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# Influence of asymmetries in the magnetic draping pattern at Titan on the emission of energetic neutral atoms

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ABSTRACT

We model the emission of energetic neutral atoms (ENAs) that are generated by the interaction between energetic ions from Saturn's magnetosphere and neutrals from the upper atmosphere of the giant planet's largest moon Titan. The trajectories of the parent ions and the resulting ENA emission morphology are highly sensitive to the electromagnetic field configuration near the moon. We therefore compare the ENA emission pattern for spatially homogeneous fields to the emission obtained from a magnetohydrodynamic (MHD) and a hybrid (kinetic ions, fluid electrons) model of Titan's magnetospheric interaction, by computing the trajectories of several billion energetic test particles. While the MHD model takes into account the draping of the magnetic field lines around Titan, the hybrid approach also considers the significant asymmetries in the electromagnetic fields due to the large gyroradii of pick-up ions from Titan's ionosphere. In all three models, the upstream parameters correspond to the conditions during Cassini's TA flyby of Titan. The shape, magnitude, and location of the ENA emission maxima vary considerably between these three field configurations. The magnetic pile-up region at Titan's ramside deflects a large number of the energetic parent ions, thereby reducing the ENA flux. However, the draped magnetic field lines in Titan's lobes rotate the gyration planes of the incident energetic ions, thereby facilitating the observable ENA production. Overall, the ENA flux calculated for the MHD model is weaker than the emission obtained for the electromagnetic fields from the hybrid code. In addition, we systematically investigate the dependency of the ENA emission morphology on the energy of the parent ions and on the upstream magnetic field strength.

## 1. Introduction

Since the arrival of Cassini in the Saturnian system in July of 2004, the spacecraft has performed 126 close flybys of the planet's largest moon Titan. Titan is usually located in the outer regions of Saturn's magnetosphere and is only rarely found outside of Saturn's magnetosphere (either in the planet's magnetosheath or exposed to the supersonic solar wind, see Bertucci et al. (2008, 2015); Edberg et al. (2013)). Thus, for nominal solar wind conditions, the upper atmosphere of Titan, which consists mainly of molecular nitrogen and methane, interacts with charged particles confined in the Saturnian magnetosphere.

Two energy regimes play an important role in the interaction with Titan's upper atmosphere: (i) the thermal corotating plasma flow, which shapes the local electromagnetic fields around the moon (e.g., Neubauer et al. (2006)) and (ii) the highly-energetic charged particles ($E > 10$ keV). The number density $n_p = 0.1 - 1$ cm$^{-3}$ (see Sittler et al. (2005); Szego et al. (2007); Coates (2009)) of the corotating plasma flow exceeds the density of the energetic plasma ($< 10^{-2}$ cm$^{-3}$, see Sergis et al. (2009, 2017); Thomsen et al. (2010)) by several orders of magnitude. Therefore, the corotating plasma has the by far strongest influence on the electromagnetic fields at Titan. The energetic particles have negligible influence on the structure of the electromagnetic fields, since they make only a very minor contribution to the currents. Therefore, they can be described as test-particles that are exposed to a pre-defined electromagnetic field configuration (Wulms et al., 2010; Regoli et al., 2016).

Titan is continuously overtaken by the nearly-corotating, thermal Saturnian plasma with a relative velocity of approximately 120 km/s (Arridge et al. (2011), see Table 6 therein). Because Titan has no significant intrinsic magnetic field (Wei et al., 2010), the plasma can directly interact with its upper atmosphere and ionosphere, thereby

