INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3, avenue Circulaire, UCCLE - BRUXELLES 18

AERONOMICA ACTA

A - N° 45 - 1966

Electron thermal conductivity in the ionosphere

by P. BANKS

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3, Ringlaan, UKKEL - BRUSSEL 18

FOREWORD

"Electron Thermal Conductivity in the Ionosphere" is a brief summary of the results of an investigation into the physical processes of electron gas heat conduction in the ionosphere. This paper will be published in Earth and Planetary Science Letters during 1966.

AVANT-PROPOS

Le texte "Electron Thermal Conductivity in the Ionosphere" résume brièvement les résultats de recherches concernant les processus physiques de la conduction (thermique) d'un gaz électronique dans l'ionosphère. Cet article sera publié en 1966 dans Earth and Planetary Science Letters.

VOORWOORD

"Electron Thermal Conductivity in the Ionosphere" is een korte samenvatting der resultaten van een onderzoek betreffende de fysische processen van warmtegeleiding van een elektronen-gas in de ionosfeer. Deze verhandeling zal gepubliceerd worden in Earth and Planetary Science Letters in de loop van 1966.

VORWORT

Der Text "Electron Thermal Conductivity in the Ionosphere" ist die Zusammenfassung einer Forschung über den physikalischen Prozessen der Elektronenwärmeleitung in der Ionosphäre. Diese Arbeit wird im laufenden 1966 in Earth and Planetary Science Letters herausgegeben werden.

ELECTRON THERMAL CONDUCTIVITY IN THE IONOSPHERE

by

P. BANKS

Institut d'Aéronomie Spatiale de Belgique, Bruxelles 18

and

Ionosphere Research Laboratory, Pennsylvania State University

University Park, Pennsylvania 16802

Abstract

The flow of thermal energy through the electron gas of the ionosphere in response to gradients in electron temperature plays an important part in determining the actual electron temperature profile. In this paper it is shown that the neutral atmosphere can significantly reduce the electron thermal conductivity by decreasing the electron mean free path below these distances typical of a fully ionized gas. A basic equation for the thermal conductivity is developed and several examples are given of its application. It is shown that for typical atmospheric conditions there is essentially no heat conduction below 150 km while significant reductions must exist to at least 200 km.

Résumé

Le flux d'énergie thermique passant à travers le gaz d'électrons de l'ionosphère et imposé par les gradients de la température des électrons joue un rôle important dans la détermination du profil réel de la température électronique. Dans ce travail, nous montrons que l'atmosphère neutre peut réduire la conductivité thermique électronique de façon significative, en raccourcissant le libre parcours moyen des électrons sous les distances limites caractéristiques d'un gaz complètement ionisé. Nous développons une équation fondamentale pour la conductivité thermique et nous l'appliquons à plusieurs exemples. Nous montrons que pour des conditions typiques de l'atmosphère, il n'y a essentiellement aucune conduction thermique au-dessous de 150 km et que des réductions importantes existent certainement jusqu'à 200 km au moins.

Samenvatting

De stroom van thermische energie, in het electronengas in de ionosfeer ten gevolge van gradiënten in de electronen temperatuur, speelt een voorname rol bij het vaststellen van het huidig profiel der electronentemperatuur. In deze bijdrage wordt aangetoond dat de neutrale atmosfeer in belangrijke mate de thermische geleidbaarheid der electronen kan verminderen door de gemiddelde vrije weglengte der electronen te beperken tot waarden die veel kleiner zijn dan deze voor een volledig geïoniseerd gas. Er wordt een grondvergelijking opgesteld voor de thermische geleidbaarheid en enkele voorbeelden van toepassingen worden gegeven. Men bewijst dat voor kenmerkende atmosferische omstandigheden er geen warmtegeleiding is beneden de 150 km ; evenzo wordt ze nog sterk beperkt tot op 200 km hoogte.

Zusammenfassung

Der vom elektronischen Temperaturgradient abhängige thermische Energiefluss ist sehr wichtig, um die richtige Elektrontemperatur festzustellen. In dieser Arbeit, zeigen wir, wie die ungeladene Atmosphäre die elektronische Wärmeleitung vermindert, da die mittlere freie Weglänge der Elektronen kleiner wird als die charakterischen Längen einer ganz ionisierten Gas. Eine fundamentale Gleichung für die Wärmeleitung wird vorgestellt und ausgenutzt in verschiedenen Fallen. Es wird gezeigt, dass, für typischen Zuständen der Atmosphäre, keine Wärmeleitung unter 150 km praktisch stattfinden kann und dass wichtige Verminderungen bis 200 km Höhe sicher existieren.

