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Preprint

HEAT INFLOW TO ELECTRON GAS AT HEIGHTS $h > 180$ km

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1. Solar ultraviolet radiation is the main source of heating the upper atmosphere. There are several theoretical papers (Refs. 1 to 5) showing that in E and F regions the heating is mainly due to thermalization of fast photoelectrons.

However, due to ambiguity of data on effective coefficients of energy losses and the absence of exact description of the processes causing these losses, altitude dependencies of electron temperature Te obtained by calculations (Refs.1 to 5) in some cases do not coincide with experimental data (Refs.7 and 8).

Taking into account additional mechanisms of energy transformation (Refs.9 to 11) and new data on the magnitudes of solar photon fluxes and photoionization cross-sections (ref.12) does not allow us so far to fully eliminate discrepancies between theoretical and experimental data.

Therefore, it was interesting for further studies of mechanisms of heat transfer to evaluate heat inflow to electron gas from results of simultaneous measurements of electron density n_e , electron temperature Te, density n and temperature T_g of neutral particles. These estimates are based on measurements carried out in the autumn of 1965 and 1966 from geophysical rockets of the USSR Academy of Sciences under the direction of Dr.K.I.Gringauz (Refs.13 to 15).

2. The estimate of heat inflow to electron gas from experimental values n_e , Te and T_g made earlier in Ref.13 was limited to consideration of only elastic collisions of electrons and ions of atomic oxygen and did not take into account thermal conductivity of electron gas.

Figs. 1 and 2 show altitude profiles T_g(h), Te (h) and n_e(h) and ratios n_e(h)/ n (h) for altitudes of 180 to 400 km. As evident from Fig.1, for all experiments the electron temperature at heights of 180 to 400 km considerably exceeded the temperature of neutral gas. Although height profiles of electron temperature are of non-monotonous character, in this height interval there is in general a trend towards the increase of Te.

It is worth noting that for all our experiments at heights of 200 to 300 km there is a correlation between the Te(h) minimum and n_e(h) maximum. The cause of the correlation between $n_{e\,max}$ and Te_{min} is explained (Ref.16) by the fact that at heights of 200 to 300 km the electron gas is cooled mainly due to Coulomb collisions with positive ions (Ref.17).

Since during the transfer of thermal energy to electrons not only charged particles take part, but also neutral ones, the Te(h) function should considerably depend on the n_e(h)/ n (h) ratio. At the same time, as evident from Figs.1 and 2, there is no correlation between Te and n_e/n for experiments of 1965 and 1966. Since it is possible to assume for altitudes of 200 to 300 km that the thermal conductivity effect is not significant, the absence of correlation between Te and n_e/n shows that in additional to Coulomb interactions in establishing equilibrium values of Te a prominent part is played by other processes. If Coulomb interactions were the main mechanism of heat transfer, greater Te values would correspond to greater values of n_e/n ratio since for greater n_e/n values nearly all suprathermal electrons should impart their energy to the electron gas.

3. To estimate heat inflow to electron gas a stationary equation of heat balance was used in the following form

$$\frac{d}{dh}\left(K_e \sin^2 I \frac{dT_e}{dh}\right) = Q_e(h) - \mathcal{L}_e(h) \qquad (1)$$

where Q_e - velocity of heat transfer to electron gas,

$\mathcal{L}_e$ - velocity of heat transfer from electron gas to neutral and ion gas,

K_e - thermal conductivity coefficient of electron gas,

I - magnetic dip angle.

In expression (1) no account was taken of such sources of heating as secondary electrons, electric fields and energetic photoelectrons injected into the atmosphere through magnetic tubes of force, as well as heat inflow due to collisions of thermal electrons with molecules N_2 whose vibrational levels are excited (Ref.9). The estimates have shown that for the heights under consideration it is possible to ignore the contribution of these processes to the heating of the electron gas.

To determine the velocity of heat transfer $\mathcal{L}_e$ in equation (1) use was made of the expressions derived by Hanson (ref.1), Dalgarno et al.(Ref.2), assuming that the main mechanisms of energy losses of the electron gas are collisions with

with neutral particles of $n(x)$ density and positive ions, namely:

a) elastic collisions with atomic oxygen

$$\mathcal{L}_e(0) = \frac{3}{2} \kappa \cdot 10^{-14} n_e \, n(0) \, T_e^{1/2} (T_e - T_g) \qquad \text{erg cm}^{-3}\text{sec}^{-1} \quad (2)$$

where K - Boltzmann's constant;

b) elastic collisions with molecular nitrogen and excitation of rotational levels of N_2 molecules:

$$\mathcal{L}_e(N_2) = \frac{3}{2} \kappa n_e \, n(N_2)(T_e - T_g) \times$$
$$\times [7{,}6 \cdot 10^{-16} T_e + (1{,}2 \cdot 10^{-11} - 5{,}6 \cdot 10^{-15} T_g)] \text{erg cm}^{-3}\text{sec}^{-1} \quad (3)$$

c) elastic collisions with molecular oxygen

$$\mathcal{L}_e(O_2) = \frac{3}{2} \kappa n_e \, n(O_2)(T_e - T_g)(4 \cdot 10^{-14} T_e - 8 \cdot 10^{-12}) \text{erg cm}^{-3}\text{sec}^{-1} \quad (4)$$

d) elastic collisions with positive ions.

