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CHARACTERICTICS OF NEUTRAL AND IONIZED COMPONENTS OF THE ATMOSPHERE AT HEIGHTS OF 100-500 KM MEASURED DURING THE FLIGHTS OF GEOPHYSICAL ROCKETS

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MOSCOW

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In the autumn of 1965 during launchings of geophysical rockets experiments aimed at exploring the upper atmosphere were carried out. In particular, they included simultaneous measurements of the electron density n_e by dispersion radio method, of the electron temperature T_e by probe methods and of solar ultraviolet radiation by a photoelectron analyzer. Measurements were performed in the height range of 100-500km on September 20 and October 1 at the Sun's zenithal angles of about 82° and 80° respectively. Rocket trajectories were close to vertical ones.

As a result the information was obtained not only on the ionized but also on the neutral components of the atmosphere. Brief description of experiments and some preliminary results have been given earlier [1] .

In the present communication the obtained results of different experiments are given in a more comprehensive form and are compared. Figure 1 shows the electron density height variations obtained on September 20, 1965 both by the dispersion interferometer method (curve a) and by the probe method (curve b). As evident from the figure, height distributions of the electron density obtained by different methods are of a similar character. Electron density values obtained by probe measurements were somewhat lower by magnitude than those obtained by the interferometer method. Therefore n_e values given in curve (b) of Figure 1 were normalized by the n_e value in the maximum of curve (a). Probe curve (a) has been obtained from data of three planar probes: a one-electrode (Langmuir) probe, two-electrode and three-electrode electron traps. The same figure gives the height distribution of the electron temperature obtained by the Langmuir probe. The values of electron temperatures T_e are averaged over the height intervals of about 50 km. The accuracy of determining T_e is ±100°C. Within these limits the T_e values from the data of three probes coincide [2] .

From the temperature curve the tendency is clear of increase with height from about 1800° K to 2400° K , although the height dependence of the temperature is of a non-monotonous type. As evident from Figure 1, the difference of T_e values obtained at various heights exceeds the possible values of experimental errors and most probably is due to the actual character of T_e distribution with height.

In the experiment on investigating of the photoemission by means of a photoelectron analyzer with a platinum photocathode the dependence of the photocurrent on the potential of the analyzing grid was measured. This experiment has been described in [3] . The recording of photocurrent began approximately from a height of 80 km, and with the ascent of the rocket the density of the saturation photocurrent corresponding to the positive (with respect to t photocathode) potential of the analyzing grid increased from 3.10^{-10} a/cm^2 to 4.10^{-9} a/cm^2. It is natural to sup

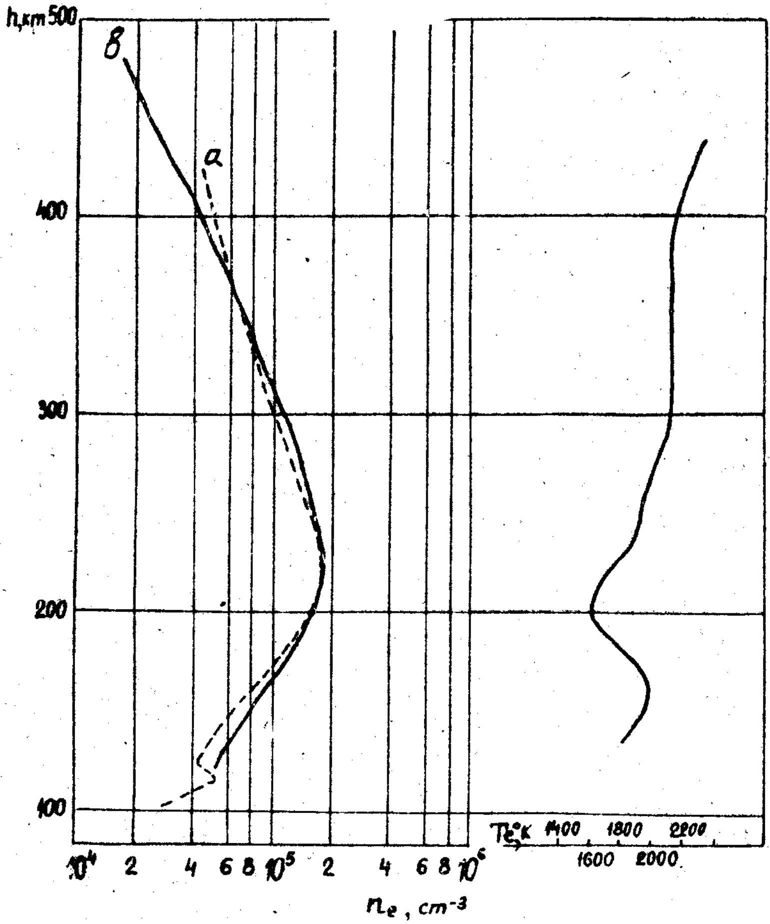
h,km 500
400
300
200
100
8
a
10^4
2
4
6
8
10^5
2
4
6
8
10^6
n_e, cm^{-3}
Te °K
1400
1800
2200
1600
2000

