Electron temperature profiles in the magnetosphere of Neptune

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Abstract.
The electron temperature in the magnetosphere of Neptune decreases with decreasing radial distance over the same distance range over which a similar decrease of the proton temperature has been explained as resulting from interaction of protons with a cloud of neutral hydrogen. We study the effect on the electron temperature of the interaction with this cloud, taking into account photoionization, electron impact ionization, radiation, and electron-ion Coulomb collisions. We find that the electron temperature should decrease with decreasing distance, in agreement with observations, but that at the outer boundary the theoretically expected electron temperatures are considerably lower than what is observed, implying a heating process or a source of hot electrons which have not yet been unambiguously identified. In the inner region, where the adiabatic increase of the proton temperature has been taken as implying the absence of any significant density of neutral atoms, the electron temperature remains essentially constant, implying a powerful cooling process that acts only on electrons. This process is also at present an object of speculation; as a possibility, we suggest thermal coupling to the ionosphere via strong pitch angle diffusion of electrons.

Introduction

The magnetospheres of the outer planets differ among themselves in many important ways. In the magnetosphere of Jupiter (as in that of Earth), the density of plasma is much higher than that of neutral particles; neutral matter plays a role only as the source of plasma in the Io torus, and otherwise the structure and dynamics are governed largely by the physics of a fully ionized plasma. At the other outer planets, on the other hand, the magnetosphere includes as a significant component a neutral gas derived from various sources: Triton in the case of Neptune, the planet in the case of Uranus, and the rings, icy satellites, and Titan in the case of Saturn. In these magnetospheres, the plasma can be modified in appreciable or even dominant ways by interactions with the neutral gas. In the particular case of Neptune, the configuration of plasma in the magnetosphere is reasonably well understood on the basis of a model in which a tenuous plasma is injected by a source at or near Triton, is transported inward by radial diffusion, and is affected by a cloud of neutral hydrogen (for details and references, see, e.g. *Eviatar et al.* [1995]). In this last paper, the unexpected radial profile of the observed proton temperatures was shown to be explainable as the result of inelastic collisions with such a hydrogen cloud, the radial extent of which is firmly delineated thereby. In this paper, we discuss the corresponding electron temperature profiles and show that while they do exhibit the expected effects of the hydrogen cloud, they also contain other features that cannot be explained as a simple consequence of the above model and require other physical mecha-

