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ION TRAJECTORIES IN SATURN'S MAGNETOSPHERE NEAR TITAN

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ABSTRACT

We numerically determine the trajectories of several ions in the vicinity of Titan using for the required electric and magnetic fields the output from a three-dimensional magnetohydrodynamic model of Titan. These trajectories are analyzed to provide insight into the external plasma interaction with that satellite as well as to make predictions for the Cassini Orbiter particle experiments (Young *et al.*, 1998).

INTRODUCTION

The plasma in Saturn's outer magnetosphere partially co-rotates with the planet and encounters Titan at a relative velocity of about 120 km/s (Neubauer *et al.*, 1984). This interaction was found to be subsonic yet super Alfvénic with sonic and Alfvénic mach numbers of $M_s = 0.57$ and $M_A = 1.9$, respectively, and a magnetosonic mach number of $M_f = 0.55$ (Neubauer *et al.*, 1984). The plasma flow in the vicinity of Titan is mass-loaded due to the ionization of neutrals associated with that satellite. The plasma analyzer on the Voyager 1 spacecraft detected H^+ and N^+ ions in the near-Titan wake with temperatures of about 200 eV and 2.9 keV, and number densities of 0.1 cm^{-3} and 0.2 cm^{-3}, respectively (Hartle *et al.*, 1982). While the source of these ions is not completely understood, it has been suggested that they may be remnants from a previous Titan encounter (see Schardt *et al.* (1984), Eviatar *et al.* (1982)). These ions will have gyroradii comparable to Titan's size (Luhmann, 1996), which has interesting consequences for the plasma interaction with that body. The gyroradii of thermal H^+ and N^+ in the outer magnetosphere were found to be 413 km (0.16 R_T) and 5790 km (2.25 R_T), respectively (Neubauer *et al.*, 1984). The magnetic field in the outer magnetosphere measured by Voyager was about 5 nT and approximately perpendicular to Titan's orbital plane. Voyager traversed Titan's wake at a distance of about 2.7 R_T and found evidence of an induced bipolar magnetic tail. This tail is associated with the draping of magnetic field lines in Saturn's magnetosphere around Titan. The wake was found to be narrow, measuring between 1-2 R_T. Voyager found no evidence of a strong intrinsic magnetic field at Titan (see Neubauer *et al.* (1984), Hartle *et al.* (1982), and Ness *et al.* (1982)).

These plasma conditions make the interaction between Titan and Saturn's magnetospheric plasma unique. Other plasma interactions with non-magnetic bodies (for example, comets, Venus, and Mars) are either supersonic and super-magnetosonic, or, in the case of Io and Jupiter's magnetospheric plasma, subsonic and subalfvénic. Titan's plasma interaction has been studied using one-dimensional (Ip, 1990; Keller *et al.*, 1994), two-dimensional (Cravens *et al.*, 1998), and three-dimensional (Ledvina and Cravens, 1998) magnetohydrodynamic (MHD) models. These fluid models cannot account for effects associated with the large gyroradii of the ions. We examine these finite gyroradii effects using the three-dimensional MHD model of Ledvina and Cravens (1998) to provide the electric and magnetic fields necessary to solve the equation of motion and calculate the ion trajectories for various initial conditions.

THE THREE-DIMENSIONAL MHD MODEL

We use a 100 × 100 × 100 uniform grid version of the single fluid three-dimensional MHD model of Ledvina and Cravens (1998). A grid spacing of $\Delta x = \Delta y = \Delta z = 500$ km was used to cover a cubic domain extending from −25000 km to 25000 km along each axis. Titan is simulated by a spherical high density plasma region of radius 2575 km, with a number density maintained at 50 cm^{-3}. Ion production is present in a region surrounding Titan extending from the surface ($r = 1\ R_T$) out to a radius of 5150 km ($2\ R_T$). The ion production rate in this region was 0.02 $cm^{-3}\ s^{-1}$, with a total production rate of the model of $1.1 \times 10^{25}\ s^{-1}$. The incident plasma conditions are representative of the Voyager 1 data mentioned above. We used a molecular mass of 14 amu.

