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HEAT INFLOW TO THE ELECTRON GAS AT HEIGHTS ABOVE 180 KM*

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The evaluation of the heating Q of the electron gas has been made from experimental data on the electron concentration n_e, electron temperature T_e, neutral gas temperature T_g and neutral particles concentration $n(O)$, $n(O_2)$, $n(N_2)$ obtained during geophysical rocket flights.

It is shown that cooling of the electron gas due to the excitation of atomic oxygen is the most effective. Inclusion of energy losses due to the interaction of photoelectrons 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.

1. Introduction

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

However, due to the ambiguity of data on effective coefficients of energy losses and the absence of exact description of the processes causing these losses, altitude dependences of electron temperature T_e obtained by calculations [1–5] in some cases do not coincide with experimental data [6, 7]. Taking into account additional mechanisms of energy transformation [8–10] and new data on the magnitudes of solar photon fluxes and photoionization cross sections [11] does not allow us so far to eliminate fully discrepancies between theoretical and experimental data.

2. Experimental Data

Therefore, it was interesting for further studies of the mechanism of heat transfer to evaluate the heat inflow to the electron gas at different altitudes using simultaneous measurements of electron density N_e, electron temperature T_e, density N and temperature T_g of neutral particles. These estimates are based on measurements carried out from geophysical rockets of the USSR Academy of Sciences in the autumn of 1965 and 1966 in middle latitudes with solar zenith angles of about 81–83° [12–14].

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Figs. 1 and 2 show altitude profiles $T_g(h)$, $T_e(h)$ and $N_e(h)$ and ratios $N_e(h)/N(h)$ for altitudes 180–400 km. It is worth noting that for all our experiments at heights of 200–300 km there is a correlation between the $T_e(h)$ minimum and the $N_e(h)$ maximum. Qualitatively, some authors attempted to explain the cause of the correlation between $(N_e)_{max}$ and $(T_e)_{min}$ by the fact that at heights of 200–300 km the electron gas is cooled mainly due to Coulomb collisions with positive ions [15, 16].

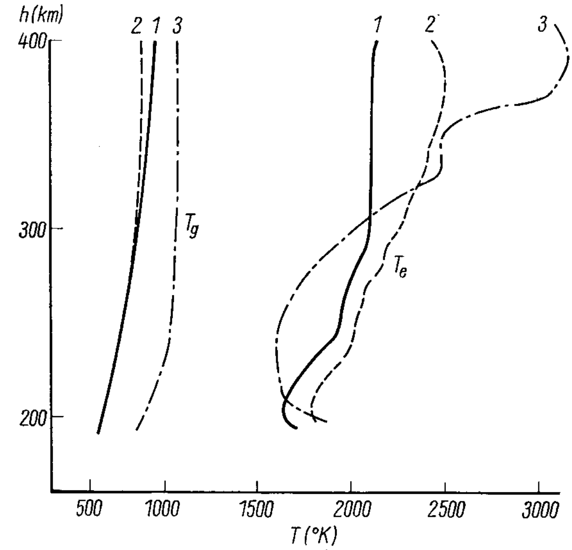

Fig. 1. Altitude dependences of electron temperature $T_e(h)$ and neutral particle temperature $T_g(h)$. 1, 20 Sept. 1965; 2, 1 Oct. 1965; 3, 13 Oct. 1966.