Fig. 1

that the increase in photocurrent observed with the rocket's ascent is due to the decrease in solar ultraviolet radiation absorption in the upper atmosphere.

The analysis of the form of the volt-ampere characteristics has made it possible to evaluate the rough spectral composition of recorded radiation. The values of the integral (by the spectrum) absorption coefficient of solar radiation at heights of 100 to 500 km are given in [1] .

The form of the volt-ampere characteristics was analyzed by comparing the experimental characteristics with the calibration characteristics obtained under laboratory conditions, as it was done in [4] .

It has been found out that the recorded photocurrent is mainly due to solar radiation with the wavelengths greater than 650 Å. The calibration curves have made it possible to divide tentatively the recorded radiation into subranges with wavelengths of about 700 to 910 Å, 910 to 1050 Å and more than 1050 Å. Near the rocket's trajectory apex the photocurrents caused by the radiation of the above regions are related as 12,5:21:66,5 respectively (see Figure 2 showing the height variation of photocurrents). It is seen that ultraviolet radiation absorption in the height range of 100 to 500 km essentially differs for various spectral intervals. At high altitudes in the range of 450 to 200 km the most absorbed spectral region is about 700 to 910 Å . Below 240 km absorption in the region about 910 to 1050 Å begins and below 12o km only radiation with $\lambda >$ 1050 Å is absorbed.

From the obtained data on absorption the neutral particle concentration n in the height range of about 100 to 450 km has been evaluated. A three-component model of the atmosphere has been considered, i.e. it has been assumed that atomic oxygen, molecular oxygen and molecular nitrogen are the main upper atmospheric components responsible for ultraviolet radiation absorption. While selecting the values of the absorption cross-sections for O_2 and N_2 use was made of the experimental data by Watanabe [5], Samson and Cairns [6] and also by Hinteregger et.al. [7] who in their turn had systematized the experimental results of a number of authors. For atomic oxygen use was made of theoretical calculations by Dalgarno et.al. [8]. Since in the case in question the density was determined from absorption of the above spectral subranges and not from individual monochromatic lines for which the absorption cross-section would have been chosen more or less unambiguously, we had to assume the possibility of using of one effective value of absorption cross-section σ_{eff} for each spectral subrange under consideration. The accuracy of computing the neutral particle concentration n is mainly determined by the accuracy of the choice of this effective cross-section. The maximum error in determining n at the expense of the uncertainty of the choice of σ_{eff} does not exceed a factor of 2 to 3 for O_2 and N_2 and for atomic oxygen it amounts to about 20 per cent since for O_2 and N_2 the absorption effective cron-section

$$\sigma_{eff} = \sum_{\lambda} \sigma_{\lambda} J_{-\lambda} \Big/ \sum_{\lambda} J_{-\lambda} ,$$

(where σ_{λ} is the absorption cross-section of the component under consideration for radiation with the wavelength

λ , $J_{-\lambda}$ is the intensity of the solar radiation with the wavelength λ in the upper atmosphere) differs from σ_{min} and σ_{max} within the limits of the spectral subranges under consideration not more then by a fector of 2 to 3 while for θ - not more than by 20 per cent.

