

Note

Energy deposition of pickup ions and heating of Titan's atmosphere

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Abstract

The deposition of energy, escape of atomic and molecular nitrogen and heating of the upper atmosphere of Titan are studied using a Direct Simulation Monte Carlo method. It is found that the globally averaged flux of deflected magnetospheric atomic nitrogen ions and molecular pickup ions deposit more energy in Titan's upper atmosphere than solar radiation. The energy deposition in this region determines the atmospheric loss and the production of the nitrogen neutral torus. The temperature structure near the exobase is also calculated. It is found that, due to the inclusion of the molecular pickup ions more energy is deposited closer to the exobase than assumed in earlier plasma ion heating calculations. Although the temperature at the exobase is only a few degrees larger than it is at depth, the density above the exobase is enhanced by the incident plasma.

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1. Introduction

Titan's atmosphere is the subject of intense scrutiny by the Cassini spacecraft because of its very dense atmosphere. This atmosphere interacts with both the solar and magnetospheric fields and particles since Titan crosses Saturn's magnetopause when the solar radiation pressure is high (Neubauer et al., 1984). Titan has a radius of 2575 km and its orbital radius is $20.3R_s$, where R_s is Saturn's radius. Titan's atmosphere consists mostly (97%) of N_2 and its exobase is located at ~ 1500 km. The estimated thermospheric temperature was initially thought to be about 180 K (Smith et al., 1982; Lindal et al., 1983; Yelle, 1991). Recently Vervack et al. (2004) reanalyzed the Voyager 1 data and found that the exospheric temperature of Titan is about 20–40 K less than those estimates, consistent with recent Cassini observations (Waite et al., 2005). Here we described the contribution to the heating of the upper atmosphere by the impact of magnetospheric ions and pickup ions when Titan is in Saturn's magnetosphere.

Saturn's magnetospheric plasma interaction with Titan's atmosphere has been studied by many groups (Ledvina et al., 2004; Michael et al., 2005; Nagy et al., 2001 and references therein). The incident plasma ionizes and excites the atmosphere, plays an important role in the chemistry of the atmosphere, and causes atmospheric sputtering which subsequently generates a neutral torus (Lellouch et al., 1990; Yelle, 1991; Fox and Yelle, 1997; Lammer et al., 1998; Michael et al., 2005; Smith et al., 2004). In addition, the energy deposited below the exobase provides a heat source that can in principle cause an increase in the exobase temperature, an expansion of the atmosphere and an extended hot corona (Johnson, 1990).

Brecht et al. (2000) used their hybrid, semi-kinetic model to study the interaction of magnetospheric plasma with Titan. They described the slowing of the heavy ions in the ambient plasma, assumed to be N^+ , and the flow of the pickup ions. Since $C_2H_5^+$ was suggested to be the major contributor to the ionospheric mass loading at higher altitudes by Fox and Yelle (1997), they used a calculated density profile for $C_2H_5^+$ to describe the formation of pickup ions. Others have suggested that the dominant pickup ions are N_2^+ or $HCNH^+$ (Hartle et al., 1982). Cassini/CAPS data has shown that the ambient plasma is

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dominated by O^+ and mass ~ 16 and ~ 28 u pickup ions were detected at Titan (Crary et al., 2005; Hartle et al., 2005). Until the Cassini data is fully analyzed representative fluxes of N^+ and N_2^+ are estimated from Brecht et al. (2000) to represent the masses (~ 14 – 16 and ~ 28 – 29 u). Earlier we described the heating by energetic H^+ , which deposits its energy much deeper in the atmosphere (Luna et al., 2003).

