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On the Kinetic Processes in the Middle Ionosphere during Sunset

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The formation of a deep "valley" above the E-layer after sunset, the layer-like formations observed within it and the patterns of their motions have been known for a long time. Thus in [1, 2, 3] we have shown that the $E2$ layer appears on the ionograms obtained by probe measurements at mid-geomagnetic latitudes mainly at sunrise-sunset periods and this was interpreted in terms of shielding of the daytime E-layer. Its critical frequencies f_0E vary more in dependence on the solar zenith angle and this results in the positive values of the difference $d=f_0E2-f_0E$ in the sunset-sunrise period and ionosondes record the presence of the $E2$ layer. The strong dynamics of the layer-like formations in the valley during the night and their intensive vertical motions are fairly well known. In particular, our analysis of the incoherent scatter radar data from Arecibo ($\varphi=18.4°$N, $\lambda=66.8°$W), published in [4], confirms the presence of multilayer-like structure in the region between 100 and 170-180 km, which is moving almost permanently during the night. Here we shall discuss again the data from this incoherent scatter radar (more details for the instrument and patterns of determination of the electron density vertical distribution see in [5, 6, 7]). The necessity of their correct interpretation would be shown in terms of possibilities to define some new physical parameters.

The problems of nighttime and sunset-sunrise variations of the electron density N_e over Arecibo have been discussed in many publications, e. g. [4, 8, 9], etc. In [9] an attempt has been made to define the height distribution of the effective recombination coefficient α_{eff} on data from the electron density N_e variations. Based on the profiles used in [4, 9], here we shall demonstrate some new possibilities for correct analysis of ionizing-neutralizing and dynamic processes in the middle ionosphere. By the term middle ionosphere here we shall understand the part between 100 and 180 km according to the definition given in [3] as the basis analysis would refer to a higher region — from 130 to 200 km. The principal balance equation from the familiar α-type is analysed in [9]:

$$\frac{dN_e}{dt}=q-\alpha_{eff}N_e^2, \tag{1}$$

where q is the ion production rate, which in the sunset period is $q\approx0$. We can find in [9] that the time variation of $1/N_e$ at constant height of [Z=const] represents almost a straight line. That is why the authors of the same paper consider the dependence (1) at $q \approx 0$ to be accurately realized for the sunrise-sunset period and the coefficient α_{eff} can be defined as an angular coefficient of the straight line (2) obtained by integrating (1):

$$\frac{1}{N_e} \approx \alpha_{eff} t + C_0, \tag{2}$$

where C_0 is constant depending on the height Z. Based on this an altitudinal profile for the effective recombination coefficient $\alpha_{eff}(Z)$ is determined in [9], which, compared to the theoretical data for the specific coefficients of the dissociative recombination of O_2^+ and NO^+ ions, demonstrates great differences from them. The α_{eff} coefficient obtained on data from $N_e(t)$ in the upper part of the discussed region (over 170 km) is smaller than the two specific coefficients $\alpha_D(O_2^+)$ and $\alpha_D(NO^+)$ and at the bottom part of the region (about 140 km) the α_{eff} thus calculated is almost equal to $\alpha_D(NO^+) \approx 2\alpha_D(O_2^+)$, which is rather impossible due to the abundance of O_2^+ ions at these heights. Therefore, the profile of $\alpha_{eff}(Z)$ is obtained in [9], which is very different from all available data of laboratory and theoretical values for the possible vertical distribution of the recombination coefficient. These significant differences are interpreted in [9] by a probably stronger temperature dependence of $\alpha_D(T_e)$ with respect to the laboratory data and deviation from the condition $q=0$, because a certain portion of the solar radiation still penetrates to these heights. But the evaluation of all possible ionization sources in the middle ionosphere (L_α, L_β, CIII, 900-1000 Å continuum, soft-X-ray radiation with $\lambda = 40$ to 200 Å, etc.) definitely shows that the integral intensity of the solar ionizing radiations disappears after sunset due to the dense atmospheric layers the sunbeam has to penetrate. The radiation scattered by the geocorona is of negligible importance to the relatively high level of the N_e presunset values, but could be of minimum importance during the sunrise period. Therefore, there are no serious arguments to explain the great difference between the $\alpha_{eff}(Z)$ distributions obtained by the electron density profile, on the one hand, and the theoretical and laboratory values of the recombination coefficient — on the other, as defined in [9].