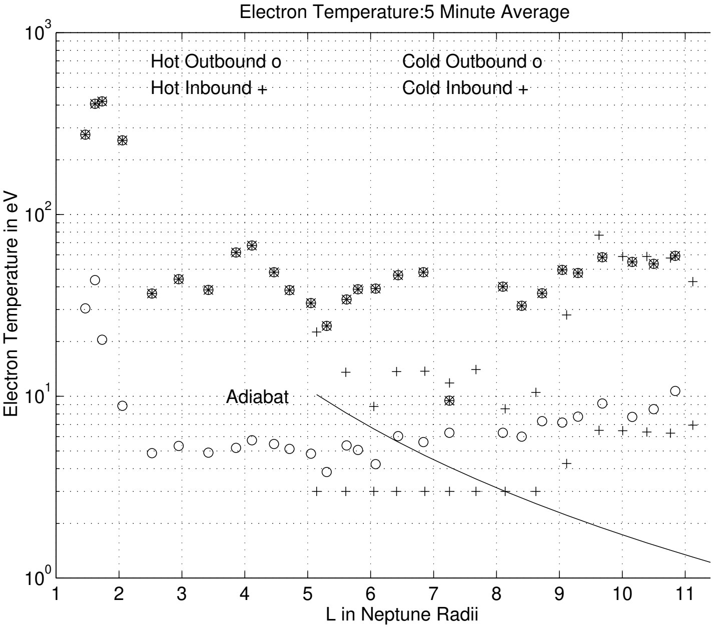

Figure 1. Electron temperature profiles

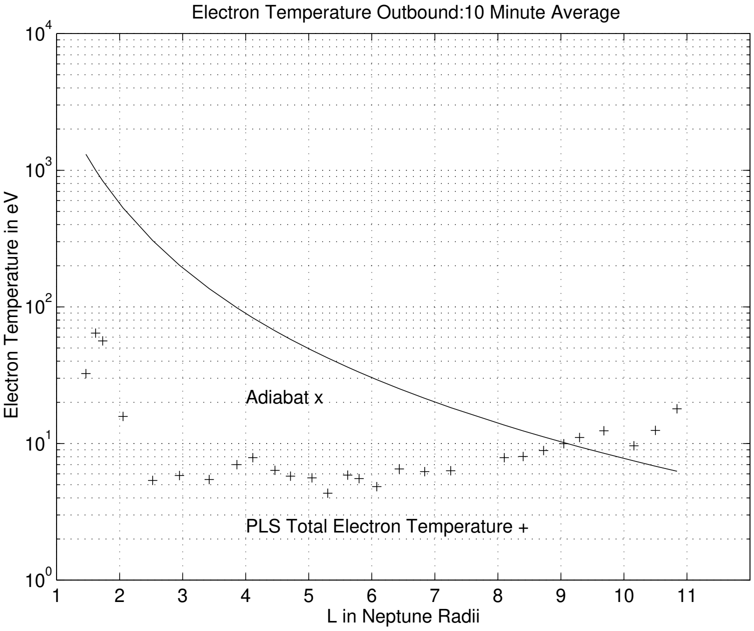

Figure 2. Total electron temperature profile

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Electron Temperature Profiles

The radial profiles of the electron temperatures measured in the magnetosphere of Neptune by the Voyager Plasma Science (PLS) instrument are shown in figures 1 and 2. Figure 1 shows separately the temperatures of the "cold" and "hot" components of the electron distribution as determined from a multiple-Maxwellian analysis by *Zhang et al.* [1991]. The temperatures generally decrease with decreasing distance from 12 R_N to 8 R_N and remain at low values throughout the inner magnetosphere (except for an uncertain and poorly understood increase near closest approach to the planet); the "cold" temperatures on the inbound pass actually drop below the instrument threshold at 8 R_N, the value 3 eV being only an upper limit. The general trend is even clearer in Fig. 2 which shows the total temperature, *i.e* the density-weighted mean of the "cold" and "hot" electron populations. The total temperature drops off from about 20 eV at 12R_N to a constant value in the inner magnetosphere and shows no tendency anywhere to increase with decreasing distance as expected from adiabatic heating. By contrast, the proton temperature profile (see Fig. 1 of *Eviatar et al.* [1995]) also decreases from 12 R_N to 8 R_N but then increases adiabatically in the inner magnetosphere.

The initial decrease can be explained by assuming that the plasma interacts with a cloud of neutral hydrogen, as suggested by *Zhang et al.* [1991] for electrons and *Eviatar et al.* [1995] for protons. This assumption, however, cannot explain the inner region of the magnetosphere where the proton temperature varies adiabatically while the electron temperature is more or less constant. In this region, the electrons must be interacting with a heat sink that is powerful enough to counterbalance adiabatic heating, to the point of maintaining a constant temperature. Furthermore, this heat sink must be one that acts on electrons only since no observable effect is seen in the proton temperature profile. It is apparent, therefore, that cooling by collisions with neutral atomic hydrogen cannot be a full description of the situation (a difficulty overlooked by *Zhang et al.* [1991], who neglected adiabatic heating, as we note further on).

We first discuss the interaction of the electrons with the neutral hydrogen cloud in the region 12 R_N

to 8 R_N. We then discuss the problem of accounting for the electron temperature in the source region beyond 12 R_N, where *Zhang et al.* [1991] show even higher values, in the hundreds of electron volts in the trans-Triton region. Finally, we discuss the problem of accounting for the nearly constant low electron temperature in the inner region inside of 8 R_N.