The results of the model showed a strong magnetic field draping pattern and a narrow wake with a width of 1-2 R_T at the location of the Voyager crossing (2.7 R_T), as illustrated in Figure 1. A set of Alfvén wings form further downstream due to the field draping. See Ledvina and Cravens (1998). The magnetic field is oriented about 60 degrees from the incident field direction within the Alfvén wings.

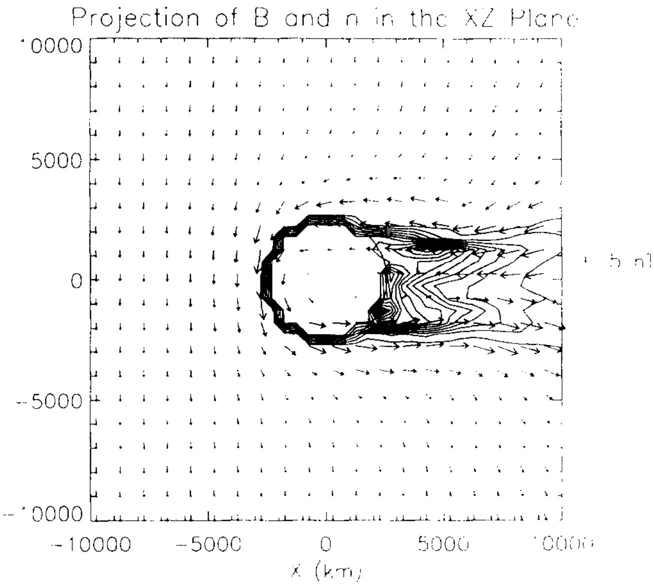


Fig. 1. Projected magnetic field vectors and density contours in the xz-plane from the three-dimensional MHD model. There are 20 density contour levels ranging from $n = 2.4$ cm^{-3} to $n = 48$ cm^{-3} with a spacing of 2.3 cm^{-3}. The magnetic barrier can be seen, as well as the draping of the magnetic field lines. The ambient magnetic field is in the $-z$ direction. The flow is in the x direction.

ION TRAJECTORY CALCULATIONS

The trajectory for each ion was found by numerically solving the equation of motion:

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1}$$

where m is the mass, q is the charge, **v** is the velocity of the ion, and **B** is the magnetic field from the MHD model. The electric field **E** was assumed to be the motional electric field.

We examined two categories of N^+ ions: ambient ions and pick-up ions. Ambient ions are the ions present in the upstream plasma flow and are started with a velocity of 200 km/s. Pick-up ions are created at rest, with a radial distance of 1.3 R_T at various locations around Titan (most of the ion production occurs below 2R_T; see Keller and Cravens (1994)). In addition, each category contained two subcategories, unperturbed plasma flow and perturbed flow. The unperturbed flow neglects the presence of Titan and has uniform fields. The perturbed flow uses the velocity field and the magnetic field from the MHD model.