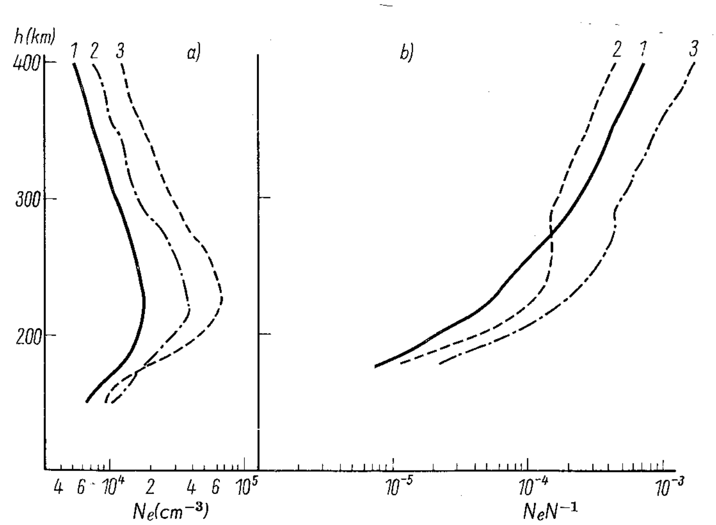

Fig. 2. Altitude dependences of: a, electron density $N_e(h)$; b, ratio $N_e(h)/N(h)$. 1, 20 Sept. 1965; 2, 1 Oct. 1965; 3, 13 Oct. 1966.

From Figs. 1 and 2 it is evident that there is no correlation between T_e and N_e/N. This fact shows that in establishing equilibrium values of T_e a prominent part is played by processes which are proportional to the absolute values of the electron density and the density of neutral particles.

3. Theory

To estimate the heat inflow to the electron gas the equation of heat balance was used in the following form:

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

where Q_e is the rate of heat transfer to electron gas, L_e the rate of heat transfer from electron gas to neutral and ion gases, K_e the thermal conductivity of the electron gas and I the magnetic dip angle.

To determine the rate of heat transfer L_e in Eq. (1) use was made of the expressions derived by Hanson [1] and Dalgarno et al. [2] assuming that the main mechanisms of energy loss of the electron gas are collisions with neutral particles of density $N(x)$ and positive ions, namely: elastic collisions with atomic oxygen, elastic collisions with molecular nitrogen and excitation of rotational levels of N_2 molecules, elastic collisions with molecular oxygen, elastic collisions with positive ions. The mechanism of cooling the electron gas due to the excitation of the fine structure of electron levels of atomic oxygen [9–11] was also taken into account.

The term of Eq. (1) due to thermal conductivity of the electron gas was estimated by using the thermal conductivity coefficient of a fully ionized plasma from [17] and taking into account that the actual ionosphere does not represent a fully ionized medium [18].

The calculated dependences of heat transfer rates $L_e(h)$ are given in Fig. 3. It may be seen from the figures that at heights of 200–400 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 collisions with positive ions up to heights of about 400 km. From these data it is evident that in the height range 200–300 km if the interaction energy losses of the electron gas with the neutral gas are approximately the same higher values of T_e correspond to higher values of N_e. When the interaction energy losses of the electron gas with the neutral gas are large then higher values of N_e do not correspond to higher values of T_e.

As is known [1] in 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

$$Q(h) = \int_0^\infty \varkappa(E, h) f(E, h)\, E\, dE\,. \qquad (2)$$

where $\varkappa(E, h)$ is the effectiveness of heat transfer to the electron gas by photoelectrons with energies E, $f(E, h)$ is the number of photoelectrons appearing

