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GEOPHYSICS

1966

SovietRxiv

Abstract

Full Text

UDC 550.388.2

GEOPHYSICS

G. S. IVANOV-KHOLODNYI

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(Presented by Academician E. K. Fedorov, 22 XII 1965)

Elucidating the relative role of X-ray and ultraviolet radiation in the ionization of region E is one of the fundamental questions in the theory of ionization of the lower ionosphere at altitudes of 100–200 km. There are a number of facts: the discrepancy between the variation of the square of the electron concentration n_e^2 and the variation of the ion-formation rate q during the day and over the solar-activity cycle ([1]), and the nonconstancy of the ratio of the concentrations of the ions NO^+ and O_2^+ with height and in the transition from maximum to minimum solar activity ([2]), which are in contradiction with the theory in which it is usually assumed that the effective recombination coefficient α' in the lower part of the ionosphere at altitudes of 100–200 km does not change during the day or as a function of the level of solar activity. However, as shown in ([3]), one should expect that α' is not a constant quantity. It will be shown below that calculations of the composition of ions formed during ionization by solar radiation confirm this conclusion, and this makes it possible to eliminate the indicated discrepancies between experiment and theory.

The relative composition of the primary ions O^+, O_2^+, and N_2^+ formed under the action of solar radiation was determined in the course of calculations on the M-20 of the total ion-formation rate q ([4]). The results of the calculation under conditions of low solar activity are presented in Fig. 1. For each ion, the curves for different z_0 are similar, but shift upward and are somewhat stretched along the altitude scale as z_0 increases. For each ion at altitudes of 200–300 km, the ion-formation rate varies approximately in proportion to the neutral composition of the atmosphere, just as at low altitudes of $\sim$ 100 km. But at intermediate altitudes $q(O_2^+)/q$ increases anomalously, while $q(N_2^+)/q$ decreases anomalously, as a result of which the ratio $q(O_2^+)/q(N_2^+)$ increases by as much as 1.5–2 orders of magnitude. The zone of anomalous increase of $q(O_2^+)/q(N_2^+)$ occupies an altitude region equal to approximately 2–3 heights of a homogeneous atmosphere; as z_0 changes from 0–50° to 80–90° its center shifts from $\sim$ 105 to $\sim$ 125 km. The cause of the anomalous change in the composition of the ions

Figure 1. Variation with height of the relative values of the formation rates of the ions O^+, O_2^+, and N_2^+ at low solar activity. Each curve corresponds to the value of $z_\odot$ indicated by the number next to the curve. Crosses correspond to the hypothetical case of absence of radiation absorption.

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Figure 2. Variation with height of the ion-formation rate $q(\Delta\lambda)/q$ for four principal spectral intervals $\Delta\lambda$: 0-165 Å, 165-740 Å, 740-911 Å (L_c), and 911-1038 Å. Calculation for low solar activity at $z_\odot = 55°$ and at $z_\odot = 90°$.

Figure 2: Figure 2. Variation with height of the ion-formation rate $q(\Delta\lambda)/q$ for four principal spectral intervals $\Delta\lambda$: 0-165 Å, 165-740 Å, 740-911 Å (L_c), and 911-1038 Å. Calculation for low solar activity at $z_\odot = 55°$ and at $z_\odot = 90°$.

formed lies in the change in the spectrum of the solar ionizing radiation as it passes through the upper atmosphere.

Indeed, let us consider Fig. 2, in which, for $z_0 = 55°$ and $z_0 = 90°$, the change with altitude is presented for the relative ion-formation rate $q(\Delta\lambda)/q$, calculated for four main spectral regions $\Delta\lambda$: 0-165 Å, 165-740 Å, 740-911 Å, and 911-1038 Å. It is seen that above $\sim$ 150 km ions are formed mainly under the action of short-wavelength radiation of 165-740 Å, while the contribution of radiation of 740-911 Å is 4-5 times smaller. Below $\sim$ 90 km the main source of ionization is X-ray radiation (with wavelength shorter than $\sim$ 10 Å). It is noteworthy that at altitudes of 100-115 km the main contribution to ion formation is made by ultraviolet radiation of 911-1038 Å. As can be seen from Fig. 2, for large zenith angles z_0 the picture is the same as for $z_0 = 0$-55°, but shifted upward and somewhat stretched along the altitude scale. Since radiation of 911-1038 Å forms only O_2^+ ions, the anomalous increase of $q(O_2^+)/q$ at the altitudes under consideration for $z_0 = 55°$ is understandable. In Fig. 1, crosses show-