Since, as evident from Figure 2, for altitudes higher than 120 km there took place the absorption only in two spectral subranges it was possible to determine the concentrations of only two components of the neutral atmosphere for these heights. Therefore neutral molecules were regarded as one component with the effective cross-section

$$\sigma_{eff} = \sum_{1}^{2} \sigma_j n_j / n ,$$

where σ_j is the absorption effective cross-section of the j-th component in the spectral interval under consideration, n_j is the concentration of the j-th component,

$$n = n(O_2) + n(N_2).$$

According to the data available on the composition of the neutral components, the ratio of the N_2 and O_2 densities varies at heights of 120 to 300 km from 4 to 10 [7, 9] . The absorption effective cross-section for the sum of N_2 and O_2 varies not more than by 10 per cent. Thus the total O_2 and N_2 concentration is determined rather well.

The n values calculated for heights of 400 to 150 km varied from 10^8 to 10^{11} cm^{-3} respectively.

Possessing the height variations in the density and approximating individual sections of this height distribution by the exponent it is feasible to determine the scale height H . If one knows the average mass of

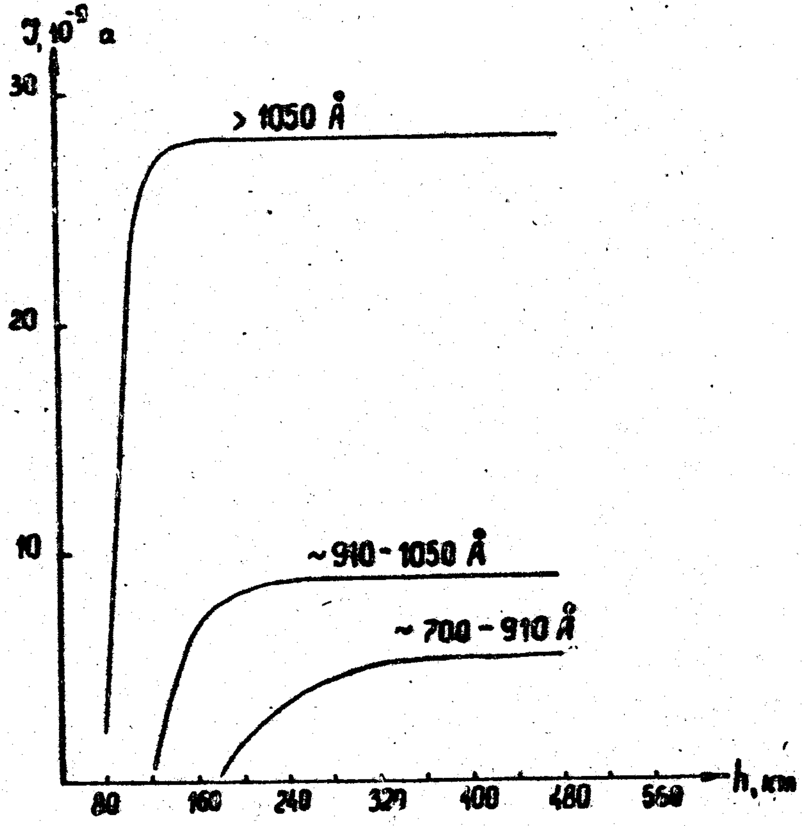
J, 10⁻⁹ a
30
20
10
> 1050 Å
~ 910 - 1050 Å
~ 700 - 910 Å
80
160
240
320
400
480
560
h, km

Fig. 2

neutral particles $\overline{m}$ it is possible to determine their temperature T_g corresponding to the atmosphere composition assumed above . Figure 3 shows T_g values obtained for September 20 and October 1 (T_g for the ascent and descent of the rockets coincide). It is seen that at heights of 200 to 400 km the temperature increases from about 600 K to about 1100 K, above 300 km the atmosphere is practically isothermal.

