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Electron Temperatures in the E-Region of the Ionosphere

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Various heating and cooling mechanisms which are operative in the lower E-region are discussed and their relative importance in different altitude range is shown. These heating and cooling rates are then used to derive the electron temperature T_e. The calculated values of electron temperature are found to be higher than neutral temperature through out the altitude range 100~150 km, with the difference increasing with increase in altitude. However, compared to observed values of T_e, the calculated values are still smaller below about 130 km. Above this altitude, the calculated values become larger. Estimation of T_e for different, suggested values of heating efficiency due to dissociative recombination, show that T_e profile obtained even by assuming a constant value of 1.3 eV is in fairly good agreement with those derived based on variable values of this parameter.

1. INTRODUCTION

Earlier, when in-situ measurements of electron temperature using rocket-borne Langmuir probe experiments reported values which were far in excess of neutral temperatures [*1*] for mid-day, mid-latitude conditions; considerable doubts were raised about the uncertainties in the technique itself, since in most of the models, it was assumed that electron temperature (T_e) is same as neutral temperature (T_n) below about 120 km [*2, 3, 4, 5*]. However, subsequently, radio absorption measurements and radar observations [*6, 7*] also showed electron temperature enhancement in the E-region. Attempts were then made to explain these enhanced or high temperatures in the high latitude regions on the basis of heating due to plasma instabilities [*8, 9, 10*] and also other theoretical considerations [*11*].

For mid-latitudes, on the other hand, hardly any quantitative estimate has been made to explain the anomalously high electron temperatures. Oyama et al [*12*] have qualitatively tried to explain these elevated electron temperatures on the basis of interactions of thermal electrons with excited neutral gases. It is also interesting to note that the electron distribution function also shows some

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electrons to be non-Maxwellian which form the high energy tail in this layer and are now known as supra-thermal electrons [*13, 14*].

In this paper, therefore an attempt has been made to estimate the electron temperatures in the E-region in the altitude range 100 to 150 km, taking into account the possible contributions from all such mechanisms which can enhance the heating rates of thermal electrons and hence can affect the electron temperature.

2. Theory

The electron temperature in the ionosphere is primarily controlled by various heating and cooling processes which cause the transfer of energy to and from thermal electrons. The extent to which the electron temperature increases, depends upon the relative importance of their heating and cooling rates and to have a quantitative idea about the same, it is the electron energy equation which needs to be considered. Since the electron temperature is in quasi-equilibrium state and for low altitudes, thermal conduction of electrons is not important, this equation simply reduces to a balance between local heating and cooling rates [5] as

$$\Sigma Q_e = \Sigma_{Le} \tag{1}$$

where the Q is the heating rate and L represents the loss mechanism and summation is over all such rates due to different processes.

2.1 Heating Rates

There are various processes through which energy is transferred to electrons and they, in turn get heated up. Basic physical processes which are considered in this study are as follow:

2.1.1 Heating Rate Due to Ionization

Solar radiations in EUV range of wavelengths ionize the neutral constituents such as N_2, O_2 and O. Since the incident photons have energy in far excess of the ionization potential of these gases, the same is carried by the photo-electrons in the form of kinetic energy and subsequently lost to thermal electrons, partly through coulomb collisions and partly through elastic and inelastic collisions with neutral particles. It is only a small part of energy which is being supplied by photo-electrons in heating the thermal electrons.

Thus to have an estimate of this heating rate, the photo-ionization rates and their heat transfer efficiency to thermal electrons should be known. The photo-ionization rates can be calculated from the following expression:

$$q_{pr} = \sum_j \sum_\lambda \sigma_{ij\lambda} n_j F_{0\lambda} \exp(-\sigma_{aj\lambda} n_j H \operatorname{Sec}\chi) \qquad (2)$$

where $\sigma_{ij\lambda}$ is the ionization cross-section of jth species (j can be N_2, O_2 or O) at wavelength λ, n_j is the concentration of jth species, $F_{0\lambda}$ is the un-attenuated flux at wavelength λ, $\sigma_{aj\lambda}$ is the absorption cross-section of jth species at wavelength λ, H is the scale height and χ is the solar zenith angle.

In the present work, these rates are calculated for the latitude of 31.25° (corresponding to Uchinoura) for conditions appropriate to Jan. 22, 1978, 1100 hr. JST, for which experimental data regarding electron density, electron temperature and energy distribution function are available. MSIS-86 [*15*] model for neutral densities and temperatures was used for conditions appropriate to flight conditions. The flux and cross-sections used were as given by Torr [*16*].

