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Exospheric heating by pickup ions at Titan

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Abstract

Titan has a very extensive atmosphere and exosphere which interact strongly with the corotating magnetospheric plasma. Some of the new pickup ions created in the vicinity of the exosphere will re-impact the upper atmosphere causing additional energy input. Previous investigations of the atmospheric collisional interaction of the pickup ions have generally assumed the atmosphere to be spherically symmetric. From the Voyager and Cassini observations, we know that the magnetic field configuration and plasma flow field is highly asymmetric. To study the possible spatial variation in the pickup ion influx, we have employed the plasma data of the three dimensional MHD simulation of Kopp and Ip [Kopp, A., Ip, W.-H. Asymmetric mass loading effect at Titan's ionosphere. J. Geophys. Res. 106, 8323–8332, 2001] to compute the trajectories of the pickup ions. In this work, we calculate the ion influx and energy deposit into Titan's exobase for the H_2^+, CH_4^+ and N_2^+ pickup ions separately. The model results of four different Titan's orbital locations are also presented.

Keywords: Titan; Exosphere; Pickup ions; Atmospheric sputtering; Exospheric heating

1. Introduction

As a planetary satellite, Titan is unique in the sense that it has a very substantial atmosphere. The surface pressure is ~1500 mbars and its chemical composition is mainly nitrogen with a small fraction of CH_4 (~2.7%) and other minor species (Waite et al., 2005). Because of its lack of an intrinsic magnetic field, Titan has direct atmospheric interaction with the Saturnian magnetosphere or the solar wind (Ness et al., 1982; Neubauer et al., 1984). Since the first in-situ measurements made by the Voyager 1 spacecraft, much effort has been spent on the detailed numerical investigations of the physical processes of Titan's plasma–atmosphere interaction (Luhmann, 1996; Ledvina and Cravens, 1998, 2005; Kabin et al., 1999, 2000; Kopp and Ip, 2001; Nagy et al., 2001; Ma et al., 2006). The issue of atmospheric sputtering is of particular interest. This is because the ejection of neutral atoms and molecules from the exobase will lead to the generation of an extended corona and the formation of a gas torus in circumplanetary space (Barbosa, 1987; Lammer and Bauer, 1993; Sittler et al., 2004; Smith et al., 2004; Michael et al., 2005). At the same time, the collisional interaction of the incoming energetic ions with Titan's upper atmosphere could lead to a significant level of heating. Some of these dynamical effects have been recently investigated by Ledvina and Cravens (2005), Michael and Johnson (2005), Michael et al. (2005), and Sillanpää et al. (2006). For example, Michael and Johnson (2005) used a Direct Simulation Monte Carlo (DSMC) method to study the energy deposit and heating of the upper atmosphere of Titan. They showed that the pickup ions can deposit more energy near the exobase than solar radiation. However, due to the loss of the energy by escaping neutrals and collisional transport to the lower atmosphere, the temperature increase near the exobase is only a few degrees. Such sputtering heating might be related to the enhancement of neutral density as observed by the Cassini INMS experiment (Waite et al., 2005). Ledvina

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and Cravens (2005) used the numerical output from a 3D single-fluid MHD model (Ledvina and Cravens, 1998) combined with a test particle/Monte Carlo model to study the distribution of the pickup ions in the vicinity of Titan. These authors found that Titan's exobase absorbs 1.4×10^{22} 1 amu ions per second, 5.6×10^{23} 14 amu ions per second, and 8.7×10^{23} 28 amu ions per second, respectively.

The many close encounters of the Cassini spacecraft with Titan will provide a wealth of information on the interaction of Titan's atmosphere with Saturn's magnetosphere. Hartle et al. (2006) analysed the data from the CAPS instrument obtained during the TA flyby. They found that many of the basic plasma features were similar to the results from the Voyager 1 encounter (Sittler et al., 2005). In particular, the atmospheric absorption pattern of the ambient O^+ ions displayed a certain asymmetry which might be caused by the finite gyroradius effect. It is important to note that under Titan's plasma conditions with an ambient magnetic field strength of 5 nT and a plasma flow speed of about 120 km s^{-1}, the gyroradius of a new N^+ ion is comparable to the size of Titan. This has important consequences. As a result of the orientation of the convective electric field the heavy pickup ions newly created in the Saturn-facing hemisphere will likely re-impact Titan's atmosphere. But those new pickup ions created in the opposite hemisphere will be carried away from Titan by the corotating plasma flow. As mentioned before, the exosphere could be subject to an additional heating effect because of the re-impacts of the pickup ions. The finite gyroradius effect would then produce an asymmetric energy deposit on Titan's exobase. In this work, we will report on the results obtained from a series of computer simulations with a view to study the asymmetric energy deposits from pickup ions under different plasma flow conditions. In Section 2, the 3D MHD model and the test particle code will be briefly described. In Section 3, the results for the situation of a uniform source distribution of pickup ions will be compared to those for Titan interactions at different orbital positions around Saturn. Finally, a general discussion and a summary will be given in Sections 4 and 5.

