Titan in subsonic and supersonic flow

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[1] The Titan-Saturn plasma interaction is studied using a global numerical kinetic model. The developed self-consistent three-dimensional quasi-neutral hybrid model is used to study Titan's interaction with supersonic and subsonic plasma flow. The subsonic flow case represents Titan in the Kronian magnetosphere during the Voyager-1 flyby. The supersonic and weakly supermagnetosonic flow cases are used to study a disturbed magnetospheric plasma flow event. In both cases the magnetic field is found to pile up against Titan and forming a magnetotail on the wake side. The subsonic flow case does not produce a bow shock in front of Titan, in contrast to the supersonic case. The magnetic field is found to have a Saturn facing side-anti Saturn facing side asymmetry in both cases. The subsonic case resulted in a twisting of the magnetotail toward Saturn that is qualitatively in agreement with the magnetic field observations made by Voyager 1. *INDEX TERMS:* 2732 Magnetospheric Physics: Magnetosphere interactions with satellites and rings; 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 2753 Magnetospheric Physics: Numerical modeling; 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736). **Citation:** Kallio, E., I. Sillanpää, and P. Janhunen (2004), Titan in subsonic and supersonic flow, *Geophys. Res. Lett.*, *31*, L15703, doi:10.1029/2004GL020344.

1. Introduction

[2] Titan has a dense atmosphere but presumably no significant intrinsic magnetic field. The interaction between Titan and the nearby flowing plasma is therefore anticipated to result in many similar kinds of plasma physical processes that take place at Mars and Venus, such as deviation of the flow around the object due the ionospheric currents, deceleration of the plasma speed due to the newly formed ions from the exosphere and atmosphere, and escape of the ions.

[3] However, the Titan-plasma flow interaction is anticipated to contain several unique features which do not take place at Mars and Venus. First of all, the maximum photoionization rate is not necessarily found on the hemisphere that is facing against the co-rotating plasma flow [see, e.g., *Keller and Cravens*, 1994]. Another ionization mechanism that is importance at Titan, electron impact ionization, is different on the (ram) hemisphere that faces against the co-rotating flow than on the opposite (wake) hemisphere [see, e.g., *Keller et al.*, 1994; *Keller and Cravens*, 1994]. Consequently, from the ionization point of view one can identify four different hemispheres; the dayside, the nightside, the ram hemisphere and the wake hemisphere. Titan therefore meets a variety of different ionization cases during its 16 day revolution around Saturn.

[4] The second feature that has substantial plasma physical consequences is that Titan meets a subsonic and super-Alfvénic co-rotating Kronian plasma, as observed during the Voyager 1 flyby in 1980 [*Neubauer et al.*, 1988]. In such a case, no bow shock is expected to form around Titan, and, indeed, no bow shock was found near Titan from Voyager 1 data. This sets Titan apart from Mars and Venus, since the latter reside in supersonic and super-Alfvénic solar wind flow and thus do have bow shocks.

[5] Titan-Saturnian co-rotating plasma interaction has so far been studied by one-dimensional (1-D) [*Keller et al.*, 1994; *Keller and Cravens*, 1994], two-dimensional (2-D) [*Cravens et al.*, 1998] and three dimensional (3-D) [*Ledvina and Cravens*, 1998; *Kabin et al.*, 1999, 2000; *Nagy et al.*, 2001; *Kopp and Ip*, 2001] magnetohydrodynamic (MHD) models. These global MHD model studies provided valuable global information about the properties of the plasma and magnetic field near Titan. However, ion gyroradius effects can be of importance at Titan because the gyroradii of the observed thermal N^+ ions are $\sim$2.25 Titanian radii [*Neubauer et al.*, 1988], that is, large compared with the size of the interaction region as was clearly illustrated by global test particle simulations [*Luhmann*, 1996; *Ledvina et al.*, 2004].

[6] The need for a self-consistent model, such as a quasi-neutral hybrid model, that takes in account finite gyroradius effects has been emphasized [*Nagy et al.*, 2001; *Cravens et al.*, 1998]. Recently, a self-consistent quasi-neutral hybrid simulation has been used for the first time to study the case when Titan meets a supersonic co-rotating Kronian magnetospheric plasma [*Brecht et al.*, 2000]. The model produced an asymmetric magnetotail with respect to the direction of the convective electric field, and, consequently, illustrated the importance of kinetic effects.

[7] In this paper the Titan-subsonic flow-interaction is studied, to the authors' knowledge, for a first time with a self-consistent 3-D multi-ion species quasi-neutral hybrid model. The model is used to study kinetic effects by using axially symmetric ion production functions and ionization on the ram side. The paper is organized as following. First, the basic features of the model and the approximations used in the model are described. Then, the results for supersonic and subsonic upstream flow cases are compared. Finally, the limitations of the current hybrid model and plans for a more comprehensive model are discussed.

