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Estimation of Electron Heating Rates in the Topside Ionosphere during Medium Solar Activity

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Considering the heat balance in the topside ionosphere, the heat input rates Q_e for electron gas are calculated from the electron heat loss rates using electron density, electron temperature and ion composition measurements at different altitudes obtained by incoherent back-scatter radar during medium solar activity conditions. The relative importance of various collisional and conduction heat loss terms are examined in detail. The values of Q_e estimated in this manner vary from $1{\cdot}5\times10^4$ eV cm^{-3} sec^{-1} at 300 km to $1{\cdot}5\times10^2$ eV cm^{-3} sec^{-1} at 600 km.

1. Introduction

Since electrons attain thermal equilibrium in a very short interval of time,[1] the direct estimation of electron heating rates from experimental observations in the ionospheric F-region can be performed either from a consideration of the heat input or by heat loss mechanisms. The heating mechanism is through photoelectron interactions with thermal electrons but it is generally difficult to get reliable measurements of photoelectron fluxes throughout the F-region altitudes. On the other hand, the heat is lost through conduction and the collisions of electrons with ions and neutrals, and it is relatively easy to calculate the heat loss-rates through the measurements of electron temperature and ion densities made by incoherent back-scatter radar, rockets and satellites.

Brace *et al.*[2,3] have followed the second approach of estimating electron heating rates Q_e from loss rates (L) using rocket measurements of electron temperature (T_e) and electron density (N_e) profiles in the bottomside F-region. Similar estimates have also been made by Swartz and Nisbet[4] using incoherent back-scatter radar measurements of T_e and N_e. However, there does not seem to be any such estimate of Q_e from observations in the topside ionosphere which are needed to compare with the theoretically calculated values of Q_e. In the present paper, an attempt is made to estimate Q_e from heat loss rates in the topside ionosphere using the available back-scatter radar measurements at Arecibo during medium solar activity period and compare them with theoretical values.

2. Theory of Thermal Balance and Method of Estimation

The energy balance equation for electrons and ions in the ionosphere may be written as follows:

For electrons:

$$Q_e = L_{col} + L_{con} \qquad \ldots(1)$$

where

$$L_{col} = L_{ei} \qquad \ldots(2)$$

$$L_{con} = -\sin^2 I \frac{d}{dz}\left(k_e \frac{dT_e}{dz} \right) \qquad \ldots(3)$$

For ions:

$$Q_i = L_{in} \qquad \ldots(4)$$

where Q_e and Q_i are electron and ion heating rates

L_{col} and L_{con} are the electron-ion collisional and total heat conduction loss rates;

L_{ei} and L_{in} are electron and ion collisional heat loss rates;

K_e is the thermal conductivity of electrons given by $7{\cdot}7 \times 10^5 \times T_e^{5/2}$ eV cm^{-1} deg^{-1} sec^{-1};

and I is the magnetic dip

Since K_e is a function of electron temperature T_e, L_{con} will consist of two parts, i.e.

$$L_{con} = -C_1\, T_e^{3/2}\left(\frac{dT_e}{dz}\right)^2 - C_2\, T_e^{5/2}\frac{d^2T_e}{dz^2} \qquad \ldots(5)$$

where $C_1 = 19{\cdot}25 \times 10^5 \sin^2 I$

and $C_2 = 7{\cdot}7 \times 10^5 \sin^2 I$

In the ion heat balance equation, conductivity is neglected since it is almost negligible below 600 km (ref. 5). At heights of 400 km and above, L_{col} consists of collisions between electron and ions[6] only, which in turn serves as heat input to ions (Q_i). If the electron density is quite high ($N_m \sim 10^6$), as in the case of low latitudes, the dominance of electron-ion collisions in L_{col} prevails even at 300 km (ref. 7). The ion heat loss L_{in} consists of collisional loss to neutrals. The ion temperature T_i may be taken from measurements, if they are available, or it may be calculated from ion heat balance equation [Eq.(4)] which becomes:

$$L_{ei} = L_{in} \qquad \ldots(6)$$

This equation may be written as :

$$L(e)\ (T_e - T_i) = L(n)\ (T_i - T_n) \qquad \ldots(7)$$

from which T_i may be derived as :