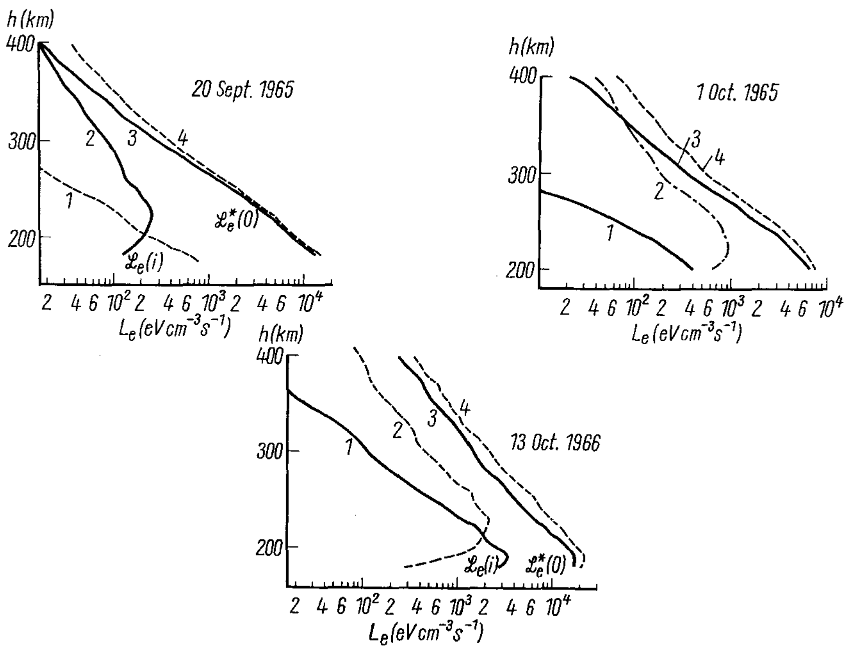

Fig. 3. Velocity of heat transfer from the electron gas: 1, $\Sigma_x L_e(x)$ due to collisions with neutral particles; 2, $L_e(i)$ due to collisions with positive ions; 3, $L_e^*(O)$ due to excitation of atomic oxygen; 4, $\Sigma_x L_e(x) + L_e^*(O)$.

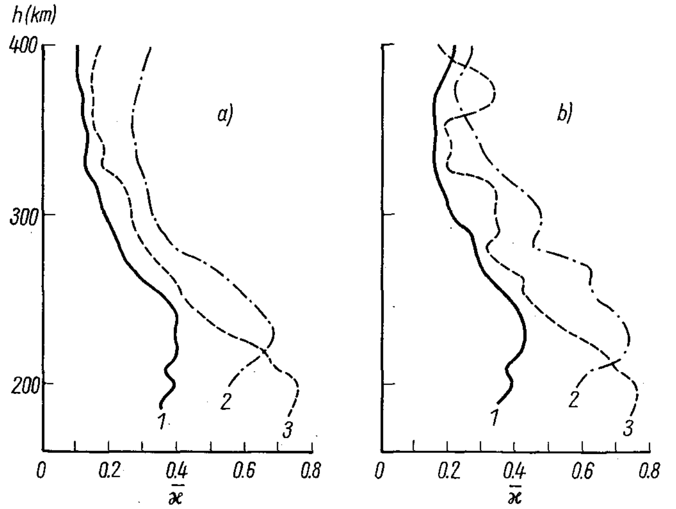

Fig. 4. Effectiveness of heating the electron gas $\bar{\varkappa}(h)$: a, thermal conductivity not taken into account; b, thermal conductivity taken into account. 1, 20 Sept. 1965; 2, 1 Oct. 1965; 3, 13 Oct. 1966.

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 spectrum ranges of solar radiation [14]: $\lambda = 1050$ to 910 Å, 910–600 Å, 600–370 Å, 370–165 Å and 165-31 Å. In this connection expression (2) determining $Q_e(h)$ assumes the following form:

$$Q_e(h) = \bar{\varkappa}(h)\, E(h) \sum_{\Delta\lambda} q(\Delta\lambda, h) \quad (\text{eV cm}^{-3}\,\text{s}^{-1}) \tag{3}$$

where $q(\Delta\lambda, h)$ is the number of ion–electron pairs produced in 1 cm³ under the effect of radiation in the wavelength range $\Delta\lambda$.

The dependences $\varkappa(h)$ obtained are given in Fig. 4. The values of $\bar{\varkappa}(h)$ in Fig. 4a correspond to the case when the thermal conductivity of the electron gas was not taken into account. In Fig. 4b thermal conductivity was taken into account. The comparison of Figs. 4a and 4b shows that thermal conductivity of the electron gas alters the $\bar{\varkappa}(h)$ profile at heights above 300 km.

