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Ambient ion distributions in Saturn's magnetosphere near Titan during a non-Voyager type interaction

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Abstract

The interaction of Titan's ionosphere with the Saturn's magnetospheric plasma was found to be subsonic, superAlfvénic and submagnetosonic. However, the plasma conditions along Titan's orbit are highly variable [cf. J. Geophys. Res., 87 (1982) 881; Ph.D Dissertation, University of Michigan, Ann Arbor, 2001] resulting in a wide range of possible Mach numbers for the interaction. We consider the effect Titan would have on the ambient (or magnetospheric) ion population during a supermagnetosonic interaction, which might occur in the outer magnetosphere. The trajectories of several thousand ions in the vicinity of Titan are calculated using the fields from the output of a three-dimensional MHD model of Titan's plasma interaction. We have simulated the Voyager Plasma Spectrometer (PLS) response to the ambient ions using the determined ion trajectories. These results are compared with the Voyager distribution functions in order to illustrate how upstream conditions might affect the observed distributions, as will likely be observed during the Cassini mission Titan flybys.

Keywords: Saturn; Saturn's magnetosphere; Titan; Titan's ionosphere

1. Introduction

The plasma in Saturn's outer magnetosphere near Titan at the time of the Voyager encounter was found to be subsonic, super Alfvénic and submagnetosonic with respective Mach numbers of 0.57, 1.9 and 0.55. The ambient plasma contained both H^+ and N^+ with respective number densities of 0.1 and 0.2 cm^{-3}; and temperatures of 210 eV and 2.9 keV. Both species had a thermal speed of 200 km/s. The flow speed of the ambient plasma with respect to Titan ranged between 80–150 km/s. The magnetic field was directed nearly perpendicular to Titan's orbital plane with a magnitude of about 5 nT. The gyroradii of the incident H^+ and N^+ ions were relatively large compared to the size of Titan at 413 km and 5790 km (0.16 and 2.25 R_T) respectively. Voyager 1 passed through Titan's wake and found evidence that Saturn's magnetospheric plasma interacts directly with Titan's atmosphere and ionosphere rather than a strong intrinsic magnetic field. This observed plasma interaction is unique among non-magnetic bodies studied in the solar system (cf. Neubauer et al., 1984; Hartle et al., 1982 and references therein for further details).

Several models of Titan's interaction with its surrounding plasma environment have been developed, including one-dimensional single and multi-species hydrodynamic and magnetohydrodynamic (MHD) models (cf. Ip, 1990; Keller et al., 1994; Keller and Cravens, 1994), a two-dimensional quasi-multifluid MHD model with three generic ion species (Cravens et al., 1998), and a number of three-dimensional MHD models (cf. Ledvina and Cravens, 1998; Kabin et al., 1999, 2000; Nagy et al., 2001 and Kopp and Ip, 2001). Each of these models is a "fluid" model and is unable to account for finite ion gyroradii effects that are present at Titan.

Finite ion gyroradii effects have been addressed using test-particles and hybrid simulations. Luhmann (1996)

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illustrated the gyromotion of pick-up ions in the vicinity of Titan by calculating the trajectories of testparticles in a two-dimensional comet-like wake field structure. This paper suggested that the dips in the magnetic field strength observed just outside Titan's wake by Voyager might be accounted for by currents related to the collective motion of mass 28 amu pick-up ions. Ledvina et al. (2000) and Ledvina (2000) also examined ion trajectories near Titan; they traced testparticles in the output fields from a 3-D MHD simulation. The trajectories of the ambient ions were found to be unaffected by the presence of Titan unless they passed within about 2 Titan radii (2 R_T) or interacted with the wake structure. Ion trajectories within the simulated wake were found to be very complicated. Brecht et al. (2000) self-consistently accounted for finite ion gyroradii effects in their hybrid (kinetic ions, fluid electrons) simulation of Titan's interaction with Saturn's magnetospheric plasma. They found that the offset of the wake direction with respect to the incident plasma flow observed by Voyager is due in part of the finite gyroradii effects.