It was mentioned above, that photocurrents due to radiation of spectral regions I- ~700 -910 Å, II- ~910-1050 Å and III-λ>1050 Å near the rocket's trajectory apex are related as 12,5:21:66,5 . Using the known values of the platinum quantum yield [10] and ignoring the ultraviolet absorption at large heights, the absolute values of solar radiation fluxes Φ have been determined in the above three spectral subranges: Φ_I = 0,6 erg cm^{-2}sec^{-1}, Φ_{II} = 1 erg cm^{-2}sec^{-1}, Φ_{III} = 2,6 erg cm^{-2}sec^{-1}. Comparisons of the obtained values of the fluxes with the results of measurements performed by Hinteregger [7, 11] have shown that they coincide within a factor of 1,5, i.e. essentially within the limits of the uncertainty of the platinum quantum yield. From the results of measuring the ultraviolet solar radiation absorption and from the calculated n values the ion productirn rate q has been found similarly as it was done in [12] . The use of the ratio valid for monochromatic radiation is quite justifiable since for λ < 950 Å the quantum yield for platinum does not depend on the wavelength and for the region $\lambda \simeq$ 1100-950 Å the average value of the quantum yield differs from the maximum and minimum ones not more than by a factor of 1,2 [10] .

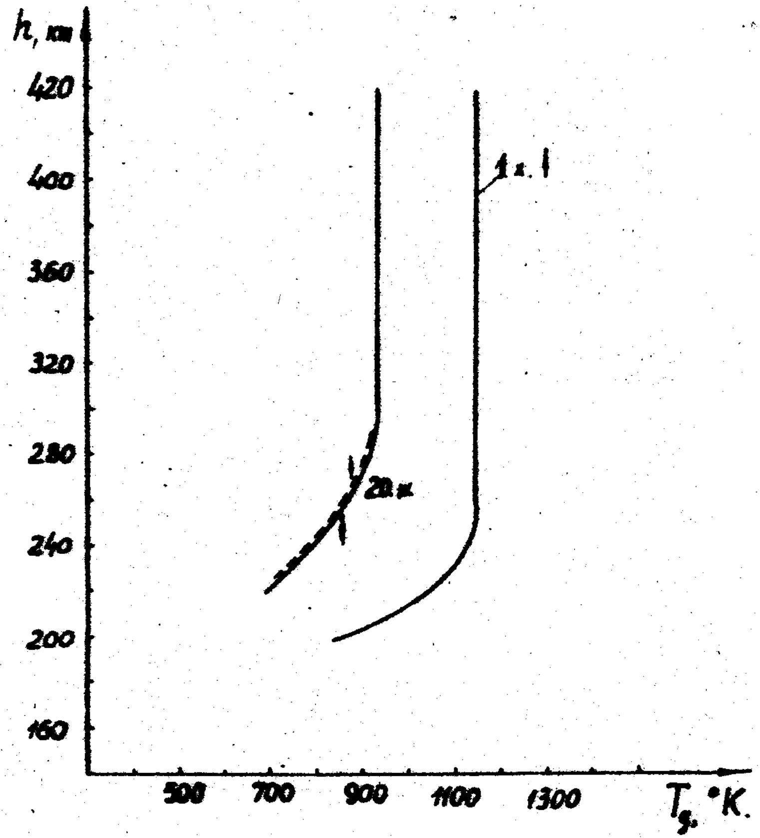
h, km
420
400
360
320
280
240
200
160
500
700
900
1100
1300
T_g, °K.
1 x. 1
20 x

Fig. 3

The curve of the relative values of $q(h)$ obtained for September 20 is shown in Figure 4. The upper portion of the curve is due to the radiation of about 700 to 910 Å and the lower portion is due to the radiation of about 910 to 1050 Å. Our $q(h)$ curve differs from the curves obtained for the total spectrum [7, 12, 13] by the presence of a sharp minimum in the range of 140 to 190 km. It may be assumed that this minimum is accounted for by the fact that while plotting the graphs we did not take into account the contribution of radiation with $\lambda < 650$ Å for which, according to calculations performed by Watanabe and Hinteregger [12], the maximum of the ion production rate during this time of the day corresponds to the above mentioned heights. The obtained $q(h)$ are in good agreement for the spectral subranges under consideration with the data calculated by Ivanov-Kholodny, Hinteregger and Watanabe [12, 13], and with the experimental data of the Hinteregger group that performed spectral measurements up to heights of 235 km [7]. While comparing the obtained values of the ion production rates for heights above 250 km with the theoretical calculations [12, 13] one may conclude that at these heights the ionization is mainly caused by radiation of about 700 to 910 Å.