The heating of Titan's atmosphere by solar radiation and low-energy magnetospheric electrons had been studied by Friedson and Yung (1984). Lellouch et al. (1990) studied the heat budget in Titan's atmosphere and discovered an error in the model of Friedson and Yung (1984). Yelle (1991) calculated the thermal structure for Titan's upper atmosphere including solar IR radiation and suggested that the HCN cooling was important. Later Lammer et al. (1998) calculated the sputter-induced heating by undeflected, co-rotating magnetospheric nitrogen ions of energy 2.9 keV. Michael et al. (2005) showed that the deflected magnetospheric atomic nitrogen ions and molecular pickup ions, which have energies less than 1.25 keV, are more efficient in sputtering the atmosphere of Titan. This flux also deposits more energy near the exobase than the assumed flux of corotating N^+ , and hence, should be more effective at heating the atmosphere near the exobase region. Here we re-calculate the temperature and density profiles near the exobase region accounting also for the sputter removal of energy. Since an extended corona is formed by the energy deposited by the heavy pickup ions, the results here can be scaled to the local energy deposition rate and to the coronal structure as the Cassini data on pickup ions and the neutral corona are analyzed.

2. Simulation

A 3-D Direct Simulation Monte Carlo (DSMC) model developed to study sputtering of Titan's atmosphere is discussed in Michael et al. (2005). To describe the heating of the atmosphere we also used a DSMC model, but without an energy threshold below which particles are not followed. This increases the computational cost enormously but allows us to fully describe the effect of the plasma. Although the heating of the atmosphere can be estimated with fewer incident particles than required to study the escape or the enhancement in coronal density, the computational times are long. Therefore, we used a 1-D model to describe atmospheric heating tracking all of the representative atmospheric particles, whereas in Michael et al. (2005) particles with energy less than 0.1 eV were assumed to be stationary. Due to forward scattered particles and particles that escape from the flanks of the atmosphere, atmospheric sputtering requires a 3-D model. However, the average effect of the incident plasma on atmospheric heating can be studied using a 1-D globally symmetric atmosphere and a globally averaged incident flux.

Test particles are followed from 1600 to about 1000 km above the surface of Titan using the algorithm of Bird (1994). The incident N^+ and N_2^+ ions make energy transfer collisions with the atmospheric neutrals (N_2) producing non-thermal recoils and the dissociation of N_2 . Therefore, in addition to tracking the incident particles, we track the cascade of N_2 molecules and N atoms set in motion with energies above the assumed background temperature. The collisions of non-thermal N and N_2 with atmospheric (thermal) N_2 is described by cross sections discussed in Michael et al. (2005) and the principal energy deposition process near the exobase is the impact of pickup N_2^+ on N_2 . The number density and temperature of N_2 at the lower boundary are fixed at a density of $8 \times 10^9 \text{ cm}^{-3}$ and a temperature of either 180 K (Smith et al., 1982; Keller et al., 1998) or 155 K (Vervack et al., 2004). We use estimates of the incident fluxes of ambient flowing N^+ and molecular pickup ions from Brecht et al. (2000). These are globally averaged fluxes based on the statistics of individual ion trajectories that intersect the exobase. The energy and angular spectrum are given in Shematovich et al. (2003). The deflected magnetospheric N^+ ions ($1.1 \times 10^7 \text{ N}^+ \text{ cm}^{-2} \text{ s}^{-1}$) have energies less than 750 eV and the representative molecular pickup ions ($1.4 \times 10^7 \text{ N}_2^+ \text{ cm}^{-2} \text{ s}^{-1}$) have energies less than 1.25 keV. Because of the large ion gyro-radii the impacting ions are not uniformly distributed over the ram face of Titan (Sittler et al., 2005). Therefore, there are regions where the flux can be much larger or smaller than the average incident ions flux used here. The cross sections and model atmosphere used in the present study are discussed in Michael et al. (2005).

