Submitted to Planetary & Space Sci. on 13 Nov. 2004

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

M. Michael*, R.E. Johnson
Materials Science and Engineering, University of Virginia, Charlottesville, VA 22904 USA

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 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 pick-up ions more energy is deposited closer to the exobase than assumed in earlier plasma ion heating calculations, however, the temperature at the exobase is only a few degrees larger than it is at depth.

Keywords: Titan, Satellites of Saturn, Magnetospheres, Ionospheres, Heating

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 20.3 Rs, where Rs 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. Here we described the heating of the upper atmosphere by the impact of magnetospheric ions and pick-up 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., 2004; 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 generate a neutral torus (Lellouch et al., 1990; Yelle, 1991; Fox and Yelle, 1997; Lammer et al., 1998; Michael et al., 2004; Smith et al., 2004). In addition, the energy deposited below the exobase provides a heat source that can in principal cause an increase in the exobase temperature and an expansion of the atmosphere (Johnson, 1990).

Brecht et al. (2000) used their hybrid, semi-kinetic model to study the interaction of magnetospheric plasma with Titan. 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 represent the possible pick-up ions. Others have suggested that the dominant heavy pick-up ions are N_2^+ or $HCNH^+$ (Hartle et al., 1982). Since all these heavy molecular ions have similar masses we treat them as N_2^+. Therefore, in the present study the fluxes of N^+ and N_2^+ are estimated from Brecht et al. (2000). 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. (2004) 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 profile in the exobase region accounting also for the sputter removal of energy.

Simulation

A 3-D Direct Simulation Monte Carlo (DSMC) model developed to study sputtering of Titan's atmosphere is discussed in Michael et al. (2004). To study 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. 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 very long. Therefore, we used a 1-D model to describe atmospheric heating tracking all of the representative atmospheric particles, whereas in Michael et al. (2004) 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 atmospheric heating can be studied using a 1-D globally symmetric atmosphere and a globally averaged incident flux.

Test particles are followed from 1600 km to about 1000 km above the surface of Titan using the algorithm of Bird (1994). The number density and temperature of N_2 at the lower boundary are fixed at $8x10^9$ cm^{-3} and at either 180 K (Smith et al. 1982, Keller et al. 1998) or at 155 K (Vervack et al. 2004). Test particles are followed from 1600 km to about 1000 km above the surface of Titan using the algorithm of Bird (1994). 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 ($1.1x10^7$ N^+ cm-^{2} s^{-1}) have energies less than 750 eV and the representative molecular pickup ions ($1.4x10^7$ N_2^+ cm^{-2} 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., 2004). Therefore, there are regions where the flux can be larger or smaller than the average incident ions flux used here. The collision cross section and the model atmosphere used in the present study are discussed in Michael et al. (2004).

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 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.

Figure 1 presents the energy deposition of the slowed and deflected magnetospheric N^+ ions and the molecular pick up 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 Figure 1. Since the photons are primarily absorbed deeper into the atmosphere, it is clear that in the region of interest the pick up ions deposit more energy than photons. The energy deposited by the pick up 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 Figure 1 we also compare these results to an estimate 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 results 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 km to 1000 km and the rest of the energy is used to penetrate further the atmosphere. The deposition near the exobase is reasonably well described by this simple method but not at depth.

The escape of atomic and molecular nitrogen was calculated by Michael et al., (2004). Figure 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. Figure 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.

Temperature Profile

Figure 3 presents the temperature structure of Titan's upper atmosphere due to heating by the incident magnetospheric nitrogen ions and molecular pick up ions. The temperature is fixed at 180 K or 155K at our lower boundary to account for the heating at lower altitudes than that considered here. As seen in Figure 3 the temperature change between 1000-1200 km is 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 even though collisions are unlikely. 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 critical 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 pick-up ions is substantially more than that assumed by Lammer et al. (1998), the temperature near the exobase is only a few degrees higher than that much deeper into the atmosphere. This conclusion does not change in going from a 155 K to 180 K thermosphere.

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 K 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.

