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Abstract

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IONIZATION IN THE EARTH' S IONOSPHERE AND THE ENERGY OF SHORT-WAVE ULTRAVIOLET RADIATION FROM THE SUN

(Presented by Academician E. K. Fedorov, 10 XI 1960)

One of the remarkable scientific achievements made possible by the launching of artificial Earth satellites and rockets is the direct acquisition of new data on the physical properties of the upper atmosphere. Completely new ideas about the ionic composition of the upper layers were obtained by means of mass-spectrometric studies by V. G. Istomin ($^{1-4}$). Especially surprising in these results is the establishment of the presence of a large number of different molecular ions at all altitudes up to 500 km, where, according to a number of estimates, all molecular constituents of the atmosphere, except N_2, should be entirely dissociated. In the works of A. D. Danilov (^{5,6}) it was shown that the apparently unusual distribution with altitude of the molecular ions NO^+ and O_2^+ is naturally explained with the aid of cycles of reactions:

$$\begin{array}{ll} O^+ + N_2 \to NO^+ + N, & \left.\begin{array}{l} O^+ + O \to O_2^+ + h\nu, \\ O_2^+ + e \to O' + O'' \end{array}\right\} \\ NO^+ + e \to N + O; & \end{array} \tag{1}$$

Reactions of type (1) explain the relative concentrations of atomic and molecular ions at all the considered altitudes, 100–500 km.

The most interesting consequence of the reaction cycles (1) is that very intense processes are asserted for the ionosphere: for the disappearance of atomic ions—charge exchange with the formation of molecular ions, and for the neutralization of ions—dissociative recombination.

In accordance with this, our ideas about the sources of ionization in the upper atmosphere must also be completely changed.

Indeed, the rate of the reaction of dissociative recombination ($\alpha^* = 10^{-6}$—10^{-7} cm^3 sec^{-1}) is 5-6 orders of magnitude greater than the rate of neutralization of atomic ions; therefore the main channel of particle neutralization in the ionosphere is the conversion of atomic ions into molecular ions and the subsequent neutralization of molecular ions. The effective rate of recombination will be determined mainly by the latter mechanism, whose rate exceeds by 2-3 orders of magnitude the currently existing estimates of recombination rates in the ionosphere, obtained on the basis of radio measurements and observational data during solar eclipses.

Let us calculate the total number of recombinations in a column of the ionosphere with cross section 1 cm^2. The rate of electron disappearance at any altitude h is equal to

$$\frac{dn_e}{dt} = \alpha^* n_e n_2^+ + \alpha_1 n_e n_1^+, \tag{2}$$

where n_2^+, n_1^+, and n_e are the concentrations of molecular and atomic ions and electrons, respectively; α^* and α_1 are the coefficients of dissociative recombination and recombination of atomic ions, respectively.

The electron concentration at altitudes above 80 km was measured on rockets by K. I. Gringauz (^{7}), Seddon and Jackson ($^{10-15}$), and with the aid of Soviet-

···of artificial Earth satellites ($^{16-19}$). Table 1 gives the variation of n_e with altitude for the daytime ionosphere, obtained on the basis of these measurements.

The fraction of positive molecular ions in the ionosphere was estimated according to the work of V. G. Istomin ($^{1-4}$), Johnson et al. (^{20,21}). For altitudes of 400–700 km we also used Rice' s data (^{22}) on the altitude variation of the concentration of N_2^+, obtained from observations of sunlit auroras; for these, evidently, the altitude variation of N_2^+ should not differ greatly from ordinary conditions.

Table 1

	100	150	200	250	300	400	500	600	700
h, km	100	150	200	250	300	400	500	600	700
n_e, cm^{-3}	$1 \cdot 10^5$	$2 \cdot 10^5$	$5 \cdot 10^5$	$1 \cdot 10^6$	$1.5 \cdot 10^6$	$1.2 \cdot 10^6$	$1 \cdot 10^6$	$6 \cdot 10^5$	$4 \cdot 10^5$
$\frac{n_2^+}{n_1^+ + n_2^+}$	1	0.9	0.6	0.18	$7 \cdot 10^{-2}$	$7.6 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$6.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
$\alpha^* n_e n_2^+$, cm^{-3} sec^{-1} *	$1 \cdot 10^4$	$3.5 \cdot 10^4$	$1.5 \cdot 10^5$	$1.8 \cdot 10^5$	$1.57 \cdot 10^5$	$1.1 \cdot 10^4$	$2 \cdot 10^3$	$2.3 \cdot 10^2$	50

* Under the assumption that $\alpha^* = 10^{-6}$ cm^3 sec^{-1}.

