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Nitrogen loss from Titan

V. I. Shematovich
Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia

R. E. Johnson and M. Michael
Engineering Physics Program and Astronomy Department, University of Virginia, Charlottesville, Virginia, USA

J. G. Luhmann
Space Sciences Laboratory, University of California, Berkeley, California, USA

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[1] Dissociation and dissociative ionization of molecular nitrogen by solar UV radiation and by photoelectrons and sputtering by the magnetospheric ions and pickup ions are the main sources of translationally excited (hot) nitrogen atoms and molecules in the upper atmosphere of Titan. As Titan does not posses an intrinsic magnetic field, Saturn's magnetospheric ions can penetrate Titan's exobase and sputter atoms and molecules from it. The sputtering of nitrogen from Titan's upper atmosphere by the corotating nitrogen ions and by photodissociation was addressed earlier [*Lammer and Bauer*, 1993; *Shematovich et al.*, 2001]. Here penetration of slowed and deflected magnetospheric N^+ and carbon-containing pickup ions is described using a Monte Carlo model. The interaction of these ions with the atmospheric neutrals leads to the production of fast neutrals that collide with other atmospheric neutrals producing heating and ejection of atoms and molecules. Results from *Brecht et al.* [2000] are used to estimate the net flux and energy spectra of the magnetospheric and pickup ions onto the exobase. Sputtering is primarily responsible for any ejected molecular nitrogen, and, for the ion fluxes used, we show that the total sputtering contribution is comparable to or larger than the dissociation contribution giving a total loss rate of $\sim 3.6 \times 10^{25}$ nitrogen neutrals per second. *INDEX TERMS:* 5407 Planetology: Solid Surface Planets: Atmospheres–evolution; 5780 Planetology: Fluid Planets: Tori and exospheres; 6280 Planetology: Solar System Objects: Saturnian satellites; *KEYWORDS:* Saturn's system, satellite atmosphere, magnetospheric plasma, hot corona, escape, kinetic modeling

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1. Introduction

[2] The satellite Titan possesses a unique, dense, mainly molecular nitrogen atmosphere and is an important source of neutral atoms and molecules in Saturn's system [*Hunten et al.*, 1984]. For Titan's molecular atmosphere nonthermal mechanisms of particle escape are important [*Hunten*, 1982; *Johnson*, 1994]. Dissociation of N_2 is a source of suprathermal nitrogen atoms produced by magnetospheric electron impact [*Strobel and Shemansky*, 1982], by exothermic chemical reactions [*Cravens et al.*, 1997], and by magnetospheric ion N^+ sputtering of the upper atmosphere [*Lammer and Bauer*, 1993; *Shematovich et al.*, 2001]. The dissociation and momentum transfer processes result in the formation of translationally excited (or suprathermal) nitrogen atoms and molecules that populate the corona and contribute to atmospheric escape. Using atmospheric airglow emissions measured by Voyager UVS experiment, *Strobel and Shemansky* [1982] initially estimated an escape flux of 3×10^{26} N atoms per second from Titan. The revised estimate [*Strobel et al.*, 1992] of the nonthermal N atom escape rate of $\leq 1 \times 10^{25}$ s^{-1} was based on detailed N_2 dissociation rates by magnetospheric electron and photoelectron impact. These studies did not take into account the deflection of the flow and the newly formed pickup ions. The latter are ions from Titan's upper ionosphere that are accelerated by the local fields and can reimpact Titan's atmosphere [*Hartle et al.*, 1982]. These are included here, based on estimates from the model by *Brecht et al.* [2000], and compared with escape driven by dissociation processes and by slowed, corotating N^+. These hybrid simulations can give much more three-dimensional detail in the description of the incident ions, but we have not used all that capability in these initial calculations.

[3] It has been shown [*Shematovich*, 1999; *Shematovich et al.*, 2001] that the flux of escaping particles is typically formed over a wide transition region in which the character of the gas flow changes from the thermospheric collision dominated regime to an exospheric collisionless regime.

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Table 1. Nitrogen Loss From Titan's Upper Atmosphere

Causes of Atmospheric Sputtering	N^+ Ions[a]	$C_2H_5{}^+$ Ions[a]	Photodissociation and Electron Impact Dissociation[b]
Ion influx, $\times 10^7$ ions cm^{-2} s^{-1}	1.0	1.0	–
N escape flux,[c] $\times 10^6$ atoms cm^{-2} s^{-1}	6.65	6.86	9.25
Yield[d]	0.67	0.69	–
N loss rate,[e] $\times 10^{25}$ atoms s^{-1}	1.33	1.37	0.93
Mean energy[f] of escaping N eV	6.43	6.95	1.13
Mean energy[g] of escaping N_2 eV	2.21	6.90	0.05

[a] Energy spectra and pitch angle distribution were estimated from the results of *Brecht et al.* [2000].

[b] Mean level of solar activity, solar zenith angle is equal to 60°.

[c] Calculated total N flux is equal to the sum of escape fluxes of atomic nitrogen and twice of molecular nitrogen.

[d] Yield is equal to total N escape flux/ion influx.

[e] Total N atom loss rate is equal to escape flux multiplyed by the exobase surface at height 1500 km.

[f] Mean kinetic energy of escaping N atom at exobase height 1500 km is reduced by the value 0.34 eV of N escape energy.

[g] Mean kinetic energy of escaping N_2 molecule at exobase height 1500 km is reduced by the value 0.68 eV of N_2 escape energy.

Therefore this study is aimed at a detailed investigation of the production, kinetics, transport, and formation of escaping fluxes of suprathermal nitrogen atoms and molecules in the transition region in Titan's upper atmosphere.

2. Physical Model

[4] The principal source of suprathermal particles for the exosphere is transport from the atmospheric transition region in which the suprathermal particles are produced, and the flow is characterized by velocity distribution functions that vary over both microscopic and macroscopic scales. The following dissociation and momentum transfer processes for molecular nitrogen in Titan's upper atmosphere were considered here as important sources of suprathermal nitrogen atoms and molecules:

[5] 1. The dissociation and dissociative ionization of N_2 by solar UV photons with wavelengths shorter 1000Å and by high-energy photoelectrons and magnetospheric electrons

$$N_2 + h\nu, e_\nu \rightarrow N\left({}^4S\right) + N\left({}^4S, {}^2D, {}^2P\right) + e_\nu + \Delta E_{dis} \qquad (1)$$

$$N_2 + h\nu(X - rays) \rightarrow \begin{cases} N_2^+ + e_\nu \\ \left(N_2^+\right)* + e_\nu \rightarrow N_2^{++} + e_{Auger} + e_\nu \\ N^+ + N({}^4S) + e_\nu + \Delta E_{di}. \end{cases} \qquad (2)$$

[6] The dissociation processes occur through a predissociation mechanism which implies that a whole spectrum of bound electronic states of the N_2 are excited. The excited molecule dissociates into nitrogen atoms in states ^{4}S, ^{2}D, and ^{2}P, and their excess kinetic energy distribution is characterized by a set of discrete peaks at the energies ΔE_{dis} = 0.7 to 1.2 eV and 2 eV [*Cosby*, 1993]. The processes (2) of ionization and Auger ionization of N_2 by soft X rays with wavelengths in the range 11–50 Å were also taken into account. These processes are sources of high-energy photoelectrons and Auger electrons, which through the electron impact dissociation produce additional suprathermal N atoms [*Shematovich*, 1998].

