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The Negative Ions in the *F*-Region under Night Conditions

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It was believed until recently that the negative ions limit their effects at night to the height of the night *E*-layer (about 120 km — cf. [1, 2, 3]). However, a number of new studies have indicated that notwithstanding the low densities of the negative ions, their integral abundance is significant and, taking into account their activity in a number of basic aeronomical processes, it will become necessary to undertake a basic re-examination of their role [4, 5, 6]. For instance, it is stated in [6] that at high geomagnetic latitudes the abundance of negative ions in the *F*-region is sufficient for them to contribute essentially to the neutralization processes, i. e. the ion-ion recombination in the circumpolar regions between the positive and the negative ions in the high ionosphere is not negligible. On that basis it would be necessary to re-examine the neutralization processes and to assess the role of the dissociative recombination in the above geographic regions. In addition to that, as a sequence of the essential influence of the ion-ion recombination, we should find a considerable portion of oxygen atoms in a $O(^1D)$ state, which are emitted by the red oxygen line λ_w 6300 Å in the spectrum of the night airglow. However, this line is generated also at the dominant neutralization mechanism — the dissociative recombination which also leads to considerable $O(^1D)$ densities. It has been pointed out in [4, 5] that the negative ion densities in the *F*-region are so low that their role in the neutralization processes and in the generation of the red line is negligible. The aim of our present work was to create a model for the altitudinal and seasonal variations of the coefficient of the negative ions λ in the *F*-region, through which to provide objectification for the examination of that problem, both for the aims of the studies of the neutralization processes and of night airglow and for the independent morphological investigation of the ionosphere, the analysis of the night plasmasphere included.

Initial data for the development of models for the variations of the negative ion night coefficient in the high and outer ionosphere in the work undertaken will be provided by the international models for the neutral atmosphere — CIRA 72 (see [7] and for the ionosphere [8]). The CIRA-72 model has many deficiencies, particularly under low solar activity, but we shall not dwell on them here. Similar is the situation with the International Model for the Ionosphere [8], which is still far from being a unified representation of the average night conditions. In particular, we showed a group of Bulgarian ionospheric models in [9] which, at medium geographic latitudes at least, offer better approximations to the real ionosphere. Particularly convenient for the above-maximal, outer ionosphere, in which the negative ions have their influence, is the model developed in [10] which provides for convenient analytical calculations. Notwithstanding the deficiencies of the international models, at the present stage they are the only internationally accepted approximation to reality, and on that account they are at the basis of the present work.

The generation of the negative ions takes place mainly through the radiative attachment reaction, and these ions are almost entirely of the atomic oxygen on account of its familiar electron affinity

(1) $$O+e\longrightarrow O^-+h\nu,\ K_1$$

where $h\nu$ is a continuum photon ($\lambda_w<8463$ Å), as the coefficient K_1 of (1) is in accordance with [11]: $K_1=1.3\times10^{-15}$ cm^3s^{-1}. Part of the negative ions disappear by an associative detachment reaction

(2) $$O^-+O=O_2+e^-,\ K_2$$

where the velocity $K_2=1.4\times10^{-10}$ cm^3s^{-1} [12], while the other essential part is involved in the ion-ion recombination:

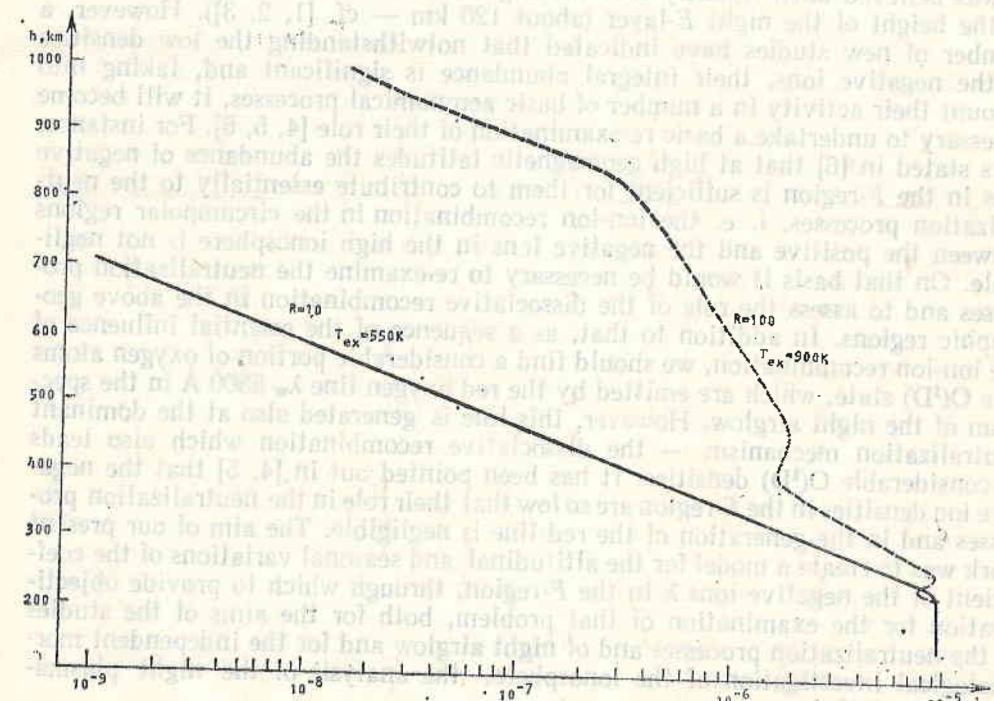


Fig. 1

(3) $$O^+ + O^- \longrightarrow O^* + O^* + KE,\ K_3$$

where the velocity $K_3=1.5\times10^{-7}$ cm^3s^{-1} [5, 13].

Consequently, the equilibrium equation of the negative oxygen ions in the F-region for the photochemical processes in first approximation will be

$$\frac{d[O^-]}{dt} = K_1[O]N_e - \{K_2[O] + K_3[O^+]\}[O^-]. \tag{4}$$

Under conditions of equilibrium we have

$$O^- = \frac{K_1[O]N_c}{K_2[O] + K_3[O^+]} = \frac{K_1[O]N_e}{K_2O + K_3R_eN_e}, \tag{5}$$

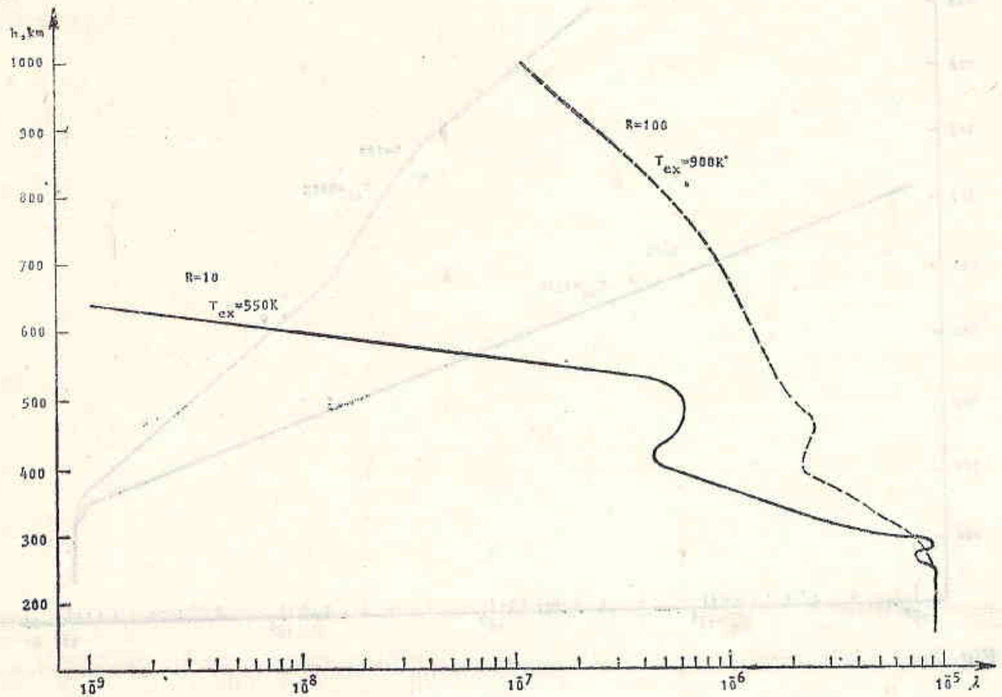


Fig. 2

where $R_2(h) = [O^+]/N_e$, and N_e is the electron density which, just as [O], [O⁺] and R_e, is a function of the altitude h.

