

Plasma environment in the wake of Titan from hybrid simulation: A case study.

Ronan Modolo, G.M. Chanteur, J.-E. Wahlund, P. Canu, W.S. Kurth, D. Gurnett, A.P. Matthews, C. Bertucci

▶ **To cite this version:**

Ronan Modolo, G.M. Chanteur, J.-E. Wahlund, P. Canu, W.S. Kurth, et al.. Plasma environment in the wake of Titan from hybrid simulation: A case study.. Geophysical Research Letters, 2007, 34 (24), pp.L24S07. 10.1029/2007GL030489 . hal-00153874

HAL Id: hal-00153874
https://hal.science/hal-00153874

Submitted on 17 Feb 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Plasma environment in the wake of Titan from hybrid simulation: A case study

R. Modolo,[1] G. M. Chanteur,[2] J.-E. Wahlund,[1] P. Canu,[2] W. S. Kurth,[3] D. Gurnett,[3] A. P. Matthews,[4] and C. Bertucci[5]

Received 24 April 2007; revised 15 August 2007; accepted 13 September 2007; published 18 October 2007.

[1] On 26 December 2005, the Cassini spacecraft flew through Titan's plasma wake and revealed a complex and dynamic region. Observations suggest a strong asymmetry which seems to be displaced from the ideal position of the wake. Two distinct plasma regions are identified with a significant difference on the electron number density and on the plasma composition. Simulation results using a three-dimensional and multi-species hybrid model, performed in conditions similar to those encountered during the flyby, are presented and compared to the observations. An acceptable agreement is shown between the model predictions and the observations. We suggest that the observed asymmetries, in terms of density and plasma composition, are mainly caused by the a combination of the asymmetry in the ion/electron production rate and the magnetic field morphology, where the first plasma region is connected to the dayside hemisphere of Titan's ionosphere while the other is connected to the nightside hemisphere. **Citation:** Modolo, R., G. M. Chanteur, J.-E. Wahlund, P. Canu, W. S. Kurth, D. Gurnett, A. P. Matthews, and C. Bertucci (2007), Plasma environment in the wake of Titan from hybrid simulation: A case study, *Geophys. Res. Lett.*, *34*, L24S07, doi:10.1029/2007GL030489.

1. Introduction

[2] Voyager 1 and Cassini observations of the plasma environment of Titan have shown the presence of an induced magnetosphere [*Neubauer et al.*, 1984, 2006]. The partial ionisation of the neutral atmosphere forms a dense and cold ionosphere which acts as an obstacle against the kronian plasma flow. This conductive obstacle modifies the plasma flow and twists the magnetic field lines around the body since the magnetic field lines diffuse slowly through the conductive obstacle. The Cassini and Voyager observations therefore show a complex and highly variable plasma environment in the vicinity of Titan.

[3] Saturn's magnetospheric dynamics also contribute to the variable picture of the interaction with Titan. For instance, the Cassini Langmuir Probe observations suggest the presence of an extended plasma sheet (M. Morooka et al., unpublished manuscript, 2007). This relatively dense plasma ($n_e \leq 1$ cm^{-3}), coming from the inner magnetosphere and observed out to 40 Saturnian radii (R_S), rotates mainly in phase with the Saturn Kilometric Radiation (SKR) period. This plasma may have an influence on Titan's interaction.

[4] The Cassini encounter with Titan studied here (flyby T9), occurred on the 26th of December 2005, and offers the opportunity to investigate the structure and the dynamics of the far plasma wake of Titan. For this flyby, the Cassini Plasma Spectrometer (CAPS) indicates a deviation of the magnetospheric flow from the corotation direction >40° outward (i.e. in the clockwise direction) [*Szego et al.*, 2007]. In addition, *Bertucci et al.* [2007] suggest from magnetic field measurements a deflection of the incoming plasma of 36°, assuming that Titan's tail is symmetric with respect to the incoming flow and that Cassini crossed its central axis. This deviation modifies the position of the source of ionisation by electron impacts and affects the interaction between the co-rotating plasma and Titan's upper atmosphere. Here we use a three-dimensional and multi-species hybrid model to investigate the structure of Titan's plasma wake and compare the predictions of the model to the observed cold plasma parameters derived from the analysis of the Radio and Plasma Wave Science - Langmuir Probe (RPWS-LP) observations [*Modolo et al.*, 2007], and the plasma composition measured by the CAPS experiment [*Szego et al.*, 2007].