In the atmosphere, these photo-electrons produced by initial photo-ionization, called the primary electrons undergo inelastic collisions because of the excess kinetic energy and also produce secondary electrons. Lilensten et al [*17*] have estimated the efficiency of production of these secondary electrons and have shown that it increases significantly in the E-region reaching a peak value of 2 to 3 between 120 to 150 km depending upon the intensity of solar flux. In this work therefore, the secondary electron production is computed using the following expression:

$$\eta_{sec} = A(\chi)\exp\left(-((z_m(\chi)-z)/\sigma)^{2\alpha_1}\right) \quad \text{if } z \leqq z_m \qquad (3)$$

$$\eta_{sec} = (A(\chi)-C)\exp\left(-((z-z_m(\chi))/\sigma)^{2\alpha_2}\right)+C \quad \text{if } z > z_m \qquad (4)$$

where $A = \alpha_3/\operatorname{Cos}(\chi) + \alpha_4 + \alpha_5 \operatorname{Sin}(\text{latitude})$

$z_m = \alpha_6/\operatorname{Cos}(\chi) + \alpha_7 + \alpha_8 \operatorname{Sin}(\text{latitude})$

and $\alpha_1 = 0.661$; $\alpha_2 = 1.36$; $\alpha_3 = 0.209$; $\alpha_4 = 3.52$;

$\alpha_5 = -0.86$; $\alpha_6 = 6.28$; $\alpha_7 = 120$; $\alpha_8 = -4.31$;

$\sigma = 22.1$; $C = 0.364$

appropriate to high solar activity conditions [*17*]. The corresponding production rate is then given by

$$q_{sec} = \eta_{sec} \cdot q_{pr} \qquad (5)$$

Now knowing the production rates of primary and secondary electrons, the transfer of heat due to them is estimated taking in to account the possibility of excitation of low energy states of nitrogen and oxygen. Swartz and Nisbet [*18*] have suggested an analytical expression for the heating efficiency as:

$$\eta_t = \exp(-6.354 + 4.193R + 0.722R^2 + 0.04938R^3 + 0.001203R^4) \quad (6)$$

where $R = \ln\{[e]/([O_2] + [N_2] + 0.1[O]\}$

and [e], $[O_2]$, $[N_2]$ and [O] are the concentration of electron, molecular oxygen, molecular nitrogen and atomic oxygen respectively. In fact Williams and McDonald [*19*] have considered the division of photo-electron energy between electrons and neutral constituents and obtain a similar expression. It has been found that using either of them for heating efficiency does not make appreciable difference. Therefore in the present work, heating rates due to photoelectrons are calculated as:

$$H_p = (q_{pr} + q_{sec})\,\eta_t \quad (7)$$

2.1.2 Heating Due to Supra-thermal Electrons

The supra-thermal electrons are those which do not follow Maxwellian distribution and constitute the high energy tail in the observed energy distribution functions [*20*]. It has been suggested that interaction of these supra-thermal electrons with the ambient electron gas is the principal source of electron heating in the ionosphere [*21*]. The heating rate due to supra-thermal electrons is given by

$$q_{sup}(z) = [e] \int_{E_c}^{\infty} L(E, z)\, I(E, z)\, dE \quad (8)$$

where I(E, z) is the total supra-thermal electron intensity at altitude z integrated over solid angle, E_c is the energy at which cross over from thermal to supra-thermal electrons takes place. L(E, z) is the stopping cross section given by [*22*].

$$L(E, z) = \frac{3.37E-12}{[e]E^{0.94}}\{(E-E_c/(E-0.53E_c)\}^{2.36} \quad (9)$$

where $E_c = 8.618E{-}05\ T_e$

The concentration and hence the intensity of supra-thermal electrons was available from the rocket measurement [*20*]. The cross over energy was also determined from the energy distribution where the curve deviates from the Maxwellian distribution and it was found to be 0.35 eV. Though only limited number of supra-thermal electron concentrations were available experimentally, same were used to estimate their heating rates in the present work.

2.1.3 Heating due to Electron-nitrogen Vibrational Energy Exchange

The vibrationally excited nitrogen molecules N_2* in the atmosphere can also transfer their energies to thermal electrons thereby acting as a heat source [*23*]. Varnum [*24*] has also pointed out that thermal excitation and de-excitation of N_2 vibration can take place depending upon $T_e >$ vibrational temperature of N_2 (T_v) or $T_e < T_v$ respectively. Many workers [*23, 24, 25, 26*] earlier reported values of T_v as high as 3000°K but subsequently it was pointed out that quenching of N_2* by atomic oxygen and carbon dioxide result in T_v not much different from T_n. However, recently Zalpuri and Oyama [*28*] have shown from their theoretical estimates that T_v is considerably higher than T_n below about 120 km even if quenching of N_2* by O and CO_2 is taken into account though not so substantially as suggested by earlier workers [*27, 28, 29, 30*]. In this study therefore, the heating due to vibrational energy transfer from N_2* to thermal electrons is also considered and the heating rates are calculated using the following expression [*23*]:

$$q_v = 1.5E{-}10\ T_e^{-0.5}\ (1+T_e/2200)\ [\exp(-3400/T_v)$$

$$-\exp(-3400/T_e)]\ [1+\exp(-3400/T_v)]^{-1}[e]\ [N_2] \qquad (10)$$

In these calculations, the vibrational temperature values as estimated by Zalpuri and Oyama [*28*] for the case when there is no quenching of N_2* by O and CO_2, are adopted.

