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Titan's induced magnetosphere under non-ideal upstream conditions: 3D multi-species hybrid simulations

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ABSTRACT

A 3D, multi-species hybrid model (kinetic ions, fluid electrons) has been applied to the interaction between Saturn's largest satellite Titan and the plasma in the giant planet's outer magnetosphere. In contrast to the idealized picture deduced from Voyager 1 data, recent observations made by the Cassini magnetometer instrument suggest that the ambient magnetic field is not directed perpendicular to Titan's orbital plane. Therefore, our purpose is to investigate systematically how Titan's induced magnetosphere is affected by a tilt of the upstream magnetic field. In the first part of our study, the structure of Titan's induced magnetosphere is analyzed as a function of the angle between the ambient magnetic field $\underline{B}_0$ and the bulk velocity $\underline{u}_0$ of the corotating plasma flow. Our simulations show that introducing a flow-aligned magnetic field component goes along with an asymmetrization of Titan's magnetotail, in addition to the asymmetry that already arises from the large gyroradii of the ion species involved in the interaction. In the vicinity of Titan, the field lines become strongly twisted, permitting the wakeside magnetic lobe structure to even penetrate into the satellite's geometric plasma shadow. However, despite the increased complexity of Titan's magnetic environment, the overall characteristics of the pick-up tail remain practically the same as in the case of "ideal" magnetic field orientation ($\underline{B}_0 \perp \underline{u}_0$). In the second part of our study, we investigate in real-time the transition that Titan's plasma interaction undergoes during a change of the ambient magnetic field direction. In contrast to earlier analyses of Titan's plasma environment under non-stationary upstream conditions, the tilt of the ambient magnetic field is again taken into account. While in the case of $\underline{B}_0$ being perpendicular to $\underline{u}_0$, the reconfiguration of Titan's induced magnetosphere is mainly governed by reconnection, our simulations suggest that when a flow-aligned field component is included, convection of the field lines around the obstacle's ionosphere plays the key role for the reconfiguration process.

1. Introduction

Since the arrival of the Cassini spacecraft at Saturn in July 2004, more than 50 flybys of the giant planet's largest satellite Titan have already been accomplished. Plasma and magnetic field data collected by the Cassini instruments have greatly improved our understanding of the interaction between Titan's dense, nitrogen-rich atmosphere and the at least partially corotating plasma of the outer magnetosphere. This interaction leads to the formation of a magnetic pile-up region at Titan's ramside and a bipolar magnetotail in the moon's wake region (see e.g. Neubauer et al., 1984, 2006 for details). Simultaneously, newly generated exospheric particles are being picked up by the corotational plasma flow, forcing them on cycloidal trajectories in a plane perpendicular to the magnetic field. The spatial extension of the cycloidal arcs can exceed the diameter of Titan by more than a factor of 5 (Luhmann, 1996). The asymmetry in the shape of the pick-up ion trajectories (Saturn-facing versus anti-Saturn-facing hemisphere) also leaves a pronounced imprint on the overall magnetic field topology near Titan (Simon et al., 2006b).

In the past years, a variety of global simulation models have been applied to study Titan's plasma interaction and to support the interpretation of Cassini plasma and magnetic field measurements. The pallet of available models encompasses magnetohydrodynamic codes (see e.g. Nagy et al., 2001; Backes, 2005; Backes et al., 2005; Neubauer et al., 2006), a multi-fluid approach (Snowden et al., 2007) as well as several semi-kinetic models (cf. Brecht et al., 2000; Kallio et al., 2004; Ledvina et al., 2004; Modolo and Chanteur, 2008; Simon et al., 2009a and references therein). Recently, Winglee et al. (2009) presented the first realization of a two-body simulation scenario, allowing to study

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the coupled interaction between the Kronian magnetosphere and Titan's ionosphere.

Most of the simulation models discussed above assume the background magnetic field $\underline{B}_0$ inside Saturn's magnetosphere to be oriented perpendicular to Titan's orbital plane, which is consistent with the "idealized" picture of the satellite's plasma interaction deduced from Voyager 1 measurements (see e.g. Neubauer et al., 1984; Ledvina et al., 2004). In this geometry, Titan's orbital plane is defined by the bulk velocity $\underline{u}_0$ of the impinging magnetospheric flow and the undisturbed convective electric field $\underline{E}_0 = -\underline{u}_0 \times \underline{B}_0$. This plane also contains the cycloidal trajectories of the newly generated pick-up ions. Simulations have shown that in the Voyager 1 scenario, Titan's exospheric tail possesses a "flat" structure, in such a way that the magnetic lobes prevent it from expanding significantly into the regions above or below the orbital plane (Simon et al., 2006b, 2007b). For this reason, the Voyager 1 scenario permits easy and straightforward access to many physical processes involved in Titan's plasma interaction. However, recent Cassini observations imply that during many flybys, the assumption of $\underline{B}_0$ being perpendicular to Titan's orbital plane does not reflect the real situation.