At heights below 120 km the ion production rate at the expense of radiation $\lambda > 1050$ Å has turned out to be 10^{-3} cm^{-3} sec^{-1}.

The obtained height dependecies of the ion production rate have been compared with the values of the electron density. Figure 4 gives also the curve of relative values

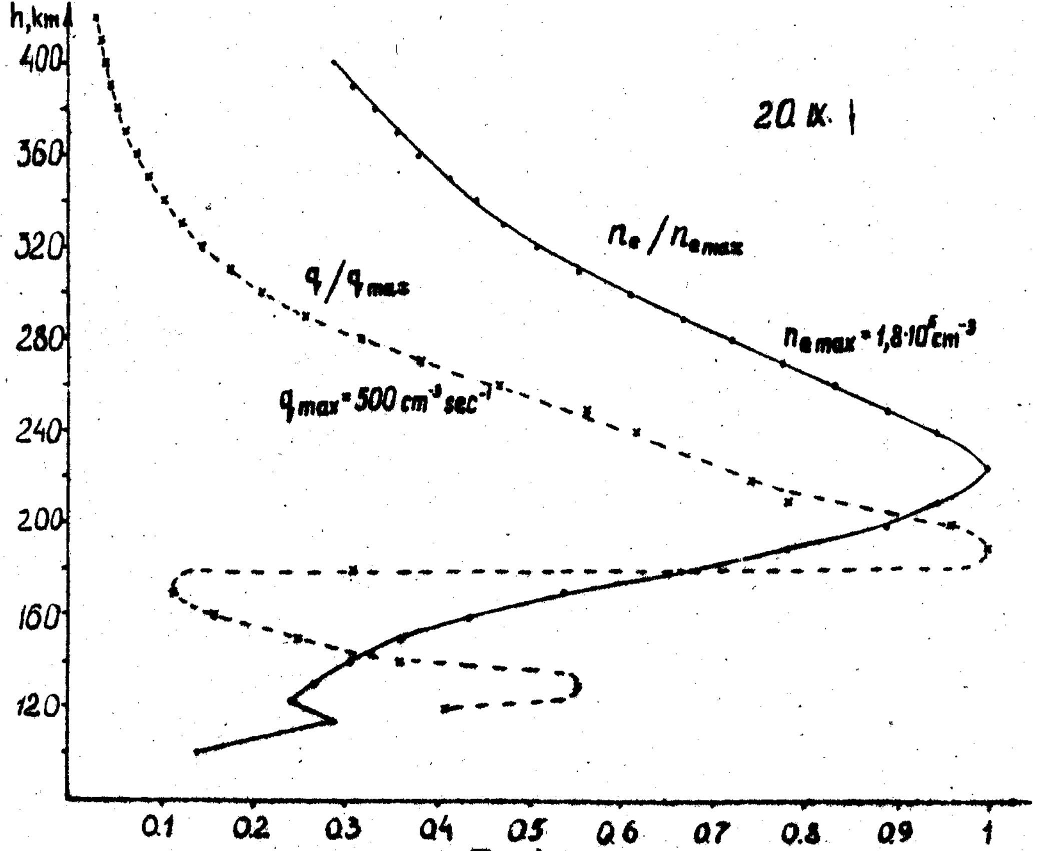
h,km
400
360
320
280
240
200
160
120
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20 IX. |
$n_e / n_{e\,max}$
$n_{e\,max} = 1{,}8 \cdot 10^5\,cm^{-3}$
q / q_{max}
$q_{max} = 500\,cm^{-3}\,sec^{-1}$