For the height range of 200 to 400 km, which we are interested in, the O^+ ion was considered the main ion, since the results of mesurements of the neutral composition have shown (Refrs.13 and 15) that the mean molecular mass at these altitudes is close to 16:

$$\mathcal{L}_e(i) = \frac{3}{2} \kappa \frac{n_e^2 (T_e - T_g)}{268} \, T_e^{3/2} \qquad \text{erg cm}^{-3}\text{sec}^{-1} \quad (5)$$

It was shown in the paper by Dalgarno and Degges (Ref.10) and then in the papers (Refs.11 and 12) that the excitation of the fine structure of electron levels of atomic oxygen $[e + O(^3P_J) \rightarrow e + O(^3P_{J'})]$ is one of effective mechanisms of cooling the electron gas. Energy losses due to this process were estimated as

$$\mathcal{L}_e^*(0) = 10^{-25} n_e n(0) T_g^{-1} (T_e - T_g) \times$$
$$\times (5{,}92 - 4{,}68 \cdot 10^{-4} T_e)(9{,}06 + 6{,}57 \cdot 10^{-4} T_g) \text{ erg cm}^{-3}\text{sec}^{-1} \quad (6)$$

Hence the heat transfer velocity $\mathcal{L}_e$ was determined as

$$\mathcal{L}_e = \mathcal{L}_e(0) + \mathcal{L}_e(N_2) + \mathcal{L}_e(O_2) + \mathcal{L}_e(i) + \mathcal{L}_e^*(0) \quad (7)$$

The excitation of the metastable level ^1D of atomic oxygen (Ref.18) was not taken into account since the cooling of the electron gas due to this process turned out to be negligibly small as compared to processes (2) to (6).

It should be noted that while deriving the expressions for $\mathcal{L}_e(x)$ different authors use different values of the moment of the energy transfer by means collisions of an electrons with a neutral particles (Refs.6 and 19). Possible uncertainty of absolute values $\mathcal{L}_e(x)$ may reach a factor of 2.

The second term of equation (1) due to thermal conductivity of electron gas was estimated proceeding from the fact that the thermal-conductivity coefficient of the fully ionized plasma is (Ref.20): $K_{ei} = 7{,}7 \cdot 10^5 T_e^{5/2}$ ev cm^{-1} $^{\circ}$K^{-1} sec^{-1} (8)

Taking into account that the actual ionosphere does not represent a fully ionized medium, thermal conductivity of electron gas was determined as follows (Ref.19):

$$K_e = \frac{K_{ei}}{1 + K_{ei}/K_{en}} \quad (9)$$

where K_{en} has the following expression (Ref.6)

$$K_{en} = \frac{57 n_e T_e^{1/2}}{\sum_x n(x)\, \bar{Q}_D(x)} \quad (10)$$

Here $\bar{Q}_D(x)$ is the average momentum transfer cross section for O, O_2 and N_2:

$$\bar{Q}_{\mathcal{D}}(x) = 10^{-15} cm^2, \quad (11)$$

$$\bar{Q}_{\mathcal{D}}(O_2) = 2{,}2\cdot 10^{-16}(1+3{,}6\cdot 10^{-2}\, T_e^{1/2})\, cm^2 \quad (12)$$

$$\bar{Q}_{\mathcal{D}}(N_2) = 2{,}82\cdot 10^{-17}(1-1{,}21\cdot 10^{-4} T_e)\, T_e^{1/2} cm^2 \quad (13)$$

4. The calculated dependencies of heat transfer velocity $\mathcal{L}_e(h)$ are given in Figs. 3 to 5. The ambigiuty of obtained $\mathcal{L}_e(h)$ values due to uncertainty of initial values of T_g(h), $\overset{n_x(h)}{\vee}$ Te (h) and n_e(h) do not exceed a factor of 1.5.

It may be seen from the Figures that really at heights of 200 to 400 km the cooling of the electron gas due to excitation of atomic oxygen is the most effective. With the increase in atomic oxygen density the contribution of this process to the cooling of the electron gas increases and exceeds the energy losses by means collisions with positive ions up to the heights of about 400 km.

For the experiment made on October 13, 1966, the neutral particle density at heights of 200 to 400 km was much higher than for experiments of 1965 (Ref.15). Correspondingly, energy losses of electron gases due to collisions with neutral particles and positive ions in the autumn of 1966 were higher than in the autumn of 1965. From Figs.3 and 4 it is evident that on September 20, 1965 and on October 1, 1965 in the height range of 200 to 300 interaction energy losses of the electron gas with the neutral gas were approximately the same. Therefore, one may suppose that the higher electron temperature of October 1, 1965 is due to the fact that the electron density on October 1, 1965 was higher than on September 20, 1965 (see Fig.1). On the other hand, although electron density n_e in 1966 was higher and even the n_e/n ratio on October 13, 1966 was higher at the altitudes of 200 to 300 km than on September 20, 1965, the Te(h) values turned out to be the lowest. This effect can be explained from the comparison of data of Figs. 3 and 5. Obviously the rise in the density of neutral particles, especially of atomic oxygen, resulted in the rise of energy losses due to excitation of electron levels of atomic oxygen which caused the minimum of Te(h) values at these heights.