An analysis of Cassini magnetometer data presented by Arridge et al. (2008) suggests that Titan's orbital plane does not coincide with Saturn's magnetic equator, but the satellite is typically located below its parent planet's warped and dynamic magnetodisc. The magnetic field near Titan's orbit does not only possess a finite component towards Saturn, but Cassini MAG data also suggest the presence of a significant field component along the corotational flow direction (Bertucci, 2009). The non-ideal orientation of the upstream magnetic field has already been taken into account by several of the global simulation models which succeeded in reproducing magnetic field observations along Cassini's trajectory during the TA and TB flybys (Ma et al., 2006) as well as during the T9 (Ma et al., 2007; Simon et al., 2007c; Kallio et al., 2007) and the T34 encounter (Simon et al., 2008b). Nevertheless, none of these preceding studies provides an analysis of how the global characteristics of Titan's induced magnetosphere are affected by the non-ideal orientation of the upstream magnetic field. Therefore, the intention of our study is to investigate systematically how Titan's plasma interaction is affected by a tilt of the ambient magnetic field with respect to the "ideal" orientation ($\angle(\underline{u}_0, \underline{B}_0) = 90^\circ$). The analysis is based upon a sophisticated 3D hybrid simulation code, which has not only been applied to the "idealized" Voyager 1 scenario, but it also succeeded in quantitatively reproducing Cassini magnetic field measurements during several flybys with non-ideal magnetic field orientation as well (see the above cited references for details). Based on the well-understood Voyager 1 geometry, we successively reduce the angle between the corotation velocity $\underline{u}_0$ and the undisturbed magnetic field $\underline{B}_0$, the purpose being to determine the influence on the magnetic lobe structure, the magnetospheric ion flow pattern and the orientation of Titan's pick-up tail.

Most of the available models of Titan's plasma interaction assume the physical parameters of the upstream flow to be constant in space and time. However, Cassini observations revealed that the ambient conditions along the orbit of Titan possess a strong time variability. For instance, when Saturn's magnetosphere is compressed due to high solar wind dynamic pressure, Titan can leave the magnetic field of its parent body near noon local time and interact with the shocked solar wind plasma in the magnetosheath. This situation has been observed in situ for the first time during the Cassini T32 encounter on 13 June 2007. Until only a few minutes before the T32 flyby, Titan had been located inside the rotating plasma of Saturn's magnetosphere. Cassini magnetic field data indicate that during the passage through Saturn's magnetopause, Titan was exposed to an almost complete reversal of the ambient magnetic field direction (Bertucci et al., 2008). So far, two simulation models have been successfully applied to study in real-time the transition that Titan's plasma interaction undergoes during such a disruptive change of the upstream conditions: By using a hybrid model, Simon et al. (2008a, 2009a) demonstrated that Titan's induced magnetosphere is repolarized due to magnetic reconnection, with the reconfiguration process being completed on a characteristic time scale that is determined by the convection of the magnetic field in the undisturbed plasma flow outside the interaction region. In agreement with the picture drawn by Bertucci et al. (2008), these simulations suggest that the reconfiguration of Titan's induced magnetosphere features a close analogy to the passage of a comet through a sector boundary in the solar wind. The MHD study presented by Ma et al. (2009), on the other hand, focuses on the detection of fossilized magnetic fields that can remain trapped in Titan's ionosphere for several hours after the satellite has left the magnetosphere of Saturn.

Since the magnetopause is a tangential discontinuity, there was no need to include a flow-aligned magnetic field component into a real-time model of the T32 encounter. However, it is of general interest to understand how Titan's plasma environment responds to a change of the ambient magnetic field direction when a finite flow-aligned field component is present. Cassini MAG data do not only show strong spatial variability of Saturn's magnetic field along Titan's orbit inside the magnetosphere, but also large amplitude wave forms (relative magnitude $\delta B/B = 0.5$) have been detected in the background field as well (Bertucci, 2009). Even though the available studies of Titan's plasma interaction under non-stationary upstream conditions take into account sudden changes of the ambient magnetic field direction as well as periodic oscillations imposed on the fields, so far, none of these time-dependent models considers a flow-aligned magnetic field component. In our study, we therefore intend to make another step towards fully understanding Titan's magnetospheric interaction by including a flow-aligned field component into a real-time simulation scenario.

The results of this time-dependent simulation will provide some basic insights into the reconfiguration of Titan's induced magnetosphere, e.g. during oscillations of the background field, if $\underline{B}_0$ is not perpendicular to the flow direction. In order to permit a straightforward access to the involved physics and a comparison to preceding real-time models, we intend to keep the simulation geometry as simple as possible. Unlike the preceding study by Simon et al. (2008a), we do therefore not consider periodic oscillations of the background field, but only a single continuous change in the field direction is included. Despite being somewhat artificial, this scenario will allow to gain additional insights into the physics of Titan's plasma environment under time-dependent upstream conditions.

This paper is organized as follows: In Section 2, we briefly describe the key features of our five-species hybrid simulation code and provide an overview of the applied set of input parameters. Section 3 discusses the overall structure of Titan's induced magnetosphere as a function of the angle between flow velocity $\underline{u}_0$ and magnetic field $\underline{B}_0$, whereas in Section 4, the real-time study of a change in the upstream field orientation is presented. We conclude by giving a short summary of our major findings.

2. Simulation model and input parameters

The hybrid model can be considered a combination of a fluid approach and a fully kinetic code: It treats the electrons of the