[7] 2. The ion-induced sputtering [*Johnson*, 1990, 1994; *Lammer and Bauer*, 1993] of Titan's atmosphere by high-energy corotating, and pickup magnetospheric ions occurs via momentum transfer and dissociation processes. The principal impacting species are the plasma N^+ and H^+ ions, which are deflected and slowed in the interaction, and the freshly accelerated atmospheric pickup ions. Because of ion-molecule reactions in Titan's ionosphere, the dominant pickup ion is a carbon species derived from the methane gas. *Brecht et al.* [2000] assumed it is $C_2H_5^+$, which is the dominant ion at very high altitudes with H_2CN^+dominant lower in the ionosphere [*Keller et al.*, 1998]. Because both $C_2H_5^+$ and H_2CN^+ have the same number of heavy atoms, we treat them as equivalent within the accuracy of our models for the collision cross sections. Here we also ignore the effect of the incident magnetospheric H^+, which is small [*Lammer and Bauer*, 1993; *Luna et al.*, 2003]. Therefore we include

$$N_2 + N^+, C_2H_5^+, \ldots \rightarrow \begin{cases} N^+, C_2H_5^+, \ldots + N_2^* \\ N^+, C_2H_5^+, \ldots + N_2^* \rightarrow N + N^* + \Delta E_{dis} \end{cases} \qquad (3)$$

[8] Collisions lead to the kinetic energy transfer from magnetospheric plasma to the N_2 gas and to the formation of suprathermal N atoms. This energy input into the Titan's atmosphere causes an additional important atmospheric loss. *Lammer and Bauer* [1993] considered the bombardment of Titan's upper atmosphere by magnetospheric protons (with energies of ∼210 eV and a number density of 0.1 cm^{-3}) and by N^+ ions (with energies of ∼2.9 keV and a number density of 0.2 cm^{-3}) [*Neubauer et al.*, 1984]. They used a simplified estimate which suggested that atmospheric sputtering was the dominant loss process.

[9] In the atmospheric sputtering calculations we use estimates of the fluxes of N^+ and $C_2H_5{}^+$ ions from *Brecht et al.* [2000], as indicated in Table 1. These are globally averaged fluxes. The spectra of the impacting pickup ions versus velocity were estimated from *Brecht et al.* [2000] and are given in the top panel of Figure 1. These spectra mainly depend on the place in the pickup cycloid where individual ion trajectories intersect the assumed exobase. The distributions of zenith angles (measured with respect to the vertical direction on Titan) were also estimated from *Brecht et al.* [2000] and are given in the bottom panel of Figure 1. The incident ion fluxes adopted from this model are based on a single set of conditions and assumptions, which do not represent the full range of possible incident pickup ion

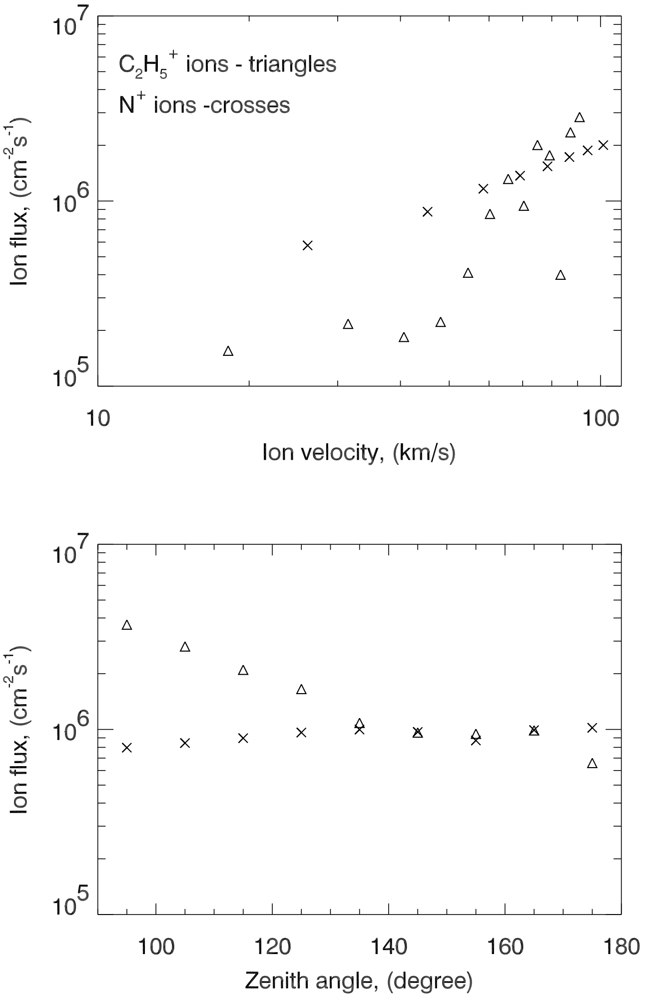

Figure 1. Dependence of the incident fluxes of pickup N^+ and $C_2H_5^+$ ions on (top) velocity and (bottom) zenith angle.

flows. For those calculations, Voyager encounter ambient conditions prevailed, whereas Titan experiences a range of conditions in its orbit around Saturn in a magnetosphere subject to temporal changes from varying solar wind. In addition, that model assumed simplified conditions for the incident magnetospheric ion temperature (cold incident ions) and for the description of the upper atmosphere source of pickup ions. The figures given by *Brecht et al.* [2000] also illustrate that the impacting ions are not uniformly distributed over the ram face of Titan because of the large ion gyroradii. This implies that there are limited regions where the flux can be larger (smaller) by an order of magnitude or more than the average incident ions flux used here. The consequences of these assumptions for the overall sputtering effects will be evaluated in future work.

[10] It is seen from Figure 1 that close to Titan the slowed and deflected corotating N^+ have energies that are much smaller than the corotation energy (2.9 keV), allowing them to interact more efficiently near the exobase. The heavier pickup ions also have large cross sections for momentum transfer to the atmospheric molecules and therefore are also very efficient at ejecting species near the exobase. Because the heavy atoms in the molecular pickup ions contribute much more to the sputtering than does the attached hydrogen and the ion charge is a secondary effect, we treat the pickup ions such as $C_2H_5^+$ as an incident N_2. We also use a collision model based on the new collisional momentum transfer and dissociation cross sections for $N + N_2$ and $N_2 + N_2$ collisions for high energies from *Johnson et al.* [2002]. For low energies ($\leq$100eV) and near threshold energies, results from *Tully and Johnson* [2002] are used. The cross sections presented in this paper are in error by a constant factor. They need to be multiplied by a factor of 2. We include also the reaction cross section, which becomes efficient at low relative impact energies. Because the energy transfer in the high-energy $N + N_2$ and $N_2 + N_2$ collisions is strongly dependent on scattering angle distribution, we use a model that roughly reproduces extrapolations of the calculated differential cross sections for these processes.