The significant differences between α_{eff} values calculated from Arecibo ionospheric data and the theoretical and laboratory data values of this magnitude may be explained considering the strong motion of sunset-sunrise ionosphere and, in particular, the intensive vertical movements between 130 and 200 km over the earth during these transition periods. This reasonable physical consideration requires the application of the following well-known form of the balance equation (see for ex. [3]) in (1):

$$\frac{dN_e}{dt} = q - \alpha N_e^2 - \operatorname{div}(N_e \mathbf{V}), \tag{3}$$

where $\mathbf{V}$ is the total plasma bulk velocity. The familiar expressions including the diffusion may be applied to the divergent term in (3), but the vertical ionization transfer is determinant for the sunset-rise plasma motions between 130 and 200 km. That is why the divergent term in (3) is often replaced by its vertical part only. Taking into consideration that $q \approx 0$ in the examined period and denoting $\operatorname{div}(N_e \mathbf{V}) \approx M$, from (3) we obtain

$$\frac{dN_e}{dt} = -\alpha N_e^2 - M. \tag{4}$$

In the time integration of (4) we obtain first approximation

$$\frac{1}{N_e} \approx \left(-\alpha - \frac{M}{N_e^2}\right) \cdot t + C_0. \tag{5}$$

The experimental fact that the dependence between $1/N_e$ and the time t is almost straightly linear is considered in (5). And such straight linearity is possible only when the factor before the time t is constant, i. e.

$$\alpha + \frac{M}{N_e^2} \approx \text{const.} \tag{6}$$

The constant of the right-hand side is equal to α_{eff} according to formula (2).

The straight linear dependence between $1/N_e$ and t is confirmed by all data available from Arecibo for thd sunset period. Therefore, if not neglecting motions, we should consider them as modifying α_{eff} to incredible values compared with laboratory measurements and theoretical calculations. It follows from (6) that

$$\frac{M}{N_e^2} = A, \tag{7}$$

where the A value is constant at sunrise-sunset period but changes with the altitude Z.

The dependence (7) is of particular interest because it demonstrates that the time variations of the motion contribution to the middle ionospheric balance during sunrise-sunset period are proportional to the square of the electron density, i. e.

$$M(t)|_{z=\text{const}} = A N_e^2(t)|_{z=\text{const}}. \tag{8}$$

It follows from (6) that the correction which should reduce the α_{eff} value to more realistic quantities is the magnitude $A(Z)$ according to [9]. In fact, the α_{eff} value of (2) is identic to the sum $\alpha_{eff} + A$ in (5). Therefore, if we have computations on the α_{eff} value from other measurements, it would be possible to calculate the factor A from (5) and from there — the contribution of the motions M. In order to obtain tentative values of the divergent term M, we have to proceed as follows: to define theoretically the value of the coefficient α as an effective coefficient of the dissociative recombination in a medium with significant concentration of molecular O_2^+ and NO^+ ions

$$\alpha = \frac{\alpha_D(O_2^+)[O_2^+]^2 + \alpha_D(NO^+)[NO^+]}{[O_2^+] + [NO^+] + [O^+]}. \tag{9}$$

The yield of (9) shows the fact that the total ion concentration between 130 and 200 km is defined by the sum of the denominator under the examined conditions, i. e.