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generating an "induced magnetosphere" around the moon (Bertucci et al., 2011). The magnetic field piles up in front of Titan and forms a bipolar magnetotail in the wake region (Neubauer et al., 1984, 2006). Ionization of Titan's upper atmosphere (mainly by solar UV radiation) leads to the generation of an ionosphere around the moon. The pick-up of these newly generated ionospheric ions decelerates the Saturnian plasma flow (e.g., Szego et al. (2007); Sittler et al. (2010); Coates et al. (2012)). The picked-up ions from Titan's ionosphere have large gyroradii (on the order of several Titan radii $R_T = 2575$ km) and, therefore, impose a pronounced asymmetry on the moon's pick-up tail (Simon et al., 2007; Modolo and Chanteur, 2008; Edberg et al., 2011; Feyerabend et al., 2015). In particular, the magnetic pile-up region is expanded towards the direction of the convective electric field. Thus, at Titan, the plasma interaction region is highly asymmetric with respect to the direction of the convective electric field. This effect is visible in the planes perpendicular to the background magnetic field ($\perp \vec{B}_0$). The pick-up tail can extend multiple $R_T$ in the direction of the convective electric field. The strength of these asymmetries depends on the ion mass (e.g., 5.5 $R_T$ for $m_{N_2^+} = 28$ u and 2.7 $R_T$ for $m_{CH_4^+} = 16$ u, see Fig. 6 in Simon et al. (2007)). However, in planes spanned by the plasma flow $\vec{u}_0$ and the magnetic filed $\vec{B}_0$, the induced magnetosphere is unaffected by the ion gyration.

Various fluid (e.g., Backes et al. (2005); Ma et al. (2007); Snowden et al. (2007)) and hybrid simulations (Kallio et al., 2004; Modolo et al., 2007; Simon et al., 2007; Feyerabend et al., 2015) have been performed to describe the complex plasma environment around Titan. A major advantage of the fluid approach is the ability to cover the complex ionospheric photochemistry in a reasonable computational time (Ma et al., 2006). However, the use of a fluid approach has some significant shortcomings. For example, the single-fluid, magnetohydrodynamic (MHD) approach cannot describe asymmetries generated by the Hall effect or by large gyroradii. Although a multi-fluid approach, as used by Snowden et al. (2007), captures the Hall effect and flow shear between light and heavy ion species, it does not reproduce the significant asymmetries associated with ion gyration.

Another important effect in Titan's upper atmosphere occurs due to charge exchange of energetic magnetospheric protons with neutral atmospheric particles. The capture of an electron from a neutral particle in Titan's upper atmosphere neutralizes the energetic ion and leads to the generation of an Energetic Neutral Atom (ENA). The newly-generated ENA is no longer affected by the electromagnetic fields. Because of the ENAs large kinetic energy, Titan's gravitational field has negligible influence on its trajectory as well. Thus, ENAs escape on almost straight trajectories from Titan's upper atmosphere and can be detected like photons by the Ion and Neutral Camera (INCA, Mitchell et al. (1993)) that is part of the Magnetospheric Imaging Instrument (MIMI, Krimigis et al. (2004)) aboard Cassini. The measured neutral flux along the line of sight, within the INCA field of view 90° × 120°, generates ENA images that depend on (1) the composition and density profile of Titan's upper atmosphere, (2) the energy-dependent cross-sections of the charge-exchange reactions, (3) the distribution of the energetic ions near Titan and (4) the local electromagnetic field configuration. The ENA emissions detected during Cassini's first Titan flyby (TA) on 26 October 2004 show a highly asymmetric pattern with the ENA flux on the upstream side of Titan being much weaker than the ENA flux on the downstream side, i.e. Cassini observed a crescent-shaped emission pattern (Mitchell et al., 2005).