3. Numerical Model

[11] An accurate analysis of the processes of production, collisional relaxation, and transfer of suprathermal nitrogen atoms and molecules in the considered transition region of Titan's upper atmosphere can be carried out with the use of the Boltzmann equations [*Shematovich*, 1999; *Shematovich et al.*, 2001]. These equations take into account both the local collisional kinetics and the spatial dynamics of suprathermal nitrogen atoms and molecules, and of high-energy N^+, $C_2H_5^+$, H_2CN^+,... ions in the transition region. Instead of a direct solution of these very complicated integro-differential kinetic equations we used a modification [*Shematovich*, 1999; *Shematovich et al.*, 2001] of the direct simulation Monte Carlo (DSMC) method [*Bird*, 1994] to simulate the physical model described above. The DSMC approach is based on the stochastic interpretation of the evolution of an ensemble of atoms, molecules and their ions in the rarefied atmospheric gas. This allows us to replace the atmospheric gas in the transition region by a system of modeling particles [*Marov et al.*, 1997]. Because we consider the evolution of the hot nitrogen fraction in the transition region at the molecular level, the characteristic scales are defined through the parameters of the ambient atmospheric gas, e.g., local free path length and the mean free time between collisions.

[12] Usually the particles with kinetic energies an order of magnitude higher than the mean thermal energy of the gas under study are called as suprathermal particles. The exospheric temperature of Titan varies over the range of 150–220 K; therefore particles with kinetic energies higher than 0.05–0.1 eV formally could be considered as a suprathermal population. Because we are interested in the nitrogen loss from Titan, we restrict this formal definition of suprathermal particles and will only consider the populations of hot atomic and molecular nitrogen with kinetic energies higher than the escape energies (i.e., 0.34 eV for N atoms and 0.68 eV for N_2 molecules).

[13] The transition region occurs in the altitude range 600–1700 km of Titan's atmosphere. The lower boundary is taken in the relatively dense thermosphere, where the suprathermal particles quickly lose their excess kinetic energy in the elastic collisions with ambient atmospheric gas. The upper boundary is taken above the exobase ($\sim$1500 km), at height where gas flow is practically collisionless.

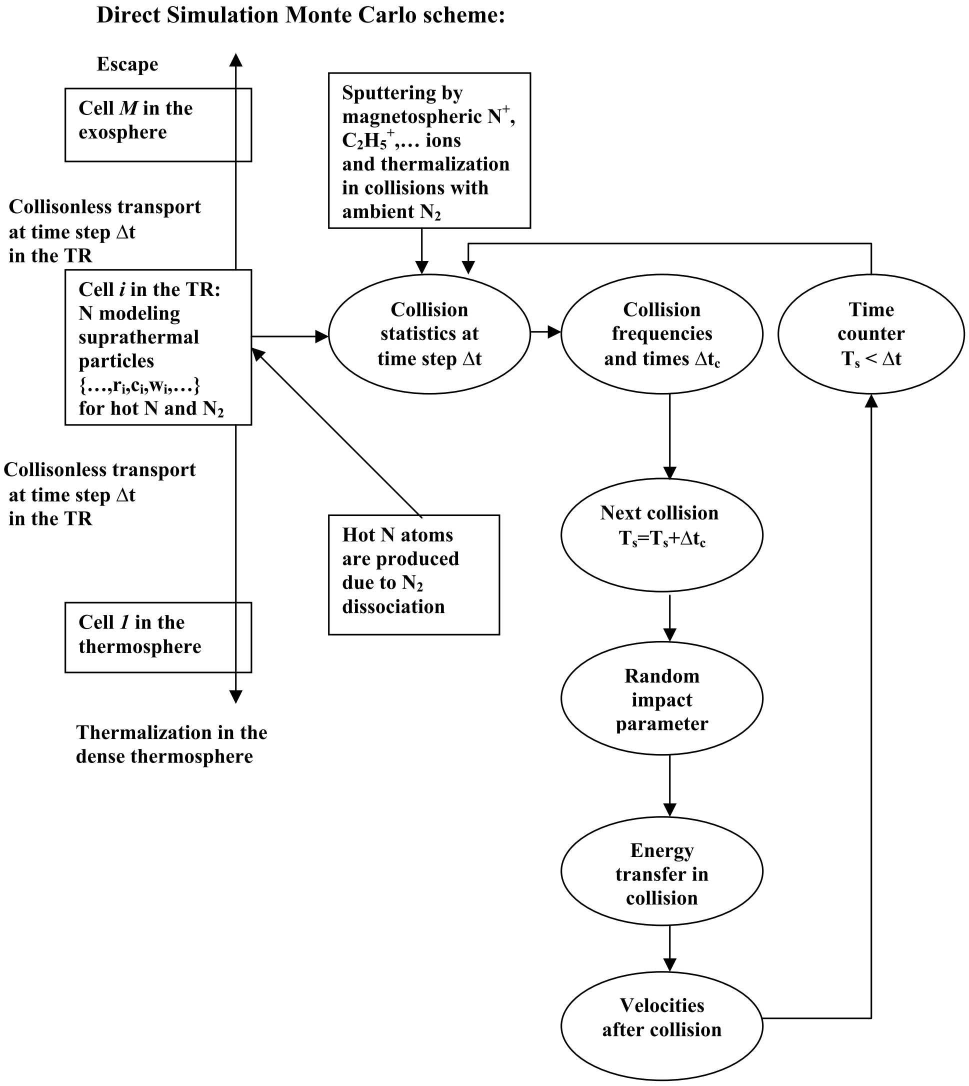

Figure 2. Stochastic modeling scheme of the suprathermal nitrogen flow in the transition region (TR) between thermosphere and exosphere of Titan's upper atmosphere.

[14] To simulate the atmospheric gas flow, the transition region is divided into a set of radial cells with a characteristic size of the order of the local free path length. In each radial cell the ambient atmospheric N_2 gas is represented by a set of modeling particles corresponding to the appropriate local values of the density and temperature [*Yelle et al.*, 1997].

[15] In accordance with the physical model, the suprathermal particles are produced because of dissociation by solar UV radiation and magnetospheric electrons. They also are set in motion by momentum transfer and dissociation collisions with magnetospheric ions, thermalize in the elastic collisions with the ambient atmospheric gas, and move in the gravitational field of Titan. Using a stochastic modeling method, the evolution of a given set of modeling particles during one time step (approximate mean collision time) is determined in the following way (see also Figure 2 which gives a flow chart for the description of the method used).