Physical Mechanisms

The distribution of electron concentration and temperature, in a magnetosphere in which plasma is transported by radial diffusion and nonadiabatic effects involving collisions with neutral atoms or charged particles are significant, may be described by the two equations for the flux tube content of particles and of energy:

$$L^2 \frac{d}{dL}\left\{\frac{D}{L^2}\frac{d}{dL}(Y)\right\} + S = 0 \qquad (1)$$

and

$$L^2 \frac{d}{dL}\left\{\frac{D}{L^2}\frac{d}{dL}\left(YTL^{\frac{8}{3}}\right)\right\} - \dot{Q}L^{\frac{8}{3}} = 0. \qquad (2)$$

Here Y is the flux tube particle content (written often as NL^2), D is the radial diffusion coefficient, S is the ionization rate:

$$S = \sum_a n_a(\phi_a + \alpha_a n_e)V \qquad (3)$$

in which n_a is the number density of the neutral atoms (hydrogen or nitrogen), suitably averaged over the volume V of the flux tube, ϕ_a is the solar photoionization rate and $\alpha_a n_e$ is the electron impact ionization rate integrated over the electron energy distribution, here approximated as a sum over the cold and hot electrons with temperatures of 5 and 50 eV and mean densities of 0.06 and 0.003 cm^{-3}, respectively [*Zhang et al.*, 1991]. $\dot{Q}$ is the sum of energy source and sink terms, defined as positive for sinks. Throughout this paper we denote the electron temperature by T.

Equations (1) and (2) for electrons are the same as the corresponding equations for ions given in *Eviatar et al.* [1995], except that the $\dot{Q}$ terms are of course different and the contribution of S to (2) has been absorbed into $\dot{Q}$. The diffusion coefficient is taken to vary as a power law of the atorial distance of field lines L,

$$D = k\left(\frac{L}{R_N}\right)^p \qquad (4)$$

(see *Eviatar et al.* [1995] for values of the parameters, and note that throughout this paper we treat L as a quantity that has the dimensions of length).

$\dot{Q}$ is a sum of terms representing various forms of energy exchange as follows:

1. Photoionization:

$$\dot{Q} = -\sum_a \frac{Y\phi_a K^a_{ph}}{n_e} \qquad (5)$$

where K^a_{ph} is the mean excess energies of the photolysis products (mean energy of the electrons produced by photoionization) and the minus sign indicates that this is a source term.

2. Impact ionization:

$$\dot{Q} = \sum_a K_a\alpha_a n_a Y \qquad (6)$$

where K_a is the ionization potential.

3. Radiation:

$$\dot{Q} = \sum_a \rho^a_c n_a Y \qquad (7)$$

where ρ^a_c is the radiation efficiency coefficient. This term describes excitation of the bound electrons in both neutral hydrogen and N^+ ions (the nitrogen ion radiation term is probably insignificant because of the low plasma density).

4. Electron-ion collisions:

$$\dot{Q} = \sum_i \nu^{e/i}(T - T_i)Y \qquad (8)$$

where the rate coefficient for energy transfer by Coulomb collisions between electrons and ions is given by *Book* [1977] (see also equations (7) and (8) of *Eviatar et al.* [1995])

$$\nu^{e/i} = \frac{\nu_0 A_i^{\frac{1}{2}} n_i \log\Lambda}{A_i T + (m_e/m_p)T_i)^{\frac{3}{2}}} \qquad (9)$$

where $\nu_0 \equiv 3.2 \times 10^{-9}$cm^{3}s^{-1} and A is the atomic mass number. (It will soon become apparent that this term is negligible for most purposes because of the very low density of charged particles in the Triton torus region.)