Above 300 km a sharp growth of Te(h) was observed for October 13, 1966 as compared to 1965 and there was no correlation between the ratio $n_e(h)/n(h)$, energy losses by means collisions with neutral particles and Te(h) values. Apparently this means that at such heights the nonlocal mechanism of heat transfer becomes important and heat inflow to the electron gas is greatly affected by the composition of the environment and variable external conditions.

Fig.6 gives the obtained altitude dependencies of heat inflow to the electron gas $Q_e(h)$. Solid curves have been obtained while taking only local processes into account. Dashed curves take also thermal conductivity into account. Thermal conductivity of electron gas begins to influence the magnitude of heat inflow at altitudes over 300 km. Apparently the maximum of electron temperature Te in the height range 380 to 390 km on October 13, 1966 is due to thermal conductivity.

5. As is known (Ref.1), in the general case the energy acquired by the electron gas as a result of ionization of the upper atmosphere by solar ultraviolet radiation can be determined from the expression

$$Q_e(h) = \int_0^\infty \varkappa(E,h) f(E,h) E\,dE \qquad (14)$$

where $\varkappa(E,h)$ - effectiveness of heat transfer to the electron gas by photoelectrons with energies E,
$f(E,h)$ - the number of photoelectrons appearing per unit volume per unit time with initial energy in the interval from E to E+dE.

For these experiments the rate of the production of ion-electron pairs was determined for rather wide spectral ranges of solar radiation (Ref.15): λ 1050-910 Å, λ 910-600 Å, λ 600-370 Å, λ 370-165 Å and λ 165-31 Å. In this connection expression (14) determining Q_e(h) assumes the following form:

$$Q_e(h) = \bar{\varkappa}(h) \bar{E}(h) \sum_{\Delta\lambda} q(\Delta\lambda, h), \quad ev, cm^{-3} sec^{-1} \qquad (15)$$

where $\bar{\varkappa}(h)$ - mean effectiveness of energy transfer by photoelectrons to the electron gas,
$\bar{E}(h)$ - mean kinetic energy of photoelectrons produced,
$q(\Delta\lambda, h)$ - the number of ion-electron pairs produced in 1 cm^3 under the effect of radiation in the wavelength range $\Delta\lambda$.

Knowing $\bar{E}$ (h) and using expressions (1) and (15), it is possible to determine height dependence $\bar{\varkappa}$ (h).

To estimate mean kinetic energy $\bar{E}$ (h) use was made of experimental data about the ion production rate due to radiation of the above-mentioned wavelength ranges and of calculation data of mean energy of photoelectrons (Ref.21) produced as a result of ionization of the atmospheric gas by solar radiation of narrow spectral ranges. At altitudes of 200 to 400 km the value $\bar{E}$ (h) changed from 20 to 10 ev. The altitude variations of $\bar{E}$ for each experiment did not exceed 30 per cent. The limit values of $\bar{E}$(h) are represented in Table 1.

Table 1

Date of experiment	$\bar{E}$ max,ev	$\bar{E}$ min,ev
October 20, 1965	14	11
October 1, 1965	20	16
October 13, 1966	21	16

According to estimates of the authors of the paper (ref.21), the mean energy of photoelectrons $\bar{E}$ at heights $h > 200$ km at zenith distances $Z_{\odot} = 80^{\circ}$ is about 15 ev and weakly depend on height.

The dependencies $\bar{\varkappa}$ (h) obtained are given in Fig.7. The values of $\bar{\varkappa}$ (h) in Fig.7a correspond to the case when thermal conductivity of electron gas was not taken into account. In Fig.7b thermal conductivity was taken into account. The comparison of Figs.7a and 7b shows that thermal conductivity of the electron gas alters the $\bar{\varkappa}$ (h) profile practically at heights $h > 300$ km. Up to altitudes of about 300 km, where the influence of thermal conductivity is small, absolute values of $\bar{\varkappa}$ (h) correlate with values n_e(h)/ n (h) (see Fig.2b).

For all experiments described here the height range of 200 to 240 km corresponded to maximum values of $\bar{\varkappa}$ (h). In the region of these heights a small height gradient was observed as a function of $\bar{\varkappa}$(h). Above 300 km the effectiveness of heating the electron gas in the general varies little with height. So far it is difficult to explain sharp variations in $\bar{\varkappa}$ (h) values for $h > 300$ km, but apparently they are due to thermal conductivity. Absolute values of $\bar{\varkappa}$ (h) for $h > 300$ km are $0.15 \div 0.3$.

Thus, the maximum effectiveness of heating the electronic gas takes place at altitudes of about 200 km. Apparently the minimum in temperature profiles of the electron gas at these heights is due to great heat losses for excitation of the fine structure of electron levels of atomic oxygen. This means that at altitudes of 200 to 300 km the processes of interaction of the electron gas with the neutral gas to a large extent regulate the equilibrium electron temperature and that effective heating of the electron gas essentially depends on the composition of neutral particles.