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Fig. 2. Variation with height of the ion-formation rate $q(\Delta\lambda)/q$ for four principal spectral intervals $\Delta\lambda$: 0-165 Å, 165-740 Å, 740-911 Å (L_c), and 911-1038 Å. Calculation for low solar activity at $z_\odot = 55°$ and at $z_\odot = 90°$.

on the curve of the presumed change in the rate of ion formation that would take place in the absence of absorption of radiation. In the present case, changes in $q(O_2^+)/q(N_2^+)$ are proportional to the change in $[O_2]/[N_2]$.

Calculations carried out for high solar activity also reveal an anomalous change in the ratio $q(O_2^+)/q(N_2^+)$, but with a smaller amplitude. This is due to the fact that, in going from the minimum to the maximum of solar activity, the intensity of radiation at 911–1038 Å, which forms only O_2^+ ions, changes by less than a factor of 1.5, while the intensity of radiation at 0–740 Å changes by more than a factor of 4–5.

Using the data of Fig. 2, one can find the nature of the change in the equilibrium concentrations of the principal molecular ions O_2^+ and NO^+. From (2) it follows that the ratio of the concentrations of these ions at heights of 200–150 km is

$$\frac{[NO^+]}{[O_2^+]} = \gamma\frac{\alpha_{O2^+}}{\alpha_{NO^+}}\left[1 + \frac{(1+\gamma)q(O_2^+)}{q(O^+)+q(N_2^+)}\right]^{-1}, \quad (1)$$

where α_{O2^+} and α_{NO^+} are the coefficients of dissociative recombination of the ions O_2^+ and NO^+; $\gamma = [N_2]\gamma_1/[O_2]\gamma_2$; γ_1 and γ_2 are the rate constants of the ion-molecular reactions $O^+ + N_2 \to NO^+ + N$ and $O^+ + O_2 \to O_2^+ + O$, respectively. In expression (1), the ratio $\alpha_{O2^+}/\alpha_{NO^+}$ and the quantity γ depend little on height or on $z_\odot$; therefore variations of the ratio $[NO^+]/[O_2^+]$ are determined mainly by variations of the expression enclosed in the square brackets in (1). From Fig. 2 it is seen that, with decreasing height in the region 200–150 km and with increasing $z_\odot$ in the interval 60–90°, the ratio $q(O_2^+)/(q(O^+)+q(N_2^+))$ increases; consequently, the ratio $[NO^+]/[O_2^+]$ should decrease. At high solar activity, first, the value of the ratio $q(O_2^+)/(q(O^+)+q(N_2^+))$ is smaller (and, consequently, $[NO^+]/[O_2^+]$ is larger), and second, it varies less strongly with height and $z_\odot$, which leads to smaller variations of $[NO^+]/[O_2^+]$.

In the region of anomalous increase of the ratio $q(O_2^+)/(q(O^+)+q(N_2^+))$, the primary ion formed is mainly O_2^+. The ion NO^+ can apparently be formed only by the reaction $O_2^+ + N_2 \to NO^+ + NO$ (with rate constant γ_3); therefore, at equilibrium for it we shall have

$$\gamma_3[N_2][O^+] = \alpha_{NO^+}[NO^+]n_e, \quad (2)$$

whence we obtain

$$[NO^+]/[O_2^+] = \gamma_3[N_2]/\alpha_{NO^+}n_e. \quad (3)$$

At this height, with increasing $z_\odot$ or decreasing solar activity, n_e decreases; therefore, in contrast to heights of 150–200 km, below $\sim$ 150 km the ratio $[NO^+]/[O_2^+]$ should increase. Hence it follows that $\gamma_3 \approx (3\text{–}10)\cdot 10^{-14}$ cm^{3}s^{-1}.

These conclusions are important in two respects:

1) They explain one of the main discrepancies between theory and experiment, noted at the beginning of the paper. The character of the variations of $[NO^+]/[O_2^+]$ predicted above as a function of $z_\odot$ and the level of solar activity (opposite for heights of 150–200 km and below 150 km) agrees with the data of the most reliable mass-spectrometric measurements, in particular with the data of (5, 6).