According to mass-spectrometric measurements, the concentration of negative ions is negligibly small in comparison with the concentration of positive ions; therefore $n_1^+ + n_2^+ = n_e$. Starting from the data of Table 1 and from the fact that α^* exceeds α_1 by 5—6 orders of magnitude, it is easy to see that the recombinations in equation (2) are determined at all the altitudes considered by the first term, i.e., by dissociative recombination of molecular ions; therefore

$$-\frac{dn_e}{dt} = \alpha^* n_e n_2^+ = \alpha^* \frac{n_2^+}{n_1^+ + n_2^+} n_e^2. \tag{3}$$

The last row of Table 1 gives the number of recombinations occurring in 1 sec in 1 cm^3 at different altitudes. From these data it follows that, in a column of the ionosphere with a cross section of 1 cm^2, in all $3 \cdot 10^{11}$—$3 \cdot 10^{12}$ acts of neutralization occur. This estimate exceeds earlier estimates by 2—3 orders of magnitude (see, for example, ([23])).

Thus, interpretation of the new data on the ionic composition obtained with the aid of rockets and satellites indicates the existence in the ionosphere of much more intense recombination processes, and consequently also ionization processes, than was previously thought. In essence, these data indicate a crisis in our ideas about the ionosphere and the sources of its formation. It is enough to point out that, to maintain the observed degree of ionization in the ionosphere, a significantly more powerful flux of ionizing radiation is necessary (10—100 $\mathrm{erg/cm^2}$ sec) than has hitherto been thought ($<$ 1 $\mathrm{erg/cm^2}$ sec ([24])). In this connection let us consider the new data on the short-wavelength radiation of the Sun.

In 1958 and 1959, Violett and Rense ([25]) obtained spectra of the short-wavelength radiation of the Sun from 1200 to 83.9 Å. In this spectral region more than 150 emission lines were found, the brightest of which, He II λ 304 Å, is comparable in intensity with the $L\alpha$ line. If one takes into account that the intensity of $L\alpha$, according to the latest rocket measurements using various radiation detectors, is 1—10 $\mathrm{erg/cm^2}$ sec at the Earth ([26]), then it is obvious that the new value of the intensity of the line radiation of the Sun with wavelength shorter than 800 Å (capable of ionizing any molecule or atom of the atmosphere) is significantly greater than the former indirect estimates ([23,24]). In all, the lines with $\lambda \leq 800$, as can be seen from the spectrum ([25]), carry a radiation flux at least 20 times greater than that in the line λ 304 Å.

The intensity of the λ 304 Å line was recently estimated for one of the rocket experiments by Rice and Rense ([27]). Assuming that the intensity of the $L\alpha$ line is 3 $\mathrm{erg/cm^2}$ sec, they obtained for the λ 304 Å line an intensity

15 $\mathrm{erg/cm^2}$ sec at the Earth. However, the authors of ([27]) used unreliable information on the density of the atmosphere, based on a somewhat inaccurate model, and overestimated values for the effective absorption cross section. As a result, they obtained that the atmosphere above the 200 km level, at the solar

zenith angle $z_\odot = 79.5^\circ$, attenuates the intensity of $\lambda 304$ Å by a factor of 18! Let us estimate the intensity of $\lambda 304$ Å anew. If I_0 is the intensity outside the atmosphere, then at height h

$$I(h_0) = I_0 e^{-\tau(h)},$$

where

$$\tau(h) = k \sec z_\odot \int_0^\infty n\, dh$$

is the optical thickness of the atmosphere; k is the absorption coefficient of the atmosphere;

$$\int_h^\infty n\, dh \equiv N$$

is the number of absorbing particles in a column of the atmosphere with cross section 1 cm^2 above the level h. Writing equation (3) for two heights h_1 and h_2, by simple transformations one can obtain, without making any assumptions about the nature of the absorbing gas in the atmosphere, that