2.1.4 Heating Due to Dissociative Recombination

In the E-region of the ionosphere, the main ions are NO^+ and O_2^+. These ions are lost primarily due to dissociative recombination with electrons and this reaction is found to be dependent upon electron temperature and hence on energy. It has been further noticed that cold electrons recombine more readily than hot electrons and consequently by selectively removing cold electrons, this process provides heat to the thermal electrons [*5*]. The efficiency with which the heat generated by this loss reaction is transferred to the thermal electrons is estimated by many workers but their values differ considerably. Walker and Rees [*30*] had used its values varying in the range of 0.324 to 3.71 eV for the altitude region 90 to 150 km where as Chandra and Sinha [*29*] had adopted 3.69 and 1.31 eV as efficiency values for O_2^+ and NO^+ ions respectively. Hamlin and Myers [*31*] showed that this efficiency is a function of electron temperature which varies between 0.5 and 1.0. Bank [*32*] had however used constant value of 18.0 eV as efficiency in his estimation of heating rates in the auroral zone. Thus we find that as per existing knowledge, the value of this parameter is known with large uncertainty. In the present work, therefore all these different values are considered to see their effect on calculated values of T_e.

2.2 Cooling Rates

The thermal electrons lose their energies due to various local physical and chemical processes and result in the cooling of the electron gas. These processes essentially involve elastic collisions or excitation of rotational, vibrational and the fine structure states of atmospheric gases. The various cooling mechanisms considered and their rates used are as follows:

2.2.1 Elastic Collisions with Neutral Particles

The thermal electrons can lose part of their energy by colliding with the neutral gas particles depending upon the momentum transfer cross-sections, which, from the laboratory measurements are fairly well known [*32, 33*]. The corresponding cooling rates used in the present work are:

$$L_{cN2} = 1.77 \times 10^{-19}\,[e]\,[N_2]\,\{1-1.21\times10^{-4}Te\}\,T_e(T_e-T_n) \qquad (11)$$

$$L_{cO2} = 1.21 \times 10^{-18}\,[e]\,[O_2]\,\{1+3.6\times10^{-2}T^{1/2}\}\,T_e^{1/2}(T_e-T_n) \qquad (12)$$

$$L_{cO} = 7.9\times10^{-19}\,[e]\,[O]\,\{1+5.7\times10^{-4}T_e\}\,T_e^{1/2}\,(T_e-T_n) \qquad (13)$$

The contribution due to elastic collisions with positive ions is expected to be very small [*34*] in the altitude region of interest and therefore has been neglected.

2.2.2 Vibrational Excitation of N_2 *and* O_2

The neutral gas molecules of N_2 and O_2 can be vibrationally excited by their interaction with the thermal electrons and in this process result in cooling of the electron gas. The energy loss rate depends upon the cross-section of these gases. Stubbe and Varnum [*34*] have given an analytical expression for this cooling rate as follows, which is adopted in the present work.

$$L_{vO2} = 7.45\times10^{-13}\,[e]\,[O_2]\,\exp\,(f(T_e-700)/700T_e)$$
$$\{\exp\,(-3000(T_e - T_n)/T_eT_n)-1\} \qquad (14)$$

where $f = 3.902\times10^3 + 4.38\times10^2\tanh\,(4.56\times10^{-4}(T_e-2400))$

$$L_{vN2} = 2.99\times10^{-12}\,[e]\,[N_2]\,\exp\,(f(T_e-2000)/2000T_e)$$
$$\{\exp\,(-g(T_e - T_n)/T_eT_n)-1\} \qquad (15)$$

where $f = 1.06\times10^4 + 7.51\times10^3\tanh\,(1.10\times10^{-3}(T_e-1800))$

and $$g = 3300 + 1.233(T_e-1000) - 2.056\times10^{-4}(T_e-1000)(T_e-4000)$$

2.2.3 *Rotational Excitation of* N_2 *and* O_2

The other important heat loss process for thermal electrons in the lower E-region is by exciting the rotational levels of N_2 and O_2. These cooling rates are based on Born approximation in which it is assumed that it is the quadrupole moment of gas molecules which, while interacting with the thermal electrons cause the rotational excitation. Mentzoni and Row [*35*] have suggested a formula for calculating the cooling rates for species X as:

$$L_{rX} = 1.17\times10^{-10}\,[e][X\}\,q^2\,B\,(T_e-T_n)/T_e^{1/2} \tag{16}$$

where q is the quadrupole moment of the molecules in atomic units and B is the rotational constant in eV. For N_2, $B = 2.49\times10^{-4}$ and $q = -1.0$