Proceeding as in *Eviatar et al.* [1995], multiplying the particle content (1) by $TL^{\frac{8}{3}}$ and subtracting the result from the energy equation (2), we obtain, after some manipulation, an equation with the diffusion operator acting on temperature alone:

$$YL^2\frac{d}{dL}\left\{\frac{D}{L^2}\frac{d}{dL}\left(TL^{\frac{8}{3}}\right)\right\}+2D\frac{dY}{dL}\frac{d}{dL}(TL^{\frac{8}{3}})=$$
$$YL^{\frac{8}{3}}\sum_a n_a\left\{\alpha_a(T+K_a)-\frac{\phi_a K_{ph}^a}{n_e}+\rho_c^a\right\}+$$
$$YL^{\frac{8}{3}}\sum_i \nu^{e/i}(T-T_i) \qquad (10)$$

(The lh side of (10) differs from the corresponding expression in [*Zhang et al.*, 1991], who wrote T instead of $TL^{\frac{8}{3}}$, thus neglecting adiabatic heating, and also assumed that T is advected with the mean flow, neglecting the effects of diffusion.)

We proceed further as in *Eviatar et al.* [1995] and seek a cooling mechanism that will counterbalance the adiabatic heating, in order to explain the gross deviation from adiabaticity in *all* components of plasma in the magnetosphere of Neptune. The rired condition for electrons, ivalent to the condition for ions given by Equation (10) of *Eviatar et al.* [1995], is then the following:

$$\frac{n_H R_N^p}{kL^{p-2}}\left\{\alpha_H\left(1+\frac{K_H}{T}\right)+\frac{\rho_c^H}{T}-\frac{\phi_H}{n_e}\frac{K_{ph}^H}{T}\right.$$
$$+\frac{n_N}{n_H}\left(\alpha_N\left(1+\frac{K_N}{T}\right)+\frac{\rho_c^N}{T}-\frac{\phi_N K_{ph}^N}{n_e T}\right)$$
$$\left.+\frac{n_p}{n_H}\nu^{e/p}\left(1-\frac{T_p}{T}\right)+\frac{n_{N+}}{n_H}\nu^{e/N^+}\left(1-\frac{T_{N+}}{T}\right)\right\}$$
$$>\frac{8}{3}(p-\frac{1}{3})+\frac{16}{3}\frac{d\log Y}{d\log L} \qquad (11)$$

(the subscripts p and N^+ designate protons and nitrogen ions, respectively). Equation (11) represents in dimensionless form the balance between adiabatic heating per electron (rh side) and the net cooling per electron from all the loss and source terms (lh side). If the two sides are al, adiabatic heating is precisely balanced by the cooling and the electron temperature is constant. If the lh side is larger, cooling predominates and the electron temperature decreases with decreasing radial distance.

Effect of the Hydrogen Cloud

A cloud of atomic hydrogen of Triton origin extending from $14R_N$ inwards, suggested by model calculations of *Smyth and Marconi* [1993] and *Cheng and Decker* [1993], was invoked to account for the nonadiabatic behavior of proton temperatures by *Eviatar et al.* [1995], who derived two limits bracketing the value of n_H/k, the ratio of hydrogen density to radial diffusion coefficient. The upper limit is set by the requirement that the hydrogen density be high enough for collisional cooling of protons to overcome the adiabatic heating, the lower limit by the requirement that radial diffusion be adequate to remove the protons produced by ionization of the hydrogen. If the proton temperature is equal to the local pick-up temperature, as is approximately the case for $L > 8R_N$, the two limits coincide and equation (10) of *Eviatar et al.* [1995] gives

$$\frac{n_H R_N^p}{kL^{p-2}}(v_i\sigma_c)=\frac{8}{3}(p-\frac{1}{3})+\frac{16}{3}\frac{d\log Y}{d\log L} \qquad (12)$$

where $v_i\sigma_c$ is the proton inelastic scattering rate ($1.6\times 10^{-8}\mathrm{cm}^3\mathrm{s}^{-1}$, cf. *Eviatar et al.* [1995]) . Inserting equation (12) into (11) to eliminate the rh side and cancelling n_H/k from both sides gives