$$\lg I_0 = \frac{N_1 \lg I_2 - N_2 \lg I_1}{N_1 - N_2}. \tag{4}$$

Violett and Rense (^{25}) report two experiments in which the $\lambda 304$ Å line was measured at two heights. Applying equation (4) to these data and using new data (experimental, not based on a theoretical model) on the density of the atmosphere at altitudes of 150-200 km (^{28,29}), one can readily obtain, in agreement with both experiments (see (^{30})), that $I_0 = 1.2$ erg/cm^{2}sec (assuming that the intensity of $L\alpha$ is 3 erg/cm^{2}sec). The agreement of the results obtained in the two different experiments is very good. However, in one of the experiments (March 1959) the effective absorption cross section of the $\lambda 304$ Å line by the atmosphere was thereby found to be 1-1.5 $\cdot 10^{-17}$ cm, which agrees well with modern data, whereas according to the other experiment (June 1958) it was 4.3 times smaller. The principal source of this extremely large discrepancy is the error of the authors of (^{27}) in estimating the lower height h_2 for this experiment. As indicated in (^{27}), for h_2 the mean height of the rocket during the exposure was taken. However, with the sharp change in the velocity of the rocket at these heights, and also with the sharp change in the intensity of the line because of absorption in the atmosphere, the use of mean values gives a very large error. During the 40 sec exposure (^{25}), the rocket passed from a height of 165 km to a height of 115 km. In this interval the intensity of the $\lambda 304$ Å line at $z_\odot = 79.5^\circ$ should have changed approximately from 0.05 to $\sim 10^{-10}$ erg/cm^{2}sec. It is clear that the effective height of registration of the emission line on the photographic plate will correspond to the position of the rocket somewhere at the beginning of the exposure. It can be shown that the principal share of the blackening on the photographic plate is produced by the first few seconds of the exposure, while the rocket is still sufficiently high. Therefore the estimate of the height in ([27]) is greatly understated. Allowance for these corrections may somewhat affect our calculation of I_0 for the June 1958 experiment. However, this effect cannot be significant, since the absorption at the height $h = 212$ km is small. From equation (4) it follows, if the new data on atmospheric density ([28,29]) are taken into account, that at a height of 212 km $I/I_0 = 1.5$.

Absolute calibration of rocket measurements of the intensity of short-wave solar radiation is an extremely difficult problem, and therefore the results of such measurements require careful verification. One of the most reliable methods of verification is comparison of data on solar ultraviolet radiation, originating from the corona and from the transition layer between the corona and the photosphere, with data on radiation in other regions of the spectrum. For this, however, it is necessary to have exact knowledge of the structure and physical conditions in the transition layer. In ([30]) a model was constructed based on a combination of rocket data on ultraviolet radiation and data on solar radio emission. This mo-

the transition-layer model is very sensitive to the value used for the intensity of the short-wave radiation; it confirms the correctness of the above estimate of the intensity of the line $\lambda 304$ Å.

To summarize, it may be said that the intensity of the total solar ultraviolet radiation outside the Earth' s atmosphere is ~ 30 erg/cm^2 sec, or, as summation of all the radiation lines on the basis of the data on energy calibration given in ([30]) shows, amounts to $5—10 \cdot 10^{11}$ quanta/cm^2 sec.

Comparing these data on the energy of solar short-wave radiation with the data given above on the rate of ionization and recombination processes in the ionosphere, we see that they are in excellent agreement with one another. Thus the latest data on the Sun's ultraviolet radiation confirm the new ideas about the principal elementary processes in the ionosphere. Indeed, the Sun' s radiation is capable of providing the ionization rate that was estimated in the first part of the article. The new ideas about the principal processes in the ionosphere make it possible to explain a number of phenomena occurring in the upper atmosphere that are connected with sources of release of large amounts of energy and with intense recombination processes: heating of the ionosphere and the loss by the F layer of a large quantity of heat through thermal conductivity, the state of the nighttime ionosphere and during solar eclipses, and other questions, to which separate articles will be devoted.

Principal conclusions. The principal process of neutralization in the ionosphere is dissociative recombination of molecular ions; atomic ions are converted into molecular ions as a result of charge-exchange processes. The total number of recombination and ionization processes in an atmospheric column of cross section 1 cm^2 is equal to $3 \cdot 10^{11}$—$3 \cdot 10^{12}$ cm^{-2} sec^{-1}.

The new ideas about the principal processes in the ionosphere are consistent with the new data on the short-wave radiation of the Sun, in which, for the spectral region $\lambda \leqslant 800$ Å, 5—$10 \cdot 10^{11}$ quanta/cm^2 sec are contained.

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