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TRITON: TOPSIDE IONOSPHERE AND NITROGEN ESCAPE

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The principal ion in the ionosphere of Triton is N^+. Energetic electrons of magnetospheric origin are the primary source of ionization, with a smaller contribution due to photoionization. To explain the topside plasma scale height, we postulate that N^+ ions escape from Triton. The loss rate is 3.4×10^7 cm^{-2} s^{-1} or 7.9×10^{24} ions s^{-1}. Dissociative recombination of N_2^+ produces neutral exothermic fragments that can escape from Triton. The rate is estimated to be 8.6×10^6 N cm^{-2} s^{-1} or 2.0×10^{24} atoms s^{-1}. Implications for the magnetosphere of Neptune and Triton's evolution are discussed.

Introduction

The ionosphere of Triton discovered by Voyager 2 [Tyler *et al.*, 1989] is remarkable in many ways. First, the maximum electron concentration in ingress and egress is 2.3 × 10^4 and 4.6 × 10^4 cm^{-3}, respectively. These are very large numbers indeed, if we recall that Titan, with a similar atmosphere (N_2) but much closer to the sun, has a peak electron density of less than 3 × 10^3 cm^{-3} [Lindal *et al.*, 1983]. The same experiment in Neptune reported an electron density that is less than 3 × 10^3 cm^{-3} (in an H_2 atmosphere). The second puzzling feature of the ionosphere is the topside plasma scale height $H_p = 128 \pm 25$ km. Now for either a molecular ion in photochemical equilibrium *or* an atomic ion in diffusive equilibrium (in the absence of large winds), we have $H_p = 2H_n$ where H_n is the scale height of the corresponding neutral species [Atreya, 1986]. Therefore, $H_n = 64$ km, a value very close to the neutral atmospheric scale height of 60 km (corresponding to 90 K) deduced from the observations of the UVS experiments on the Voyager [Broadfoot *et al.*, 1989]. Hence, it is tempting to identify the major ion as N_2^+ [Tyler *et al.*, 1989]. We will show that this model will have disastrous consequences. Third, the electron densities drop off rapidly below the peak in a manner consistent with the classical Chapman profile [Chamberlain and Hunten, 1987]. Finally, there is an asymmetry between ingress (dawn) and egress (dusk) electron profiles by a factor of 2.

In this article we attempt to examine the simplest hypotheses needed to provide a satisfactory account of the topside ionosphere of Triton. We rely heavily on the neutral modeling work of Strobel *et al.* [1990]. No attempt has been made to provide a model that is self–consistent with the neutral species. Rather this is a preliminary attempt to propose and explore a new and bold hypothesis: the topside ionosphere implies a massive escape rate of N^+ from Triton. The details are worthy of further investigation only if the major concepts prove correct. Unless otherwise stated, all results in this article are obtained by solving the coupled continuity equations for ions and electrons in a spherical atmosphere with transport by ambipolar diffusion [Banks and Kockarts, 1973] using the numerical code described in Allen *et al.* [1981]. Charge neutrality is rigorously preserved at each level of the atmosphere.

Photochemical Models

The model atmosphere adopted in this study is taken from Strobel *et al.* [1990] for exospheric temperature equal to 95 K, as shown in Figure 1. The simplest model we can think of is one with energetic electrons impacting a pure N_2 atmosphere as first proposed by Atreya [1989]. N_2 is readily ionized,

$$N_2 + e \rightarrow N_2^+ + 2e \quad , \qquad \text{(R1a)}$$

followed by rapid recombination,

$$N_2^+ + e \rightarrow N + N \quad . \qquad \text{(R7)}$$

(See Table 1 for listing, numbering of reactions, and rate coefficients.) By trial and error we discovered that a monoenergetic electron beam with $E = 20$ keV per electron and energy flux $F = 0.4$ erg cm^{-2} s^{-1} can simulate the essential features of the observed egress electron profile (for present purposes, further fine tuning is not necessary). But this model grossly violates other observations. The thermospheric temperature of 95 K suggests an energy influx of 1.6×10^{-3} erg cm^{-2} s^{-1} [Broadfoot *et al.*, 1989], which is considerably less than 0.4 erg cm^{-2} s^{-1}! In addition, this large flux of energetic electrons will be accompanied by an induced $N_2 c_4'$ state emission of about 200 R, which should be compared with the observed emission of 3–5 R. Hence, this model is entirely incompatible with the upper atmosphere energetics of Triton.