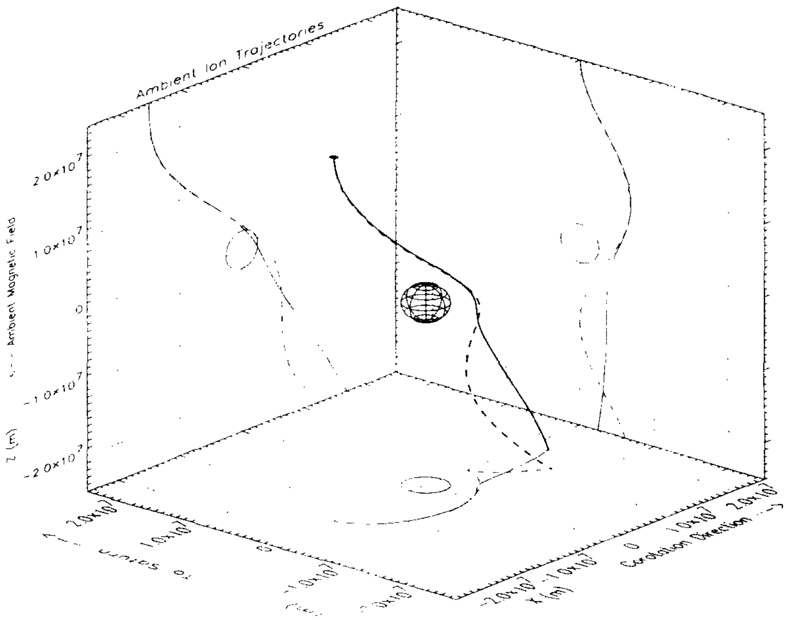
RESULTS -- ION TRAJECTORIES

Ambient Ions

Figure 2 shows the trajectories for an ion in both an unperturbed and a perturbed flow. Both trajectories start in the xy-plane at z = +25000 km. The trajectories are identical until the ion in the perturbed flow encounters Titan's wake structure. After the encounter with Titan's wake the ion follows an almost linear path until it leaves the computational domain at z = –25000 km. In this case the ion is moving roughly parallel to the draped magnetic field lines. This trajectory is within the magnetic barrier created by the Alfvén wings (see Ledvina and Cravens, 1998). This barrier acts as an obstacle to the plasma flow in the

MHD model, so the flow speed of the plasma within this region is quite low. This results in a small value for the electric field. For these reasons the Lorentz force on this ion is small for the last part of its trajectory. The unperturbed flow ion does not encounter a wake and continues to spiral along the uniform field lines.

Fig. 2. Ambient ion trajectories in both an unperturbed (dashed line) and a perturbed (solid line) flow. The square indicates the starting positions at z = +25000 km. The projection of each trajectory in the various planes is shown. The projection of the ion's trajectory in the unperturbed flow is represented by the thin dashed line. The thin solid line is the projection of the trajectory of the ion in the perturbed flow. Titan is represented by a sphere, which is projected onto each plane.



Pick-Up Ions

The trajectory for a pick-up ion created in the ram direction is shown in Figure 3. The ion moves within the slow flow region near Titan (see Ledvina and Cravens, 1998) until it exits this region in Titan's flank. Once leaving the slow flow region the ion's trajectory resembles the motion of the ion in the unperturbed flow region. The turning point of the ion in the perturbed flow occurs about 1.3 R_T farther downstream than the turning point of the ion in the unperturbed flow. The motion of the ion in the perturbed flow slightly deviates from the plane motion, unlike the motion of the ion in the unperturbed flow.

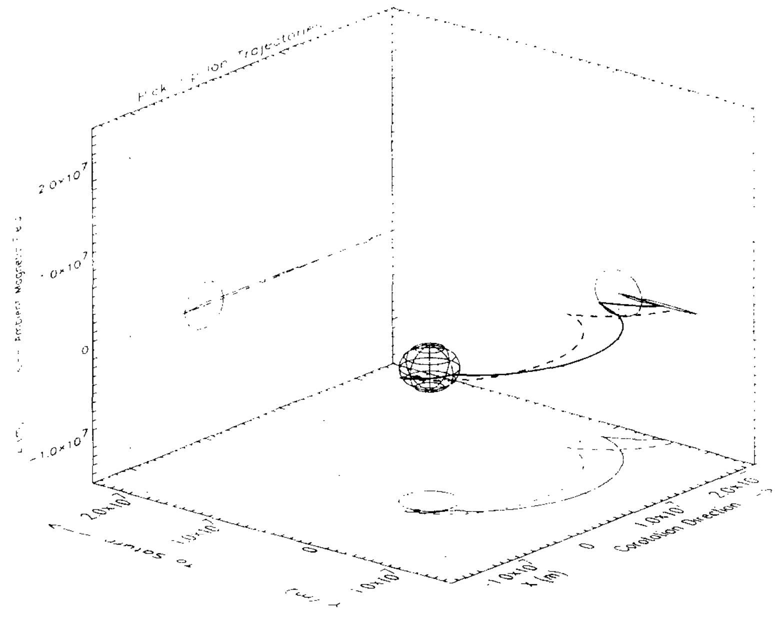


Fig. 3. Pick-up ions created at 1.3 R_T in the ram direction. Otherwise the same as Figure 2.