The models for the [O⁻] distribution can be obtained from (5) by using the profiles for $[O_2]$ (h) for the CIRA-72 model under different conditions and the model for O^+ (h) from [8]. For the sake of convenience we here propose models for the coefficient of the negative ions λ determined by

$$\lambda = \frac{[O^-]}{N_e} = \frac{K_1[O]}{K_2[O] + K_3[O^+]}. \tag{6}$$

From [7, 8] we can obtain averaged approximating models for the variations of λ which may be applied to concrete profiles $N_e(h)$ obtained, in order to calculate the density [O⁻] by means of (6). Of course, this will be a first approximation which makes it possible, under any normal conditions, using a profile $N_e(h)$ obtained from vertical probing (with ionospheric stations or rockets), from the incoherent scatter, or by any other method, to determine the profile of the negative ions $[O^-](h)$ by using a model for the standard averaged values of λ. Likewise, using such a model of λ, it is possible to restore any value for [O⁻] at a given altitude, geographic conditions and phase of solar activity.

The data on N_e and $[O^+]$ in [8] are provided for two levels of solar activity — at $R=10$ and at $R=100$, where R is the average monthly number of the sunspots. The transition from these data about the solar activity to the parameter used in [7], namely, the exospheric temperature (T_{ex})is done as in [14], according to the following dependence

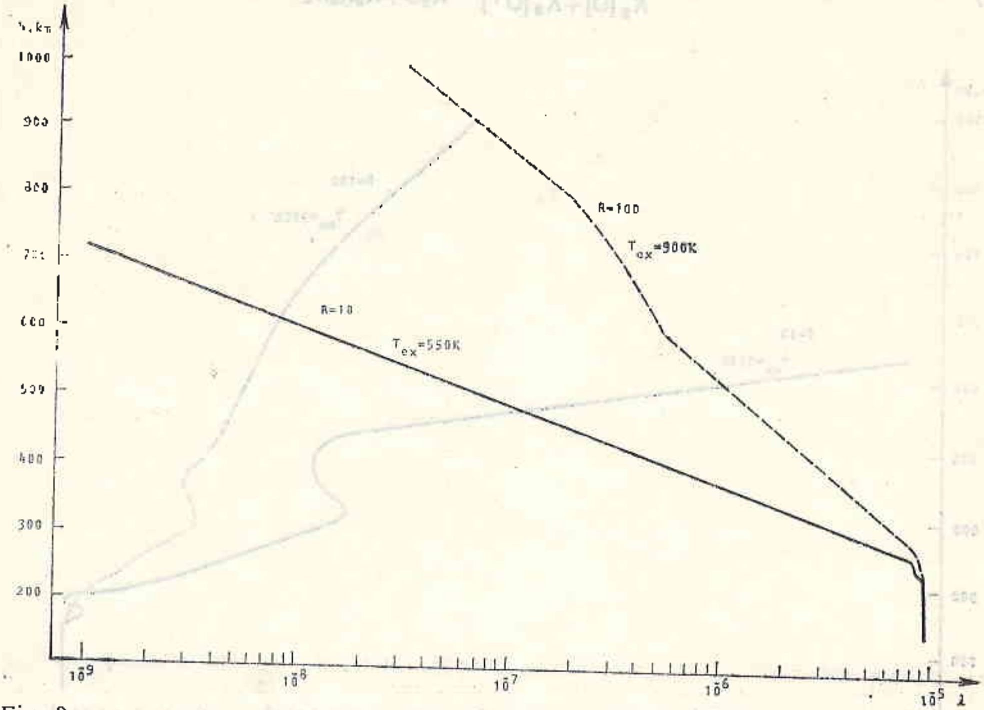


Fig. 3

$$\overline{T}_{ex}\approx 513+3.4\,\overline{R}. \tag{7}$$

Hence at $\overline{R}=10$ we have $\overline{T}_{ex}=550$ K, while at $\overline{R}=100$ the corresponding $T_{ex}\approx 900$ (in first approximation, according to the available data on T_{ex} in [7]).

The models obtained for the variations of λ according to initial data of the international models [7, 8] for 00:00 h local time have been shown in Fig. 1 — for the 6th month at $\varphi=45^0$ and for both levels of solar activity, in Fig. 2—for the 9th month and $\varphi=45^0$, in Fig. 3 — for the 12th month and $\varphi=45^0$, and in Figs. 4 and 5 — for the months of June and January, respectively, though at $\varphi=18^0$.