$\bar{\varkappa}$ (h) profiles obtained are characterized by high absolute values of $\bar{\varkappa}$ (h) near 200 km and lower values of $\bar{\varkappa}$ (h) in the region of 400 km unlike $\bar{\varkappa}$ (h) values given in Ref.13 are accounted for by the fact that in this case mechanisms of interaction of electrons with neutral particles in processes of heat transfer to the electron gas are taken into account. Registration of energy losses due to interaction of "hot" electrons with the neutral gas, especially excitation of the fine structure of electron levels of atomic oxygen makes it possible to explain the main peculiarities of experimental profiles of electron temperatures and their correlation with profiles of electron and neutral particle densities.

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FIGURE CAPTIONS

Fig.1. Altitude dependencies of electron temperature Te(h) and neutral particle Te(h) and neutral particle temperature T_g(h).

Fig.2. Altitude dependencies of electron density n_e(h)-a and the ratio $n_e(h)/n$ (h) -b.

Fig.3. Velocity of heat transfer from the electron gas on September 20, 1965: $\sum_x \mathcal{L}_e(x)$ due to collisions with neutral particles; $\mathcal{L}_e(i)$ due to collisions with positive ions; $\mathcal{L}_e^*(0)$- due to excitation of atomic oxygen.

Fig.4. Velocity of heat transfer from the electron gas on October 1, 1965 (symbols the same as in Fig.3).

Fig.5. Velocity of heat transfer from the electron gas on October 13, 1966 (symbols the same as in Fig.3).

Fig.6. Heat inflow to electron gas $Q_e(h)$.

———— thermal conductivity is not taken into account,

- - - - - thermal conductivity is taken into account.

Fig.7. Effectiveness of heating the electron gas

$\varkappa$ (h): a - thermal conductivity is not taken into account

b - thermal conductivity is taken into account

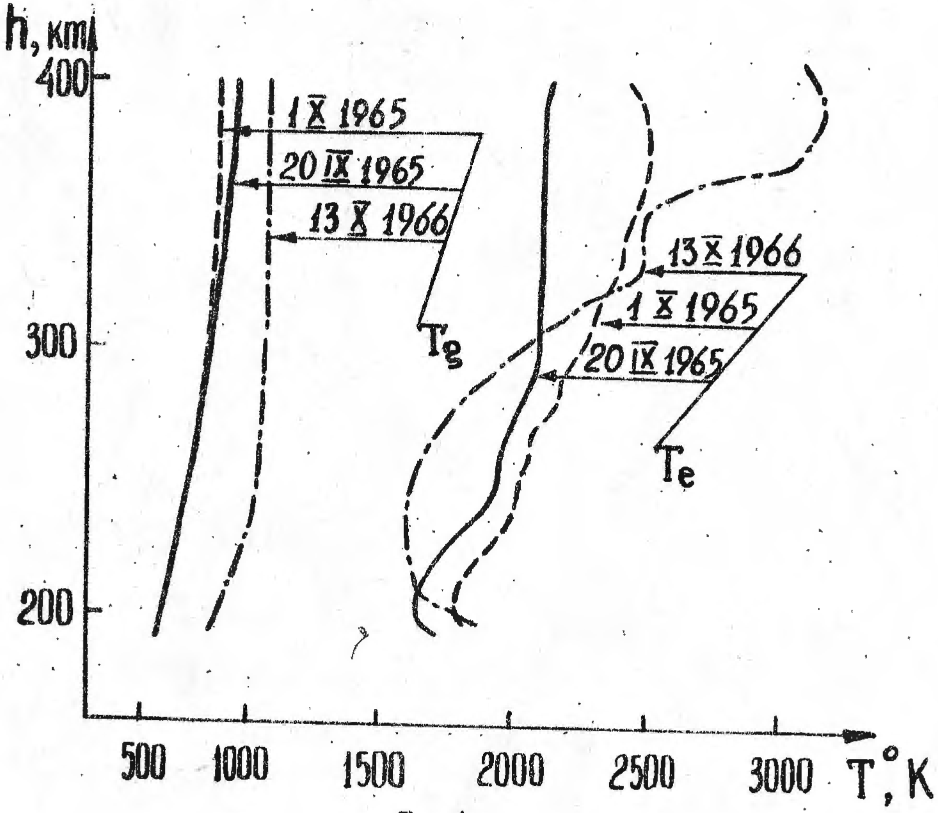

h, km
400
300
200
500
1000
1500
2000
2500
3000
T°, K
1 X 1965
20 IX 1965
13 X 1966
Tg
13 X 1966
1 X 1965
20 IX 1965
Te