2. Model

[5] The model used is a three-dimensional multi-species hybrid model previously developed for Mars [*Modolo et al.*, 2005] and adapted for Titan [*Modolo and Chanteur*, 2007]. In this model, the full ion dynamics are described while a fluid description is used for electrons.

[6] In order to simplify the boundary conditions for the injection of the macro-particles, the coordinate system is chosen such that the X axis is aligned with the incoming direction of the plasma flow. For this simulation, the incoming plasma flow direction differs by a given angle to the ideal co-rotating direction as suggested on Figure 1 (cf section 3). Thus, the coordinate system used is centered on Titan such that the X axis is parallel to the incoming plasma flow direction **V**, the Z axis is perpendicular to the equatorial plane and oriented northward, the Y axis completes the right-handed system. The direction of the Sun and the trajectory of the Cassini spacecraft in this coordinate system are shown on Figure 1.

[7] The size of the simulation box is $-5.4 \leq X \leq 9.4$ Titan radii (R_T) and $-10.8 \leq Y,Z \leq +10.8$ R_T. Simulations

[1]Swedish Institute of Space Physics, Uppsala, Sweden.
[2]Centre d'Etudes des Environnements Terrestre et Planétaires, Institut Pierre Simon Laplace, Velizy, France.
[3]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.
[4]School of Physics, University of KwaZulu-Natal, Durban, South Africa.
[5]Space and Atmospheric Physics Group, Imperial College London, London, UK.

Copyright 2007 by the American Geophysical Union.
0094-8276/07/2007GL030489

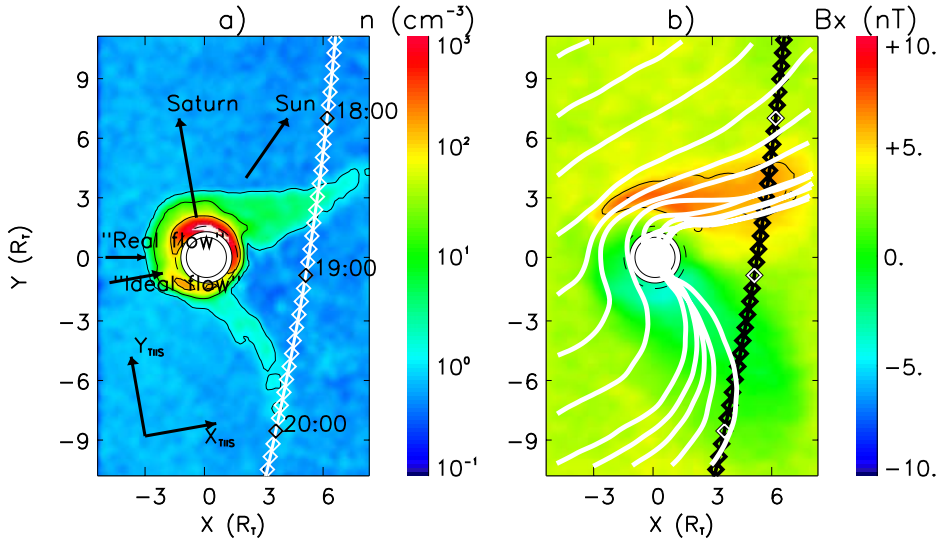


Figure 1. (a) Map of the total density in the equatorial plane of Titan (XY plane). The direction of the Sun, the incoming plasma flow, and Saturn are indicated in the simulation coordinate system. (b) Map of the Bx component at 4 R_T in a plane perpendicular to the incoming plasma flow (YZ plane). The trajectory in this reference frame is overlaid, where each tickmark corresponds to the position of the spacecraft every 5 minutes. Titan and the simulated obstacle (R_{obst} = R_T + 700 km) are represented by the small and large white circles respectively. The farthest dashed black circles indicate the exobase level located at an altitude of 1430 km [*Waite et al.*, 2005].

are performed on a three dimensional cartesian grid with a spatial resolution of 509 km. Titan is modeled as a fully absorbing obstacle, where ions penetrating the obstacle are stopped. We assumed that ions can not penetrate below 700 km leading to an obstacle radius (R_{obst}) of 3275 km. Note that the description of the collisional region below the exobase is limited in this model since the complex ionospheric chemistry is not included. Nevertheless, the model describes the photoabsorption and the slowing down of ions in the atmosphere due to elastic collisions. The boundary conditions used for this model are presented in detail by *Modolo and Chanteur* [2007].