$$L_{rN2} = 2.9\times10^{-14}\,[e]\,[N_2]\,(T_e-T_n)\,T_e^{1/2} \tag{17}$$

For O_2, the quadrupole moment is very small and short range interactions have a very important effect on the rotational cross-sections [*38*]. The reported values for quadrupole moment show variations from 0.29 to 1.8 [*39, 40, 41, 42, 43, 44*]. In the present study, a value of 0.3 is used as suggested by Lawton and Phelps [*41*] which in fact is modification of their earlier value [*43*]. The rotational constant B used in this case was 1.81×10^{-4} [*37*] and accordingly the cooling rates for O_2 are given by:

$$L_{rO2} = 1.906\times10^{-15}\,[e]\,[O_2]\,(T_e-T_n)\,T_e^{1/2} \tag{18}$$

2.2.4 *Fine Structure Excitation of* O

The thermal electrons in the lower ionosphere get cooled by transferring their energies in excitation of fine structure levels of ground state of atomic oxygen. Hoegy [*45*] and Carlson and Mantas [*46*] have suggested these cooling rates using available cross-section values [*47, 48*]. In the present work, these cooling rates are calculated using Carlson and Mantas [*46*] expression as:

$$L_{fO} = 1.73\times10^{-9}\,[e]\,[O]\times\sum_{j=0}^{2}\sum_{j'>j}^{2} X_{jj'}Y_{jj'}/T_e^{1/2}\,Z^* \tag{19}$$

where $$Z^* = 1+0.6\exp(-228/T_n)+0.2\exp(-325/T_n)$$

$$X_{jj'} = E_{jj'}\exp(-E_{j'}/kT_n)\{\exp(-E_{jj'}/kT_e)-\exp(-E_{jj'}/kT_n)\}$$

$$Y_{jj'} = (a_{jj'}T_e^2 + b_{jj'}T_e + c_{jj'})/(d_{jj'}T_e + 1)$$

$$E_{jj'} = E_j - E_{j'}$$

and $E_0 = 0.028$, $E_1 = 0.02$, $E_2 = 0$. The values of constants $a_{jj'}$, $b_{jj'}$, $c_{jj'}$ and $d_{jj'}$ used are as given [46] for Le Dournef and Nesbet cross-section values [48].

Next, the electron temperature T_e is determined using these heating and cooling rates. It may be seen that all these rates except heating due to primary ionization are complex functions of electron temperature itself and hence the equation (1) cannot be solved algebraically. An iterative method is therefore adopted to solve this equation starting with initial value of T_e equal to neutral temperature. The corresponding values of T_e is determined for which the sum of all heating rates is equal to sum of all cooling rates with an accuracy of 5%.

3. Results and Discussion

The electron temperature profiles were derived using the method described above for different values of parameters contributing to the heating rates. The ion density profiles for NO^+ and O_2^+ used in the present work were theoretically generated for the rocket flight conditions [49]. These profiles along with the measured electron density profile [20] are shown in Fig. 1.

The heating rates due to different processes were calculated individually to examine their relative contribution. The height profiles of these heating rates

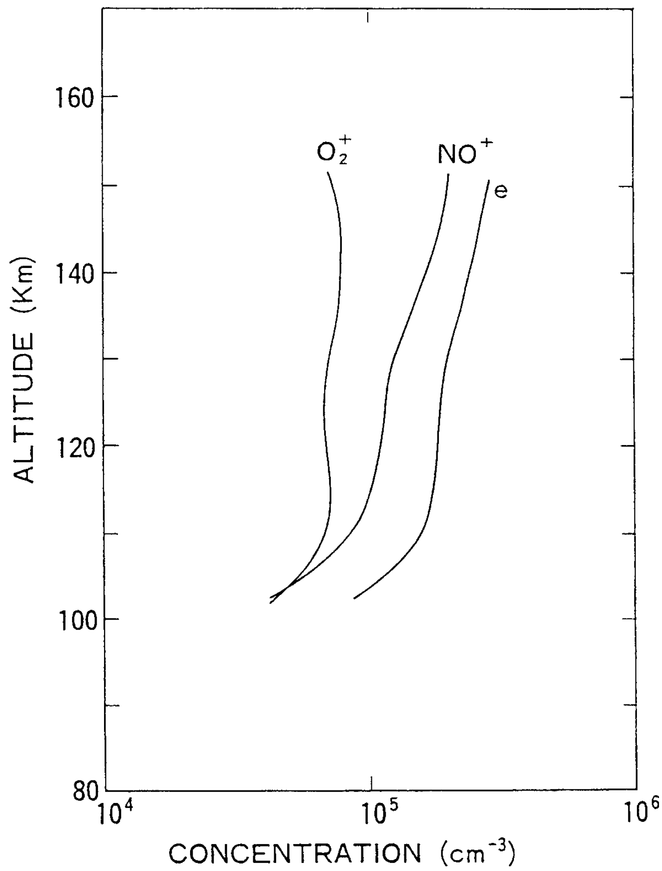

Fig. 1. The altitude profile of NO^+, O_2^+ and electron densities used in the present work. The ion densities are theoretical estimates appropriate to rocket flight conditions [49] whereas electron densities were measured on this flight [20].