Fig. 1

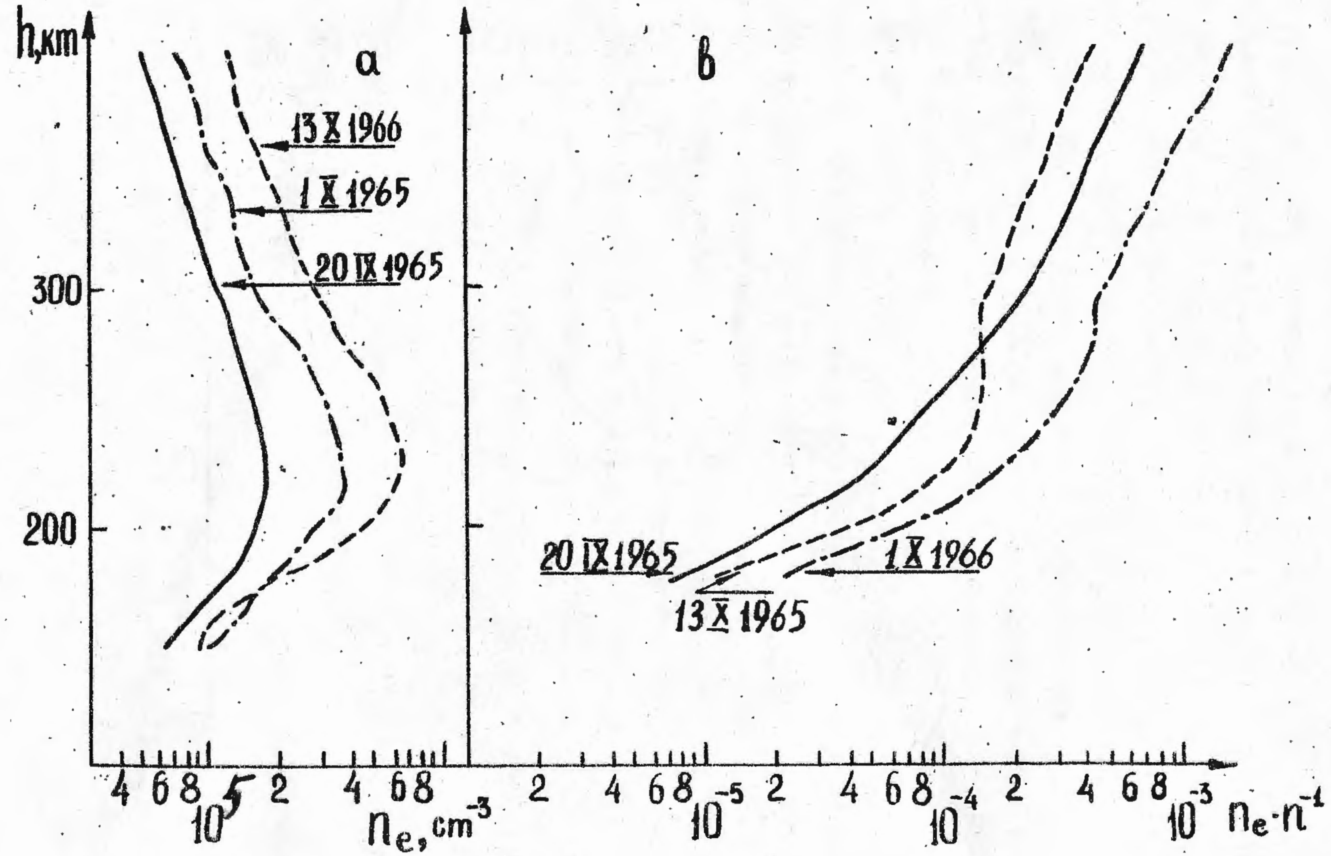

h,km
300
200
a
13 X 1966
1 X 1965
20 IX 1965
4 6 8 10^5 2 4 6 8
n_e, cm^{-3}
b
20 IX 1965
13 X 1965
1 X 1966
2 4 6 8 10^{-5} 2 4 6 8 10^{-4} 2 4 6 8 10^{-3}
$n_e \cdot n^{-1}$