I.- INTRODUCTION

It is known from rocket, satellite, and ground-based radio experiments that the temperatures of the charged and neutral gases of the upper atmosphere can differ by at least 1000°K. As a result of several theoretical studies [1-3] it appears that the principal source of heat for the electron gas, at least during the daytime, arises from the energy released in the photoionieation of O, O_2 and N_2. The theoretical calculation of charged particle temperatures in the ionosphere requires an accurate knowledge of the various terms entering into the heat budget equations. In the early studies of Hanson and Johnson [1], Hanson [2], and Dalgarno et al. [3], the effect of energy conduction through the electron gas was ignored and the temperature profiles were computed on the basis of localized energy production and loss. A later study by Geisler and Bowhill [4] attempted to correct this situation through the introduction of an expression for the electron thermal conductivity appropriate to a fully ionized gas. It is noted, however, that the regions of the ionosphere below 200 km are only weakly ionized (less than 10^{-2} %), and, as shown in this letter, the neutral atmosphere can significantly reduce the electron thermal conductivity below the value predicted for a fully ionized gas. This effect is responsible for appreciable changes in the computed profiles of electron temperature.

II.- DERIVATION.

At any altitude the energy flux q_p, along the lines of geomagnetic force arising from a gradient in electron temperature is given by

$$q_p = - K \frac{dT_e}{ds} \qquad (1)$$

where K is the electron gas thermal conductivity and the distance s is measured along the magnetic field lines. This equation is generally valid only above 70 km since below this altitude the effect of magnetic constraint upon electron motions is gradually lost due to electron collisions with neutral gas particles. By introducing the magnetic dip angle, I, the energy balance for the electron gas at any altitude z becomes

$$\frac{\partial U_e}{\partial t} = P_e - L_e + \sin^2 I \frac{d}{dz} \left[K \frac{dT_e}{dz} \right] \qquad (2)$$

where U_e is the total electron gas thermal energy per unit volume, P_e and L_e are the respective rates of energy production and loss per unit volume and the final term is the conduction effect which acts as a shaping factor for the temperature profile by interrelating the temperature gradients at all altitudes.

A basic assumption in previous work [2, 4] has been that K is correctly given by the density independent expression $K = 7.7 \times 10^5 T_e^{5/2}$ ev cm^{-1} sec^{-1} $°K^{-1}$ which was originally derived by Spitzer and Härm [5] for a fully ionized gas. For the problem of electron heat conduction in the ionosphere it is necessary to extend this result to take account of the reduction in electron mean free path brought about by electron-neutral collisions.

The derivation of the electron thermal conductivity differs from the more usual gas kinetic calculations because in the present case we are not concerned with the total energy transported by the mixture of charged and neutral particles but only with the portion which travels within the electron gas in response to electron temperature gradients. With a simple mean free path approach it is found that the electron thermal conductivity, K', for a partially ionized gas, can be expressed as

$$K' = \frac{K_i}{1 + K_i \sum (1/K_n)} \qquad (3)$$

where K_i is the conductivity of a fully ionized gas and K_n is the thermal conductivity of a very weakly ionized gas where the effects of charged particle collisions can be ignored. The indicated summation extends over all neutral gas species present. For low neutral particle densities where K_n becomes large $K' \simeq K_i$, while for high neutral densities $K_i \sum (1/K_n) >> 1$ and $K' \simeq 1/\sum (1/K_n)$.

The thermal conductivity given by (3) is not complete. As shown by Spitzer and Härm [5] thermoelectric effects in the ionosphere act to prevent divergences of electric current arising from gradients in electron temperature by creating a secondary electric field which, in turn, results in a reduction factor $\varepsilon = 0.419$ in the total electron thermal conductivity. Strictly taken, this factor has been derived only for a fully ionized gas but it can be assumed that it also applies to the problem of electron-neutral collisions. Hence, the effective value, K, of the electron thermal conductivity is taken to be $K = \varepsilon K'$.