Fig.4

of n_e normalized, like q values, to the maximum value. As evident from the figure, the n_e maximum lies 25 km above the q maximum. The fall in the $n_e(h)$ curve above the main ionization maximum takes place more slowly than the fall of the $q(h)$ curve. It should be noted that the radiation in the region $\lambda < 650$ Å which was not taken into account has a little effect on the position of the main maximum of the $q(h)$ curve. However, the fall of the $q(h)$ curve above the maximum apparently would have been less sharp if absorption of this spectral region had been taken into account. The fact that the $n_{e_{max}}$ is situated above the q_{max} attests to a decrease in the effective recombination coefficient with height. If at height interval 200-230 km $\alpha_{eff} \approx q/n_e$, then, from the difference in heights corresponding to the $n_{e_{max}}$ and q_{max} it follows that the effective recombination coefficient at these heights decreases approximately by a factor of 2. This conclusion about the decrease of the effective recombination coefficient at these heights is also in agreement with the form of the height T_e distribution since the increase in the electron temperature (see Figure 1) should apparently be accompanied by the decrease in the effective recombination coefficient [14] .

Near 130 km the $q(h)$ curve has a second maximum. On the n_e curve the second maximum is also observed although at a height of about 115 km. This noncoincidence seems to be caused by the increase in the effective recombination coefficient with height in this height region. The discrepancies of the second maxima of these curves at low altitudes could not be caused by the fact that the radiation with $\lambda < 650$ Å was not taken into account since, according to the data calculated by Watanabe and Hinteregger, the radiation with $\lambda < 650$ Å should only have raised the height of the position of the second maximum on the $q(h)$ curve, i.e. it should have increased the discrepancy of heights $n_{e_{max}}$ and q_{max} [12]. Taking into account that $\alpha_{eff} \sim q/n_e^2$ it follows from the observed ratio between the heights $n_{e_{max}}$ and q_{max} that in the region of 100 to 140 km the effective recombination coefficient increases approximately by a factor of 2. Thus in the range of 140 to 200 km a break is observed which could have been expected from theoretical considerations [15]. A detailed change of the effective coefficient in the height range of 100 to 200 km could not be safely determined since the true values of q at these heights are unknown. The estimate of the values of the effective recombination coefficient in the height range of 100 to 200 km following from equations of ionization balance for these heights:

$$\frac{dn_e}{dt} = q - \alpha_{eff}\, n_e^2$$

has shown that α_{eff} varies from 2.10^{-8} to $6 \cdot 10^{-8}\,\mathrm{cm}^{-3}\,\mathrm{sec}^{-1}$ respectively. In these estimates the dn_e/dt and n_e^2 values were taken from the our experimental data for the ascent and descent of the rocket.

For heights of 200 to 400 km the calculation of the effective recombination coefficient has been performed. In the equation of ionization balance for these heights

$$\frac{dn_e}{dt} = q - \beta_{eff}\, n_e - \mathrm{div}\,(n_e \vec{v})$$

the term dn_e/dt was equated to zero since within the accuracy of determining the electron density in our experiment the difference of n_e values at the ascent and descent of the rocket at identical heights in the interval of 200 to 400 km was practically zero. Figure 5 shows the values of β_{eff} calculated in assumption that $\operatorname{div}(n_e\vec{v})$ is equal to zero (curve 1). Besides, the values of β_{eff} have been calculated assuming that the term $\operatorname{div}(n_e\vec{v})$ is determined only by vertical diffusion according to the expression

$$\operatorname{div}(n_e\vec{v}) = \frac{2kT_g}{\bar{m}n\nu}\sin^2 I\left(\frac{d^2n_e}{dh^2}+\frac{3}{2H}\frac{dn_e}{dh}+\frac{n_e}{2H^2}\right),$$

were ν is the collision frequency, I is magnetic inclination, and that this equation of diffusion is valid up to heights of about 400 km (curve 2). Curve 3 in this figure corresponds to the values of the effective recombination coefficient calculated according to the expression [14] :

$$\beta_{eff} = 6{,}8\cdot 10^{-4}\exp\left(\frac{300-h}{103}\right)\sec^{-1}.$$

At large heights the obtained experimental values of the recombination coefficient are in good agreement with theoretical ones. Below 300 km they begin to disagree considerably. This disagreement can be caused by the term of motion in the equation of ionization balance which was omited in our consideration. The maximum difference between the theoretical and experimental curves is observed at heights of about 230 km, i.e. near the electron dinsity maximum, which allows one to think that precisely here in the equation of ionization balance the influence of the term of the chatged particle motion is especially noticeable. From the difference of the theoretical and experimental curves the contribution of the term of notion in the equation of ionization balance was evaluated: for the height h =400 km $\operatorname{div}(n_e\vec{v})\sim 10\,cm^{-3}sec^{-1}$, for h =200 km