[8] The neutral environment of Titan is described by three spherically symmetric coronae of methane, molecular nitrogen and hydrogen. Density profiles of N_2, CH_4 and H_2 have been adjusted to the Ion and Neutral Mass Spectrometer (INMS) observations for Ta [*Waite et al.*, 2005; *Yelle et al.*, 2006]. The neutral environment is partially ionised by solar photons (in minimum solar conditions), electron impact and charge exchanges between the incoming ions and the neutral components of the atmosphere. The production rate for each ion species is calculated self-consistently, locally as a function of the neutral density and the different ionisation frequencies and cross-sections [see *Modolo and Chanteur*, 2007].

[9] Cassini's observations reveal an important variability of the surrounding plasma environment making difficult the selection of upstream parameters. With these uncertainties, we used the previous plasma composition and upstream parameters derived from Voyager 1 and Cassini observations: magnetospheric plasma composed of light ions (H^+) and heavy ions (O^+) with average number densities of 0.1 cm^{-3} and 0.2 cm^{-3} respectively [*Neubauer et al.*, 1984; *Hartle et al.*, 2006].

[10] The upstream magnetic field was set as **B** = [2.1, 4.8, −1.] nT in the Titan interaction coordinate system [see *Backes et al.*, 2005], which is slightly different from the average upstream magnetic field provided by the MAG observations (**B** = [3.68, 4.69, −2.36] nT [*Bertucci et al.*, 2007]). Simulations have been performed with different upstream magnetic field values around the MAG average estimate. The parameters used in the simulation allow us to describe the main features observed in the magnetic field.

3. Simulation Results

[11] Simulation results are presented after 4000 time steps, corresponding to 1080 s, after which the global picture of the plasma environment is no more evolving significantly. Figures are presented in the equatorial plane of Titan (XY plane), where the spacecraft trajectory is located for this particular flyby. Since *Szego et al.* [2007] have suggested that the incoming plasma differed from the rigid corotation by more than 40° anti-Saturnward deflection, different simulations have been performed with various angles. Deflection angles of 65°, 50°, 30°, 20°, 15°, 12° and 0° have been tried and only simulations with an outward deflection below 20° reproduce the split signatures in the ion plasma composition and the electron number density observed by Cassini. The best agreement between the observations and the simulation results, presented here, have been found for a 12° deflection outward with respect to the ideal co-rotation direction.

[12] The electron density computed in the simulation, assuming quasi-neutrality of the plasma ($n_e = \Sigma_S n_i^s$, where n_i^s is the density of ion species s), is given in Figure 1. It is clear that the asymmetry in the production rate, mainly due to the day-night asymmetry in the plasma production rate, contribute to break the symmetry of the plasma environment.

[13] Figure 1a emphasizes a strong asymmetry of the plasma wake of Titan with a global shape similar to a delta wing. Analogous features have been noticed by *Neubauer et*

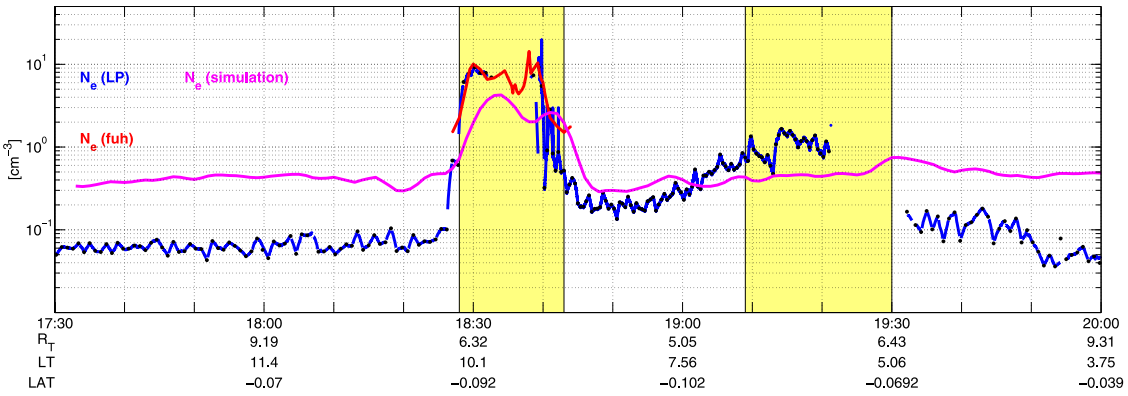


Figure 2. Comparison of the electron densities provided by the RPWS experiment (blue and red curves) and the total density computed from hybrid simulations (magenta line) along the spacecraft trajectory of the T9 flyby. See *Modolo et al.* [2007] for data description.

al. [2006] with the three-dimensional MHD simulation model developed by *Backes et al.* [2005]. For $\beta \gg 1$ (β = 11.4 for this simulation), *Neubauer et al.* [2006] suggested the presence of Alfvèn wings and slow mode wings downstream of Titan.