2. Model description: MHD model and test particle model

The numerical results of a 3D MHD simulation of the interaction between Titan and the Saturnian magnetosphere by Kopp and Ip (2001) are used in the present work. Kopp and Ip used a one-fluid model which was itself derived from the resistive MHD code developed by Otto (1990) and Kopp (1996) for the study of the magnetospheres of the Earth and Jupiter. In the Titan simulation, the local ambient magnetic field at Titan is the dipole field of Saturn with a strength of $B_0 = 5$ nT. The magnetospheric plasma is consisting of electrons and ions with an average mass unit = 10 (namely, a ratio of 2:1 for N^+:H^+ ions in the ion number density). The number density of the ions at upstream boundary is assumed to be $n_0 = 0.3$ cm^{-3}, the plasma temperature $T_0 = 2.0$ keV, and the ambient plasma flow speed is taken to be $v_0 = 120$ km s^{-1}. The plasma beta is $\beta = 9.7$, the Alfven Mach number $M_A = 1.9$ and the acoustic Mach number $M_s = 0.67$ in the numerical simulations. In the cylindrical coordinate system centered at Titan's center, the radial direction r (and x-direction in the rectilinear coordinate system) points from Saturn to Titan, the azimuthal angle ψ-direction (and y-direction) points along the corotating plasma flow direction, and z-direction is parallel to Saturn's rotational axis. More detailed information on the MHD simulation can be found in Kopp and Ip (2001).

In lieu of full-fledged kinetic models similar to those produced by Sillanpää et al. (2006), we could implement the simulation of the finite gyroradius effect by computing the ion trajectories according to a prescribed model description of the magnetic field and electric field distribution obtained by a MHD fluid model. This is the approach we have followed in this study. We have therefore computed many cases of the motions of test particles (or pickup ions) with the masses of ${H_2}^+$, ${CH_4}^+$, and ${N_2}^+$. The pickup ions are generated randomly within a spherical shell with an inner radius of 1.6 R_T (e.g., the exobase) and an outer radius of 2.6 R_T. Note that the weighting of the number of ions so generated is proportional to the neutral density at the source location which is described by an exponential function:

$$N(R) = N_0 \times \exp\left(\frac{1}{H}(R^{-1} - R_0^{-1})\right)$$

with H, the atmospheric scale height, given by $H = kT/mg$ where k is the Boltzmann's constant, g is the gravitational constant at radial distance R from the center of Titan, T is the temperature of the neutral atmosphere (which is assumed to be isothermal), and m is the mass of individual test particles. From the Cassini INMS observations (Waite et al., 2005), the neutral densities of H_2, CH_4, and N_2 at 1400 km altitude are 6×10^5 cm^{-3}, 3.0×10^6 cm^{-3}, and 3×10^7 cm^{-3}, respectively. The photoionization rates of H_2, CH_4 and N_2 are 5.9×10^{-10} s^{-1}, 3.9×10^{-9} s^{-1} and 3.9×10^{-9} s^{-1}, respectively (Huebner and Giguere, 1980).

All pickup ions were assumed to be at rest in the stationary frame of Titan. The trajectory of a pickup ion was calculated numerically by solving the equation of motion $m\frac{\mathrm{d}\underline{v}}{\mathrm{d}t} = q(\underline{E} + \underline{V} \times \underline{B})$ where m is the ion mass, q is the charge, v is the particle velocity, and E and B are the electric and magnetic fields. The magnetic field B could be obtained from an interpolation of the numerical data from the Kopp and Ip model and the electric field $E = -U \times B$ could be derived if the plasma velocity (U) in the MHD model is known. In short, we linearly interpolate the B and U values from the MHD simulation grids to the location of the ion. Note that we use the MHD simulation for the symmetrical mass loading case in our computations for five cases with different Saturn local times.

If an ion was found to impact the exobase of Titan, its trajectory calculation would be terminated with the corre-