$$[O_2^+] + [NO^+] + [O^+] = N_i = N_e. \tag{10}$$

In order to define altitudinal variations of α, we use most recently determined values of the temperature dependence of $\alpha_D(O_2^+)$ and $\alpha_D(NO_2^+)$ which according to [10] are:

$$\alpha_D(O_2^+) = 1.6 \times 10^{-7} \left(\frac{T_e}{300}\right)^{-0.55}, \tag{11}$$

$$\alpha_D(NO^+) = 4.2 \times 10^{-7} \left(\frac{T_e}{300}\right)^{-0.85}. \tag{12}$$

When there is no available evidence on the vertical distributions of the ion densities over Arecibo, for the examined period we use the data on the relative ion densities: $[O_2^+]/N_e$ and $[NO^+]/N_e$ according to the IRI model [11]. We also apply the IRI model for the vertical distribution of the electron tempera-

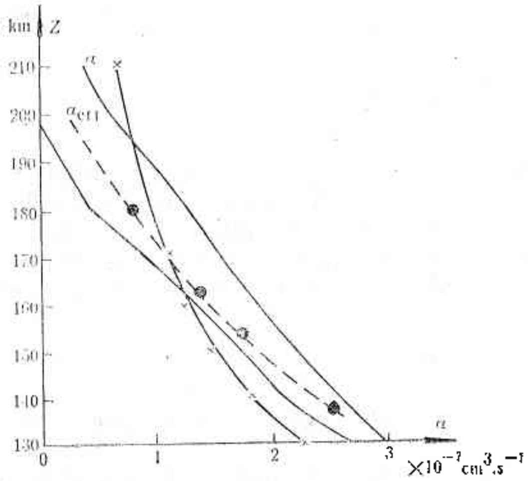

Fig. 1

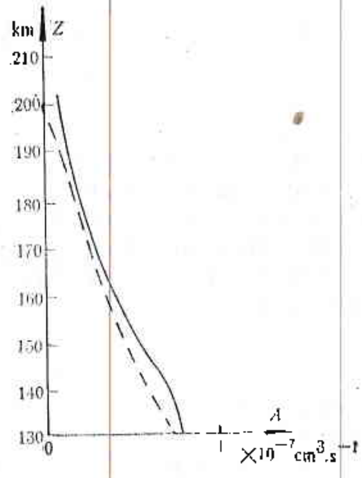

Fig. 2

ture $T_e(Z)$ but with the corrections from our measurements performed with IRI the Vertical series rockets (see [12]). If we denote $K_{O_2^+}=[O_2^+]/N_e$ and $K_{NO^+}=[NO^+]/N_e$, we shall obtain

$$\alpha=\alpha_D(O_2^+)K_{O_2^+}+\alpha_D(NO^+)K_{NO^+} \quad (13)$$

for α according to [9]. The vertical profiles of $\alpha_D(O_2^+)$ and $\alpha_D(NO^+)$ are built according to [11], [12] and the $T_e(Z)$ vertical profile — according to IRI and the corrections from [12]. The coefficients $K_{O_2^+}$ and K_{NO^+} are determined using IRI, and the altitudinal profile of V is defined from [11], as shown in Fig. 1. The same Figure demonstrates as an example the profile of α_{eff} as obtained in [9] on data from sunset values of $N_e(t, Z)$ for Sept. 9, 1966 and calculated according to formula (2), i. e. neglecting motions. The analysis of avialable sunset-sunrise data from Arecibo, computed by formula (2) although with certain variations, confirms the curve in Fig. 1. The data scatter is shown with hatched area in the Figure. In first approximation we may consider the values of α_{eff} from [9] as close to the average ones for this quantity obtained with the primitive analysis performed by formula (2). The comparison between theoretical α and the field of α_{eff} values shows that the deviations between these two values are not a random phenomenon but are rather of a basic nature. This confirms the important role of motions in the nocturnal middle ionosphere and Fig. 1 clearly shows that α is greater than all the values of α_{eff} obtained for $Z>190$ km and $\alpha<\alpha_{eff}$ for heights $Z<160$ km. An approximate equality exists between 160 and 190 km and for the particular case of Sept. 9, 1966 this equalization appears at 170 km.