In the preceding plots (and in others not shown in this paper) the ion trajectories in the perturbed flow varied only slightly from ion trajectories in the unperturbed flow. Figure 4 shows a striking difference. The pick-up ion is born in the wake region, where the field configuration is drastically different from the case of the unperturbed uniform field. The pick-up ion tightly spirals around the draped magnetic field lines. At about $x = 1.8 \times 10^7$ m the ion reflects off a mirror point and returns to collide with Titan. In order to avoid confusion only the first half of this trajectory is shown. The ion in the unperturbed flow does not exhibit this behavior.

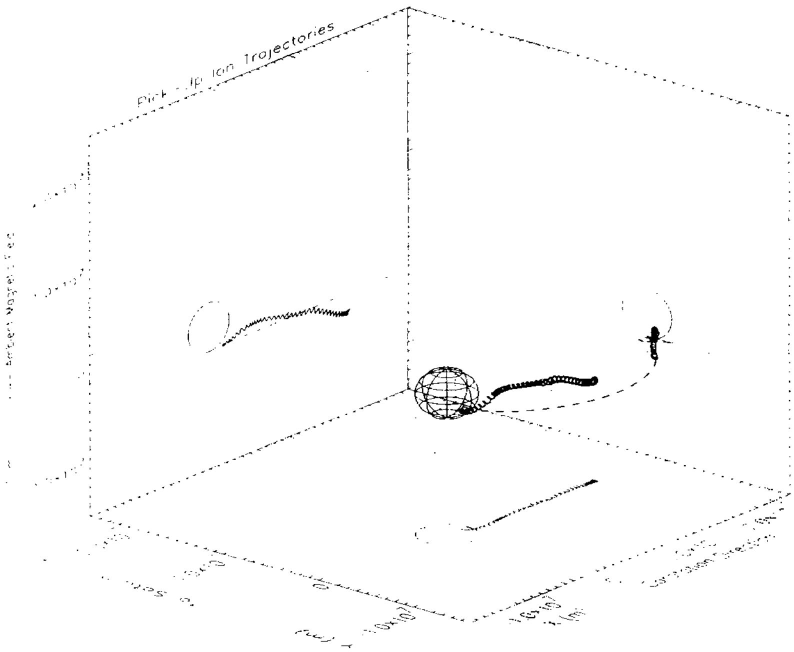


Fig. 4. Pick-up ions created in the wake just below the $x = 0$, $y = 0$ plane. Otherwise the same as Figure 2.

CONCLUSIONS

The effects Titan has on various ion trajectories are listed below.

1. The trajectories of the ambient ions are unaffected by the presence of Titan unless they pass within the magnetic barrier located between 1-2 R_T in the ram, flank or polar regions, or interact with Titan's wake structure. Outside this region the ion trajectories resemble the trajectories of ions in the unperturbed plasma flow with a uniform electric and magnetic field.
2. The gyroradii of pick-up ions are much smaller in the near-Titan region, due to the magnetic barrier, and in the wake structure than they are outside of these regions.
3. Once pick-up ions leave the near-Titan region, their trajectories resemble the trajectories of ambient ions in the outer region and the trajectories of ions in an unperturbed plasma flow.

In this work we have taken a look at how the trajectories of N^+ ions in Saturn's magnetosphere are affected by the presence of Titan. We have used the output from the three-dimensional model of Ledvina and Cravens (1998) to find the forces acting on the ion and solve the equation of motion (eq. 1) for the ion's trajectory. The results indicate that Titan has a minimal effect on the trajectories of the ambient ions. The trajectories of the pick-up ions in the perturbed flow differ significantly from pick-up ions in the unperturbed flow while the ions are within the near-Titan and wake regions. Future work will include a more realistic obstacle and higher spatial resolution MHD model. In addition, more work will be done on the statistics in order to further understand this plasma interaction and the roles of the ambient and pickup ions.

This work illustrates the need for self-consistent hybrid simulations, to better understand this interaction, due to the large gyroradii of ions in Saturn's magnetosphere. Ultimately the Cassini mission (Matson, 1992) is needed to collect data and provide further insight on the plasma interaction between Titan and Saturn's magnetosphere.

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