2. Model Description

[8] The Titan model is a modified version of the self-consistent quasi-neutral hybrid (QNH) model that was developed earlier to study Mars-solar wind interaction. In

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the QNH model ions are treated as particles while electrons form a massless charge neutralizing fluid. Other details of the model can be found in previous publications [see *Kallio and Janhunen*, 2002].

[9] In the coordinate system employed by the model, +X points against the co-rotating plasma flow, −Z points to the direction of the Kronian magnetic field and Y completes the right-handed coordinate system. In this paper, the $Y < 0$ ($Y > 0$) hemisphere of Titan is referred to as the Saturn facing (the anti Saturn facing) hemisphere because −Y points to Saturn. In the analyzed runs the extreme ultraviolet (EUV) source is on the X-axis with +X pointing to the Sun, i.e., $X > 0$ ($X < 0$) hemisphere of Titan is the dayside (nightside) hemisphere. The case therefore corresponds Titan at ~18 Saturnian Local Time (LT). The size of the simulation box is $-13.9R_T < X < 8.3R_T$ and $-25R_T < Y < 25R_T$ ($R_T = 2575$ km = radius of Titan). In the supersonic case, $-25R_T < Z < 25R_T$ and in the subsonic case $-16.6R_T < Z < 16.6R_T$. The grid size is $0.1735R_T$ near Titan and $0.3471R_T$ about $6R_T$ above the surface. Titan is modelled by placing a spherical shell, the obstacle boundary, around Titan at 1000 km from the surface. The same boundary conditions on the model boundary are used as in the previous Mars model, namely, an ion is removed from the simulation if it hits the obstacle.

[10] In the Titan model, the undisturbed Kronian magnetic field was taken to be [0, 0, −5] nT. The model contains three ion species, First, the co-rotating plasma with the following plasma parameters: m = 9.6 amu, $\mathbf{U} = [-120,0,0]$ km s^{-1}, n = 0.3 cm^{-3}, $M_S = 7.0$ (the supersonic case) and $M_S = 0.67$ (the subsonic case). Here M_S is the sonic Mach number ($=U/U_{sonic}$, $U_{sonic} = \sqrt{\gamma kT/m_p}$, $\gamma = 5/3$). Consequently, the bulk velocity corresponds the ion gyroradius of 2400 km ($=0.93R_T$) for 9.6 amu ions, and Alfvén mach number, M_A, was 1.9. The velocity distribution is assumed to be Maxwellian. The magnetic field, the total plasma density, and M_S of 0.67 correspond to the plasma parameters during Voyager 1 flyby in 1980 [see *Neubauer et al.*, 1988]. However, the ion mass of 9.6 amu is chosen to represent observed Kronian co-rotating two ion species H^+ ($n(H^+) = 0.1$ cm^{-3}), N^+ ($n(N^+) = 0.2$ cm^{-3}) plasma with a single ion species, following previous single fluid 3-D MHD studies [*Kabin et al.*, 1999, 2000].

[11] Two other ion species are N^+ ions (m = 14 amu) produced from the nitrogen neutral corona by photoionization, and N_2^+ ions (m = 28 amu) escaping from Titan's ionosphere. In the former ion source, referred to as the corona source in this paper, the functional form of neutral density profile $n(N^+) \sim \exp(-(r - 3500)/3200)$ is adopted as an approximation for the previously used nitrogen density profile [*Amsif et al.*, 1997] (r is the distance from the center of Titan in km). The local ion production rate, q_{hf}, is consequently $f_{hf}n(N^+)$ (f_{hf} is the photoionization rate) in sunlight. Finally, the total ion production rate within the simulation box from the neutral corona is taken to be 1×10^{25} s^{-1}.

[12] The second heavy ion source, the ionosphere source, is implemented by emitting 2×10^{25} ions per second uniformly at the model obstacle boundary with the thermal energy of 9 eV. Ion emission at the wake side is chosen to mimic electron impact ionization on the wake side. The ionosphere source is included in order to at least approximately take into account ions that are produced below the obstacle boundary of the model and whose production cannot be modelled self-consistently because of the quite a large grid size and also because the Titan model does not include chemical processes.