Before Cassini arrived in the Saturnian system, Dandouras and Amsif (1999) developed a three-dimensional ENA production model for Titan. The ambient magnetospheric field at Titan was assumed to be homogeneous and pointing southward i.e., the magnetic field draping around the moon was neglected. The energetic parent ions were assumed to be homogeneously distributed in Titan's upper atmosphere, performing circular motions rather moving along cycloidal trajectories (i.e., the convective electric field was neglected). The results of Dandouras and Amsif (1999) show that the large gyroradii ($1.6 - 2.5\,R_T$ for energies of $E = 20 - 50$ keV) of the energetic protons lead to the formation of "shadow" regions in the ENA flux from Titan's atmosphere. This effect is caused by the counterclockwise motion of the energetic ions around the magnetic field lines, due to the parent ions hitting the dense atmosphere at the upstream side of Titan before they can generate ENAs that are able to reach the detector, which was located at the Saturn-averted side of Titan during TA. Thus, only ENAs generated on the downstream side were detected, thereby resulting in a crescent-shaped ENA morphology. The ENA images modeled by Dandouras and Amsif (1999) are in qualitative agreement with the Cassini INCA data obtained during TA (Mitchell et al., 2005).

Based on this ENA production model, Garnier et al. (2007) proposed a new exosphere model for Titan, which is consistent with the Ion and Neutral Mass Spectrometer (INMS) data. Subsequently, Garnier et al. (2008) studied the ENA dynamics in Titan's upper atmosphere and determined the thermalization altitude (i.e., the height below which the parent ions no longer possess sufficient energy to generate ENAs). This study improved the ENA production model from Dandouras and Amsif (1999) by including the $\vec{E} \times \vec{B}$-drift ($\vec{E}$: convective electric field, $\vec{B}$: magnetic field). Therefore, their model takes into account cycloidal motion rather than just the circular motion of the energetic protons. However, the authors considered only particles with pitch angles of 90° i.e., they did not take into account the observed isotopic pitch-angle distribution in velocity space (Krimigis et al., 2005) and thus, the influence of energetic parent ions impinging on Titan's atmosphere at various angles. Garnier et al. (2008) also assume a homogeneous magnetic field at Titan (similar to Dandouras and Amsif (1999)) and neglect the complex draping pattern at the moon (Simon et al., 2014). Moreover, Garnier et al. (2008) assumed the parent ions to be homogeneously distributed around Titan, which does not take into account the transport of the upstream ions past Titan. This simplification leads to ENA generation in the wake that would not be accessible to these energetic ions in a realistic interaction geometry, as shown by Regoli et al. (2016), see Fig. 3 therein.

To determine whether the observed crescent-shaped ENA morphology during TA is continuously present, Garnier et al. (2010) performed a statistical analysis of the ENA flux and position of the ENA halo around Titan for 11 close Cassini flybys. They showed that the observed ENA flux variability between different flybys is mainly driven by the parent ion dynamics in the time variable magnetic field near Titan. In a second step, the authors performed a phenomenological study of the asymmetries in the ENA emission and confirmed that the crescent-shaped ENA morphology observed during TA is visible in most of the analyzed ENA images. Garnier et al. (2010) suggest that the observed asymmetries are mainly caused by the large gyroradii of the energetic parent ions as already suggested by Dandouras and Amsif (1999). However, the authors also found that the magnetic field draping and asymmetries generated by the pick-up tail may have an influence on the ENA morphology as well.

Subsequently, Wulms et al. (2010) provided the first analysis of ENA production at Titan that considers a realistically draped electromagnetic field configuration. These authors combined the MHD model calculations for the Cassini TA flyby done by Backes et al. (2005) with a test particle approach for the energetic parent ions. They traced a large number of energetic parent ions through the spatially inhomogeneous field configuration provided by the MHD simulation and calculated the resulting ENA emission pattern. By comparing the ENA emission patterns in homogeneous and draped electromagnetic fields, Wulms et al. (2010) demonstrated that considering the inhomogeneity of the magnetic field near Titan is essential for understanding the ENA emission morphology observed by INCA during the TA encounter. For a spacecraft position similar to Cassini's location during TA (and a camera "looking" from infinity), these authors found that, for homogeneous background fields, the maximum of the ENA flux would be located in the upstream hemisphere of Titan. However, in the case of draped fields, the maximum is shifted into Titan's downstream hemisphere. Therefore, the results