The altitudinal profile for

$$A(Z)=\alpha_{eff}-\alpha \quad (14)$$

can be built using euaqtions (5), (6) and (7). Figure 2 shows this profile for the conditions in [9].

Figure 3 demonstrates three vertical profiles of M for the sunset period of Sept. 9, 1966 (for the beginning of the sunset at 18 h 28 min LT; for a typical moment at 19 h 29 min LT and for one of the final moments at 20 h 02 min LT, respectively).

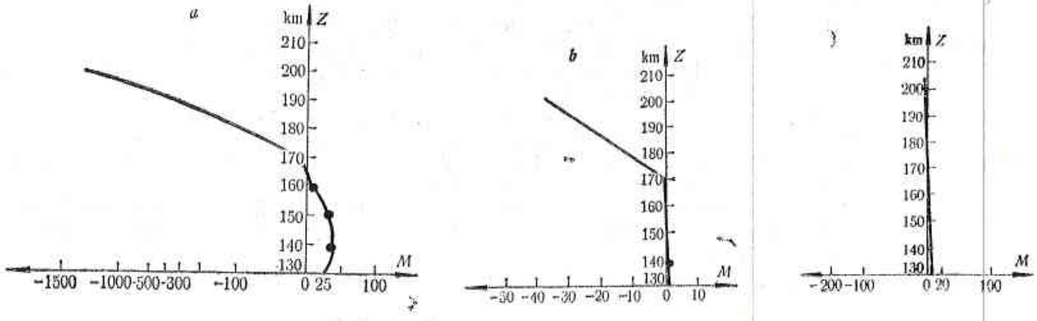

Fig. 3

The absence of M values in the altitudinal region between 140 and 160 km is due to the decrease of N_e below the measurement possibilities of the incoherent radar. The calculations of M are performed according to formula (8).

It is seen from Fig. 3 that the value $M(Z)$ changes in sign at altitude of about 165 km. It is clear from Fig. 1 for the dependence (14) that for the altitudinal region from 160 to 190 km we shall obtain a systematic change in sign of M for all cases available in Arecibo. In the upper part the electron transfer increases the electron density and in the sunset period it reacts as a particular ionizing factor. The reverse phenomenon takes place in the bottom part — the electron transfer decreases the electron density and is equivalent of the neutralization increase.

Of course, factor M is not precisely adequate to the contribution of motions in the balance equation (3) because the coefficient α was theoretically found and all the measurement errors as well as the deviations of the IRI model from reality are included in the magnitude M. But in first approximation we may consider that M represents values similar to the divergent term in (3) and when using other methods to find for instance the electron temperature and the ion composition the contribution of the motions can be determined accurately.

From this paper we can make the conclusion that the contribution of motions to the formation of the night structure of the middle ionosphere is not to be neglected and the complete analysis of the neutralizing processes cannot be performed on the basis of chemical eduilibrium only. Together with this we assume that it is useful and important to define the constant ratio between motions M contribtion to the squared electron density (see formula (6)).

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О кинетических процессах в средней ионосфере при закате Солнца

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Резюме)

Показано, что для полноценного анализа временных и высотных изменений электронной концентрации в ночной и восходно-закатной средней ионосфере (в пределах от 130 до 200 km над Землей) необходимо учитывать перенос электронов и ионов. Учет этого переноса по данным инкогерентного радара в Arecibo приводит к выводу, что временные изменения переноса на данной постоянной высоте пропорциональны N_e^2. Исходя из модели IRI и данных об электронной концентрации, полученных в Arecibo, определены теоретические изменения эффективного рекомбинационного коэффициента α, а по его разностям с значениями α_{eff}, вычисленными по ионосферным данным (пренебрегая движениями), вычислены высотные изменения дивергентного члена в основном уравнении баланса электронной концентрации.