[16] Suprathermal N atoms produced due to photolytic and electron impact processes (equations (1) and (2)) are injected at each cell corresponding to the source function Q^{hot} [*Shematovich*, 1999]. High-energy magnetospheric N^+, $C_2H_5^+$,… ions are injected at the upper boundary with energy spectra and entry pitch angle distributions taken from *Brecht et al.* [2000] (see Figure 1).

[17] In each cell the time sequence and statistics of collisions between the ambient atmospheric gas and suprathermal N and N_2 particles, and the high-energy N^+, $C_2H_5^+$ ions are augmented. This is the most complicated and time-consuming step of the model. The detailed description of the algorithms used to calculate the local collision kinetics in each cell is given by *Marov et al.* [1997]. Here we will discuss the most important steps of the stochastic modeling of collision kinetics:

[18] 1. In each cell the suprathermal atomic and molecular nitrogen, the ambient (thermal) atmospheric nitrogen, and the local fluxes of magnetospheric ions N^+ and $C_2H_5^+$ are represented by a finite set of modeling particles corresponding to each species. Each modeling particle is characterized by its space coordinate, velocity, and statistical weight, because the hot nitrogen and ion

densities are much lower than the density of atmospheric nitrogen.

[19] 2. The frequencies of momentum transfer and dissociation collisions of thermal atmospheric nitrogen with suprathermal particles and magnetospheric ions are calculated for all possible pairs of modeling particles in the given cell as

$$\omega_{N2,\alpha} = \sum_{i,j} g_{ij}\sigma_{N2,\alpha}\left(g_{ij}\right)/V, \alpha = N_2, N^{(hot)}, N_2^{(hot)}, N^+, C_2H_5^+. \tag{4}$$

Here g_{ij} is the relative velocity of colliding particle i of atmospheric N_2 and particle j of hot population α; $\sigma_{N2,\alpha}$ is the total (momentum transfer and dissociation) cross section for this kind of collision; V is the volume of the cell. On the basis of the collision frequencies (equation (4)), the local kinetics of the suprathermal particles in the given cell can be interpreted as a random process belonging to the class of homogeneous jump-like Markovian processes [*Marov et al.*, 1997; *Shematovich*, 1999]. This allows us to determine the time Δt_c between two consecutive collisions using the current numerical model state

$$\Delta t_c = -ln\xi/\sum_{\alpha}\omega_{N2,\alpha} \tag{5}$$

where ξ is a random number uniformly distributed in the interval [0,1]. Formula (5) is a consequence of the exponential distribution of waiting times between consecutive state transitions for jump-like Markovian process. It allows us to determine the time sequence of collisions in each cell;

[20] 3. When the next collision is selected, it is necessary to determine the species and particle pairs participating in the collision. The chemical channel is randomly selected through the conditional probabilities $\omega_{N2,\alpha}/\Sigma\alpha\omega_{N2,\alpha}$. After that, the collision impact parameter is chosen randomly. This allows us to determine the energy transfer from suprathermal and high-energy magnetospheric particles to the translational and inner degrees of freedom of the atmospheric thermal nitrogen based on the distributions calculated by *Johnson et al.* [2002] and *Tully and Johnson* [2002]. If the value of energy transfer to the inner degrees of freedom (energy transfer to the center of mass of N_2 molecule) is higher than the dissociation threshold both the dissociation and momentum transfer channels are considered. The particle velocities after collision are calculated based on the scattering angle distributions from *Johnson et al.* [2002] and *Tully and Johnson* [2002].

[21] 4. This procedure is carried out for each time step in each cell. If the collisions of magnetospheric ions with ambient N_2 molecule are accompanied by the formation of suprathermal N or N_2 with kinetic energies higher than the escape energies, then these primary suprathermal particles are created in the cell. The collisions of primary suprathermal nitrogen particles with atmospheric thermal nitrogen can result in the production of secondary suprathermal particles with kinetic energies higher than the escape energy. This means that the numerical model evolves with a variable number of modeling particles representing the suprathermal populations of atomic and molecular nitrogen.

[22] In the same time step, the transport of each modeling particle in the transition region is calculated. The N and N_2 modeling particles, which escape from Titan's atmosphere, or collisionally lose their kinetic energy below the escape energy, or penetrate deep into the thermosphere (i.e., crossing the lower boundary) are removed from the system.

[23] Finally, the statistics of velocity distributions for the suprathermal N and N_2 particles are accumulated. With this numerical model we obtain the atmospheric density, temperature, and escape flux versus altitude for the suprathermal nitrogen in the atomic and molecular forms.

4. Results

[24] To study the relative importance of photodissociation (equations (1) and (2)) and sputtering (equation (3)) processes for the formation of suprathermal populations of N and N_2 in the upper atmosphere of Titan, we modeled these two sources separately. The production rate and energy spectra of the suprathermal N atoms produced due to the dissociation and dissociative ionization by the solar EUV radiation and by the corresponding flux of photo- and magnetospheric electrons were calculated using the model [*Shematovich* 1998, 1999]. These fresh, hot nitrogen atoms are thermalized in collisions with the ambient atmospheric gas producing the secondary hot nitrogen atoms and molecules. Some of these suprathermal primary and secondary nitrogen atoms and molecules reach exospheric altitudes with kinetic energy greater than the escape energy and escape to Saturn's environment. Calculations were made for mean solar activity level $F_{10.7}$ = 150 and when Titan is inside the Saturn's magnetosphere, which are the conditions for the Voyager 1 encounter.

[25] In Figure 3 the production rates of the primary and secondary hot N and N_2 formed because of photodissociation (bottom panel) and sputtering processes (top and middle panels) are shown. The magnetospheric electron contribution is much smaller, as shown earlier [*Keller et al.*, 1992]. It is seen that atmospheric sputtering (equation (3)) by pickup ions leads to the efficient momentum transfer to the main constituent of the ambient atmosphere, molecular nitrogen. On the other hand, the N_2 photodissociation and electron impact dissociation processes (equations (1) and (2)) are an efficient source of suprathermal nitrogen atoms.

[26] In Figure 4 the height profiles of the number densities of suprathermal N and N_2 populating the transition region due to sputtering (top and middle panels) and photodissociation processes (bottom panel) are shown. Again, the N_2 fraction of hot gases is formed mainly because of the sputtering processes, and atomic nitrogen fraction is formed because of both photodissociation and ion-induced dissociation of the ambient nitrogen molecules.