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 pick up ions deposit more energy near the exobase than solar radiation. Sputter escape occurs close to the exobase where the molecular pick up 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 of the upper atmosphere of Titan is also calculated for the incident N^+ and N_2^+ ions. The maximum temperature increase near the exobase over that for solar heating alone was found to be only ~ 4-7K 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. New values of the pick-up ion flux will be included when available from Cassini.

Acknowledgements: This work is supported by NASA's Planetary Atmospheres Program and by a travel grant from the NSF International program.

References

Bird, G.A., 1994. DSMC Procedures in a homogenous gas. In: Molecular gas dynamics and the direct simulation of gas flows, Clarendon Press, Oxford, England, 218-256.

Brecht, S.H., Luhmann, J.G., Larson, D.J., 2000. Simulation of the Saturnian magnetospheric interaction with Titan. J. Geophys. Res., 105, 13119-13130.

Fox, J.L., Yelle, R.V., 1997. Hydrocarbon ions in the ionosphere of Titan. Geophys. Res. Lett., 24, 2179-2182.

Friedson, A.J., Yung, Y.L., 1984. The thermosphere of Titan. J. Geophys. Res., 89, 85-90.

Hartle, R.E., Sittler, E.C., Ogilvie, K.W., Scudder, J.D., Lazarus, A.J., Atreya, S.K., 1982. Titan's ion exosphere observed from Voyager 1. J. Geophys. Res., 87, 1383-1394.

Johnson, R.E., 1990. Energetic charged particle bombarded at atmospheres and surfaces. Springer-Verlag, New York.

Keller, C.N., Anicich, V.G., Cravens, T.E., 1998. Model of Titan's ionosphere with detailed hydrocarbon ion chemistry. Planet. Space Sci., 46, 1157-1174.

Lammer, H., Stumptner, W., Bauer, S.J., 1998. Dynamic escape of H from Titan as consequence of sputtering induced heating. Planet. Space Sci., 46, 1207-1213.

Ledvina, S.A., Brecht, S.H., Luhmann, J.G., 2004. Ion distributions of 14 amu pickup ions associated with Titan's plasma interaction. Geophys. Res. Lett., 31, L17S10, 10.1029/2004GL019861.

Lellouch, E., Hunten, D.M., Kockarts, G., Coustenis, A., 1990. Titan's thermosphere profile. Icarus, 83, 308-324.

Lindal, G.F., Wood, G.E., Holz, H.B., Sweetnam, D.N., Eshleman, V.R., Tyler, G.L., 1983. The atmosphere of Titan: An analysis of the Voyager 1 radio-occultation measurements. Icarus, 53, 348-363.

Luna, H., Michael, M., Shah, M.B., Johnson, R.E., Latimer, C.J., McConkey, J.W., 2003. Dissociation of N_2 in capture and ionization collisions with fast H^+ and N^+ ions and modeling of positive ion formation in the Titan atmosphere. J. Geophys. Res., 108, 5033, 10.1029/2002JE001950.

Michael, M., Johnson, R.E., Leblanc, F., Liu, M., Luhmann, J.G., Shematovich, V. I., 2004. Ejection of Nitrogen from Titan's Atmosphere by Magnetospheric Ions and Pick-up Ions. Icarus, In Press.

Nagy, A.F. and 8 colleagues, 2001. The interaction between the magnetosphere of Saturn and Titan's ionosphere. J. Geophys. Res., 106, 6151-6160.

Neubauer, F.M., Gurnett, D.A., Scudder, J.D., Hartle, R.E., 1984. Titan's magnetospheric interaction. In: Gehrels, T., Matthews, M.S. (Eds), Saturn. University of Arizona Press, Tucson, pp.760-787.

Shematovich, V.I., Tully, C., Johnson, R.E., 2001. Suprathermal nitrogen atoms and molecules in Titan's corona. Adv. Space Res., 27, 1875-1880.

Shematovich, V.I., Johnson, R.E., Michael, M., Luhmann, J.G., 2003. Nitrogen loss from Titan. J. Geophys. Res., 108, 5086, 10.1029/2003JE002096.

