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Electron Temperatures in the Jovian Ionosphere

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The daytime electron temperature profile of the Jovian ionosphere was calculated, taking into account the effects of thermal conduction and heat inflow from the plasmasphere. The photoelectron fluxes and electron heating rates were determined by using the two-stream approach of Banks and Nagy (1970) and Nagy and Banks (1970). The calculated electron temperatures were found to follow the neutral temperature up to an altitude slightly above the electron density peak, while at higher altitudes they were significantly enhanced above the assumed neutral temperature value.

INTRODUCTION

Theoretical calculations of the electron temperatures in the Jovian ionosphere were carried out, assuming local energy balance, by *Henry and McElroy* [1969] and *Prasad and Capone* [1971]. This assumption is appropriate, because of high cooling rates, up to an altitude slightly above the electron density peak, the region for which these calculations were made. However, at higher altitudes, thermal conduction plays an important role in the electron energy balance and has to be considered. In this brief note we present the results of electron temperature calculations for the Jovian ionosphere, which take into account thermal conduction effects as well as heat inflow from the plasmasphere.

CALCULATION OF THE PHOTOELECTRON FLUXES AND HEATING RATES

A wide variety of techniques have been developed for calculating the photoelectron fluxes and heating rates for the terrestrial ionosphere (for review and comparisons, see *Cicerone et al.* [1973], *Nagy* [1974], and *Swartz* [1976]). The early calculations of photoelectron heating rates for Jupiter [*Henry and McElroy,* 1969; *Prasad and Capone,* 1971] were carried out neglecting transport effects, but the more recent work of *Swartz et al.* [1975] and *Kutcher et al.* [1975] on heating rates and photoelectron fluxes did take transport into account. *Swartz et al.* [1975] used the modified diffusion approach first described by *Nisbet* [1968], while *Kutcher et al.* [1975] used a Monte Carlo method to calculate the photoelectron fluxes and heating rates. In the present work we calculated these quantities by using the two-stream approach outlined by *Banks and Nagy* [1970] and *Nagy and Banks* [1970]. The results of the calculations presented here are appropriate for closed midlatitude field lines ($L \sim 2$).

The solar EUV flux values (for solar zenith angle of 60°), photoabsorption and photo-ionization cross sections, and neutral atmosphere model (K, T, He/H_2) used in calculating the primary photoelectron production rates are described in the work of *Atreya and Donahue* [1976]. The neutral atmospheric model was generated by assuming $T = 150°K$ (constant), $He/H_2 = 0.10$, and $K \propto 1/(M)^{1/2} = 3 \times 10^7$ cm^2 s^{-1} at the turbopause. The altitude $z = 0$ km refers to the level where atmospheric number density $M = 10^{16}$ cm^{-3}. The ions created by photo-ionization were taken to be in their ground state [*Swartz et al.,* 1975]. The inelastic electron impact cross sections, used in the photoelectron flux calculations, were obtained by using the analytic semiempirical formulation of *Green and Barth* [1965] and *Miles et al.* [1972]. The fitted parameters for H, H_2, and He were taken from *Olivero et al.* [1973], *Jusick et al.* [1967], and *Miles et al.* [1972], respectively. The correction to the $C^1\Pi_u$ transition of H_2 given by *Stone and Zipf* [1972] was also incorporated in the calculations. In a manner similar to that in the work of *Swartz et al.* [1975], H_2 transition thresholds falling within ±0.5 eV of an integer energy level were summed, thus yielding a series of effective cross sections with integer energy thresholds. The vibrational cross-section values for H_2 were adopted from *Ehrhardt et al.* [1968]. The elastic electron impact cross-section values were taken from the review of *Moiseiwitsch* [1962] for energies less than 12 eV and were extrapolated to higher energies. The elastic and inelastic backscatter probabilities adopted here were outlined by *Banks et al.* [1974]. The electron-electron collisions were handled in the manner described by *Nagy and Banks* [1970], and the electron heating rates were calculated by using the analytic expression given by *Swartz et al.* [1971]. Finally, the electron profile used in the photoelectron flux calculations was the 'low temperature model' of *Atreya and Donahue* [1976], which is consistent with the input data used.