From Figs. 1, 2, 3, 4, 5 it is possible to deduce the following principal laws related to the altitudinal, latitudinal, cyclic and seasonal specifics of the coefficient of the negative ions λ:

1. The maximum value of λ is at the beginning of the F-region where, under any conditions up to altitudes of 220 km we gave

$$K_2[O]\gg K_3[O^+]. \tag{8}$$

It follows in this case that

$$\lambda=\frac{K_1}{K_2}=0.93\times 10^{-5}. \tag{9}$$

2. The absolute values of λ in the F-region are rather low and they always remain below the value of 0.93×10^{-6}.

3. At low solar activity for the sector $h \geqslant h_m F$ the distribution of $\lambda(h)$ is close to the exponential one, with the exception of the equinoxes. With the rise in the solar activity there occurs a considerable complication in the $\lambda(h)$ profile, showing a number of extrema and inflex regions in the summer and at the equinox periods.

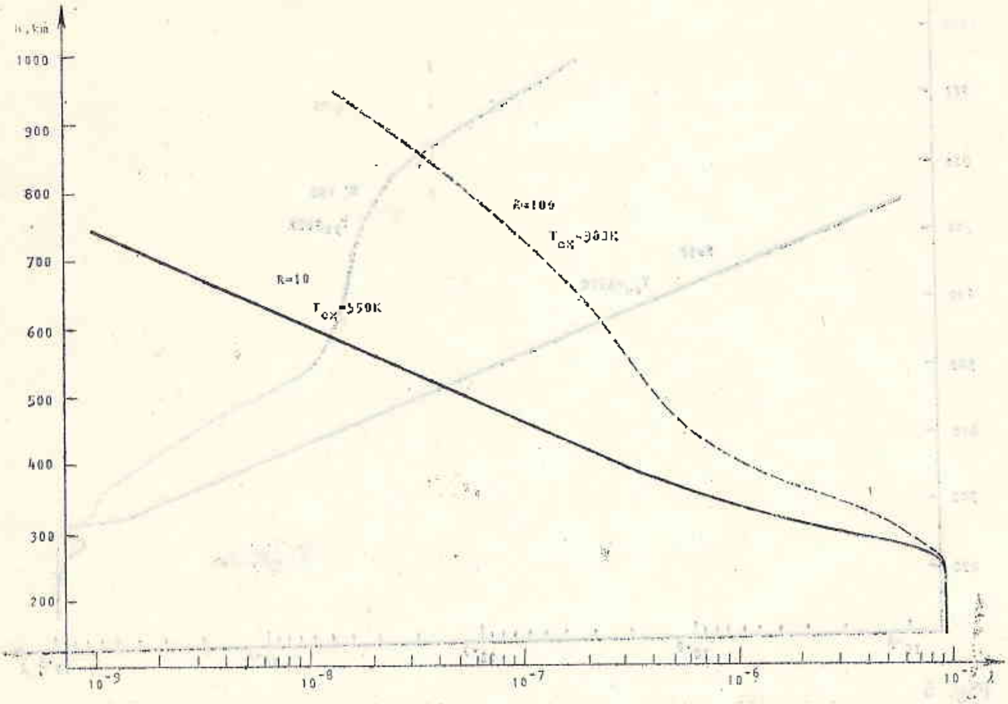


Fig. 4

4. The rise in the solar activity is accompanied by a sharp rise in the values of λ, the rise reaching one order and more for the above-maximal outer ionosphere. Since the model value of R for high activity used by us, $R=100$, is far from being maximal, it follows that λ may have higher values as well, though always lower than the limiting value (9).

5. At mid-latitudes the seasonal run shows maxima of λ for most of the F-region during equinox and two slightly outlined maxima during the summer and winter.

6. The $\lambda(h)$ profiles for relatively low geographic latitudes ($\varphi = 18°$) are generally of the same nature as at mid-latitudes and bear confirmation for the regularities 1, 2, 3 and 4 mentioned above.

7. Under low solar activity λ shows no particular geographic variations in the latitudinal interval of 18 to 45°. At high activity the increase in the geographic latitude within the above interval is accompanied by a rise in λ as well.

The absolute values of the night densities of the negative ions $[O^-]$ are of particular interest. By way of example, Fig. 6 shows the respective altitudinal profiles $[O^-](h)$ for 00:00 h of the month of June at $\varphi = 45°$ for both levels ($R=$

$=10$ and $R=100$) of the solar activity according to the data for λ in Fig. 1 and the electron density model [8]. It is obvious that there is a considerable increase in the ion density $[O^-]$ at high solar activity. The total number of the negative ions in the F-region