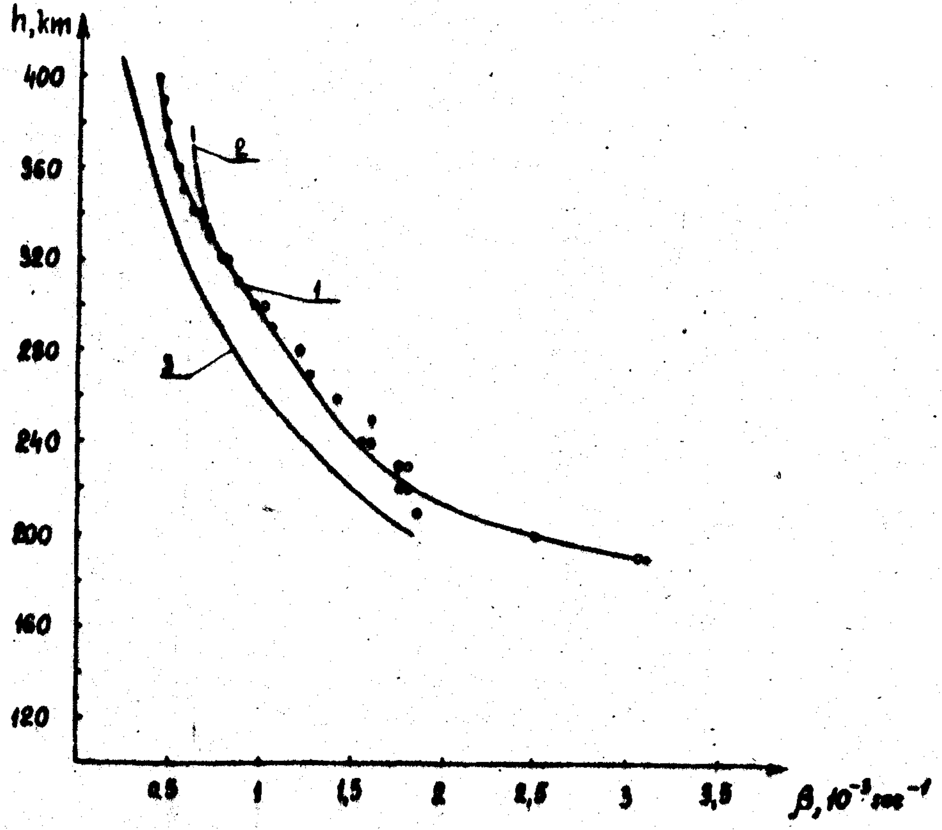
h, km
400
360
320
280
240
200
160
120
0,5
1
1,5
2
2,5
3
3,5
$\beta, 10^{-3}\,sec^{-1}$
1
2
3

Fig. 5

$\mathrm{div}(n_e\vec{v}) \sim 10^2 \mathrm{cm}^{-3}\mathrm{sec}^{-1}$.

From the experimental values of the electron density n_e and the temperature T_e and the calculated values of the neutral gas temperature the estimate of the heat inflow has beed made at heights above 200 km (see Fig. 6). Only elastic collisions with atomic oxygen ions have been considered [16] . The heat flow responsible for the observed difference in temperatures at heights of about 200 km has turned out to be equal approximately to 200 ev $\mathrm{cm}^{-3}\mathrm{sec}^{-1}$ and approximately to 10 ev $\mathrm{cm}^{-3}\mathrm{sec}^{-1}$ at 400 km. The character of the height dependence $Q(h)$ coincides with other experimental data, for instance, those by Evans [17] , although our absolute values of Q are somewhat lower. This is accounted for by the high values of T_e , which seem to be due to the time of the experiment.