[27] From Figures 3 and 4 it follows that elastic thermalization of primary hot N atoms and molecules causes a significant production of the suprathermal nitrogen in Titan's upper atmosphere. On other hand, bombardment of an atmospheric gas by the high-energy N^+ and $C_2H_5^+$ ions from Saturn's magnetosphere leads to the formation, through the momentum transfer and dissociation collisions, of both N and N_2 with relatively high kinetic energies. Momentum transfer collisions of $C_2H_5^+$ pickup ions with the

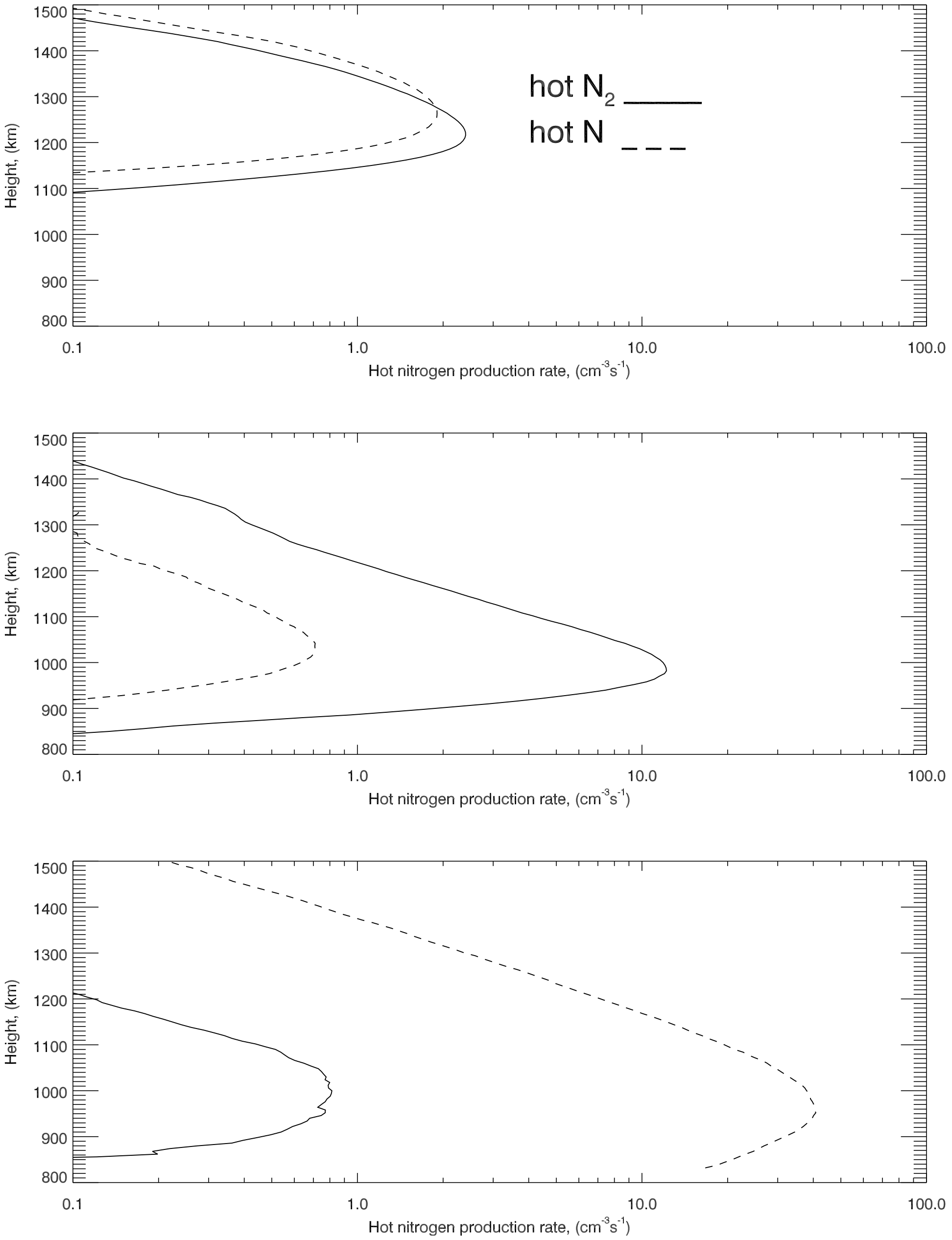

Figure 3. Production rates of the hot N_2 (solid curves) and N (dashed curves) formed because of (bottom) photodissociation and sputtering by (top) $N^+$and (middle) $C_2H_5^+$ ions.

ambient N_2 molecules are more efficient than of N^+ ions because they are heavier and more energetic on the average and have larger momentum transfer cross sections. From Table 1 we also see that the mean energy of the ejecta produced by photodissociation and by sputtering are very different [*Shematovich et al.*, 2001], which will affect the morphology of the torus of neutral nitrogen at Titan's orbit.

[28] The height profiles of local (dashed lines) and integrated (solid lines) escape fluxes of the hot N_2 and N are given in Figures 5 and 6, respectively. In the top and middle panels the escape fluxes are due to sputtering, and in the bottom panel the escape fluxes are due to photodissociation processes. It is seen that sputtering by the slowed corotating magnetospheric ions and the pickup ions causes the nitrogen escape in both atomic and molecular forms. On the other hand, photodissociation and electron impact dissociation processes cause the nitrogen escape mainly in atomic form. The dashed lines in Figures 5 and 6 confirm that the origin of the escaping particles can be well below the exobase [*Shematovich*, 1999; *Shematovich et al.*, 2001].

[29] Earlier we showed that the atmospheric sputtering rate by magnetospheric N^+ ions penetrating the exobase at the corotation energies was much smaller than the photodissociation-induced loss rate [*Shematovich et al.*, 2001]. Here it is seen that when the magnetospheric N^+ are deflected and slowed by the local fields [*Brecht et al.*, 2000], they produce a loss rate comparable to the photo-