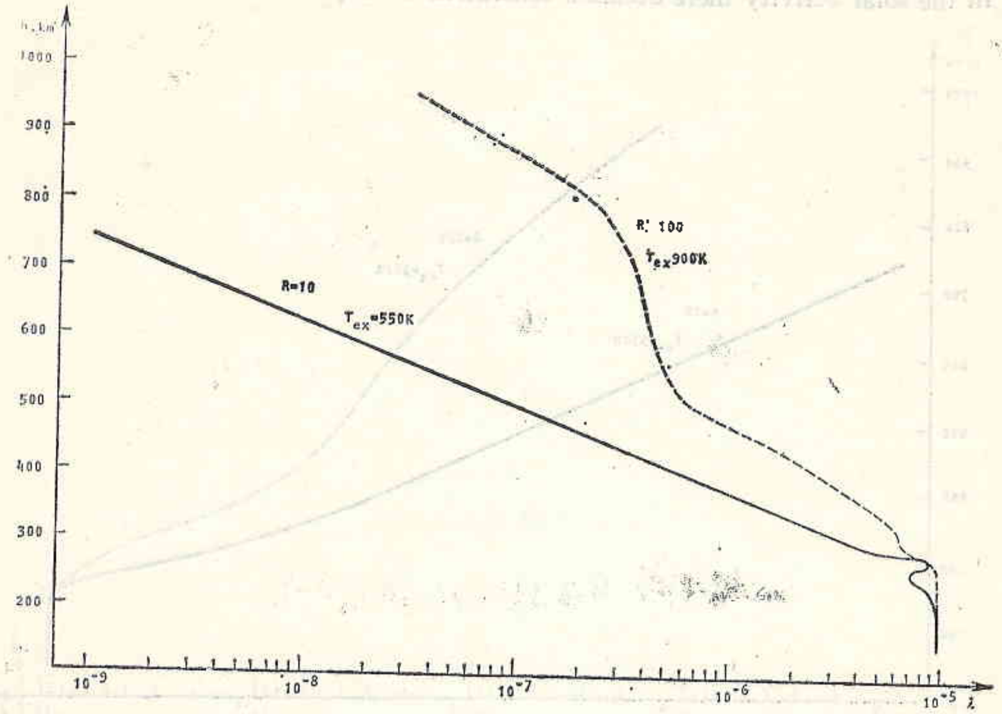


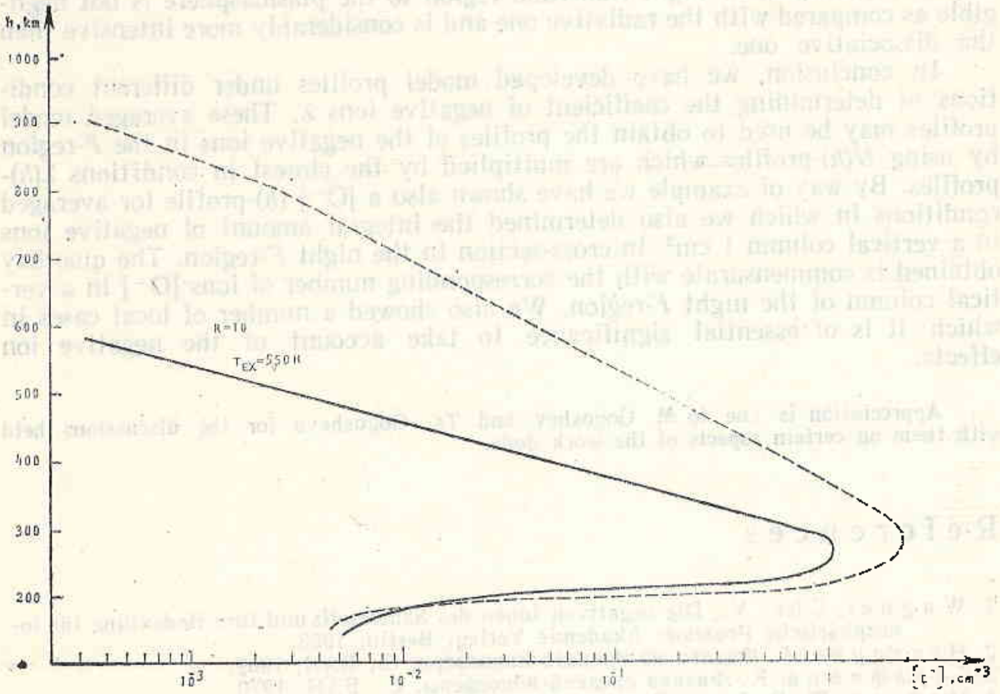
Fig. 5

$$N_g^- = \int_{160}^{1000} [O^-]\,dh \tag{10}$$

is obtained in the order of 10^7 ions per column of 1 cm^2 cross-section (in the example examined from Fig. 6, this number at $R=100$ is approximately 3.35×10^7 cm^{-2}). According to the data in [1, 2, 3], the averaged abundance of negative ions in the vertical column of the night D-region is about 10^8 up to several times 10^9 cm^{-2}, the total amount of O^- ions in the vertical column varying from 10^6 to 10^8 cm^{-2}. It is obvious that the total abundance of O^- negative ions in the D-region and in the F-region is comparable during the night, notwithstanding the very low densities of these ions in the high ionosphere. Of course, the integral number of the negative ions in the night D-region is appreciably larger than in the night F-region, mainly at the expense of ions heavier than the O^- ion.

It should be pointed out that there are only assumptions about the densities of the negative ions in the night F-region in the equatorial and circumpolar regions. It has been assumed in [6], for instance, that the role of the ion-ion recombination and of the negative ions increases poleward, because there is a density increase of atomic oxygen compared to molecular oxygen. It is obvious that this will raise λ and O^-, but at the rather frequent excessive increases of the electron density at high geographic latitudes λ will decrease to its value at average conditions.

The low ion densities of O⁻ may lead to certain interesting effects, particularly in the case of local measurements. For instance, if we compare the local intensity of the night airglow obtained from the dissociative I^{d}_{6300} and from the ion-ion recombination I^{i}_{6300} we shall obtain the following expression:



gFi. 6

$$\frac{I^{i}_{6300}}{I^{d}_{6300}}=\frac{A}{A_{6300}}\cdot\frac{\beta_{6300}K_1K_2[O][O^+][1+B(h)]}{A_{6300}\{K_3[O^+]+K_2[O]\gamma_1[O_2]\}}, \tag{11}$$

where $B(h)=\frac{\gamma_1[O_2]}{\alpha_1 N_e}+\frac{\gamma_2[N_2]}{\alpha_2 N_e}$, the coefficients γ_1 and γ_2 are the rates of recharging the oxygen and nitrogen molecules respectively with the oxygen atomic ions, while d_1 and α_2 are the coefficients of dissociative recombination of O_2^+ and NO^+; $A=0.0091$ s⁻¹; $A_{6300}=0.0069$ s⁻¹; $\beta=0.12$.