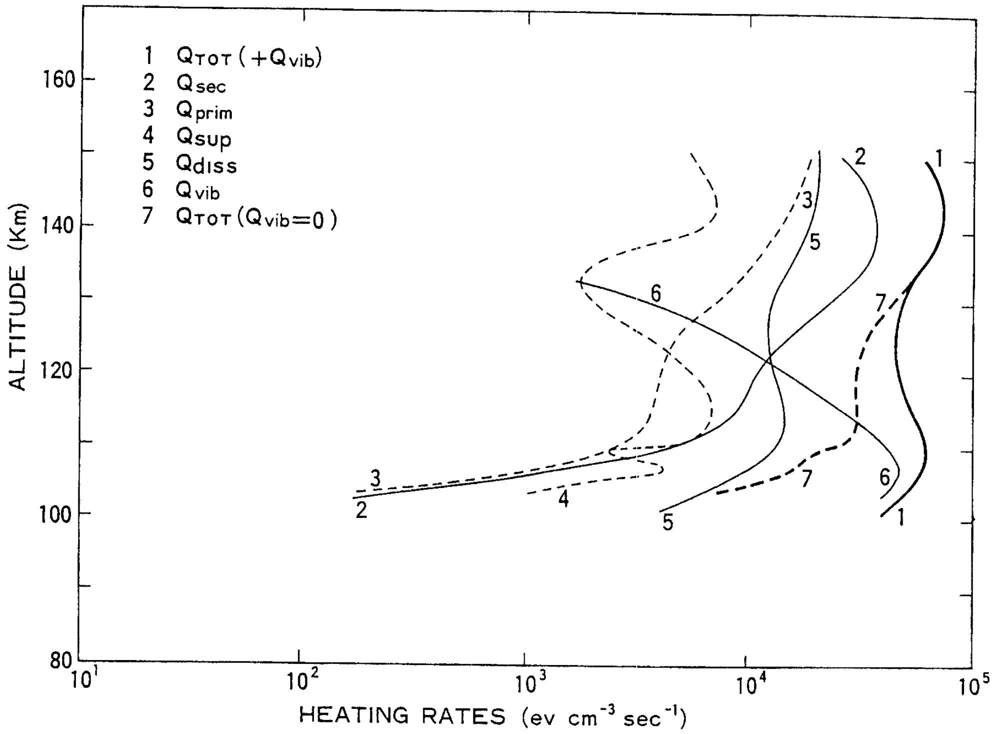

Fig. 2. Various heating rate profiles in the lower E-region. Two cases for total heating rates were considered (i) with contribution from vibrationally excited N_2 and (ii) without its contribution.