3. Energy deposition and escape

The major energy sources for Titan's upper atmosphere are solar radiation and Saturn's magnetospheric ions and electrons. Solar UV and EUV radiation is absorbed in the upper atmosphere with the most important contribution to the heating coming via absorption of Lyman α radiation by methane (Lellouch et al., 1990). This occurs at lower altitude (800–900 km) than those considered here where a large fraction of the heat can be removed from the atmosphere by infrared cooling (Lellouch et al., 1990; Yelle, 1991). Therefore, the thermospheric/exospheric temperature is primarily a function of the N_2 heating at EUV wavelengths (150–350 Å) and the plasma heating described here, although these are less important global heat sources. Lellouch et al. (1990) showed that solar heating of nitrogen is more important than CH_4 and C_2H_2 in the upper atmosphere of Titan by up to about a factor of four. Friedson and Yung (1984) showed that low-energy magnetospheric electron precipitation is a very small contribution to the heating. Strobel et al. (1992) estimated that the heating by magnetospheric electrons is only 10% of that by solar energy. Lammer et al. (1998) studied the energy deposition by magnetospheric protons, solar wind

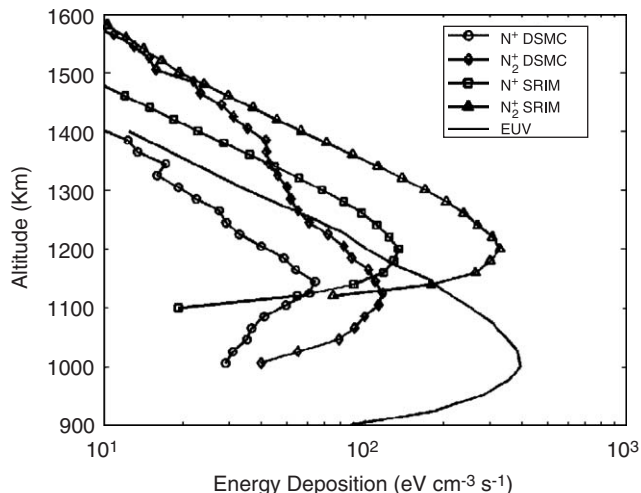


Fig. 1. Energy deposition by the slowed and deflected magnetospheric N^+ ions and molecular pick up ions calculated using DSMC and SRIM methods, and by solar photons.

protons and co-rotating N^+ ions of energy 2.9 keV and suggested that the co-rotating N^+ ions are more important than the former two. Luna et al. (2003) calculated the energy deposition of energetic protons to the atmosphere of Titan and found it is less than deposited by photons, but comparable to that of magnetospheric electrons.

Fig. 1 presents the energy deposition of the slowed and deflected magnetospheric N^+ ions and the molecular pickup ions in the atmosphere of Titan close to the exobase calculated using the DSMC model described above. The energy deposited by solar photons is also shown in Fig. 1. Since the photons are primarily absorbed deeper into the atmosphere, it is clear that in the region of interest the pickup ions deposit more energy than photons. The energy deposited by the pickup ions is also larger and deposited closer to the exobase than the energy deposited by the assumed, undeflected corotating ions estimated by Lammer et al. (1998).

In Fig. 1 we also compare these results to an estimate of the energy deposition profile obtained using the Stopping and Range of Ions in Matter (SRIM) software (Ziegler et al., 1985). This very useful 1-D software has been developed to describe the effect of ions impacting a gas or solid for a large set of atomic species. Here we considered an energy distribution of N^+ and N_2^+ ions corresponding to the incident flux and follow the particles into the atmosphere of Titan. The atmosphere of Titan was considered equivalent to an atomic density of N that is twice the density of N_2 and incident N_2^+ was assumed to deposit its energy like two energetic nitrogen ions at half the energy. The energy lost is calculated at each 20 km between 1700 and 1000 km and the rest of the energy is used to penetrate further the atmosphere. The deposition near the exobase is, fortuitously, well described by this simple method but not at depth. Because of its very tight binding, treating molecular nitrogen as two N atoms is much less successful than treating molecular oxygen as two