$$\alpha_H\left(1+\frac{K_H}{e}\right)+\frac{\rho_c^H}{e}-\frac{\phi_H}{n_e}\frac{K_{ph}^H}{T}$$
$$+\frac{n_N}{n_H}\left(\alpha_N\left(1+\frac{K_N}{e}\right)+\frac{\rho_c^N}{e}-\frac{\phi_N}{n_e}\frac{K_{ph}^N}{T}\right)$$
$$+\frac{n_p}{n_H}\nu^{e/p}\left(1-\frac{p}{T}\right)+\frac{n_{N+}}{n_H}\nu^{e/N^+}\left(1-\frac{N^+}{T}\right)$$
$$>v_i\sigma_c \qquad (13)$$

as the condition that interaction with the atomic hydrogen cloud be strong enough to overcome the adiabatic heating of electrons.

The numerical values of rates of hydrogen and nitrogen electron impact ionization and photoionization are given in Table 1. The mean excess energies of the photolysis products for hydrogen and nitrogen are given by *Huebner and Carpenter* [1979]:

$$K_{ph}^H = 3.6\mathrm{eV}$$
$$K_{ph}^N = 14.8\mathrm{eV}$$

and the ionization energies are

$$K_H = 13.6eV$$

and

$$K_N = 14.5eV$$

respectively. The radiation coefficient for hydrogen ρ_c^H is taken from *Shemansky and Hall* [1992]. Radiative cooling by nitrogen is neglected, since the plasma

Table 1. Process Rates

Process	Rate	Source
Hydrogen Photoionization	$9.8 \times 10^{-11}\,\mathrm{s}^{-1}$	*Huebner and Carpenter* [1979]
Nitrogen Photoionization	$1.85 \times 10^{-10}\,\mathrm{s}^{-1}$	*Huebner and Carpenter* [1979]
Hydrogen electron impact ionization		*Lotz* [1967]; *Zhang et al.* [1991]
$T = 5\,\mathrm{eV}$	$9.41 \times 10^{-10}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$	
$T = 50\,\mathrm{eV}$	$2.54 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$	
Nitrogen electron impact ionization	$3.7 \times 10^{-9}\mathrm{cm}^3\mathrm{s}^{-1}$	*Lotz* [1967]
$T = 5\,\mathrm{eV}$	$9.41 \times 10^{-10}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$	
$T = 50\,\mathrm{eV}$	$5.60 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$	

density is so low that collisional excitation of N^+ is insignificant while neutral nitrogen is a very inefficient radiator [*Garstang*, 1952].

With assumed typical values (cf. *Eviatar et al.* [1995]) $n_e = 0.06\mathrm{cm}^{-3}$ and $T = 5\mathrm{eV}$ for cold electrons, $n_e = 0.003\mathrm{cm}^{-3}$ and $T = 50\mathrm{eV}$ for hot electrons, ion/neutral density ratio $\approx 10^{-3}$, and $n_N \approx n_H$, the various terms on the lh side of equation (13) contribute the values given in Table 2 (in units of $\mathrm{cm}^3\,\mathrm{s}^{-1}$). (Note that the contribution of nitrogen is small compared to that of hydrogen, primarily because the mean energy of electrons from photoionization is comparable to the ionization energy for nitrogen but much smaller than the ionization energy for hydrogen; hence the ratio n_N/n_H, which is poorly known, is not important. The effect of Coulomb collisions, here evaluated only roughly on the basis of the ssumption $p - T \approx T$, is manifestly negligible, as surmised already by *Eviatar et al.* [1995].) The net cooling rate, 5.4×10^{-8}, is larger than the adiabatic heating rate on the rh side of the equation, 1.6×10^{-8}. Hence, cooling of electrons by interaction with the atomic hydrogen cloud is strong enough to overcome the adiabatic heating associated with the inward diffusion and to produce an electron temperature profile that decreases with decreasing radial distance, in agreement with observations at all L down to $8R_N$.