To derive a suitable expression for K_n we use the results of Chapman and Cowling [6] for the approximation of a Lorentzian gas :

$$K_n = \frac{1}{3} k \frac{n_e}{n_n} [(\bar{A}, \bar{A}) - (\bar{A}, \bar{D})^2 / (\bar{D}, \bar{D})] \tag{4}$$

where k is Boltzmann's constant, n_e is the electron number density, n_n is the neutral particle number density, and the bracketed quantities involve various weighted integrals of the electron velocity distribution and the electron scattering cross section. These, in turn, can be further reduced through the identification of the electron-neutral momentum transfer cross section, $\bar{Q}_D$. The result of this manipulation is that

$$K_n = \frac{2}{3} \frac{n_e}{n_n} \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} \frac{1}{\bar{Q}_D} \tag{5}$$

where m_e is the electron mass.

In terms of K_i, K_n and ε the total electron thermal conductivity now becomes

$$K = \frac{7.7 \times 10^5 \; T_e^{5/2}}{1 + 3.22 \times 10^4 \; \frac{T_e^2}{n_e} \sum n_n \bar{Q}_D} \text{ ev cm}^{-1} \text{ sec}^{-1} \, {}^\circ\text{K}^{-1} \tag{6}$$

where the summation in the correction term again extends over the different neutral gases. For low neutral particle densities (6) reduces to the result for a fully ionized gas. At the opposite extreme, however, the correction factor becomes large and

$$K = \frac{20.4 \; n_e T_e^{1/2}}{\sum n_n \bar{Q}_D} \text{ ev cm}^{-1} \text{ sec}^{-1} \, {}^\circ\text{K}^{-1}, \tag{7}$$

which de-emphasizes the importance of changes in electron temperature. The transition between the two limiting conditions is shown in Figure 1 for several values of T_e. The effect of electron-neutral collisions is noted at all points where the curves depart from the horizontal.

The application of (6) to the problem of electron heat conduction in the ionosphere requires a knowledge of the electron momentum transfer cross section for O, O_2, and N_2. From recent work [7] we adopt

$$N_2 \quad : \quad \bar{Q}_D = 2.82 \times 10^{-17} \, (1 - 1.21 \times 10^{-4} \, T_e) \, T_e^{1/2} \ \mathrm{cm}^2 \qquad (8a)$$

$$O_2 \quad : \quad \bar{Q}_D = 2.2 \times 10^{-16} \, (1 + 3.6 \times 10^{-2} \, T_e^{1/2}) \ \mathrm{cm}^2 \qquad (8b)$$

$$O \quad : \quad \bar{Q}_D = 3.4 \times 10^{-16} \ \mathrm{cm}^2 \qquad (8c)$$

as representing the electron momentum transfer cross sections over the range $200 \leq T_e \leq 4500$°K.

III.- APPLICATION.

The reduction in the electron thermal conductivity brought about by the neutral atmosphere plays an important part in diminishing the flow of electron thermal energy to low altitudes where electron energy losses to diatomic molecules become large. For the daytime (solar zenith angle of 60°) density and temperature values reported by Spencer, et al. [8] during rocket flight 6.07 it is calculated that the conductivity was reduced at 160 km and 130 km by the factors 4.2 and 43, respectively. For lower altitudes the reduction factor increases rapidly and, at 100 km, it is found that there was essentially no heat conduction in the electron gas.