Sittler, E.C., Hartle, R.E., Viñas, A.F., Johnson, R.E., Smith, H.T., Mueller-Wodard, I., 2004. Titan interaction with Saturn's magnetosphere: Voyager 1 results revisited. J. Geophys. Res., submitted.

Smith, G.R., Strobel, D.F., Broadfoot, A.L., Sandel, B.R., Shemansky, D.E., J.B. Holberg, 1982. Titan's upper atmosphere: Composition and temperature from the EUV solar occultation results. J. Geophys. Res., 87, 1351-1359.

Smith, H.T., Johnson, R.E., Shematovich, V.I., 2004. Titan's atomic and molecular nitrogen tori. Geophys. Res. Lett., 31, L16804, 10.1029/2004GL020580.

Strobel, D.F., Summers, M.E., Zhu, X., 1992. Titan's upper atmosphere: structure and ultraviolet emissions. Icarus, 100, 542-526.

Vervack, R.J., Sandel, B.R., Strobel, D.F., 2004. New perspectives on Titan's upper atmosphere from a reanalysis of the Voyager 1 UVS solar occultations. Icarus, 170, 91-112.

Yelle, R.V., 1991. Non-LTE models of Titan's upper atmosphere. Astrophys. J., 383, 380-400.

Ziegler, J.F., Biersack, J.P., Littmark, V., 1985. The stopping and Ranges of ions in solids. Pergamon, New York, 1985.

Figure Captions

Figure 1. Figure 2. Altitude distribution of the escape flux of N and N_2 by incident N^+ and N_2^+.

Figure 3. Temperature profile of Titan's upper atmosphere by the heating due to slowed and deflected magnetospheric N^+ and molecular pick up ions keeping the temperature at 180 K (Smith et al. 1982) (solid line) and at 155 K (Vervack et al. (2004) (dashed line).

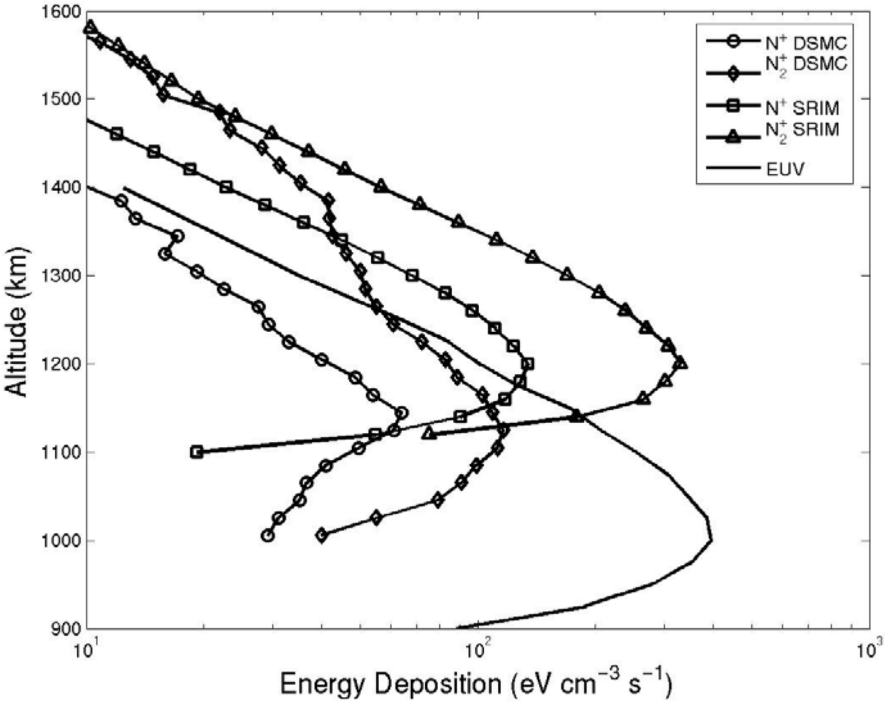

Figure 1 Energy deposition by the slowed and deflected magnetospheric N^+ ions and molecular pick up ions calculated using DSMC and SRIM methods, and by solar photons.