For a more extensive quantitative test, we rewrite (13) as

$$F(T, L) - 1 > 0 \tag{14}$$

where the function $F(T, L)$ is simply the lh side of (13) divided by $v_i \sigma_c$. We plot F as a function of T and L in Fig. 3 and note that $F > 1$ throughout the region of interest and for all plausible values of T.

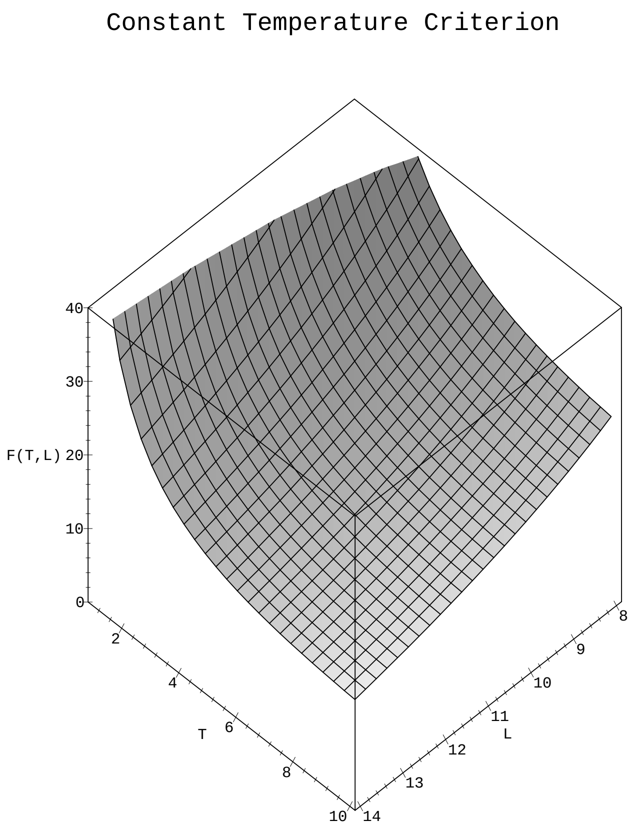

Figure 3. The function $F(T, L)$ given in (14)

Table 2. Cooling Rates

Process	Hydrogen Rates	Nitrogen Rates
Electron impact ionization	1.3×10^{-8}	2.65×10^{-8}
Radiation	2.2×10^{-8}	$\approx 10^{-21}$
Coulomb collisions	-6×10^{-12}	-3×10^{-12}
Photoionization	-0.08×10^{-8}	-0.6×10^{-8}
Total (net) cooling	3.4×10^{-8}	2.0×10^{-8}

The Problem of the Source Region Temperature

The cooling rates described in the previous section depend relatively sensitively on the electron temperature. The photoionization rates are of course independent of the temperature, but the electron impact ionization rates decrease sharply as the electron temperature drops well below the ionization energy. The hydrogen radiation efficiency coefficient ρ_c^H varies as $T^{1.66}$ ([*Shemansky and Hall*, 1992]. The Coulomb collision rate coefficient varies as $T_i/T^{\frac{3}{2}}$ as long as T is in the range

$$T_i \gg T \gg (m_e/m_i)T_i$$

(cf. Equation (9)). The cooling rate as a whole decreases with decreasing temperature (thus insuring that the system is thermally stable and not subject to temperature runaway). As noted already, with the observed mixture of $T = 5$eV "cold" and $T = 50$eV "hot" electrons, the cooling rate is well in excess of the adiabatic heating rate inferred from the proton profiles. With cold electrons only, the cooling rate becomes equal to this adiabatic heating rate at $T \simeq 5$eV (allowing a constant temperature profile to be maintained); it becomes equal to zero, i.e. the heating and cooling effects on the rh of Equation (11) balance by themselves (allowing a constant temperature in the absence of adiabatic heating) at $T \simeq 3$eV. Coulomb collision effects do not become significant until T drops below 0.5eV; heating of electrons by Coulomb collisions with ions, proposed as an effective process in the Io torus of Jupiter [*Barbosa et al.*, 1983; *Barbosa*, 1994], appears to play no role in the outer magnetosphere of Neptune.