Detailed ion distributions near Titan were recently studied by Ledvina (2000) and Ledvina et al. (2004b). They combined the output from a MHD simulation with a testparticle (or Monte Carlo) model of the ion motion. Velocity Space distributions were examined for both ambient (magnetospheric), and pickup ion both upstream and in Titan's wake. Ledvina et al. (2004b) also considered the possibility that the ambient N^+ distribution may be a drifting shell rather than a drifting Maxwellian distribution. The combined MHD/testparticle approach has been used before to study plasma interactions with many non-magnetic bodies (cf. Ledvina et al., 2004b and references therein). The main drawback to this approach is that the ion trajectories and the fields are not calculated self-consistently as they are in the hybrid approach.

Titan's plasma environment is highly variable. The local variations within Saturn's magnetosphere can lead to very different plasma conditions along Titan's orbit. The magnetosonic Mach numbers of the incident plasma could range from a low value of 0.02 (Wolf and Neubauer, 1982) to a value of 2.0 (Hansen, 2001). In addition there is a chance that Titan's orbit may take it into Saturn's magnetosheath or even out into the solar wind depending on the solar wind conditions. Most of the detailed models of Titan's interaction with its plasma environment to date have focused on the upstream Voyager conditions (though Ledvina and Cravens, 1998 and Hansen, 2001 have examined supermagnetosonic examples and Ledvina et al. (2004a) have examined the induced magnetosphere for a large range of incident parameters).

In this study we examine the effect Titan has on the ambient magnetospheric ion distributions during a supermagnetosonic interaction by using the same combined MHD/testparticle approach used by Ledvina et al. (2000, 2004b). This type of interaction is likely to occur when Titan is in Saturn's outer magnetosphere or within the magnetosheath (cf. Wolf and Neubauer, 1982; Hansen, 2001). The recent MHD simulations by Hansen (2001) suggest that this may be the situation most likely to be encountered during a Cassini Orbiter flyby. We generate simulated PLS responses to the ambient ions in the magnetosphere and in the wake and compare the results with the Voyager observations in order to show the contrast that might have been seen had Voyager had many flybys.

2. Description of the models

2.1. The MHD simulation

The MHD model used in this study is an improved version of the single fluid (N^+) MHD model of Ledvina and Cravens (1998). The model includes ion-production and hence mass loading, dissociative recombination, ion neutral friction, gravity and electron pressure contributions. Ion production rates, neutral densities, and electron temperatures are adopted from Cravens et al. (1998). The dissociative recombination rate varies from 10^{-7} cm^3 s^{-1} in Saturn's magnetosphere to 10^{-6} cm^3 s^{-1} in Titan's ionosphere. An ion-neutral collision coefficient of 10^{-9} cm^3 s^{-1} was used. The coordinate system is essentially the same as in Ledvina and Cravens (1998). The grid is Titan centered and extends a distance of 25,000 km along each axis. The incident plasma flows along the x-axis. Saturn's unperturbed magnetic field is anti-parallel to the z-axis. The motional electric field points away from Saturn and is anti-parallel to the y-axis. We used 150 non-uniformly spaced zones along each axis, with a ratio between neighboring zones dimensions of 1.02. The zone sizes range from 146 km near the origin to 631 km at the edge of the computational domain. Our upstream plasma conditions are similar to the case II in Ledvina and Cravens (1998), though our incident plasma temperature is lower. The resulting magnetosonic Mach number is 1.5, consistent with the upper limit of both Wolf and Neubauer (1982) and Hansen (2001). Table 1 summarizes the characteristic interaction parameters.

2.2. The testparticle model

The single-fluid used in the MHD simulations was assumed to be N^+ at 100 eV. We apply the Voyager PLS results (Hartle et al., 1982) to our test particle simulations and assume that the upstream ion distributions are drifting Maxwellian's with a drift speed of 120 km/s, and that both species have the same thermal velocity . The corresponding thermal speed of the 100 eV N^+ (and

Table 1
Incident plasma conditions derived from the Voyager observations near Titan (Neubauer et al., 1984) and those used in the MHD simulation

	Voyager	MHD
Flow speed (km/s)	80–150	120
Number density, species (cm^{-3})	0.1 (H^+) 0.2 (N^+)	0.2 (N^+)
Magnetic field (nT)	5	5.1
Temperature (eV)	210 (H^+) 2900 (N^+)	100
Plasma beta	11.1	0.31
Sonic speed (km/s)	210	42
Alfvén speed (km/s)	64	67
Sonic Mach number	0.57	2.9
Alfvénic Mach number	1.9	1.8
Magnetosonic Mach number	0.55	1.5

hence the H^+) is 37 km/s. The ambient H^+ temperature is 7 eV.