Can N^+ be the dominant ion in the ionosphere of Triton? N^+ is readily produced by electron impact,

$$N_2 + e \rightarrow N^+ + N + 2e \qquad \text{(R1b)}$$

and by photoionization,

$$N_2 + h\nu \rightarrow N^+ + N + e \quad . \qquad \text{(R2b)}$$

But this ion has the wrong scale height as explained in the Introduction. Now the relation $H_p = 2H_n$ as discussed earlier holds in an *equilibrium* situation, but not in a *dynamic* situation. If the plasma in the atmosphere of Triton interacts with the Neptunian magnetosphere, this

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Table 1. List of reactions considered in our models. The units for rate coefficients are s^{-1} and $cm^3\ s^{-1}$ for dissociative and two–body reactions, respectively. The values for photodissociation coefficients refer to diurnally averaged values at the top of the atmosphere.

R1a	$N_2 + e$	$\rightarrow$	$N_2^+ + 2e$	see text	(a)
R1b		$\rightarrow$	$N + N^+ + 2e$	see text	(a)
R2a	$N_2 + h\nu$	$\rightarrow$	$N_2^+ + e$	$J_{2a} = 5.4 \times 10^{-10}$	(b)
R2b		$\rightarrow$	$N + N^+ + e$	$J_{2b} = 6.7 \times 10^{-11}$	(b)
R3	$N_2^+ + N$	$\rightarrow$	$N_2 + N^+$	$k_2 = 1.0 \times 10^{-11}$	(c)
R4	$N_2^+ + H_2$	$\rightarrow$	$N_2H^+ + H$	$k_3 = 1.7 \times 10^{-9}$	(c)
R5	$N_2^+ + H$	$\rightarrow$	$N_2 + H^+$	$k_4 = 1.9 \times 10^{-10}$	(c)
R6	$N^+ + H_2$	$\rightarrow$	$NH^+ + H$	$k_5 = 7.0 \times 10^{-10}$	(c)
R7	$N^+ + H$	$\rightarrow$	$N + H^+$	$k_6 = 1.9 \times 10^{-10}$	(d)
R8	$N_2^+ + e$	$\rightarrow$	$N + N$	$k_7 = 1.8 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.39}$	(c)
R9	$N_2H^+ + e$	$\rightarrow$	$N_2 + H$	$k_8 = 5.0 \times 10^{-7}$	(d)
R10	$NH^+ + e$	$\rightarrow$	$N + H$	$k_9 = 2.0 \times 10^{-7} \left(\frac{T}{300}\right)^{0.5}$	(c)
R11	$N^+ + e$	$\rightarrow$	$N + h\nu$	$k_{10} = 3.8 \times 10^{-12} \left(\frac{T}{300}\right)^{-0.62}$	(c)
R12	$H^+ + e$	$\rightarrow$	$H + h\nu$	$k_{11} = 3.5 \times 10^{-12} \left(\frac{T}{300}\right)^{-0.7}$	(c)

(a) Cross–sections for electron impact are based on Ajello *et al.* [1989] and Krishnakumar and Srivastava [1990]. (b) Adopted in model B. Cross–sections taken from Kirby *et al.* [1979], Wu *et al.* [1984], and Morioka *et al.* [1984]. (c) Prasad and Huntress [1980]. (d) Estimated by analogy with similar reactions.

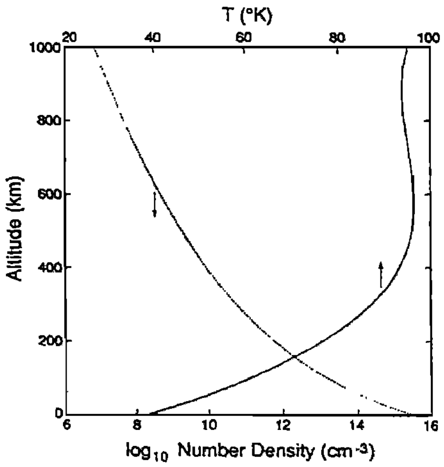

Figure 1. Model atmosphere of Triton adopted for ionospheric studies.

might lead to a loss of N^+ by escape from the exosphere. The loss of ionized particles at the upper boundary will lead to a steepening of the plasma gradient, resulting in a scale height $H_p < 2H_n$, as previously noted in the study of the ionosphere of Venus [Nagy *et al.*, 1975].