$$T_i = \frac{L(e)\ T_e + L(n)\ T_n}{L(e) + L(n)} \qquad \ldots(8)$$

where $L(e)$ is a function of T_e, N_e, $n(O^+)$, $n(He^+)$ and $n(H^+)$, and $L(n)$ is a function of T_i, T_n, $n(O^+)$, $n(He^+)$, $n(H^+)$, $n(O)$, $n(He)$ and $n(H)$ and also the relevant collision cross-sections, for which the expressions are taken from the work of Banks[8] and are given below:

$$\begin{aligned} L(e) &= 0{\cdot}48 \times 10^{-6}\ N_e\ n(O^+)\ T_e^{-3/2} \\ &+ 1{\cdot}9 \times 10^{-6}\ N_e\ n(He^+)\ T_e^{-3/2} \\ &+ 7{\cdot}7 \times 10^{-6}\ N_e\, n\ (H)\ T_e^{-3/2} \qquad \ldots(9) \end{aligned}$$

$$\begin{aligned} L(n) &= 10^{-14}\ [0{\cdot}21\ n(O^+)\ n\ (O)\ (T_i + T_n)^{1/2} \\ &+ 2{\cdot}8\ n(O^+)\ n(He) + 0.4\ n(O^+)\ n(H)\ T_n^{1/2} \\ &+ 5{\cdot}8\ n\ (He^+)\ n(O) + 0{\cdot}4\ n(He^+)\ n(He)\ (T_i + T_n)^{1/2} \\ &+ 10{\cdot}0\ n(He^+)\ n(H) + 0{\cdot}36\ n(H^+)\ n\ (O)\ T_i^{1/2} \\ &+ 5{\cdot}5\ n(H^+)\, n\ (He) + 1{\cdot}4\ n(H^+)\ n(H)\ (T_i + T_n)^{1/2}] \\ &\qquad \ldots(10) \end{aligned}$$

Let us now look at the factors required for the estimation of collisional and conduction loss terms in Eq. (1) which determine the value of total loss which, in its turn, is equal to Q_e.

To calculate the collisional loss rates in the topside ionosphere, it is obvious that one should know electron temperature T_e and the densities of various ions (N_i). Usually the information on N_i is not available along with many of the satellite T_e measurements. In fact, this lack of information is one of the reasons which generally stand in the way of making reliable estimates of L_{ei} in the topside ionosphere, particularly in low latitudes. However, such information is available with rocket and incoherent backscatter radar measurements. The value of T_i can either be estimated from Eq. (8) with the help of T_e and N_i, and neutral density model or the experimental values, if available, can be used to get L_{col}. The second factor needed in calculating the loss rate is the estimation of the conduction term L_{con} which requires the height distribution of T_e. Satellite data do not give the height profiles of T_e whereas rocket and back-scatter radar data give these profiles and as such L_{con} can be calculated from the latter measurements. The conduction terms so calculated at different heights may then be used as representative values to estimate Q_e from satellite data also, if the latitudes and solar activity conditions are similar.

3. Evaluation of Different Heat Loss Terms

The calculations of different conduction and collisional loss terms are made, according to the method described in Sec. 2, from T_e and N_i profiles obtained through radar measurements over Arecibo[9] at 1436 hrs LT on 10 Feb. 1972, corresponding to medium solar activity, the 10·7 cm solar radio flux being 115 units. Fig. 1 shows the different components of L_{col} and L_{con} calculated in the altitude range 300-800 km. $L(dT_e/dz)$ and $L(d^2T_e/dz^2)$ are the first and second terms on the right hand side of Eq. (5) and are functions of first and second derivatives, respectively, of electron temperature (T_e). $L(O^+)$ and $L(H^+)$ are the electron heat loss rates for the O^+ and H^+ ions. It may be noted from the diagram that $L(dT_e/dz)$ remains negative throughout the altitude range of our interest, i.e. 300-800 km. The second conduction loss term $L(d^2T_e/dz^2)$ remains negative from 300 to 450 km and is negligible in comparison to the first term. Near 450 km this term becomes zero and then changes its sign to become positive and dominant over the first term. Above 600 km the second derivative of electron temperature becomes very noisy and is very difficult to estimate it correctly with confidence. This noisy nature of second derivative of electron temperature makes the heat loss rates very unreliable above 600 km and for this reason we are restricting this method of estimating Q_e only upto 600 km.