Fig.2

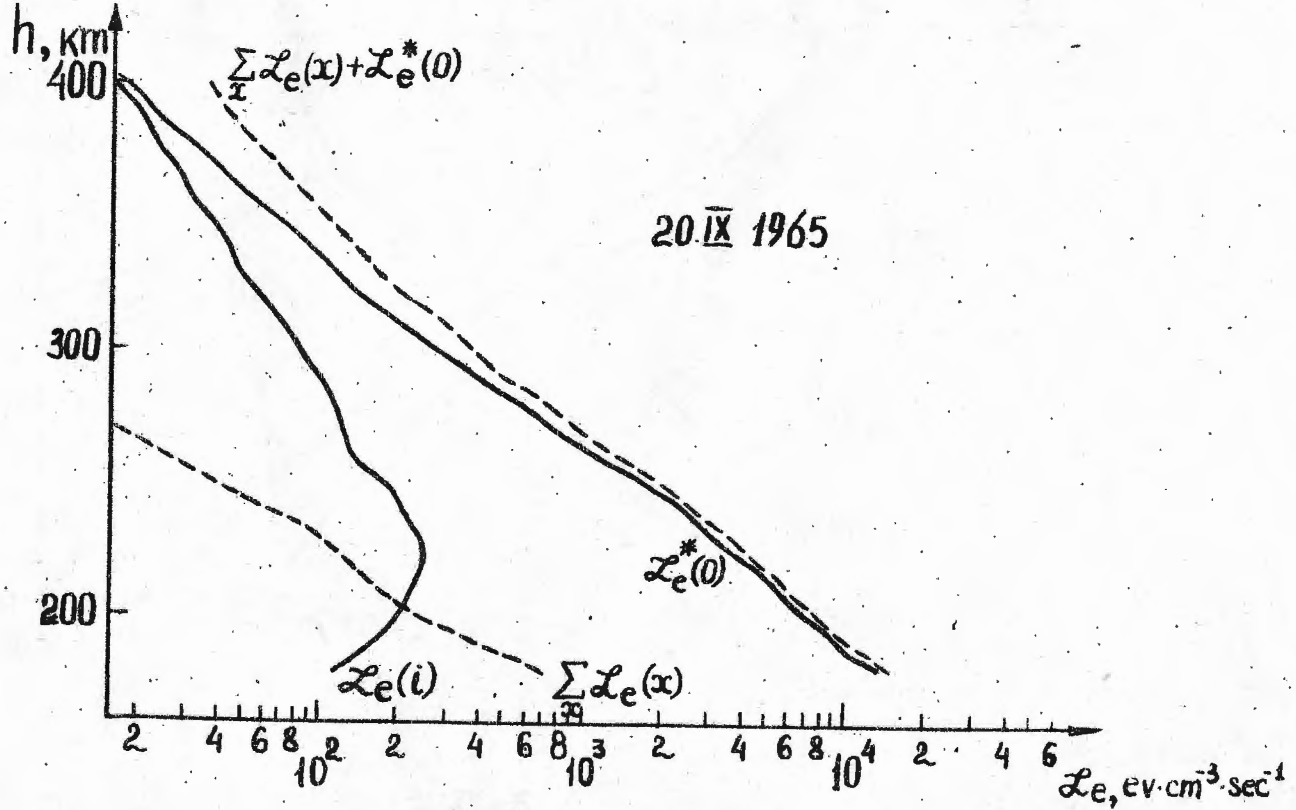

20.IX 1965

fig.3

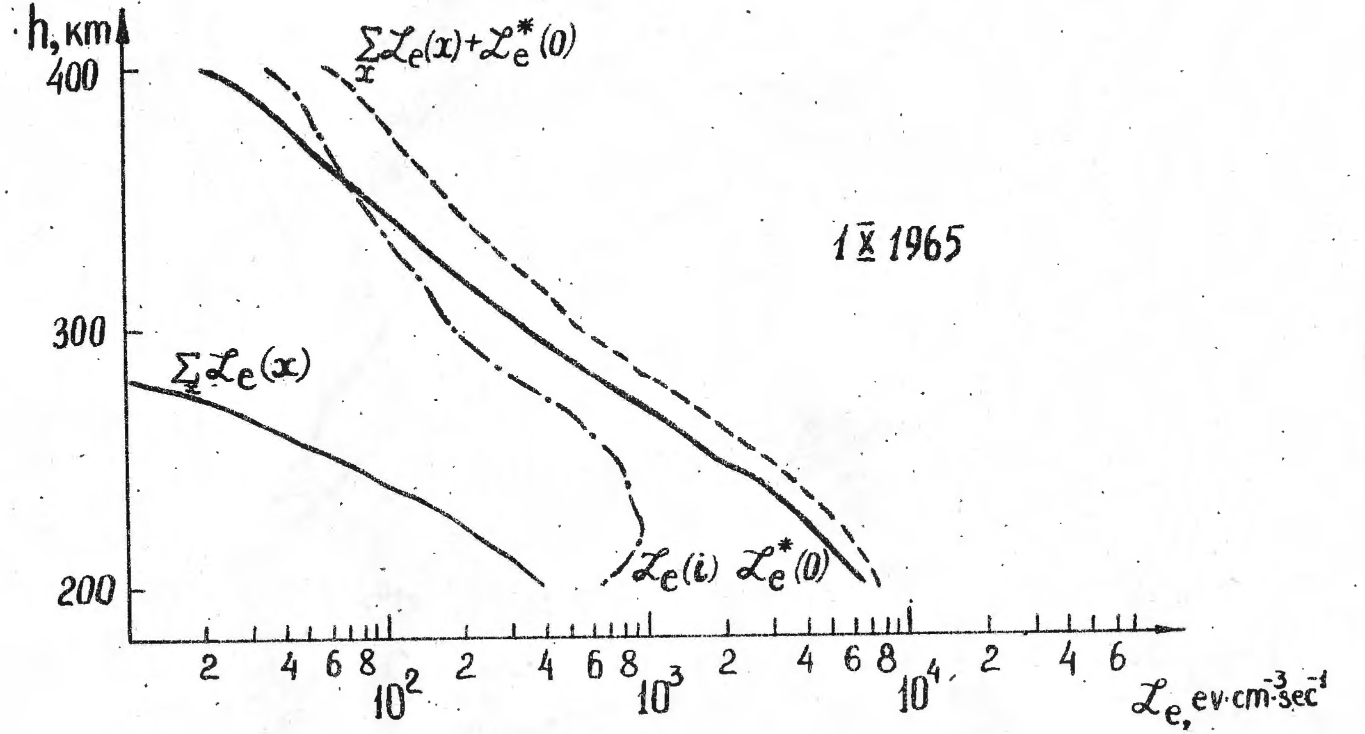
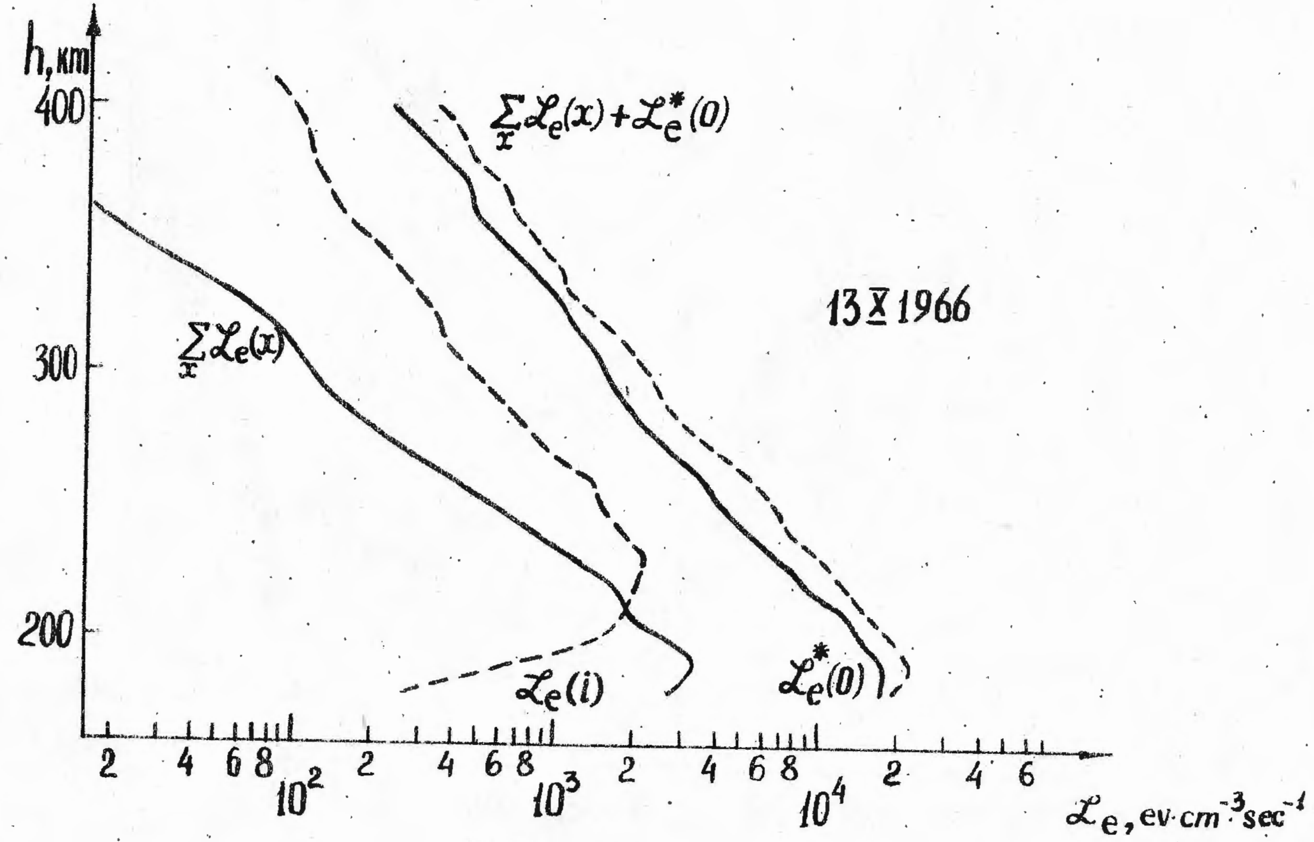

h, км
400
300
200
$\sum_x \mathcal{L}_e(x)+\mathcal{L}_e^*(0)$
$\sum_x \mathcal{L}_e(x)$
$\mathcal{L}_e(i)$
$\mathcal{L}_e^*(0)$
1 X 1965
2
4
6
8
10^2
2
4
6
8
10^3
2
4
6
8
10^4
2
4
6
$\mathcal{L}_e$, $ev \cdot cm^{-3} \cdot sec^{-1}$