For all experiments described here the height range of 200–240 km corresponded to maximum values of $\bar{\varkappa}(h)$. Above 300 km the effectiveness of heating the electron gas varies little with height. The large values of $\varkappa(h)$ near 200 km attract attention. If solar ultraviolet radiation is really the main source of heating at F-region heights our data show that the effectiveness of heating the electron gas by photoelectrons may in certain cases reach 70–80%. Otherwise a certain part is played by additional sources of heating the electron gas at altitudes of about 200 km not taken into account in this paper; in particular, no account is taken of such sources of heating as electron fluxes, electric fields, magnetohydrodynamic waves and so on.

It should be noted that values of the atomic oxygen concentration used in this paper might be overestimated because we used the theoretical values of effective absorption cross section of atomic oxygen of Dalgarno and Parkinson [19]. The laboratory measurements of the absorption cross section for O are about 50% higher than the theoretical values [20]. If atomic oxygen concentration were overestimated the values of energy losses due to excitation of the fine structure of electron levels of atomic oxygen are also overestimated. This fact might account for the large values of $\bar{\varkappa}(h)$ at altitudes of 200–300 km.

Apparently the minimum in the electron temperature profiles at altitudes of about 200 km is due to heat losses from excitation of the fine structure of electron levels of atomic oxygen. This means that at altitudes of 200–300 km the processes of interaction of the electron gas with the neutral gas to a large extent regulates the equilibrium electron temperature, since effective heating of the electron gas essentially depends on the density of neutral particles.

4. Summary

Inclusion of energy losses due to interaction of photoelectrons 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.

References

[1] W. B. HANSON, Space Research III, North-Holland Publ. Co., Amsterdam 1963 (p. 282).
[2] A. DALGARNO, M. B. MCELROY and R. J. MOFFETT, Planet. Space Sci. **11**, 463 (1963).
[3] J. E. GEISLER and S. A. BOWHILL, J. Atmos. Terr. Phys. **27**, 457 (1965).
[4] A. V. DA ROSA, J. Geophys. Res. **71**, 4107 (1966).
[5] A. DALGARNO, M. B. MCELROY and J. C. G. WALKER, Planet. Space Sci. **15**, 331 (1967).
[6] J. V. EVANS, Planet. Space Sci. **13**, 1031 (1965); **15**, 1387 (1967).
[7] J. V. EVANS, J. Geophys. Res. **72**, 3343 (1967).
[8] J. C. G. WALKER, Planet. Space Sci. **16**, 321 (1968).
[9] A. DALGARNO and T. C. DEGGES, Planet. Space Sci. **16**, 125 (1968).
[10] J. R. HERMAN and S. CHANDRA, Planet. Space Sci. **17**, 1247 (1969).
[11] A. DALGARNO, M. B. MCELROY, M. H. REES and J. C. G. WALKER, Planet. Space Sci. **16**, 1371 (1968).
[12] K. I. GRINGAUZ, G. L. GDALEVICH, V. A. RUDAKOV and N. M. SHUTTE, Geom. i Aeron. **8**, 224 (1968).
[13] V. A. RUDAKOV and I. A. KNORIN, Ionosph. Issled., No. 20, 121 (1971).
[14] N. M. SHUTTE and I. A. KNORIN, Space Research IX, North-Holland Publ. Co., Amsterdam 1969 (p. 267).
[15] H. CARRU, M. PETIT and P. WALDENFEL, J. Atmos. Terr. Phys. **29**, 351 (1967).
[16] P. B. RAO, J. Geophys. Res. **73**, 1661 (1968).
[17] P. M. BANKS, Annls Géophys. **22**, 577 (1966).
[18] P. M. BANKS, Planet. Space Sci. **14**, 1085 (1966).
[19] A. DALGARNO and D. PARKINSON, J. Atmos. Terr. Phys. **18**, 335 (1960).
[20] R. B. CAIRNS and J. A. SAMSON, Phys. Rev. **139**, A 1403 (1965).