The photoelectron flux calculations require a priori knowledge of the downward flux at the upper boundary. We carried out calculations assuming (1) zero downflux or (2) an influx equal to the escape flux calculated by using condition 1. The actual flux arriving down along the field line is certainly bracketed by these values; on closed field lines, some photoelectrons will make it across from the conjugate hemisphere. The calculated electron heating rates and photoelectron flux values are shown in Figures 1 and 2, respectively (the shading shows the spread in the results due to the different upper boundary values). It is difficult to compare these results with those of other workers because of the difficulties in relating the different altitude scales. There is general agreement in the peak heating rates calculated here and the ones given by *Henry and McElroy* [1969], *Prasad and Capone* [1971], and *Swartz et al.* [1975]; the discrepancy at lower altitudes is probably due to the differences in the assumed electron density profiles. The heating rate profile given by *Swartz et al.* [1975] is shown in Figure 1 for comparison, where we have modified the altitude scale of *Swartz et al.* [1975] so that maxima of the two profiles coincide. The Swartz et al. reference level ($z = 0$; $M = 1.2 \times 10^{13}$ cm^{-3}) occurs at 155 km above the reference level ($M = 10^{16}$ cm^{-3}) used in the present study. This implies a discrepancy of nearly 20 km between the altitudes of the maximum heating rates caused presumably by the different model atmosphere used.

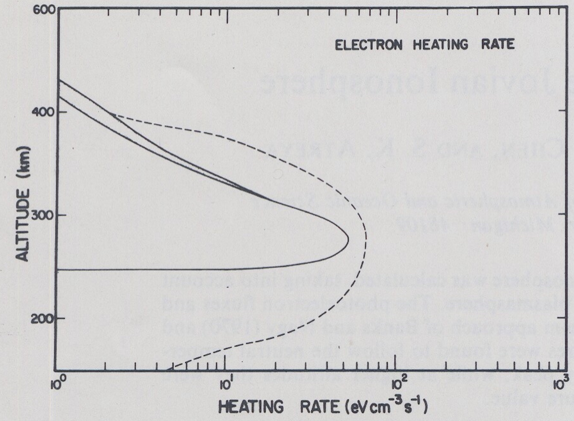

Fig. 1. The calculated electron heating rate profiles. The shading illustrates the spread in the results due to different upper boundary conditions. The dashed line represents the calculations of *Swartz et al.* [1975]. The altitude $z = 0$ km refers to the atmospheric density level of 10^{16} cm^{-3}.

ELECTRON TEMPERATURE CALCULATIONS

The time-dependent electron energy equation, appropriate for the present problem, can be written as

$$\frac{dT_e}{dt} + \frac{d}{dz}\left(K_e \frac{dT_e}{dz}\right) = Q_e - L_e$$

where z is the altitude, K_e is the electron thermal conductivity, and Q_e and L_e are the electron heating and cooling rates, respectively. The electron heating rates are obtained in the manner described in the previous section. The energy loss rates due to elastic collisions with neutral H, H_2, and He were taken from *Banks and Kockarts* [1973], *Herman et al.* [1971], and *Banks* [1966], respectively. The relations for the energy loss due to rotational and vibrational excitation of H_2 were taken from *Henry and McElroy* [1969].

The solution of the electron energy equations requires two boundary conditions. It has been the general practice to start the calculations at a low enough altitude to justify the assumption of $T_e = T_n$, where T_n is the neutral gas temperature. The other boundary condition is usually taken to be the heat inflow at the upper boundary. The choice of 200 km as the lower boundary in these present calculations is appropriate for the condition that the electron temperature equals the neutral gas temperature. It is reasonable to assume that a significant fraction of the energy carried by the escaping photoelectrons is lost, through collisions with the ambient plasma, as they move along the closed mid-latitude field lines. Under steady state conditions this energy will be returned toward the ionosphere; thus we carried out our calculations by assuming that the heat inflow at the top of the ionosphere is somewhere between half to twice the escaping photoelectron energy flux (~1 × 10^8 eV cm^{-2} s^{-1}). The reason for the latter value is that, analogous to terrestrial conditions, a magnetospheric heat source, of at least the same order as the photoelectron one, may also be present. The electron temperature profiles calculated, using the various assumptions, are indicated by the shaded area in Figure 3 (the ion temperatures are also calculated simultaneously but are not plotted here for clarity of presentation; the ion temperatures move from the neutral gas value at low altitudes toward the electron temperature at high altitudes). The results show that the electron temperatures do follow the neutral temperature values up to an altitude of about 400–500 km as shown by previous calculations [*Henry and McElroy*, 1969; *Prasad and Capone*, 1971]. However, at higher altitudes the difference between the electron and neutral temperatures becomes significant.

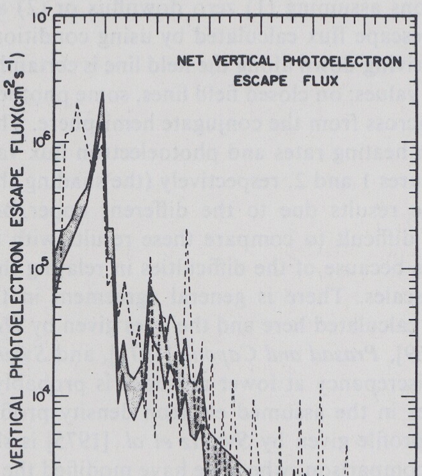

Fig. 2. The calculated photoelectron escape flux. The shading illustrates the spread in the results due to different upper boundary conditions. The dashed line represents the calculation of *Swartz et al.* [1975].