The test particle code is essentially the same as that previously used to investigate ion trajectories and distribution functions near comets, Mars, Pluto and Titan (see Ledvina et al., 2004b and references therein). The trajectories of 4.4×10^5 ions (2.2×10^5 for each species) were calculated in the vicinity of Titan using the steady-state MHD model output for the required electric and magnetic fields (see Ledvina et al., 2004a,b and Ledvina, 2000; for further details). We only examine ambient ions (ions present in Saturn's magnetosphere) in this study. Ambient ions are injected into the computational domain, both upstream and on the sides, according to a drifting Maxwellian distribution, with the properties listed above. The trajectory of each ion was determined numerically by solving the equation of motion with the Lorentz force based on the fields calculated in the 3-D MHD simulation. Ions are sampled as their trajectories cross several sampling planes (each with dimensions of $2\ R_T \times 2\ R_T$) located throughout the simulation domain (see Fig. 1). We simulate the PLS instrument on the Voyager spacecraft by calculating the angle from the look direction of each Faraday cup, that each ion makes as it crosses the sampling planes. If this angle is less than 75° than the ion was used to calculate the distribution function. The distribution function in each energy bin was calculated in the same fashion as the results of Hartle et al. (1982) and outlined in Bridge et al. (1977). The look directions of each Faraday cup were taken from Hartle et al. (1982); the D-cup is aimed upstream anti-parallel to the incident flow. The look directions of the remaining cups (A, B and C) are 20° from the spacecraft normal (parallel to the upstream motional electric field) and 60° from each other. In this case we do not separate the species but consider only the energy/charge. Further discussion of the Voyager PLS instrument and its orientation during the Titan encounter can be found in Bridge et al. (1977) and Hartle et al. (1982).

3. Results

The magnetic field strength from the MHD model is shown in Fig. 2. A bow shock is present with a standoff distance of about 4.5 R_T. The plasma upstream of the shock is unaffected by the presence of Titan. The flow speed of the magnetospheric plasma drops from 120 km/s to about 80 km/s as it crosses the shock and diverts around Titan. The wake field fluctuations shown in the xy-plane are a result of viscous flow around Titan (see discussion in Ledvina et al., 2004a,b). The magnetic field piles up as the plasma speed drops and forms a magnetic barrier upstream of Titan with peak field strength of about 18 nT. A slight increase in the field strength across

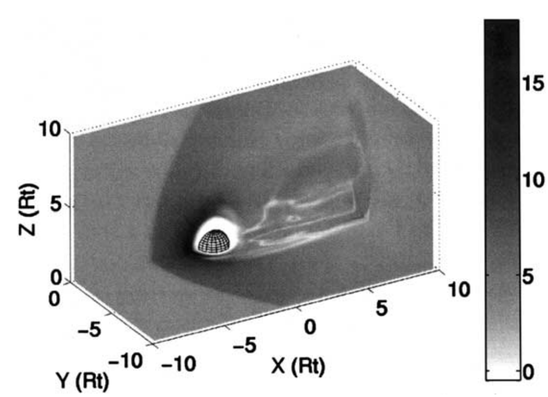

Fig. 2. Magnetic field strength (in nT) from the MHD model. The incident plasma flow is parallel to the x-axis. The magnetic field is antiparallel to the z-axis. The motional electric field points away from Saturn along the negative y-axis.

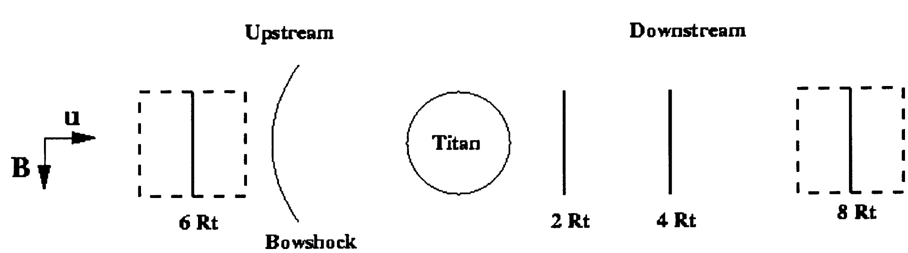

Fig. 1. The location along the x-axis of each of the $2\ R_T \times 2\ R_T$ sampling planes and the bow shock. The motional electric field points out of the page. The dashed planes are perpendicular to the motional electric field.

