. A fit between calculations and experiment is considered satisfactory if the calculation results fall within the range of instrumental precision. This approach allows us to analyze $N_{em}(q_{exp})$ and $q_m(N_{e\ exp})$ for each height h.

The best possible fit between calculations and experiment was achieved for the following model parameters [Kozlov, Nikolaishvili, 2024]: i_2 and α_{d2} — see Table 2; i_1=2.44 s^{-1}; concentrations of neutral components are taken from Aura experimental data; temperature values, from the MSIS model; expressions for α_{d1} and β are given in [Kozlov, Nikolaishvili, 2024].

The results of calculations of N_{em} and q_m allow us to draw the following conclusions.

1. The model values N_{em} and q_m for launches No. 1, 4, 5, and 6 fit into the measurement precision range for h≤75 km. The results for launches No. 2 and 3 at these heights do not fit into the range; in this case, the difference between calculation and experiment decreases with increasing height. It can be assumed that this is most likely due to the fact that launches No. 2, 3 were carried out at dawn, i.e. during the restructuring of ionospheric processes from night to day (the electron density N_e does not keep up with the increase in q).

2. For h≥80 km, the picture changes (Figure 7, *a*, *b*, h=85 km; the solid line indicates $q_m(N_{e\ exp})$; the dashed line, $N_{em}(q_{exp})$; experimental data are highlighted in gray; the thickness corresponds to the range of measurement precision; the calculation results are shown in red). q_m>q_{exp} 3–10 times, whereas N_{em}<$N_{e\ exp}$ 1.5–3 times. In our opinion, there are no more or less correct D-region models for night-day and day–night transition conditions. The development of such a model therefore becomes very relevant, which is beyond the scope of this paper.

Note that the experimental values and model estimates obtained during launches No. 1, 4, 5, and 6, which are in good agreement with each other, can be approximated by linear functions [Panofsky, Brier, 1972].

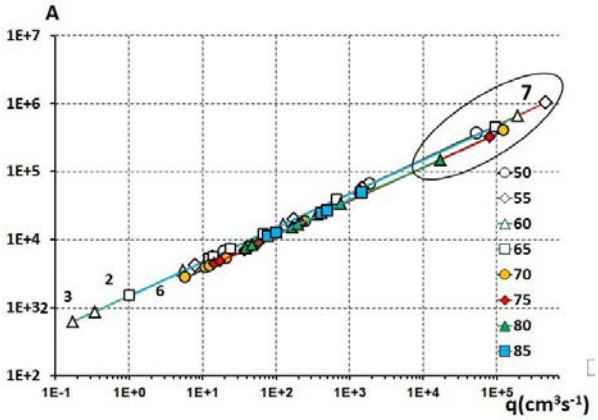

Figure 6. Behavior of the parameter A of the ionospheric D-region as a function of ionization rate q and height h

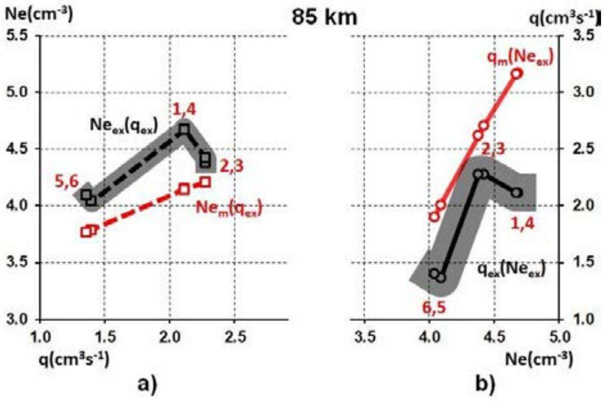

Figure 7. Dependence of N_{em} on q_{exp} (*a*) and q_m on $N_{e\ exp}$ (*b*) at h=85 km. Black lines are experimental curves; red lines, model curves. Numbers near the curves denote launch numbers

CONCLUSION

Detailed analysis of the calculation results of the parameters λ, φ^-, α_{ef}, α_i, φ^+, A, which determine the behavior of the ionospheric D-region with increased ionization has shown that values of these parameters conform to general notions of their behavior under SPE conditions.

Model calculations of $N_{em}(q_{exp})$ and $q_m(N_{e\ exp})$ have revealed that they all fit fairly well into the precision range of experimental measurements of ionization rate and electron density. There are two exceptions. The first is the behavior of q_m>q_{exp} and N_{em}<$N_{e\ exp}$ at a height of 85 km. This case should be investigated further, probably involving new photochemical mechanisms of interaction between solar protons and the ionosphere in the upper part of the D-region.

The second case is due to the fact that a decrease in $N_{e\ exp}(q_{exp})$, detected within q_{exp}≈(1.8÷2.0)·10^2 cm^{-3} s^{-1}, cannot be explained in the model. Such a decrease was recorded during launches No. 2 and 3, carried out during the transition from night to day. Launch No. 6 was also performed during the transition period, but from day to night, and the decrease in $N_{e\ exp}$ described above was not detected.

This situation makes it highly relevant to develop a D-region model at the given time of day not only under disturbed conditions discussed here, but also for the quiet ionosphere.

It is shown that the increased ionization of the medium comprising three minor components included in the model (H_2O, CO_2, and O_3) can only affect the ozone content — its concentration drops from 5 to 25 % of the normal level, depending on height. Nonetheless, this decrease did not affect the results of calculations of ΔN_e and Δq from equations (8).

In general, the results we have obtained once again confirm the possibility of widespread use of the semi-empirical method proposed in [Kozlov et al., 2022].

In the future, it would be advisable to apply this method to other situations, where only the electron density N_e is measured, in order to obtain values of the ionization rate and then compare them with other theoretical estimates.

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