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Saturn's magnetosphere interaction with Titan for T9 encounter: 3D hybrid modeling and comparison with CAPS observations

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ABSTRACT

Global dynamics of ionized and neutral gases in the environment of Titan plays an important role in the interaction of Saturn's magnetosphere with Titan. Several hybrid simulations of this problem have already been done (Brecht et al., 2000; Kallio et al., 2004; Modolo et al., 2007a; Simon et al., 2007a, 2007b; Modolo and Chanteur, 2008). Observational data from CAPS for the T9 encounter (Sittler et al., 2009) indicates an absence of O^+ heavy ions in the upstream that change the models of interaction which were discussed in current publications (Kallio et al., 2004; Modolo et al., 2007a; Simon et al., 2007a, 2007b; Ma et al., 2007; Szego et al., 2007). Further analysis of the CAPS data shows very low density or even an absence of H^+ ions in upstream. In this paper we discuss two models of the interaction of Saturn's magnetosphere with Titan: (A) high density of H^+ ions in the upstream flow ($0.1\ cm^{-3}$), and (B) low density of H^+ ions in the upstream flow ($0.02\ cm^{-3}$). The hybrid model employs a fluid description for electrons and neutrals, whereas a particle approach is used for ions. We also take into account charge-exchange and photoionization processes and solve self-consistently for electric and magnetic fields. The model atmosphere includes exospheric H^+, H_2^+, N_2^+ and CH_4^+ pickup ion production as well as an immobile background ionosphere and a shell distribution for active ionospheric ions (M_i=28 amu). The hybrid model allows us to account for the realistic anisotropic ion velocity distribution that cannot be done in fluid simulations with isotropic temperatures. Our simulation shows an asymmetry of the ion density distribution and the magnetic field, including the formation of Alfvén wing-like structures.

The results of the ion dynamics in Titan's environment are compared with Cassini T9 encounter data (CAPS).

1. Introduction

The interaction of plasma flow with moons and planets is a one of the basic problems of astrophysical plasma due to the complexity of wave–particle processes on multiple time and spatial scales. There are three types of interactions of the solar wind with planets: (a) Earth-like strong interaction; (b) Moon-like weak interaction; (c) Venus-like intermediate interaction. In the last case, the solar wind directly interacts with an ionized planetary environment via the induced magnetic field. In the case of moons of the outer planets, the mass loading of the magnetospheric plasma by pickup ions, sputtering of fragments from the surface, wave–particle interactions, and inductive magnetic field may play very important role in the interaction of the plasma flow with the moon.

Near Titan, ion reactions such as electron impact ionization, photoionization by the solar EUV flux, and charge exchange (Stebbings et al., 1964) are of significant interest. Wave–particle interactions play a very important role in the possible formation of a shock wave or an Alfvén wing, and in coupling of pickup and upstream ions via excitation of low-frequency waves. These kinetic processes become important in the formation of an obstacle for the upstream flow.

Magnetohydrodynamic (MHD) simulations have been useful for the study of the interaction between plasma flow and Titan (Keller and Cravens, 1994; Ledvina and Cravens, 1998; Cravens et al., 1998; Kabin et al., 1999, 2000; Nagy et al., 2001; Ma et al., 2007). MHD simulations demonstrated a global picture of magnetospheric

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interaction with a moon, including mass loading the magnetosphere's plasma with the atmosphere's pickup ions and possible chemical processes inside the exobase where the fluid approximation is good. However, several kinetic effects have been lost, namely: asymmetry in the form of an Alfvén wing and a magnetic barrier near a moon, an asymmetry in the atmosphere's pickup ion distribution, possible plasma structure with a thickness of the order of the heavy ion gyroradius, an overestimate of the pickup ion fluxes along the magnetic field, and the absence of the kinetic effects inside plasma structures. Many of these effects may be recovered by using hybrid simulations.

Several 3D hybrid simulations of Titan plasma interactions were performed during the last decade as described in papers by Brecht et al. (2000), Kallio et al. (2004), Sillanpää et al. (2006), Kallio et al. (2007), Modolo et al. (2007a), Simon et al. (2007a, 2007b), and Modolo and Chanteur (2008). The hybrid modeling in Simon et al. (2007a, 2007b) uses a curvilinear grid with a grid spacing about of 772.5 km. In hybrid models by Brecht et al. (2000), Modolo and Chanteur (2008), Sillanpää et al. (2006), Kallio et al. (2007), and Lipatov et al. (2011), they use a rectangular grid with a grid spacing about of 250–500 km. Both Modolo and Chanteur (2008) and Lipatov et al. (2011) use subcycling time integration for the electromagnetic field to avoid a Courant–Fridrich–Levy (CFL) restriction on time step in case of whistler excitation.

These simulations were devoted to an interpretation of Voyager 1 and Cassini data and assumed the presence of the heavy ions like O^+ in magnetospheric plasma. Kallio et al. (2007), discusses hybrid modeling for T9 in the presence of H_2^+ and H_1^+ ions in the upstream flow. However, they used a higher total density (0.4 cm^{-3}) for these ions than was observed in the CAPS T9 measurements (0.05 cm^{-3}) (Sittler et al., 2010). The main results that were obtained in these simulations are the following: asymmetry of a nonstationary bow shock (when Titan's location is outside Saturn's magnetosphere) and the magnetic barrier due to the large gyroradius of magnetospheric ions. Hybrid simulations provided good results for the TA encounter. However, an understanding and interpretation of the CAPS data for the T9 encounter requires models with other upstream environments.