the shock is also present. Sample trajectories of an ambient H^+ and N^+ ion are shown in Fig. 3. The gyroradii of the H^+ ions is noticeably smaller than the gyroradii of the N^+ ions. The relatively small gyroradii of the ambient H^+ implies that they should behave in a "fluid-like" manner. For this species an MHD description is not a bad approximation. The gyroradii of the N^+ ions is considerably larger and hence MHD is not the best description of their bulk motion near Titan. Each of the ions is sharply deflected away from Titan by the shock.

Distribution functions from the simulated PLS instrument upstream of the shock are shown in Fig. 4. The distributions in the D-cup show two peaks near 70 and

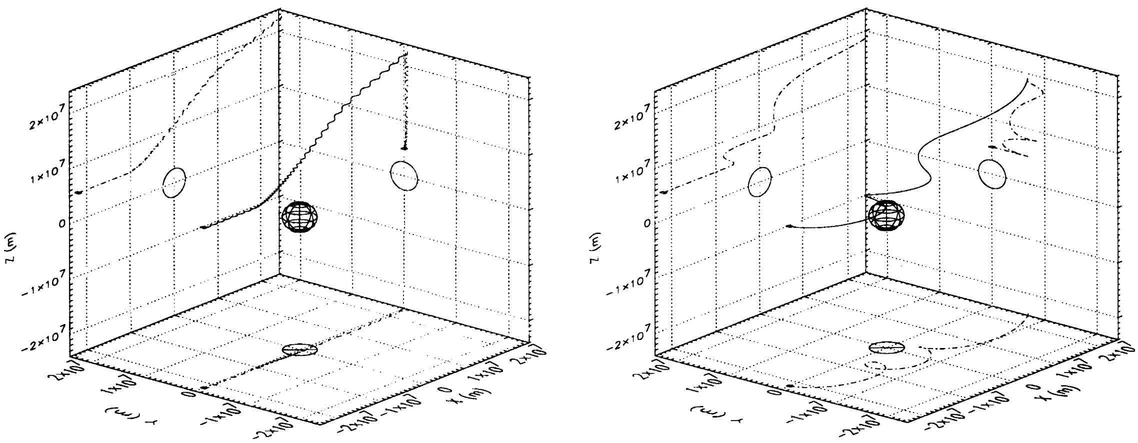

Fig. 3. Sample trajectories of a ambient H^+ ion (left) and a N^+ ion (right) are shown. The ambient ions are deflected away from Titan as they cross the bow shock.