With the observed electron temperatures in the region from $8R_N$ out to $12R_N$ well above all these critical values, cooling predominates and results in a temperature profile that decreases with decreasing radial distance. This agrees with observations but leaves unexplained the relatively high initial temperature of the electrons at the outer edge of the observed region ($\approx 12R_N$). The initial temperature cannot be the result of the ionization processes, which lead to a much lower value. It cannot be due to heating of electrons by Coulomb collisions, which (as just noted) are ineffective because of the low plasma density and consequently low collision rate. It appears, therefore, that some as yet unknown *deus ex machina* process must be invoked, about which we can only speculate at present. One possibility is some plasma (particle-wave interaction) process that transfers energy from ions to electrons more efficiently than Coulomb collisions. Another is an energization process associated with the interaction between Triton and the magnetosphere. Finally, we note that Fig. 10 of *Zhang et al.* [1991] shows total electron temperatures as high as a few hundred eV, reminiscent of magnetosheath electron temperature values, and we suggest, as an additional speculation, that there may be a steady input of hot magnetosheath electrons which maintain the high electron temperature inwards as far as Triton's orbit.

Electron Temperature in the Inner Magnetosphere

At distances smaller than $8R_N$, the proton temperature increases as expected from adiabatic heating, from which *Eviatar et al.* [1995] concluded that the neutral cloud is no longer significant and the cooling processes are absent. This holds for electrons as well, and the observation that the electron temperature, unlike the ion temperatures, does *not* increase with decreasing distance must be accounted for by some different cooling process. We suggest that this process may be coupling to the ionosphere, as discussed for Earth by *Vasyliūnas* [1968] and *Kennel* [1969]. We postulate that some strong plasma turbulence process (the detailed nature of which remains to be established) maintains the electron loss cone filled (strong pitch angle diffusion); electrons from the magnetosphere continually precipitate into the ionosphere and are replaced, in order to maintain charge neutrality, by cold electrons pulled up from the ionosphere. The resulting heat flux from the magnetosphere to the ionosphere can be written, in the strong pitch angle diffusion limit, in terms of the electron mean thermal speed and the size of the loss cone only. A corresponding cooling term replaces the rh side of equation 10 which now becomes

$$YL^2\frac{d}{dL}\left\{\frac{D}{L^2}\frac{d}{dL}\left(TL^{\frac{8}{3}}\right)\right\}+2D\frac{dY}{dL}\frac{d}{dL}(TL^{\frac{8}{3}}) = YTL^{8/3}\left(\frac{w_0}{1.1}\right)\left(\frac{R_N^3}{L^4}\right)\left(\frac{T-T_{is}}{T_0}\right)^{1/2} \quad (15)$$

where w_0 is the thermal speed of an electron at temperature T_0, T_{is} is the electron temperature corresponding to a magnetosphere in equilibrium with the ionosphere (low, but possibly higher than the temperature of the ionosphere because of parallel electric field effects), and the factor 1.1 comes from the volume-to-area ratio of a dipole flux tube ($1.1L$ for large L). The counterpart of equation 11 is

$$\left(\frac{R_N^p}{kL^{p-2}}\right)\left(\frac{w_0}{1.1}\right)\left(\frac{R_N^3}{L^4}\right)\left(\frac{T-T_{is}}{T_0}\right)^{1/2} = \frac{8}{3}(p-\frac{1}{3})+\frac{16}{3}\frac{d\log Y}{d\log L} \quad (16)$$

Balancing this cooling against adiabatic heating gives a temperature profile that is nearly adiabatic beyond a critical distance L_c and drops abruptly to T_{ion} for $L < L_c$ (*Vasyliūnas* [1968],*Kennel* [1969]). For the parameters at Neptune, L_c is appreciably larger than $8R_N$, consistent with our interpretation. (We speculate that for $8R_N < L < L_c$, the turbulence responsible for the strong pitch angle diffusion may be somehow suppressed by the presence of the neutral cloud.)