Fig. 4



13 X 1966

fig. 5

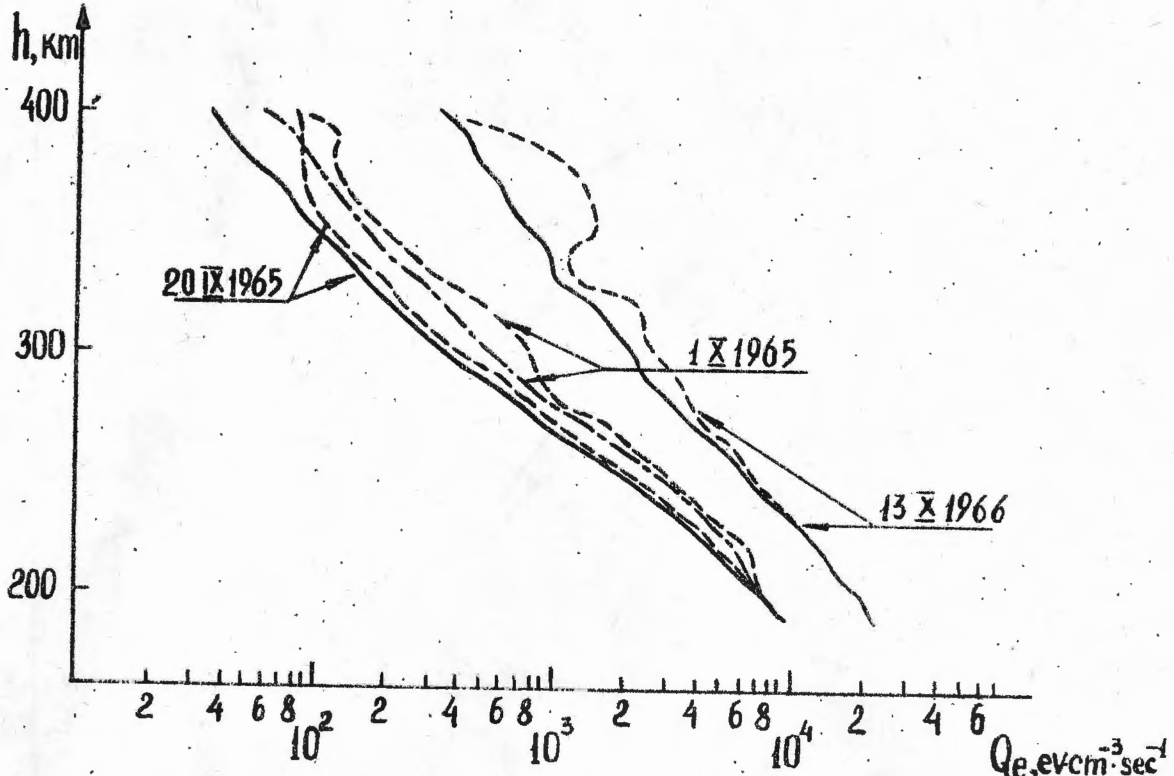

h, км
400
300
200
20 IX 1965
1 X 1965
13 X 1966
2
4
6
8
10^2
10^3
10^4
Q_e, ev·cm^{-3}·sec^{-1}

Fig.6

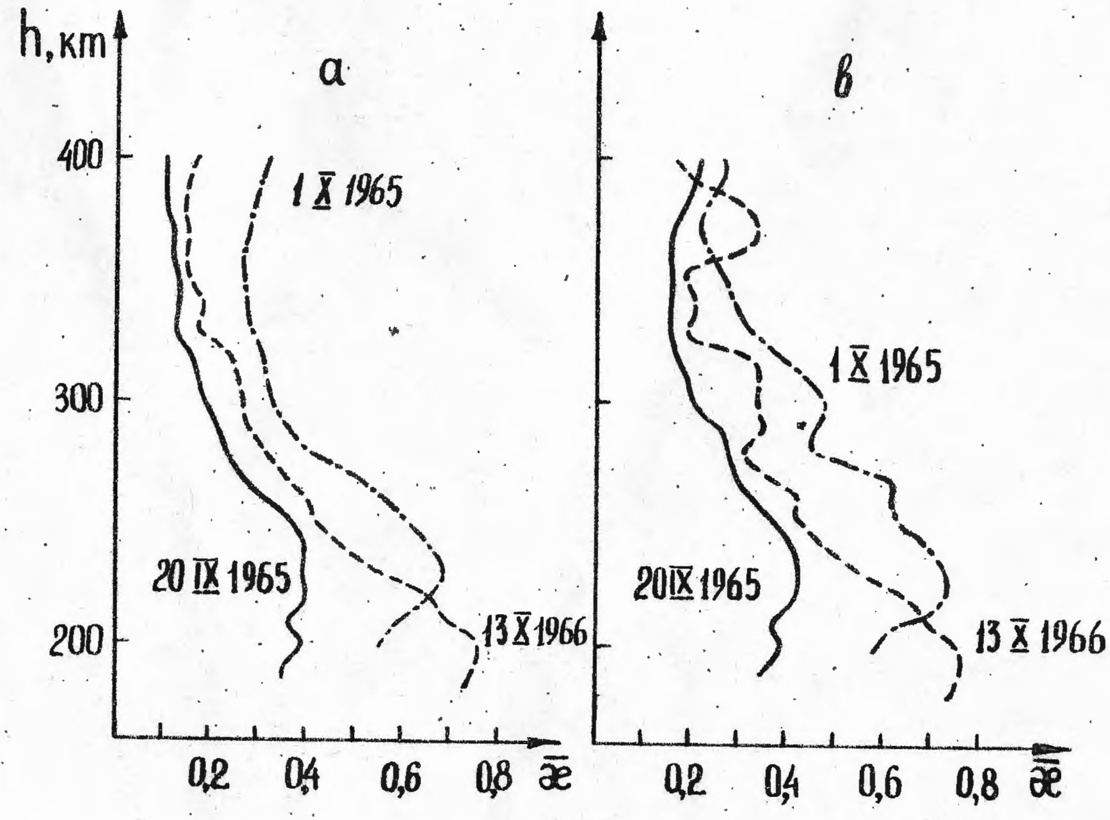


fig. 7