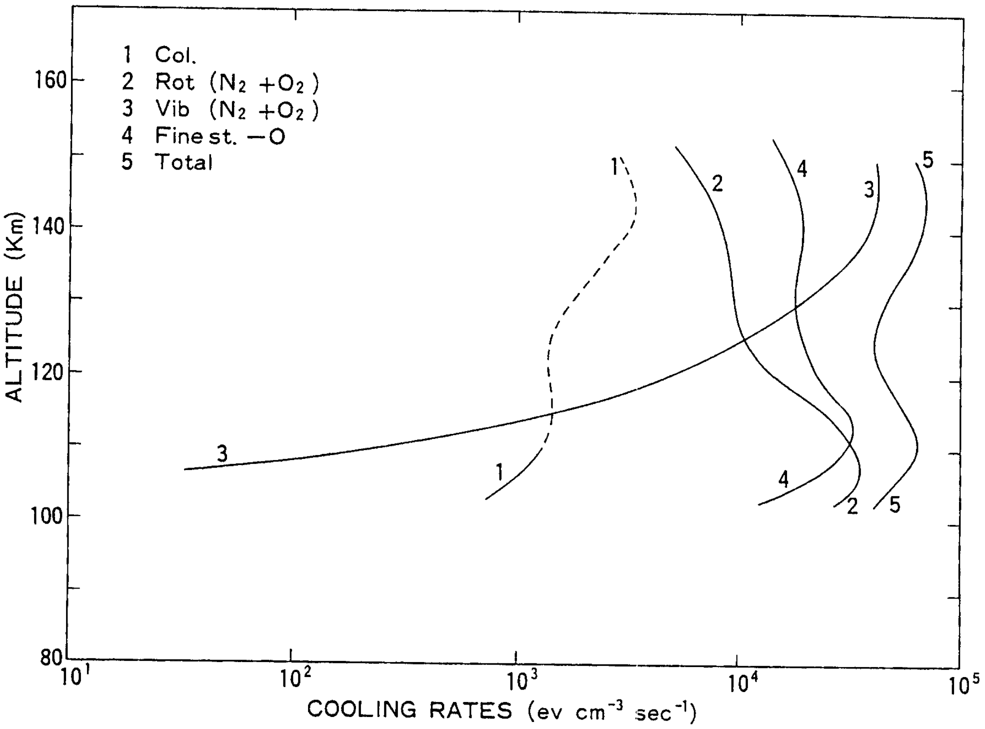

Fig. 3. The height variation of cooling rates for the electron gas. The electronic excitation of atomic oxygen which contribute very little has not been shown.

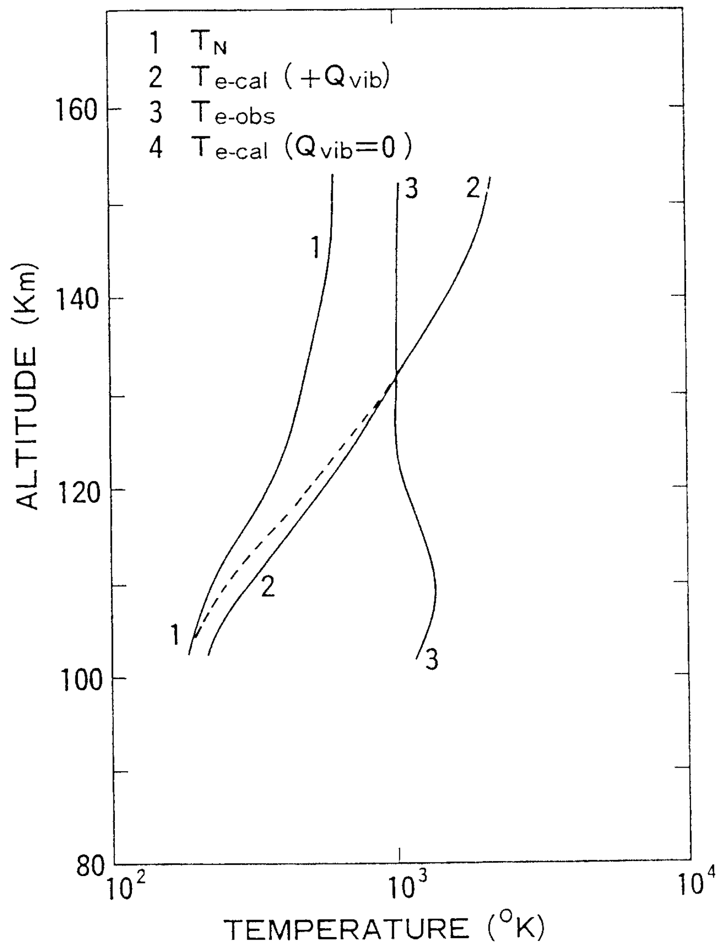

Fig. 4. Electron temperature profiles as a function of altitude. For comparison, the neutral temperature and the experimentally observed profiles are included in the same figure. The effect of not considering the heating due to vibrationally excited N_2 is also shown.

are shown in Fig. 2. It may be seen that different mechanisms contribute differently at different altitudes. However, a sort of transition takes place around 120 km from one dominating heating mechanism to other. This change is also reflected in the total heating rate profile which from almost constant value around 122 km shows a sharp increase down below, with maximum value at 110 km. Considering these profiles individually, the heating due to vibrationally excited N_2 molecules, if considered, contribute most significantly below about 120 km. Next to this process, it is heating due to dissociative recombination which is an important heat source for the thermal electrons. The contribution from other processes is much smaller to be effective. Above 120 km. However, the heating rate due to vibrationally excited N_2 molecules sharply decreases where as the heating due to secondary ionization shows a sharp increase thereby becoming the prime heat source. The heating due to dissociative recombination still remains the second important heat source. The heating due to other sources such as primary ionization, supra-thermal electrons do not contribute appreciably even in this altitude range.