In analogy to our criterion for the outer magnetosphere, we define the function:

$$G(T,L) = \frac{\left(\frac{R_N^p}{kL^{p-2}}\right)\left(\frac{w_0}{1.1}\right)\left(\frac{R_N^3}{L^4}\right)\left(\frac{T-T_{is}}{T_0}\right)^{1/2}}{\frac{8}{3}(p-\frac{1}{3})+\frac{16}{3}\frac{d\log Y}{d\log L}} - 1 > 0 \quad (17)$$

In figure 4 we see that the criterion of equation 17 is satisfied throughout the region in question.

Constant Temperature Criterion

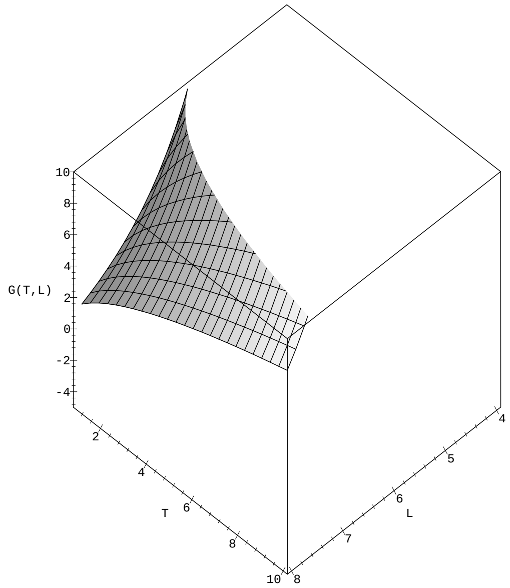

Figure 4. The function $G(T, L)$ given in (17)

Discussion

Our understanding of the spatial variation of the temperature of electrons in the magnetosphere of Neptune is not as complete as that of the protons. The proton temperature profile exhibits three principal features, all of which are accounted for by the currently accepted model (*Eviatar et al.* [1995]):

1. The proton temperature in the outer source region is of the order of the local corotational energy — explained by the pickup process of newly created ions.

2. The proton temperature decreases with decreasing radial distance from 12 R_N to 8 R_N — explained by the interaction with the neutral hydrogen cloud.

3. The proton temperature increases adiabatically with distance inside 8 R_N — explained by the assumed absence of the hydrogen cloud in this inner region.

The electron temperature profile can be similarly described in terms of three principal features in the same spatial regions, but their explanation is far less obvious:

1. The electron temperature in the outer source region is considerably higher than predicted by

models of the ionization process as currently understood. Possible explanations, all speculative at present, include: an efficient mechanism of electron-ion energy exchange by particle-wave interactions, a process of electron heating as part of the interaction between Triton and the magnetosphere, or inward penetration of electrons from the magnetosheath.

2. The electron temperature also decreases with decreasing radial distance from 12 R_N to 8 R_N. As in the case of protons, this feature is well explained by the interaction with the neutral hydrogen cloud.

3. The electron temperature remains essentially constant in the inside 8 R_N; in this region, the proton temperature sharply increases, presumably as the result of adiabatic heating in the absence of the hydrogen cloud. This requires that a powerful cooling process act on electrons and not on protons. The only possibility we can suggest at present is thermal coupling of electrons to the cold ionosphere by means of strong pitch angle diffusion; this presupposes suitable plasma waves which have not yet been either described or observed.

In summary, only the part of the electron temperature profile that lies within the postulated hydrogen cloud is well understood on the basis of the model. Both at the outer edge and inwards from the cloud, explaining the profile seems to require additional physics.

Acknowledgments We are grateful to W.F. Huebner for a helpful email discussion. The work at Tel Aviv University and at the Max-Planck-Institut für Aeronomie was supported in part by the German-Israeli Foundation for Scientific Research and Development under grant I-0199-163.07/91.

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