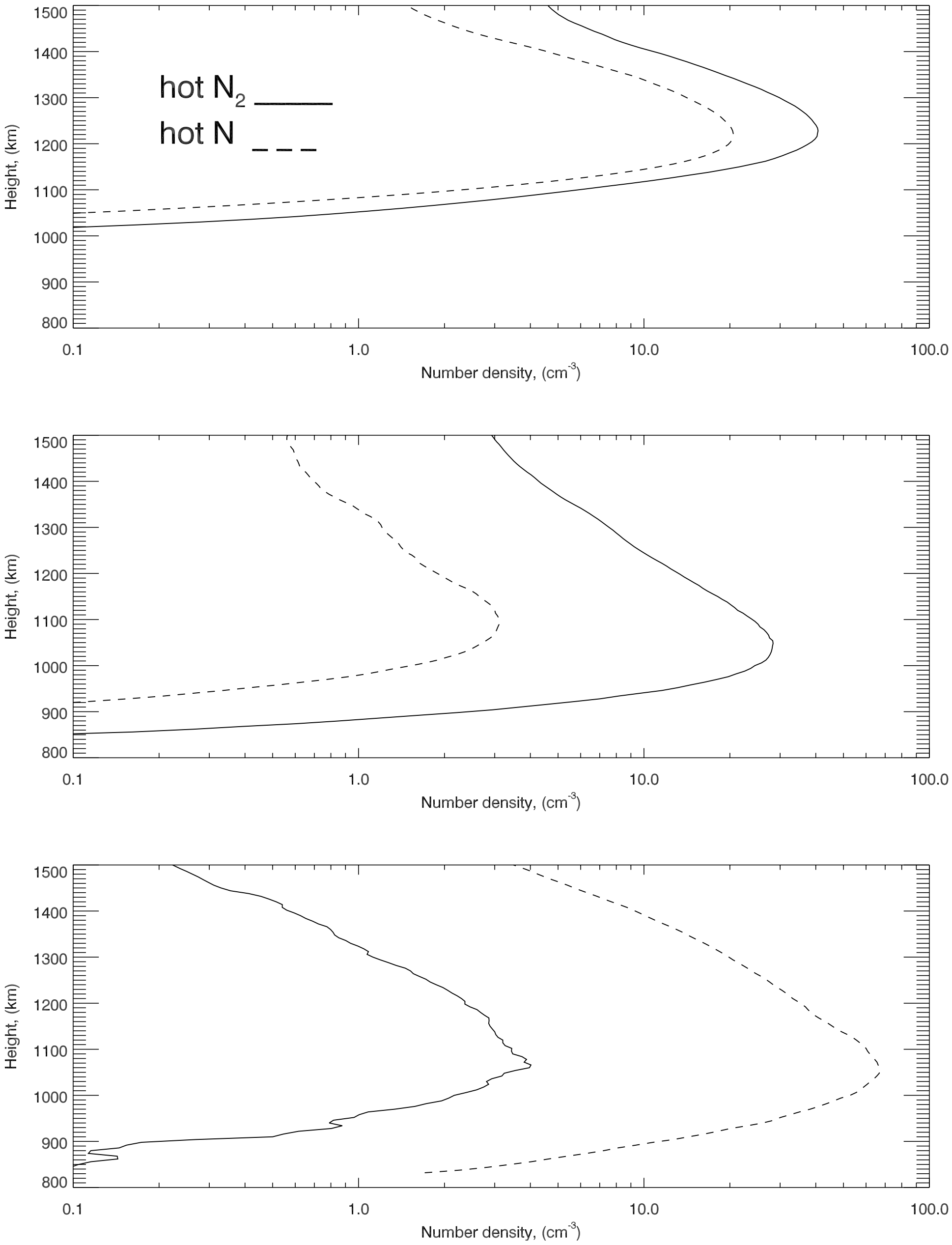

Figure 4. Height profiles of the number density of hot N_2 (solid curves) and N (dashed curves) due to the (bottom) photodissociation and sputtering by (top) N^+ and (middle) $C_2H_5^+$ ions.

dissociative loss rate. Including the pickup ion flux, as estimated here, further increases the atmospheric sputtering rate. Therefore analysis of the escape fluxes of suprathermal N and N_2 shows that the inputs of photodissociation and atmospheric sputtering into the formation of nitrogen escape flux have comparable magnitudes. Therefore these processes should both be taken into account in the models of mass loading of Saturn's magnetosphere by Titan. From Figures 5 and 6 it is also seen that the size of the exospheric escape flux is finalized in the altitude range 1400 to 1600 km, so that the effective exobase corresponds to these heights.

[30] The total loss rates for atomic and molecular nitrogen from Titan's upper atmosphere are given in Table 1 and in the top and middle panels of Figure 7. The total loss rate can be estimated as

$$S = C \times R_{ex}^2 \times F_{ex},$$

where the exobase radius is $R_{ex} \sim (1500\ \mathrm{km} + R_{Titan})$ and C is 2π for the photodissociation rate and 4π for the globally averaged ion flux. On the dayside the total atomic nitrogen escape flux is equal to

$$F_{ex} = F_{ex}(N) + 2 \times F_{ex}(N_2) = 2.28 \times 10^7 cm^{-2} s^{-1}.$$

Because the ion flux is a global average but the solar UV flux is not, the total loss rate of nitrogen from Titan's