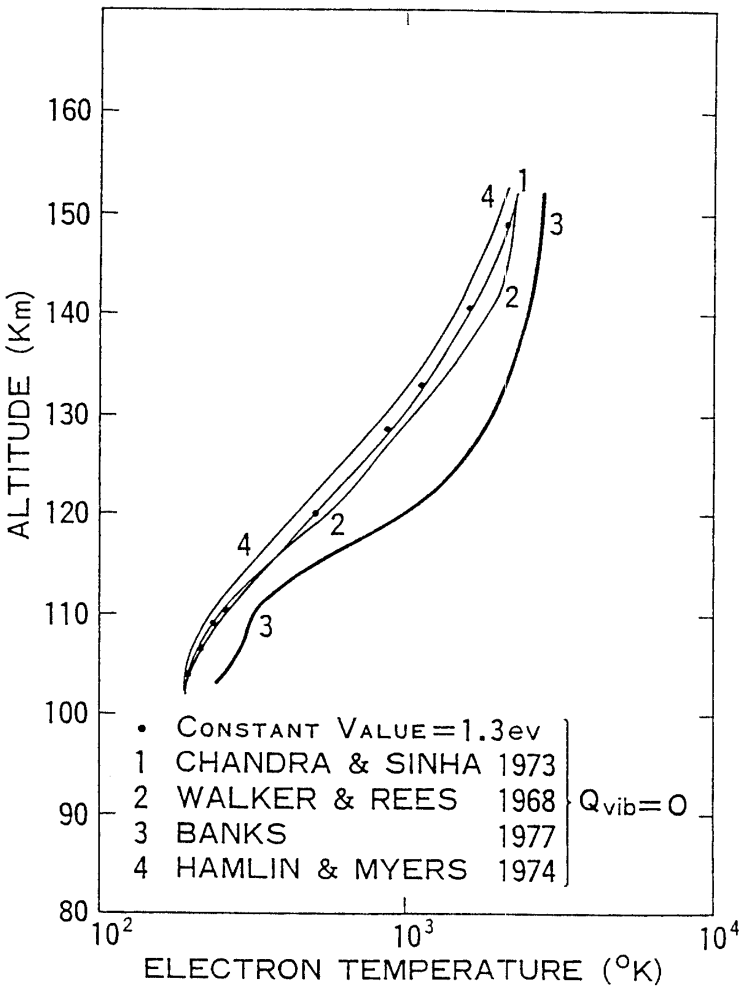

Fig. 5. The profiles of electron temperature as a function of altitude for different values of heating efficiencies due to dissociative recombination. The heating due to vibrationally excited N_2 is ignored in this case. A profile with a constant value of 1.3 eV for efficiency seems to represent well, most of the calculated profiles.

In case, the heating due to vibrationally excited N_2 molecules is not considered, the total heating rate shows a sharp increase from 100 km to about 112 km and rather a slow increase with somewhat constant slope between 112~125 km instead of a sharp increase observed in the previous case. Above 130 km, the total heating rate does not change as the heating due to vibrationally excited N_2 is even otherwise very small.

The cooling rates, more or less reflect the same features as that of total heating rate and these profiles are shown in Fig. 3. The cooling due to rotational excitation of N_2 and O_2 is found to dominate below about 112 km with cooling due to fine structure excitation of O as the second important mechanism. However, above this altitude, the role reverses and the cooling due to fine structure excitation of O takes the dominating role. The contribution from other processes such as vibrationally excited N_2 and O_2 molecules, electronic excitation of O or elastic collisions with neutrals are negligibly

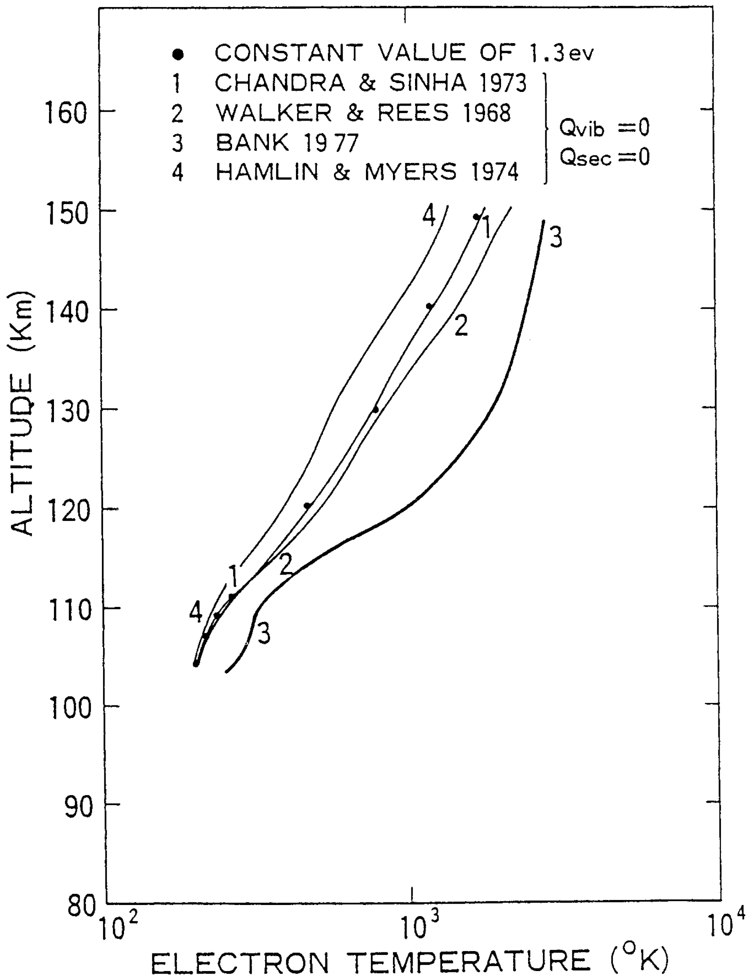

Fig. 6. The electron temperature profiles as a function of altitude for different heating efficiencies values for dissociative recombination. The heating due to secondary ionization as well as due to vibrationally excited N_2 are ignored.