To account for the loss of ions below the electron peak we invoke the presence of H_2 in Triton's atmosphere [Strobel *et al.*, 1990]. N^+ reacts with H_2,

$$N^+ + H_2 \rightarrow NH^+ + H \quad , \qquad \text{(R6)}$$

followed by,

$$NH^+ + e \rightarrow H + N \quad , \qquad \text{(R10)}$$

thus leading to a rapid loss of ionization below the ionospheric peak. H_2 is also destroyed by N_2^+ in the following reactions,

$$N_2^+ + H_2 \rightarrow N_2H^+ + H \qquad \text{(R4)}$$

$$N_2H^+ + e \rightarrow N_2 + H \quad , \qquad \text{(R9)}$$

resulting in a net conversion of H_2 to 2H. Ultimately, H^+'s are also formed. We assume that H^+ will diffuse to the lower atmosphere and charge transfer to CH_4 or diffuse to the exosphere and escape from Triton. For simplicity, we do not include H^+ in the model. As will be discussed later, we do not intend to conduct a thorough investigation of the bottomside ionosphere in this article.

Therefore, by introducing additional loss processes we may obtain an ionospheric profile that can simulate the essential features of the observed profile. However, this demands a higher ionization rate to compensate for the greater losses. Model runs (not shown) indicate that photoionization alone is far from being adequate (see later discussion). Electron impact is invoked as an additional source of ionization. By trial and error we arrived at a model shown in Figure 2. At the upper boundary, escape fluxes are given by nv_{esc} where n denotes the concentration of a species and v_{esc} is its escape velocity. At the lower boundary, the mixing ratio of H_2, f_{H_2}, is fixed, and those of N^+ and N_2^+ are set to zero. The model provides a fairly good fit to the observed topside ionosphere, except perhaps near the upper boundary, where the relative uncertanties in the observed electron densities are large. The major ion is N^+. N_2^+ is less abundant due to effi-

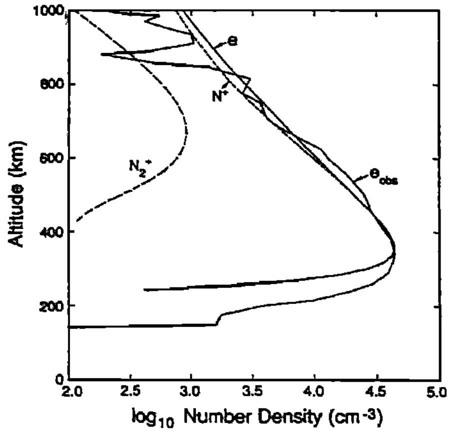

Figure 2. Comparison of model ionospheric profile (e) with Voyager egress observations (e_{obs}). The uncertainty in e_{obs} is $\pm 2.3 \times 10^3$ cm^{-3} [Tyler *et al.*, 1989]. Conditions of this model were: $f_{H_2} = 1 \times 10^{-6}$ at the lower boundary (189 km) and $v_{esc} = 7 \times 10^3$, 1.5×10^4, 0 cm s^{-1} for H_2, N^+ and N_2^+ respectively at the upper boundary (974 km).

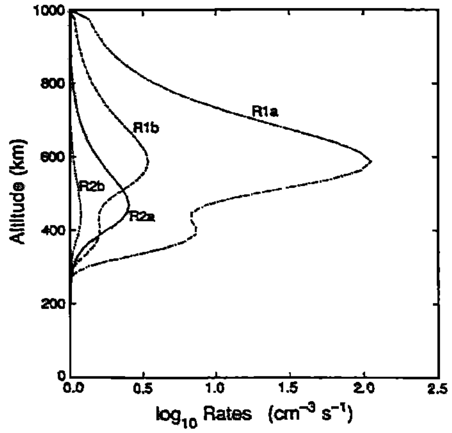

Figure 3. Ionization rates by electron impact and sunlight in the model. R1a: $N_2 + e \rightarrow N_2^+ + 2e$; R1b: $N_2 + e \rightarrow N + N^+ + 2e$; R2a: $N_2 + h\nu \rightarrow N_2^+ + e$; R2b: $N_2 + h\nu \rightarrow N + N^+ + e$. The integrated energy fluxes are 2×10^{-3}, 6.7×10^{-3} and 2.4×10^{-3} erg cm^{-2}s^{-1} for EUV solar flux (R1), 0.5 keV electrons and 20 keV electrons (R2), respectively.

cient dissociative recombination. The concentrations of the other ions N_2H^+ and NH^+ are much less than those of N^+ and N_2^+, and are therefore not shown.