The preliminary analysis of the Pioneer 10 occultation data by *Fjeldbo et al.* [1975] indicates an electron density peak near 1250 km and a topside electron density scale height of about 675 ± 300 km. In a very recent paper, *Atreya and Donahue* [1976] suggested that the observed electron density profile may be due to a relatively hot thermosphere (~1000°K). Thermal expansion of the upper atmosphere of Jupiter appears consistent with the ideas of propagation and dissipation of inertial gravity waves, a possibility explored by *French and Giersach* [1974] to explain the peculiar Jovian temperature profile inferred from the β-Scorpii occultation data of *Veverka et al.* [1974]. *Atreya and Donahue*'s [1976] electron density profile calculated on the basis of a hot thermosphere and on the assumption of thermal equilibrium between electrons, ions, and neutrals is in reasonable agreement with the measure-

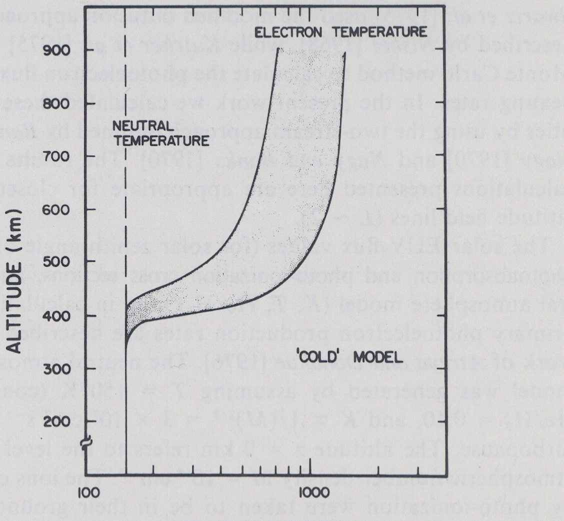

Fig. 3. The calculated electron temperatures for the 'cold' model of *Atreya and Donahue* [1976]. The shading illustrates the spread in the results due to different upper boundary conditions.

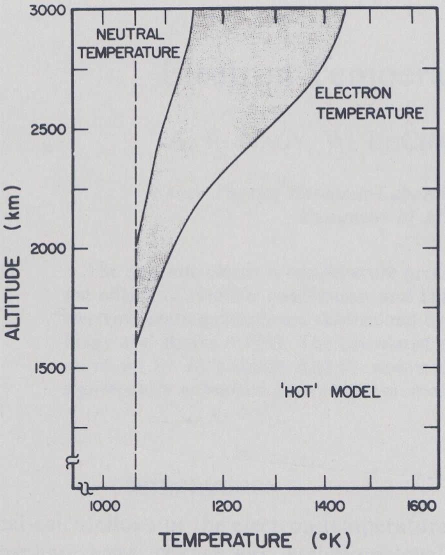

Fig. 4. The calculated electron temperatures for the 'hot' model of *Atreya and Donahue* [1976]. The shading illustrates the spread in the results due to different upper boundary conditions.

ments. Thus we repeated our calculations for the 'hot' thermosphere and ionosphere model of *Atreya and Donahue* [1976]; all other parameters were the same as those given for the 'cold' model. The assumed neutral temperature profile and the calculated electron temperatures are shown on Figure 4. Here again we found that the electron temperature follows the neutral temperature up to an altitude slightly above the electron density peak and departs significantly from the neutral gas value at higher altitudes.

We should mention that the calculations presented here could be improved by solving the complete set of equations (photoelectron transport, continuity, momentum and energy for the electrons and ions) in a self-consistent manner; however, we feel that such a complex calculation is not warranted by our present data base.

CONCLUSION

Our calculations indicate that the topside scale height observed by Pioneer 10 could be explained by the cold neutral model along with high electron temperatures as calculated; however, the altitude of the observed electron density peak implies that the temperature of the Jovian thermosphere is quite likely to be high. Thus the observations and the calculations are consistent with a hot Jupiter thermosphere (~800°–1000°K) and enhanced topside electron temperatures (~1200°–1500°K).

Late note. The work of *Goertz* [1973], which we inadvertently overlooked, was drawn to our attention after the completion of the work presented here. *Goertz* [1973] solved the coupled continuity, momentum, and energy equations for Jupiter. The numerical solutions indicated a 'warm' thermosphere and electron and ion temperatures significantly in excess of the gas temperature, similar to the results presented here. Some of the assumptions made in the Goertz calculations are now somewhat obsolete (e.g., chemistry scheme) and are highly simplified (e.g., heating rate), but nevertheless the work is an important contribution, as it is the only self-consistent set of calculations for the Jupiter ionosphere.

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