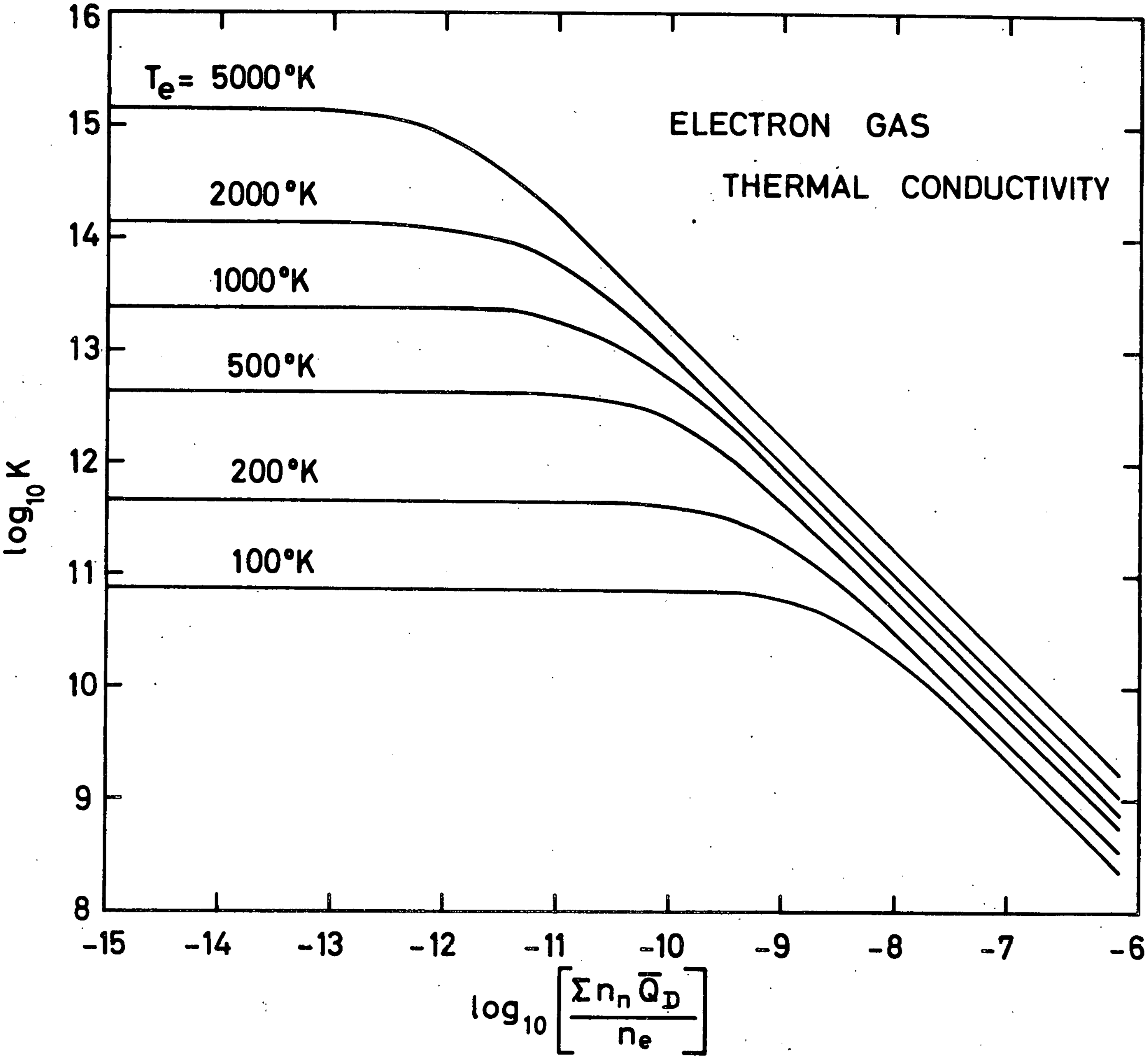
ELECTRON GAS
THERMAL CONDUCTIVITY
T_e= 5000°K
2000°K
1000°K
500°K
200°K
100°K
$\log_{10} K$
16
15
14
13
12
11
10
9
8
−15
−14
−13
−12
−11
−10
−9
−8
−7
−6
$\log_{10}\left[\frac{\Sigma n_n \overline{Q}_D}{n_e}\right]$

Figure 1.

The nighttime atmospheric conditions for the regions below 200 km are generally described by moderate (900° - 1500°K) values of T_e and greatly reduced values of electron density. Using the radio backscatter data of Doupnik and Nisbet [9] obtained at Arecibo, Puerto Rico during early morning hours, for example, it is found that the 160 km reduction factor is larger than 1800 and that a reduction larger than 10 is found through 220 km. On this basis it is not possible to accept the recent remarks of Bowhill [10] regarding the possibility of $(T_e - T)$ being negative at 125 km at night as a result of strong electron heat conduction effects.

The above examples indicate that there exists a substantial decoupling of the electron gas above 200 km from the electron energy loss processes of the E-region. If there were no reduction factor the thermal energy of the electron gas would be rapidly conducted downwards from the regions of peak energy production. The net effect of this would be to lower the calculated values of T_e at all altitudes and alter the time response of T_e to changes in the energy production rate. With the decreased heat conductivity the local effects of energy production and loss are more strongly emphasized.