2) They indicate the nonconstancy of the effective recombination coefficient α' in the ionosphere and make it possible to predict the nature of its changes as a function of height, $z_\odot$, and the level of solar activity. Let us dwell on this question by considering two methods of determining α'.

1. Neutralization in the ionosphere is accomplished through dissociative recombination of molecular ions, as a result of which

$$\alpha' = \alpha_{NO^+}[NO^+]/n_e + \alpha_{O2^+} + [O_2^+]/n_e. \tag{4}$$

For $([NO^+] + [O_2^+])n_e = \text{const}$ and $\alpha_{O2^+} > \alpha_{NO^+}$, the change in the value of α' is opposite to the change in the ratio $[NO^+]/[O_2^+]$. Therefore, in accordance with what was set forth above, in going from low solar activity to high activity at heights below ~ 150 km there should be an increase in α',

and at altitudes of 150-200 km the value of α' should decrease. Indeed, on the basis of the most reliable data from mass-spectrometric measurements of the concentrations $[NO^+]$ and $[O_2^+]$, in ([3]) precisely such variations of the value α' were found as a function of $z_\odot$ and of the level of solar activity.

2. As is known, under equilibrium conditions

$$\alpha' = q/n_e^2. \tag{5}$$

On the basis of the data on $q(h)$ in ([4]) and rocket data on $n_e(h)$ in ([1]), we calculated the profiles $\alpha'(h)$, shown in Fig. 3 for two zenith angles $z_\odot$, 55° (2) and 80° (3), under conditions of low solar activity. Let us note the main features of the profiles $\alpha'(h)$: at an altitude of 130-150 km a maximum of α' is observed; with an increase of $z_\odot$, in the region above 150 km α' increases, while below 150 km it decreases. At high solar activity an analogous picture is observed, but the value of α' at great altitudes is somewhat larger. These conclusions for $z_\odot = 55°$ agree with the conclusions on the relative variations of α' obtained from ([4]) in ([3]). For comparison, in Fig. 3 the profile $\alpha'(h)$ for $z_\odot = 55°$ from ([3]) is given by the dotted line; within a factor of 1.5 it coincides with the profile calculated from (5).

Fig. 3. Change of the effective recombination coefficient α' with altitude. Curve 1—from ([3]), 2 and 3—from equation (5) at $z_\odot = 55°$ and $z_\odot = 80°$, respectively.

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Figure 3: Fig. 3. Change of the effective recombination coefficient α' with altitude. Curve 1—from ([3]), 2 and 3—from equation (5) at $z_{\odot} = 55°$ and $z_{\odot} = 80°$, respectively.

Let us compare the conclusions about the variations of α', obtained by the first and second methods, with experimental data. a) Thus, above $\sim$ 150 km, α' increases as the Sun approaches the horizon and as solar activity decreases, i.e., it varies in antiphase with q, while below $\sim$ 150 km α' varies in phase with q. Owing to this, the change in the value n_e^2 deviates somewhat from the change in the value of q during the day (for $\alpha' = \text{const}$, $n_e^2/q = \text{const}$), and the deviations have different signs at altitudes above and below 150 km, in agreement with the conclusions from the rocket data in ([1]). b) The decrease of α' with decreasing q at altitudes < 150 km explains why, in the E region of the ionosphere, in going from the maximum to the minimum of solar activity, n_e^2 decreases twice as slowly as q. This is connected with the fact that at the minimum of activity the value of α' is approximately 2 times smaller than at the maximum of activity. Since in the E region $[NO^+] + [O_2^+] \approx n_e$, and $\alpha_{O2^+} > \alpha_{NO^+}$, it follows from this, taking (3) into account, in agreement with the conclusions given above, that at the minimum of activity the ratio $[NO^+]/[O_2^+]$ should increase. This corresponds to the results of mass-spectrometric measurements by V. G. Istomin ([5,6]) at these altitudes, but contradicts new data ([8,9]), according to which the ratio $[NO^+]/[O_2^+]$ is underestimated by almost an order of magnitude.

The conclusions obtained about the character of the variations of $[NO^+]/[O_2^+]$ and α' are important for understanding variations of physical conditions in the ionosphere at altitudes of 100–200 km.

Institute of Applied Geophysics

Received
15 XII 1965

CITED LITERATURE

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Note: Figure translations are in progress. See original paper for figures.