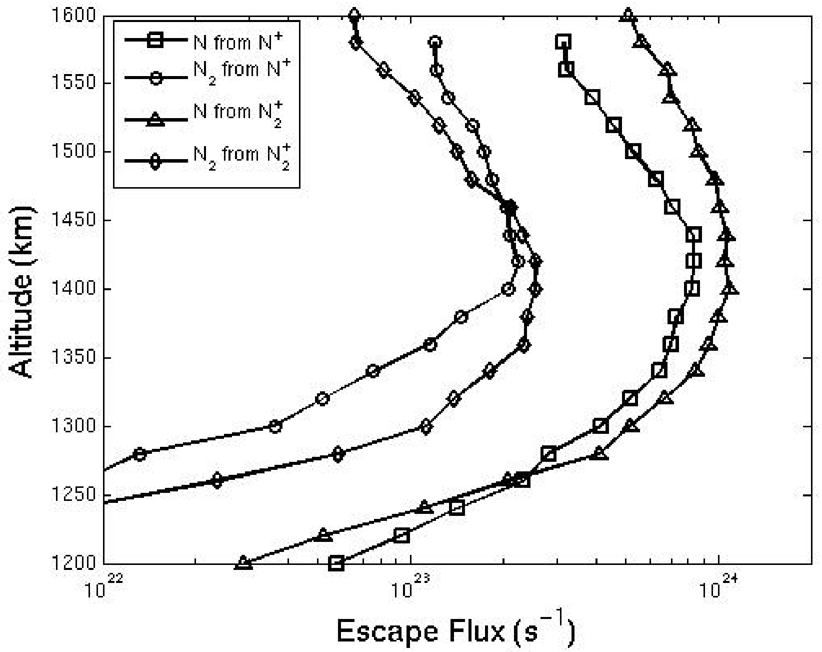

Figure 2 Altitude distribution of the escape flux of N and N_2 by incident N^+ and N_2^+.

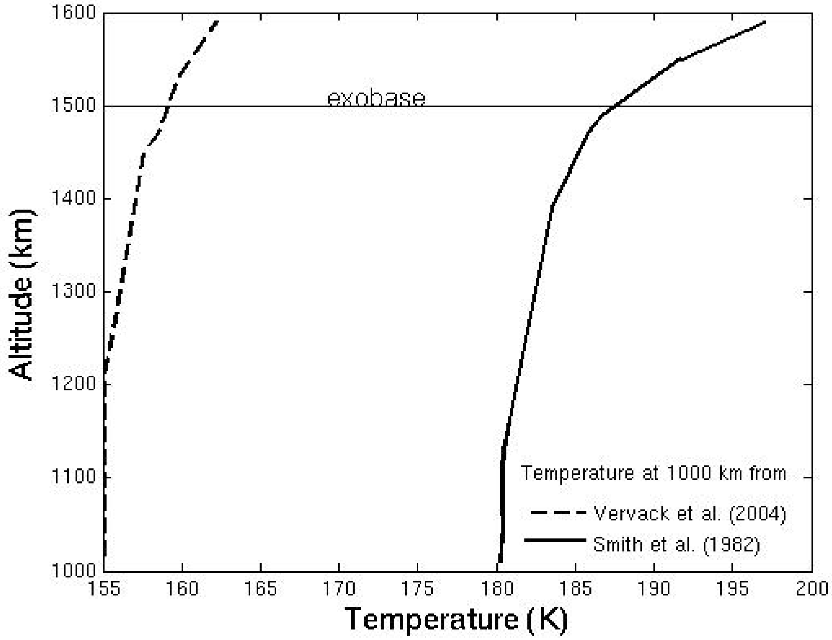

Figure 3 Temperature profile of Titan's upper atmosphere by the heating due to slowed and deflected magnetospheric N^+ and molecular pick up ions keeping the temperature at 180 K (Smith et al. 1982) (solid line) and at 155 K (Vervack et al. (2004) (dashed line).