As a specific example of the changes implied in the use of an electron thermal conductivity which is dependent upon the neutral atmosphere, a calculation has been made of the temperature profiles which result from the use of the corrected and uncorrected expressions. The results shown in Figure 2 are characteristic of quiet solar conditions with a relatively low electron density and moderate energy production rate. Curve 1, indicated on the figure, is the temperature profile which results when the thermal conductivity is completely omitted $(K = 0)$ from equation (2). Curve 2 is the profile which includes the effect of the reduced conductivity derived in this letter and can be compared with curve 3 which results from the conductivity appropriate to a fully ionized gas. Curves 4 and 5 are, respectively,

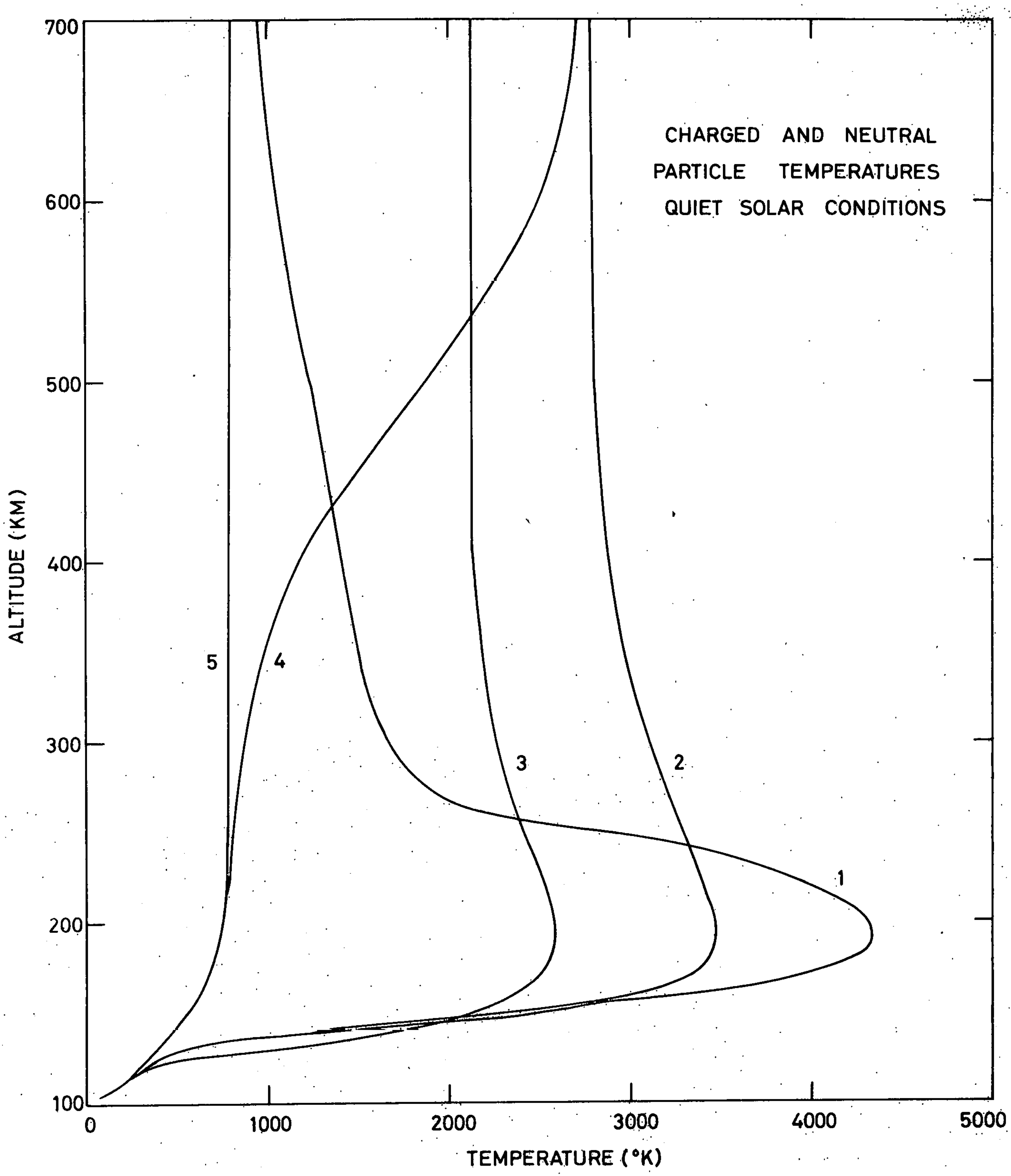
CHARGED AND NEUTRAL
PARTICLE TEMPERATURES
QUIET SOLAR CONDITIONS
ALTITUDE (KM)
100
200
300
400
500
600
700
TEMPERATURE (°K)
0
1000
2000
3000
4000
5000
1
2
3
4
5