[13] From the modelling point of view, the largest difference between the previous Mars model and the present Titan model is the boundary conditions at the faces of the simulation box. Because of the high temperature of the co-rotating subsonic ions, the ions have to be injected to the simulation box at all six faces of the box. Ion injection into the simulation at the front face ($X = 8.3R_T$) is performed as in the Mars model. However, at the Y and Z faces the ion injection into the box is introduced by returning an ion that hits the Y or Z face back to the simulation box and turning its velocity component perpendicular to the face (a reflective boundary condition). Furthermore, an injection of co-rotating m = 9.6 amu ion into the simulation box at the back face ($X = -13.9R_T$) is obtained by using the Maxwellian velocity distribution function. It should be noted that this so called back face emission is only a rough approximation to the real case because Titan disturbs the flow and, therefore, also the velocity distribution of the nearby plasma. We try to minimize the resulting errors by placing the back wall far behind Titan and the analyzed region. Also, the ion emission rate at the back wall is varied manually in order to make sure that the solution is not very sensitive to the back wall ion emission rate.

3. Supersonic Versus Subsonic Flow

[14] Plasma and field parameters in the supersonic flow case after about 27 minutes after the co-rotating plasma was injected into the simulation box are shown in Figure 1. The supersonic flow produces a bow shock at which the undisturbed flow and magnetic field slightly change. The plasma and magnetic field parameter changes are only moderate because the flow is only slightly supermagnetosonic (magnetosonic Mach number = 1.8). Magnetic field "piling-up" against Titan on the ram side and the formation of the "induced" magnetotail on the wake side are clearly seen. It is worth noting that the density of the co-rotating plasma is low and the density of the escaping plasma high near Titan and in the center of the tail. In addition, the maximum magnetic field is located on the anti Saturn facing hemisphere where the density of the escaping ions is low. A similar anticorrelation between the magnetic field pressure and the density of escaping ions takes place also on the wake side. Consequently, the Saturn facing - anti Saturn facing asymmetry seen in the density of the escaping ions in the wake results in a magnetotail that is mowed toward Saturn although the ionization is symmetric with respect to the X axis.

[15] Figure 2 shows plasma and magnetic field in the subsonic case. Although a bow shock is not produced in this case the solution is qualitative reminiscent of the supersonic case. The reason for the similarity may be associated with the fact that in the supersonic case, the bow shock transforms the flow from supersonic to subsonic. The largest quantitative differences are that in the subsonic case the draping of the magnetotail is less severe but the twisting

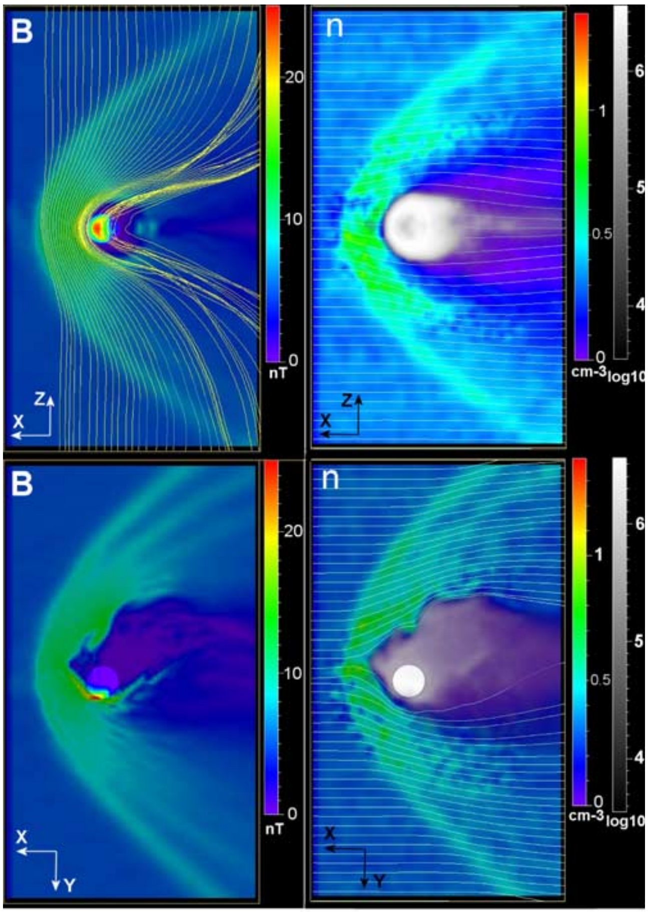

Figure 1. Titan in the supersonic flow. Top and bottom figures show parameters on the XZ-plane and on the XY-plane, respectively. −X points along the co-rotating plasma flow, −Y points to Saturn, and −Z points to the direction of the Kronian magnetic field. The figures on the left hand side depict the total magnetic field (in nanotesla) and an example of the magnetic field lines (yellow lines). The total magnetic field on the model obstacle boundary at the altitude 1000 km is also shown. The figures on the right hand sides show the density of the co-rotating plasma (color palette, linear scale, unit cm^{-3}) superimposed with the density of escaping m = 14 amu ions (black and white palette, log 10([m^{-3}]) scale) and an example of the stream lines of the co-rotating plasma (green lines). In all figures the co-rotating plasma flow from left to right. In the top (bottom) figures the +Z axis (the −Y axis) points from bottom to top. The figures show the region $-13R_T < x < 8R_T$, $-19R_T < y, z < 19R_T$.

of the magnetotail toward Saturn more intense than in the supersonic case. In addition, the position of the stagnation point on the XY plane near Titan that separates the plasma flowing toward Saturn and the plasma flowing away from Saturn is located on the $Y > 0$ side.