small. Above 130 km, once again another transition takes place with cooling due to vibrationally excited N_2 and O_2 becoming dominant heat loss mechanism. The fine structure excitation, though does not change significantly with increase in altitude, its contribution to total cooling becomes less, compared to now dominating vibrational excitation.

The electron temperatures derived as a function of altitude using these heating and cooling rates, both considering and ignoring the heating due to vibrationally excited N_2, are shown in Fig. 4. For comparison, the neutral temperature [*15*] and experimentally observed electron temperature [*20*] profiles are also shown in the same figure. It may be clearly seen that the derived values of electron temperatures are higher than the neutral temperatures through out the altitude range of interest even when the heating due to vibrationally excited N_2 is ignored and the difference increases with increase in altitude. In comparison with experimentally observed profile, the derived values were found to be smaller below about 130 km. The higher value of observed T_e still quantitatively can not be accounted for though a definite increase over neutral temperature is seen. Above this altitude, the calculated values become higher than the observed ones. It may be mentioned that normally T_e is expected to increase with increase in altitude but only in this particular case of rocket measurement, the observed T_e was found to be more or less constant in the height range of 120~150 km. This increase in derived values of T_e, it is felt, is much more than expected or as reported by other workers [*27*]. In the present work, the heating due to secondary ionization dominates this height region essentially due to higher ionization efficiency as suggested [*17*] where as Richard et al [*27*] have considered the contribution from secondary ionization as 30% of the primary one. T_e profiles are therefore computed to see the effect of ignoring the heating due to secondary ionization and vibrationally excited N_2 molecules.

Since, for the efficiency of heat generated by dissociative recombination, wide ranging values are reported [*29, 30, 31, 32*] and this process dominates the lower altitude region particularly when heating due to vibrationally excited N_2 is ignored; the effect of this parameter on electron temperature was examined. Fig. 5 shows the derived T_e profiles as a function of altitude for different reported values of efficiency. It may be seen that except for Banks [*32*] values, all other suggested values yield more or less same electron temperature values. It may also be mentioned that taking the lower limit for efficiency as suggested by Hamlin and Myers [*31*], the electron temperature values are not affected. From these set of T_e profiles, an average T_e can be obtained assuming a constant value of 1.3 eV for the heating efficiency.

Fig. 6 shows the T_e profiles obtained for different values of heating efficiencies similar to those considered in Fig. 5. However, in this case, contribution of secondary ionization is also ignored in addition to heating due to vibrationally excited N_2 molecules. It may be seen that neglecting the contribution from these two sources results in T_e value to be lower, particularly in the higher altitude region as much as by about 400~500°K and show a wide spread in values corresponding to the different efficiency values. The profile derived using Hamlin and Myers [*31*] has the lowest T_e value at 150 km and seems to be close to the one reported on theoretical considerations [*27*]. However, the value of T_e in the lower altitude range, though not affected in any way by secondary ionization, is also low even compared to profiles derived using different efficiency values. The profile with constant value of heating efficiency equals 1.3 eV still seems to be in good agreement with the values suggested [*29, 30, 31*].

4. Conclusions

1. The calculated values of heating rates show that vibrationally excited N_2 forms the most important source. In the absence of this mechanism, the heating

due to dissociative recombination dominates.

2. Different cooling rates are important in different height regions. The rotational excitation of N_2 and O_2 is the main source of heat loss below about 112 km, whereas, above, it is the fine structure excitation of O which becomes important. It continues to be so up to about 130 km above which cooling due to vibrationally excited N_2 and O_2 takes the leading role.

3. The derived electron temperature profiles show that these values are certainly larger than the neutral temperatures throughout the altitude range of interest, even when contribution from vibrationally excited N_2 to heating rates is ignored. The difference in temperatures increases with increase in altitude. However, in comparison with experimentally observed values, the derived values below about 130 km are still lower but becomes larger above. It is felt that some additional heat source is needed to explain this large discrepancy.

4. The derived values of T_e for different values of heating efficiencies for thermal electrons due to dissociative recombination of NO^+ and O_2^+ show that adopting a constant value of 1.3 eV for this parameter results in a profile which is in fairly good agreement with most of the derived profiles.

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