Figure 2.

the oxygen ion and neutral gas (Nicolet Model J1.53D [11]) temperature profiles.

The effect of the reduced heat conduction is evident at all altitudes. By restricting the downward flux of thermal energy the peak value of T_e at 190 km is raised from 2600° to 3400°K. This difference of 800°K is maintained at all higher altitudes through the action of conduction. Below 180 km the temperature of the uncorrected model (curve 3) is greater than that of the corrected model (curve 2) due to the net accumulation of transported thermal energy below 150 km.

IV.- CONCLUSIONS.

From the present analysis it can be concluded that the neutral atmosphere is important in reducing the electron gas thermal conductivity below 200 km during both day and night. It is shown by equation (6) that the magnitude of the reduction is a sensitive function of both the electron temperature and density. As a result it appears that :

1) At altitudes below 150 km during both day and night any rise in the electron gas temperature above that of the neutral atmosphere must be due to local heating effects.

2) At altitudes between 150 and 200 km there is a moderate reduction during the day and a large reduction at night, implying that night time rises in electron temperature must be local in nature.

3) At altitudes above 200 km the thermal conductivity is relatively independent of the neutral atmosphere and thermal energy can be readily conducted from regions of energy production to regions of energy loss.

4) The time dependence of the electron gas temperature profile is substantially altered. At altitudes below 200 km the time for cooling is shortened while above 200 km an increase in the cooling time should be found.

ACKNOWLEDGEMENTS.

The direction of Dr M. NICOLET is gratefully acknowledged. This study has been supported, in part, through grant ONRG-00009-66 from the U.S. Office of Naval Research, Washington D.C. While at the Ionosphere Research Laboratory, The Pennsylvania State University, the author held a N.A.S.A. predoctoral traineeship.

REFERENCES.

[1] W.B. HANSON and F.S. JOHNSON, Electron temperatures in the ionosphere, Mémoires Soc. R. Sci. Liège, Series 5, 4 (1961) 390.

[2] W.B. HANSON, Electron temperatures in the upper atmosphere, in Space Research III (Wiley, 1961), p. 282.

[3] A. DALGARNO, M.R.C. Mc DOWELL, and R.J. MOFFETT, Electron temperatures in the ionosphere, Planet. Space. Sci., 11 (1963), 463.

[4] J.E. GEISLER and S.A. BOWHILL, Ionospheric temperatures at solar minimum, J. Atm. and Terr. Phys. 27 (1965), 1119.

[5] L. SPITZER and R. HÄRM, Transport phenomena in a completely ionized gas, Phys. Rev. 89 (1953), 977.

[6] S. CHAPMAN and T.G. COWLING, Mathematical theory of nonuniform gases, Cambridge University Press, Cambridge (1952).

[7] P. BANKS, Collision frequencies and energy transfer : Electrons, to be published, 1966.

[8] N.W. SPENCER, L.H. BRACE, G.R. CARIGNAN, D.R. TAEUSCH, and H. NIEMANN, Electron and molecular nitrogen temperature and density in the thermosphere, J. Geophys. Res. 10 (1965), 2665.

[9] J.R. DOUPNIK and J.S. NISBET, Electron temperature and density fluctuations in the daytime ionosphere, in : Electron density profiles in ionosphere and exosphere (North Holland Publishing Co., Amsterdam, 1966) p. 493.

[10] S.A. BOWHILL, Origin of field aligned irregularities in the F-2 region, to be published, J. Atm. and Terr. Physics (1966).

[11] M. NICOLET, Aeronomy, to be published in Handbuch der Physik (Geophysik), Band XLIX, 1966.