The contributions to ion production rates in the model are presented in Figure 3. The principal source of ionization is electron impact by soft electrons (0.5 keV), R1a and R1b. The secondary peaks in R1a and R1b at lower altitudes are due to hard electrons (20 keV). Photoionization (diurnally averaged and appropriate for egress conditions), denoted by R2a and R2b in Figure 3, provides only a minor source of ionization. We note that a large flux of soft electrons is required to explain the bulge near 600 km in the observed electron profile. If an alternative explanation such as plasma compression were found, then this large flux would become unnecessary (see later discussion). The hard electrons are needed to reproduce the observed electron peak.

To test the sensitivity of the model to input parameters and boundary conditions we conducted a number of sensitivity runs in which one change was made at a time. The results are presented in Figure 4. In cases A and B, the soft (0.5 keV) and hard (20 keV) electrons were, respectively, "switched off." In case C, the escape velocity for N^+ at the upper boundary $v_{esc}(N^+)$ was increased by a factor of 3 to 4.5×10^4 cm s^{-1}, resulting in an electron profile with a smaller scale height than that in the standard case. In case D, $v_{esc}(N^+)$ was reduced by the same factor to 0.5×10^4 cm s^{-1}, resulting in an electron profile with a much larger scale height relative to that in case C. Thus, the magnitude of v_{esc} has a major impact on the slope of electron densities.

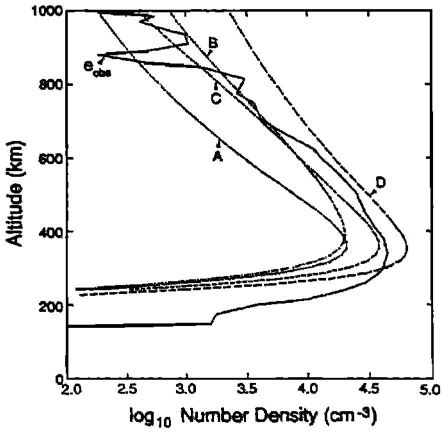

Figure 4. Sensitivity study of model electron profile to variations in input parameters and boundary conditions in the standard model (see Table 2). e_{obs}: observed; A: without 0.5 keV electrons; B: without 20 keV electrons; C: $v_{esc}(N^+) = 4.5 \times 10^4$ cm s^{-1}; D: $v_{esc}(N^+) = 0.5 \times 10^4$ cm s^{-1}.

Given the crudeness of the model described in this work, we can only point out the inadequacies, which will be remedied in a subsequent publication: diurnal variation, lower ionosphere, energy source and uniqueness.

Concluding Remarks

The interaction between Triton and the Neptunian magnetosphere is primarily responsible for generating and maintaining the ionosphere of Triton. Impact by electrons is the principal source of ionization. N^+ is the major ion. Its loss from the atmosphere by escape is surprising but the process may be characteristic of planetary bodies without a magnetic field such as Mars and Venus. The rate of loss of nitrogen (as N^+ or N) from Triton is 4.3×10^7 cm^{-2} s^{-1} (normalized to the surface of the satellite) or 1×10^{25} s^{-1}. The heavy ion in Neptune's magnetosphere observed by the Voyager Plasma Science experiment [Belcher *et al.*, 1989] has been tentatively identified as N^+. The lifetime of magnetospheric ions may be very short (~ a few days), and is independent of mass [Selesnick, 1990]. The required nitrogen flux to sustain the N^+ concentrations in the magnetosphere is of the order of 10^{25} s^{-1} [Richardson and McNutt, 1990; Richardson *et al.*, 1990], consistent with that deduced from our model. At this rate, the total integrated loss of material from Triton is 3.1×10^{24} N_2 molecules cm^{-2} or 11 mbars over the age of the solar system. The escape flux of nitrogen deduced from our model is comparable to that of hydrogen computed by Strobel *et al.* [1990] and suggest that the chemistry of N_2 and H_2 may be strongly coupled. The incident energy flux in the model (if globally uniform) is somewhat higher than that deduced by the Voyager UVS experiment [Broadfoot *et al.*, 1989].

In this article we have examined the simplest possible ionospheric models. A self-consistent diurnally varying model between the ion chemistry and that of CH_4 (which supplies H_2 to the upper atmosphere) remains to be developed, and is expected to remove some of the difficulties associated with the current simple model.

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