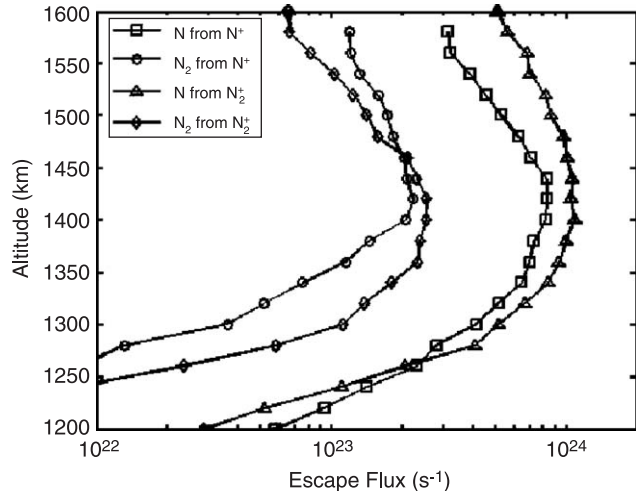


Fig. 2. Altitude distribution of the escaping particles. Line with squares shows the altitude at which the escaping N^+ particles originate in the atmosphere for incident atomic N ions. Similarly, line with circles represents the altitude at which the escaping N_2 is created in the atmosphere for incident N^+ . Lines with triangles and diamonds represent similar altitudes of escape of N and N_2 by incident N_2^+ .

oxygen atoms (Johnson et al., 2000). Further, the DSMC model describes the transport of energy better, which affects particle escape as described below.

The escape of atomic and molecular nitrogen was calculated by Michael et al. (2005). Fig. 2 shows the altitude from which the escaping particles originate. It is seen that most of the escaping molecular nitrogen are produced close to 1400 km, while the escaping atomic nitrogen shows a wider peak between 1350 and 1500 km. Fig. 2 indicates that the escaping particles are produced close to the exobase so that an accurate description of the energy deposition at these altitudes is crucial in the study of sputtering.

4. Temperature profile

Lammer et al. (1998) calculated the temperature structure of the upper atmosphere (700–1700 km) due to the heating by the undeflected corotating N^+ ions. They incorrectly fixed the temperatures at both the lower boundary (700 km) and the upper boundary (1700 km) to be 158 and 196 K, respectively. They found a temperature increase of up to 30 K at about 1100 and then decreased with altitude up to the upper boundary. Shematovich et al. (2001) suggested that the model of Lammer et al. (1998) was incorrect and also found that their estimate of escape was too large.

As an ion enters the atmosphere it generates a cascade of collisions with the atmospheric neutrals. In each collision the incident ion loses a part of its energy to the atmospheric neutral. Thus hot, non-thermal particles are produced in the atmosphere, which eventually transfer their energy to other background particles. The average temperature of the atmosphere increases in response to the energy

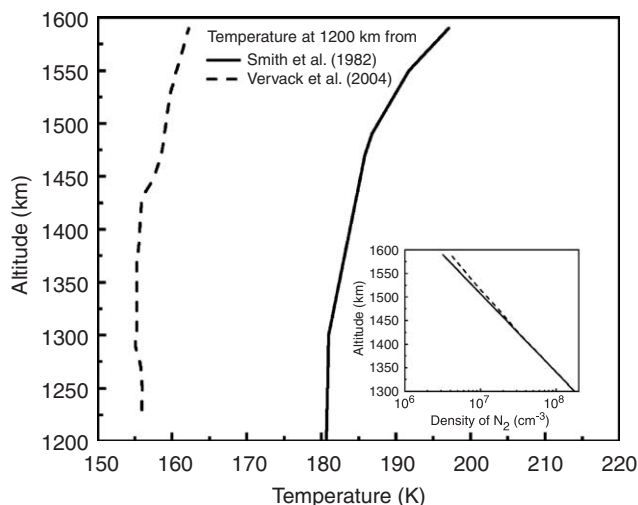


Fig. 3. The temperature profile of the upper atmosphere of Titan due to incident atomic and molecular nitrogen ions as discussed in text. The thermospheric temperature at the lower boundary (1000 km) was fixed at 180 K (Smith et al., 1982) (solid line) and at 155 K (Vervack et al., 2004) (dashed line). The figure in the inset presents the neutral density of N_2 (solid line) and the enhancement in the density of N_2 due to plasma heating represented as the dashed line.