As it has been shown at heights of 200 to 400 km, mainly the radiation in the region of about 700 to 910 Å is absorbed for which the average photon energy is about 15,5 ev. Since at these heights the main component of the atmosphere is represented by atomic oxygen whose ionization potential is about 13.6 ev, the average energy of photoelectrons produced at these heights turnes out to be of the order of 2 ev. This does not contradict to theoretical calculations [18]. After calculation of the total energy flux of photoelectrons on the basis of these data it has been possible to evaluate the portion of photoelectron kinetic energy going into the heating of the electron gas at these heights (see Fig.6).

Thus the simultaneous rocket experiments performed in 1965 have made it possible to obtain the height distributions

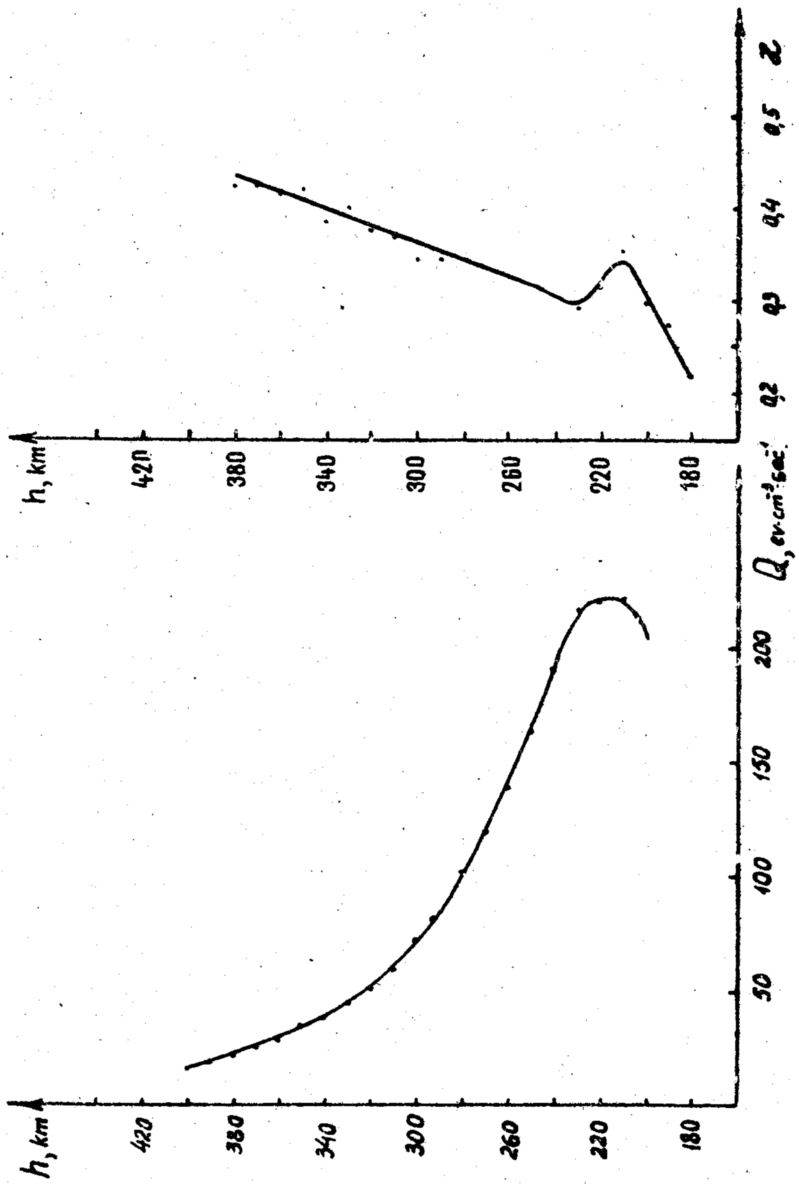
h, km
420
380
340
300
260
220
180
Q, ev·cm⁻³·sec⁻¹
50
100
150
200
h, km
420
380
340
300
260
220
180
z
0,2
0,3
0,4
0,5

Fig. 6

of the ionospheric main parameters : $n_e(h)$, $q(h)$, $T_e(h)$, solar ultraviolet radiation fluxes and absorption of this radiation in the atmosphere (with above mentioned limitations). A comparison of the obtained data has allowed us to evaluate the heat inflow $Q(h)$, the effective recombination coefficient and other parameters.

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