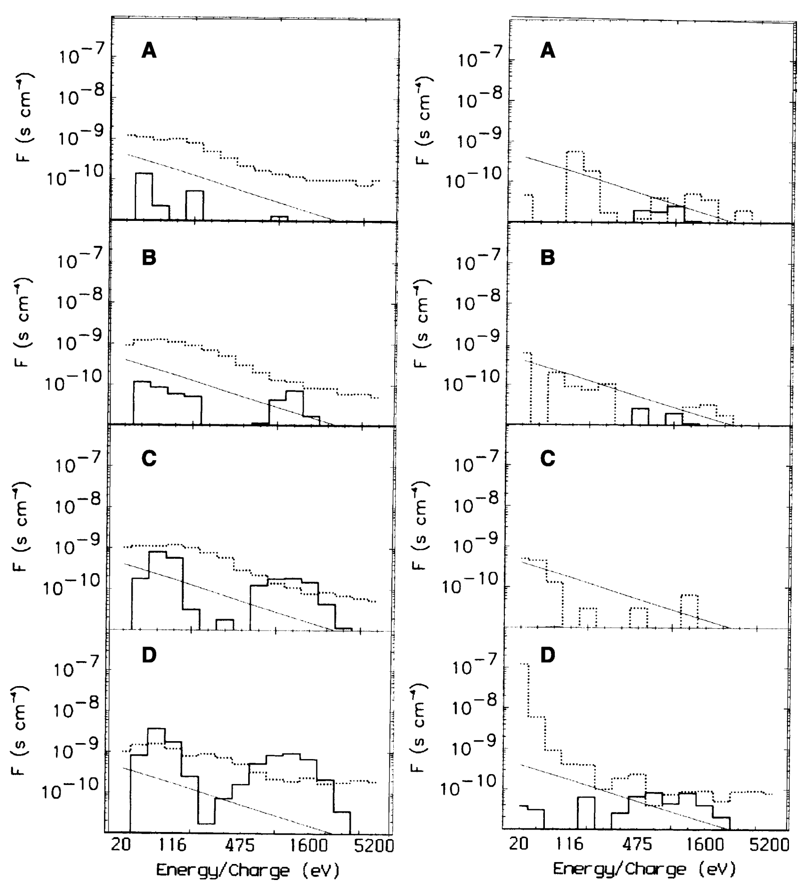

Fig. 4. Distribution functions vs. energy/charge for the ions sampled in each Faraday cup (A, B, C and D) at 6 R_T upstream (left) and 8 R_T downstream (right) of Titan. Averaged Voyager results for the magnetosphere (left) and the wake region near 2.7 R_T (right) are represented by the dotted histogram. The slanted line is the rms noise level of the PLS instrument.

1200 eV. These are the peaks of the drifting Maxwellian distributions for the H^+ and N^+ respectively. the low thermal speed of each ion species keeps the distributions separate from one another in the PLS response. This was not the case during the Voyager encounter at Titan, (dotted histogram) where the high thermal speeds mix the PLS response for each species. The strength of the distributions in the D-cup is due to the drift velocity of the distribution. This drift velocity effect is echoed in the C-cup, which has a significant component of its look direction pointing into the ambient plasma flow. However, the A and B cups have look directions that are more perpendicular to the ambient flows. Hence, the ion flux into these cups is reduced.

The bow shock present in the model is highly effective at deflecting the ambient ions out of the wake region. Not a single ion crossed the sampling planes centered at 2 and 4 R_T downstream of Titan. This is in contrast to the Voyager interaction examined by Ledvina et al. (2004b). They found that the large ion gyroradii of the N^+ would sweep around Titan and its induced magnetosphere. The study found that in the wake at 4 R_T downstream of Titan 46 % of the upstream ambient N^+ ion flux was present. Fig. 4 also shows the simulated PLS response to the ambient ions that are sampled at 8 R_T downstream of Titan (solid histogram) and the averaged PLS measurements made just inside the wake region around 2.7 R_T by Voyager. The large low energy response in the PLS D-cup is due to pick-up ions, which we do not study here. The simulated response was below the RMS noise level of the instrument in the A, B and C cups. The simulated D cup response is a result of the ambient N^+ ions and is about the same level (within a factor of 2) as the Voyager observations for energies ranging between 475 and 1600 eV.

4. Conclusions

We used a combined MHD/testparticle simulation to investigate the effect Titan has on Saturn's ambient magnetospheric ions during a supermagnetosonic interaction. We assumed that the magnetospheric plasma was composed of drifting Maxwellian H^+ and N^+, with densities and drift velocities representative of the Voyager encounter. It is easy to distinguish the resulting ion distribution functions for each species in the flow direction. However, the simulated response of the PLS instrument to ions with motions perpendicular to the flow is much weaker. We found that the ion trajectories were unaltered by the presence of Titan until they crossed the bow shock. The bow shock deflected the ambient ions away from Titan, resulting in a near wake region devoid of magnetospheric ions.

This work implies that the source of the ion population in Titan's wake is sensitive to the characteristics of the interaction. It also illustrates the need to use simulations to examine Titan's interaction for several different incident plasma conditions in order to better understand the observations. The PLS instrument was limited in many respects (such as energy resolution). The Cassini Plasma Spectrometer (CAPS) instrument onboard the Cassini spacecraft will provide important information about the plasma environment near Titan. Results from numerical simulations should be used to help plan the Cassini mission, predict instrument responses and interpret the anticipated data. Data collected by the Cassini mission together with numerical simulations will provide further insight on the interaction between Titan and its surrounding plasma environment.

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