4. Discussion

[16] This paper presents the first step of developing a quasi-neutral hybrid model that can be used to analyze not only Mars- and Venus-like highly supersonic plasma flow -object interaction but also a subsonic flow case. The analyzed two cases suggests that there are many similarities of how Titan, Mars, and Venus interacts with the nearby plasma, in agreement with previous magnetic field draping comparisons [*Luhmann et al.*, 1991].

[17] The developed model provides in many respect a simplified picture of the plasma environment of Titan. The co-rotating plasma is modelled as a single ion species. Also, the model does not take in account electron impact ionization. The electron temperature is put to zero in Ohm's law and, consequently, the electron pressure term is neglected. At the present stage of the model the grid size near Titan is too coarse to model the exosphere-ionosphere altitude region in detail. Also, the two ion source profiles were chosen to perform a preliminary study of the role of kinetic effects at Titan. Implementation of a more accurate neutral profiles, for example profiles based on 1-D atmosphere and ionosphere models [*Keller et al.*, 1992, 1994; *Keller and Cravens*, 1994], or mimicking of various chemical processes [see, e.g., *Nagy et al.*, 2001] is beyond of the present study.

[18] More improvements should therefore be performed in the future concerning both the exosphere-atmosphere-ionosphere models and the ionization processes, as well as the modelling techniques issues. Preliminary comparisons between the simulated plasma and magnetic field values calculated along the orbit of the Voyager 1 and the measured values suggest that the QNH model can reproduce several of the observed features, such as the decrease of $|B_z|$ in the

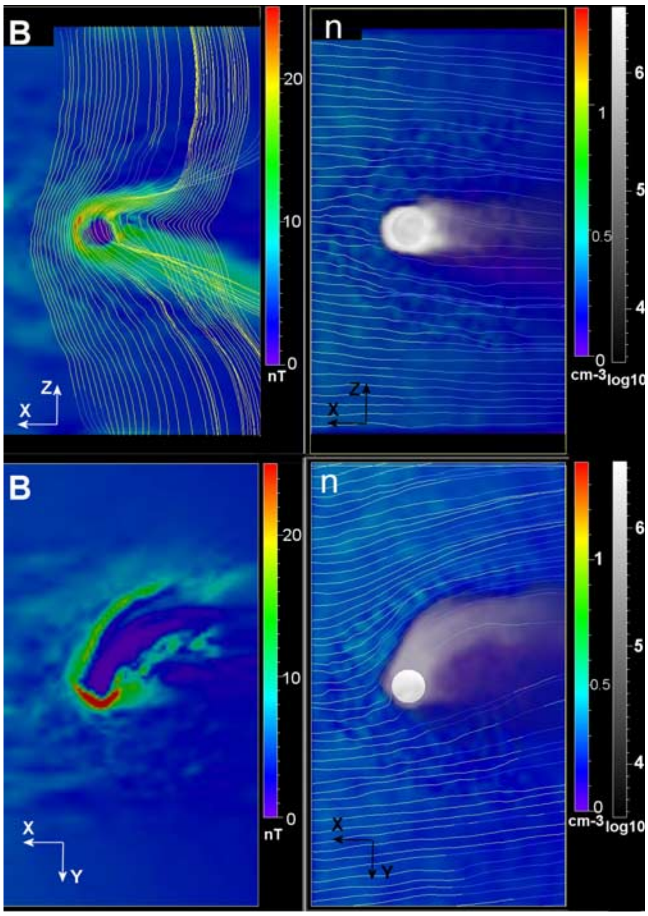

Figure 2. Titan in the subsonic flow. See Figure 1 for the description of the parameters.

wake and a $B_z > 0$ region in the wake (figures not shown). Overall, already the presented runs are anticipated to illustrate some of the basic similarities and differences between the subsonic flow case and the more Mars/Venus-like supersonic, but only slightly supermagnetosonic, flow case.

5. Summary

[19] Titan's interaction with subsonic and supersonic plasma interaction were studied by a 3-D quasi-neutral hybrid model. Both the subsonic and supersonic case result in piling up of the magnetic field on the ram side and formation of a Mars and Venus like induced magnetotail on the wake. The subsonic flow case was found to produce asymmetric and twisted magnetotail qualitatively in agreement with Voyager 1 observations implying the importance of the kinetic effects.

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