Under different conditions the ratio (11) becomes equal to or bigger than unity for h equal to 500-600 km. Under the average conditions of the examined models for a height of 600 km the ratio (11) is 6, and this signifies that at these altitudes there is a decisive predominance of the ion recombination over the dissociative one, and the local airglow is defined from the ion-ion recombination. However, the local intensity of this airglow is much lower than that at altitudes of 200 to 300 km where the predominant generating mechanism of the red oxygen line is the dissociative recombination. That is why, the examination of the ion-

-ion recombination only at high altitudes ($h>500$ km), is justified taking into account the local problems.

It is of essential significance that at very high solar activity the recombination of O^+ at altitudes of about 600 km is determined practically by the commensurate action of the ion and radiative recombination. The ion-ion recombination in this important night transition region to the plasmasphere is not negligible as compared with the radiative one and is considerably more intensive than the dissociative one.

In conclusion, we have developed model profiles under different conditions of determining the coefficient of negative ions λ. These averaged model profiles may be used to obtain the profiles of the negative ions in the *F*-region by using $N(h)$-profiles which are multiplied by the closest in conditions $\lambda(h)$-profiles. By way of example we have shown also a $[O^-]$ (h)-profile for averaged conditions in which we also determined the integral amount of negative ions in a vertical column 1 cm² in cross-section in the night *F*-region. The quantity obtained is commensurate with the corresponding number of ions $[O^-]$ in a vertical column of the night *F*-region. We also showed a number of local cases in which it is of essential significance to take account of the negative ion effects.

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Отрицательные ионы в ночной F-области

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(Резюме)

Используя международные модели нейтральной атмосферы и ионосферы, в работе решены уравнения баланса для отрицательных ионов в F-области. Получен коэффициент отрицательных ионов λ, максимальное значение которого не превышает 1.10^{-5}. Сделаны выводы об ожидаемых сезонных и пространственных вариациях λ.

Дана оценка интегральной плотности отрицательных ионов на высоте свыше 160 км порядка 10^7 см$^{-2}$. Дано сравнение локальной интенсивности свечения ночного неба, являющегося результатом диссоциативной и ионно-ионной рекомбинации. Вклад обоих механизмов соизмерим на высотах 500—600 км.