The ion composition data in the present study shows that lighter ions (H^+) are minor ions in the altitude range of our interest (below 800 km), and N_e is almost equal to $n(O^+)$. But their contribution towards the electron collisional heat loss cannot be neglected as they are efficient in cooling. It can be

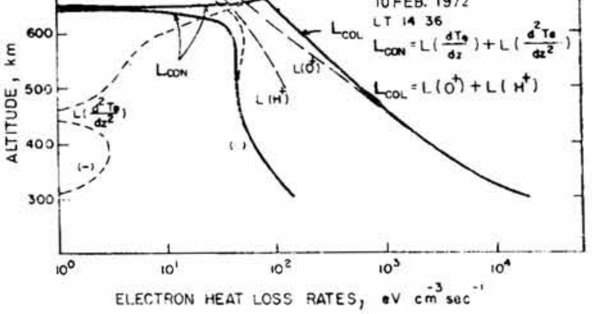

Fig. 1—Altitude profiles of different heat loss rates for medium solar activity conditions over Arecibo

seen from Fig. 1 that H^+ ions contribute 20% and 30%, respectively, at 500 and 600 km towards the total collisional heat loss though they are only 1 to 3% of total ion density at these altitudes. At higher altitudes lighter ions dominate in collisional losses. Comparing L_{con} with L_{col} in Fig. 1, it can be seen that L_{con} is only 1 to 10% of the total loss from 300 to 500 km. Therefore, total heat loss rate can be fairly represented by only collisional loss rates. Again in this height range, O^+ collisional loss represents the total loss since its value is about 90% of the total loss. From 500 to 600 km $L(H^+)$ and L_{con} both have substantial values which are not negligible in comparison to the total heat loss rate, but each of these two are of opposite signs so that when all the heat loss rates are summed up $L(H^+)$ and L_{con} will approximately cancel out each other and $L(O^+)$ will again represent the total loss even up to 600 km. Above 600 km the calculation of L_{con} is somewhat difficult and hence the estimation of total heat loss rates is quite unreliable. However, it appears from the trend of the curve, the conduction term dominates over the collisional loss terms.

From the above discussion of the various loss rates, it may be seen that below 600 km, $L(O^+)$ essentially represents total loss rate which, in turn, is equivalent to heating rate. This fortuitous simplification allows us to apply this method to estimate Q_e even when only N_e and T_e measurements are available as in the case of satellite data.

4. Estimates of Q_e in the Topside Ionosphere

Fig. 2 shows the heat input rates which are equivalent of the total heat loss rates ($L_{col} + L_{con}$) in Fig. 1. It shows that the estimated values of Q_e vary from $1{\cdot}5 \times 10^4$ eV cm^{-3} sec^{-1} at 300 km to $1{\cdot}5 \times 10^2$ eV cm^{-3} sec^{-1} at 600 km.

Recently, a number of theoretical calculations for the photoelectron production, their escape and heating of thermal electron gas were made by several workers. Cicerone *et al.*[10] have compared all the calculations by different techniques and showed their general agreement with one another. Their values of heat input rates for noon conditions of medium solar activity are also shown in Fig. 2 along with those of the present study for comparison. Fig. 2 shows clearly the difference between Q_e values estimated by these two methods at all the altitudes from 300 to 600 km. Here we have restricted ourselves only up to 600 km due to conduction loss term being unreliable above this altitude. The theoretical values of Q_e are about $1{\cdot}2 \times 10^3$ eV cm^{-3} sec^{-1} at 300 km and 3×10^1 eV cm^{-3} sec^{-1} at 600 km, and are much smaller than those obtained in the present study based on measured T_e and N_i profiles. It may be mentioned here that similar discrepancy was observed in the bottomside ionosphere[4] also and it was attributed to deficiency in atmospheric models and solar euv fluxes. Thus, there is a need for more observational estimates of Q_e for examining this problem in detail.

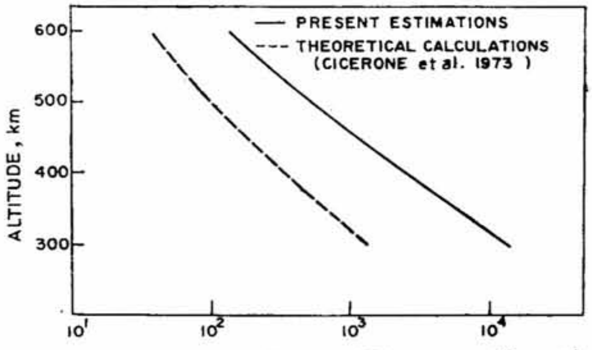

Fig. 2—Altitude profiles of heat input rates over Arecibo for medium solar activity condition

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