deposition and removal, which are both described in the DSMC simulation. Removal of energy occurs both by atmospheric sputtering and by collisional transport to the dense atmosphere at the lower boundary. Fig. 3 presents the temperature structure of Titan's upper atmosphere due to heating by the globally averaged flux of magnetospheric nitrogen ions and molecular pickup ions. The temperature is fixed at our lower boundary to account for the heating at altitudes lower than that considered here. The temperature at the lower boundary is first chosen to be 180 K as discussed earlier. The temperature change between 1000 and 1200 km is seen to be very small due to the increased density and heat transport. Close to the exobase (1500 km) the temperature increases a few degrees due to the incident plasma. Above the exobase we still assign a temperature to the mean kinetic energy of the neutrals in the non-thermal corona. It is seen that the energetic neutrals, some on escape trajectories, exhibit a sharply increasing mean energy for coronal molecules. However, the temperature in the region just below the exobase is only a few degrees higher than that at 1000 km contrary to the conclusions of Lammer et al. (1998). That is, even though the energy deposition by the slowed and deflected N^+ and the molecular pickup ions is substantially more than that assumed by Lammer et al. (1998), the temperature increase near the exobase is only a few degrees due to the loss of energy by escaping neutrals and collisional transport to depths where the atmospheric density is larger. The latter, of course, depends critically on the description of the N_2 - N_2 collisions. The simulations were then repeated by fixing the temperature at the lower boundary at 155 K according to Vervack et al. (2004), which is closer to the

temperature extracted from recent Cassini data for Titan's upper atmosphere (Waite et al., 2005). An increase in temperature of ~ 4 K was observed at the exobase. Thus the globally averaged effect of the plasma does not change significantly in going from a 180 to 155 K thermosphere.

In the inset of Fig. 3, the enhancement in the neutral density due to the plasma heating is presented. The solid line represents the thermal background density and the dashed line the calculated density. At 1600 km an increase of ~ 1.3 times the extrapolated density is obtained. A comparison is in progress with the enhancements seen by the Cassini/INMS instrument (Waite et al., 2005) with our model being extended to higher altitudes.

5. Summary

The energy deposition, escape of atomic and molecular nitrogen and the heating of the Titan's upper atmosphere are interconnected and are studied here using a Direct Simulation Monte Carlo model of the atmosphere near the exobase. This model correctly describes the energy deposition, collisional dissociation, and the transport and escape of the struck atmospheric molecules. In a number of earlier papers it was assumed that solar radiation is the most important source of heating in Titan's thermosphere. Here we show that the pickup ions deposit more energy near the exobase than solar radiation. Sputter escape occurs close to the exobase where the molecular pickup ions deposit most of their energy. Therefore, it is important to correctly describe the spatial distribution of the deposition of energy at these altitudes. The temperature profile is calculated for the upper atmosphere of Titan assuming a steady, average flux of N^+ and N_2^+ ions. The maximum temperature increase near the exobase over that for solar heating alone was found to be ~ 4 – 7 K depending on the temperature assumed at depth. This increase over the temperature at 1200 km, where the IR cooling occurs, is much smaller than that suggested earlier (Lammer et al., 1998). A more accurate estimate of the plasma ion-induced heating is obtained because we use a DSMC calculation in which we track all the particles and, therefore, include the energy carried off by escape and that deposited deeper into the atmosphere by energetic recoils. An enhancement in the density above the exobase is also seen. The globally averaged results given here can be scaled by the plasma energy deposition to obtain local estimates of the plasma heating and sputtering. Such scaling can be used to provide guidance in interpreting Cassini data. These simulations apply to regions directly impacted by ions incident from above the exobase. In addition, neutrals from the cascade of collision or ions picked up close to the exobase can cause enhanced sputtering as they exit the atmosphere in the wake regions (Michael et al., 2005). Therefore, new values of the pickup ion flux from Cassini will be used in a 3-D calculation of atmosphere near the exobase.

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