In this paper we discuss two models of the interaction of Saturn's magnetosphere with Titan: (A) high density of H^+ ions in the upstream flow and (B) low density of H^+ ions in the upstream flow. The reason for investigating these models is the uncertainty in the plasma parameters in the upstream flow. The main goal of our paper is to compare these two models of the interaction between Saturn's magnetosphere and Titan.

In our study, the model of the neutral atmosphere has been taken from Hartle et al. (2006) and Sittler et al. (2005). Photoionization, electron impact, and charge exchange rates were taken from Sittler et al. (2005). We apply a time-dependent Boltzmann's "particle in cell" approach (Lipatov et al., 1998), together with a hybrid plasma (ion kinetic) model (Lipatov et al., 2002) in three spatial dimensions (see, e.g., Lipatov and Combi, 2006) using a prescribed but adjustable neutral atmosphere and ionosphere model for Titan. A Boltzmann modeling is applied to model charge exchange between (incoming and pickup) ions and the immobile atmospheric neutrals. In this paper we discuss the results of a hybrid kinetic modeling of Titan's environment, namely, global plasma structures, e.g., the formation of a magnetic barrier, Alfvén wing, pickup ion tail, etc. The results of this kinetic modeling are compared with Cassini T9 flyby observational data (CAPS).

The paper is organized as follows: in Section 2 we present the computational model and a formulation of the problem. In Section 3 we present the results of modeling the plasma environment near Titan and compare with observational data. Finally, in Section 4 we summarize our results and discuss the future development of our computational model.

2. Formulation of the problem and mathematical model

2.1. Computational model

To study the interaction of Saturn's magnetosphere with the ionized and neutral components of Titan's environment we use a quasineutral hybrid model, namely, a kinetic description for the upstream and pickup ions, and a fluid approximation for electrons. The hybrid model well describes wave–particle interactions on the following ion spatial (λ) and time (ω^{-1}) scales: $\lambda \propto \rho_{ci} = U_0/\Omega_i$ or $\lambda \propto c/\omega_{pi}$ and $\lambda \gg \rho_{ce}$; $\omega \leq \Omega_i$, where ρ_{ci} and ρ_{ce} denote the gyroradius for ions and electrons (respectively); U_0 is the bulk velocity of the upstream flow; c/ω_{pi} denotes the ion inertial length and Ω_i is the ion gyrofrequency. The λ may represent a wavelength of the excited low-frequency waves or a spatial scale of the plasma structures and boundaries in Titan's environment. The model includes photoionization, electron impact ionization and charge exchange. We explicitly include ionization, mass-loading and charge exchange as the dominant mechanisms for the interaction above the lower boundary at Titan. We also include finite conductivity, given by the diffusion scale length, at the inner boundary. The atmosphere is considered to be an immobile component in this paper.

The general scheme of the global interaction of Saturn's magnetosphere with Titan and the Cassini T9 trajectory is given in Fig. 1. The Cassini T9 flyby occurred nearly in the equatorial plane of Titan and perpendicular to the direction of the corotating plasma flow past Titan. The spacecraft trajectory passed approximately 10,768 km (4.2R_T) down-stream from Titan (in the sense of the plasma torus flow). Here, R_T denotes the radius of Titan (R_T=2575 km). In our coordinate system the x-axis is parallel to U_0 (corotational plasma velocity), y is directed toward Saturn, and z is directed to the north.

In the hybrid model described here, the dynamics of upstream ions and implanted ions is represented with a kinetic approach, while the dynamics of the electrons is described by a hydrodynamical approximation.

The single particle ion distribution function $f_s(t,\mathbf{x},\mathbf{v})$ has to fulfill the Vlasov/Boltzmann equation:

$$\frac{\partial}{\partial t}f_s+\mathbf{v}\frac{\partial}{\partial \mathbf{x}}f_s+\frac{\mathbf{F}}{M_s}\frac{\partial}{\partial \mathbf{v}}f_s=F_{coll}+P-L_{exch}, \quad (1)$$

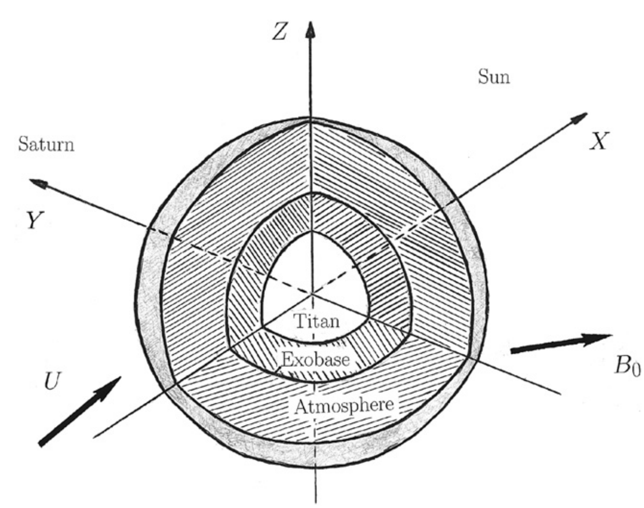

Fig. 1. Titan's plasma environment and the system of coordinates.