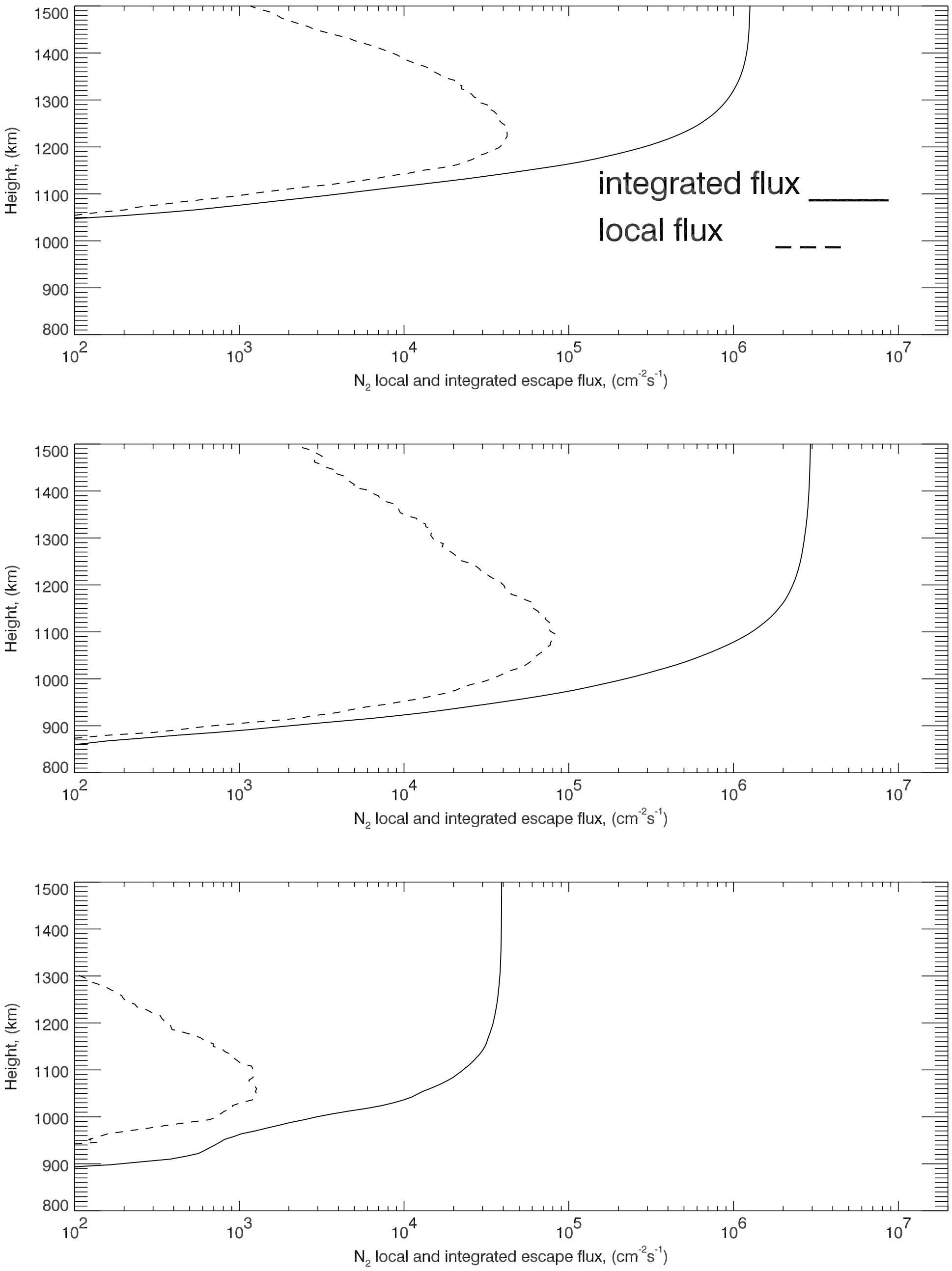

Figure 5. Local (dashed curves) and integrated by height (solid curves) escape flux of N_2 molecules due to the (bottom) photodissociation and sputtering by (top) N^+ and (middle) $C_2H_5^+$ ions.

upper atmosphere is ~3.6×10^{25} of nitrogen atoms per second and is shown in the bottom panel in Figure 7. The height profiles of its constituents due to sputtering and dissociation processes are also shown in the bottom panel of Figure 7. This loss rate strongly depends on the solar activity level and energy input from the magnetosphere. That is, the composition, energies and spatial distribution of the ion bombardment is expected to be highly variable, as stated earlier. The escape rate calculated here is close to the revised estimate of *Strobel et al.* [1992] and to the upper estimate (without taking into account the elastic thermalization of primary hot N atoms) of total nitrogen loss of 2.5×10^{25} s^{-1} due to all photochemical sources [*Cravens et al.*, 1997]. However, the composition of the ejecta is very different from those estimates. This can be important as the N_2 can be ionized prior to dissociation affecting the mass loading of the outer magnetosphere.

5. Summary and Conclusions

[31] In this paper we have carried out a detailed, collisional model of the kinetics and dynamics of suprathermal nitrogen atoms and molecules formed due to dissociation and sputtering processes in Titan's upper atmosphere. The escape fluxes of N and N_2 are seen to be formed in the transition region between thermosphere and exosphere due to the competition between elastic thermalization and hot particle production by photodissociation and atmospheric

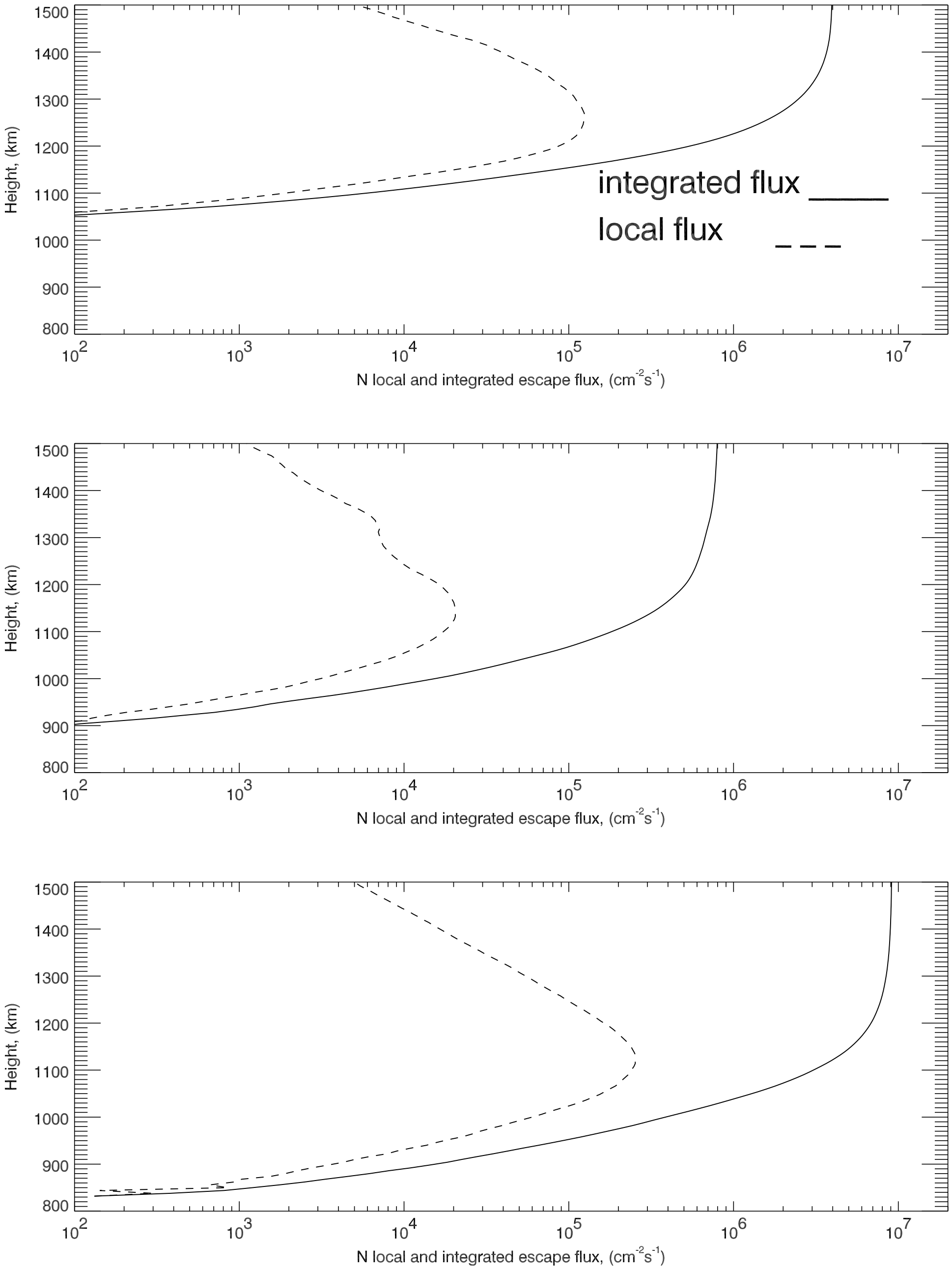

Figure 6. Local (dashed curves) and integrated by height (solid curves) escape flux of N atoms due to the (bottom) photodissociation and sputtering by (top) N^+ and (middle) $C_2H_5^+$ ions.

sputtering. We have shown that N_2 dissociation by solar EUV photons, photoelectrons and incident high-energy plasma all need to be included in describing the hot particle populations in the Titan's upper atmosphere and in estimating total nitrogen loss rate, a critical constraint in studies of evolutionary history of Titan [*Lunine et al.*, 1999; *Lammer et al.*, 2000]. On the basis of the ion flux used here, sputtering could dominate the photodissociation contribution, contrary to our earlier conclusions [*Shematovich et al.*, 2001]. Detailed models of the ion flux onto the exobase are therefore needed.

[32] This model can be extended to take into account the exothermic ion-molecule reactions in Titan's ionosphere [*Cravens et al.*, 1997]. In this way it is possible to estimate the escape rates for the chemically produced neutrals of the C- and N- families to Saturn's system. The fragmentation of the N_2 molecules in Titan's atmosphere is the initial step toward the synthesis of HCN and other prebiotic molecules [*Lara et al.*, 1999]; therefore the energy deposited from solar UV radiation and from magnetospheric plasma is essential to the issue of prebiotic chemistry in Titan's atmosphere.

[33] The dissociation-induced loss and atmospheric sputtering by the magnetospheric plasma and the pickup ions produces a hot nitrogen corona formed in the transition region. It is also the source of a neutral and ion torus along Titan's orbit [*Barbosa*, 1987; *Ip*, 1992]. The detailed density distribution and global configuration of the nitro-

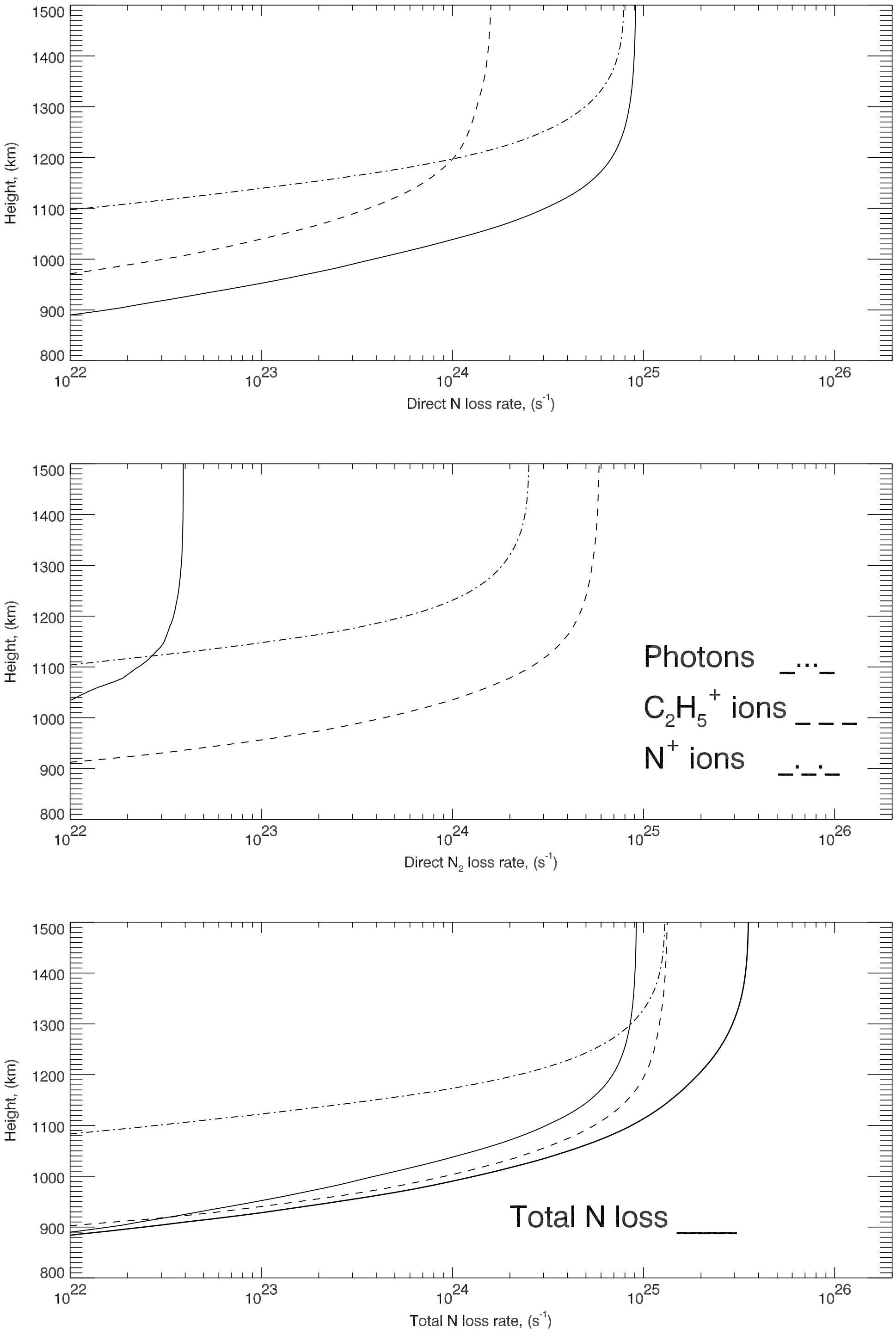

Figure 7. Direct (top) N and (middle) N_2 loss rates and (bottom) total nitrogen loss rate due to the photodissociation (dot-dot-dot-dashed curves) and sputtering by N^+ (dot-dashed curves) and $C_2H_5^+$ (dashed curves) ions.

gen torus strongly depends on input parameters such as total nitrogen loss rate, energy spectra of escaping N and N_2 fluxes, ionization lifetimes, and the rates of charge-exchange with corotating magnetospheric plasma. Here we show that N_2 is an important component of the ejecta, so that molecular nitrogen ion formation in the torus must be considered. A description of the neutral torus produced by the escaping nitrogen is in progress. Ionization of these neutrals followed by inward diffusion of the ions will also lead to the implantation of nitrogen into the small icy Saturn's satellites affecting their surface composition [*Delitsky and Lane*, 2002], so that the escape flux described here can be important throughout the Saturn's system.

[34] **Acknowledgments.** We thank Steve Brecht for providing the results of the hybrid simulation for the present calculations. This work is supported by the NSF Astronomy and International Programs, by NASA's Planetary Atmospheres Program, and by the RFBR Project 02-02-16087.

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R. E. Johnson and M. Michael, Engineering Physics Program and Astronomy Department, University of Virginia, Thornton Hall B103, Charlottesville, VA 22903, USA. (rej@virginia.edu; mm2eq@virginia.edu)

J. G. Luhmann, Space Sciences Laboratory, University of California, Centennial Drive at Grizzly Peak Blvd., Berkeley, CA 94720-7450, USA. (jgluhman@ssl.berkeley.edu)

V. I. Shematovich, Institute of Astronomy, Russian Academy of Sciences, 48 Pyatnistkaya street, Moscow, 119017 Russia. (shematov@inasan.rssi.ru)