[14] As identified in the Langmuir Probe density observations [*Modolo et al.*, 2007], two main regions, concomitant with magnetic signatures [*Bertucci et al.*, 2007], are clearly seen on the inbound and the outbound portion of the trajectory. Figure 1b highlights a two magnetic lobe structure with opposite polarity of the Bx component. However the negative lobe structure in the simulation is larger than the observed structure by $\sim$1.8 R_T. Figure 1b presents a projection of the simulated magnetic field lines which clearly emphasizes the connection between Cassini and Titan's ionosphere.

[15] For a comparison with the electron densities provided by the RPWS experiments, the total density obtained by the model has been plotted along Cassini's trajectory (Figure 2). For this flyby, the Langmuir Probe observations indicate a density of the incoming plasma of 0.06–0.1 cm^{-3}, different from the values used in the simulations by a factor three to five (0.3 cm^{-3}). This difference explains the disagreement in the upstream region between the model predictions and the observations. Figure 2 shows a reasonable agreement between the observations and the simulation results. The model reproduces the two main structures inbound and outbound of the pass highlighted by the shaded areas. According to RPWS observations, region 1 and 2 are respectively defined by the time intervals [18:26 to 18:43] UT and [19:09 to 19:30] UT. Although the observed data are more structured than the simulation results, the model predicts the density peak identified in region 1 but with a density slightly smaller (less than 5 electrons per cm^3). Moreover, the model shows an increase in the density 2 min earlier than the observations. The second density signature, in region 2, appears earlier in the observations than in the model, but are in reasonable agreement in amplitude ($\simeq$0.8–1.7 cm^{-3}). Some model deficiencies, like the coarse spatial resolution (500 km) as well as substantial magnetospheric dynamics, such as a change in the direction of the incoming plasma flow during the flyby, may contribute to the time mismatch noticed between the observations and the simulation results. It is worth noticing that the outward deflection of 12° of the incoming plasma flow used in the simulation provides an acceptable agreement with the electron density observations, while a simulation with an outward deflection of 40° or 36°, as suggested by the CAPS or MAG experiment [*Szego et al.*, 2007; *Bertucci et al.*, 2007], gave a completely different picture of the plasma environment. This issue suggests either deficiencies in the model or a non steady state of the upstream plasma flow direction.

[16] The early Voyager 1 observations showed an asymmetry in the plasma wake of Titan [*Neubauer et al.*, 1984]. It has been argued that the newly born pickup ions are accelerated by the motional electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, where $\mathbf{V}$ is the background velocity of Saturn's magnetosphere and $\mathbf{B}$ is its magnetic field, and move in a plane which is perpendicular to $\mathbf{B}$, forming an asymmetry due to their large gyroradii. The asymmetry observed between outbound and inbound for this flyby seems not relevant to the finite gyro-radius effect since the motional electric field was pointing out of the trajectory plane. Moreover, in region 1 of the induced magnetosphere the gyroradius of a CH_4^+ ion is of the order of 300 km $\ll$1 R_T, assuming a magnetic field of $\simeq$5 nT [*Bertucci et al.*, 2007] and a temperature of 15 eV [*Modolo et al.*, 2007]. The observed asymmetry can therefore not be explained only by finite gyroradii effects. In addition, region 1 and 2 are associated to a positive and negative Bx component respectively. The two magnetic lobes produced by the draping of the magnetic field around Titan, and associated with the main density regions, are related to the dayside and nightside hemisphere. We suggest that the remaining asymmetry is a consequence of the asymmetry in the plasma outflow, mainly due to the day/night asymmetry in the photoproduction rate in Titan's ionosphere, and the morphology of the magnetic field line draping.

[17] A difference of plasma composition, between inbound and outbound, have been observed by the CAPS experiment [*Szego et al.*, 2007]. Heavy ions of mass 14–18 AMU and mass $\simeq$30 AMU were only observed on the Saturn-facing edge (region 1) of the wake while the light ions with an ion mass of 2 AMU are present on the anti-Saturn edge (region 2). These observations can be compared with the simulation results of the plasma composition presented in Figure 3. Figures 3 (left) and 3 (right) show

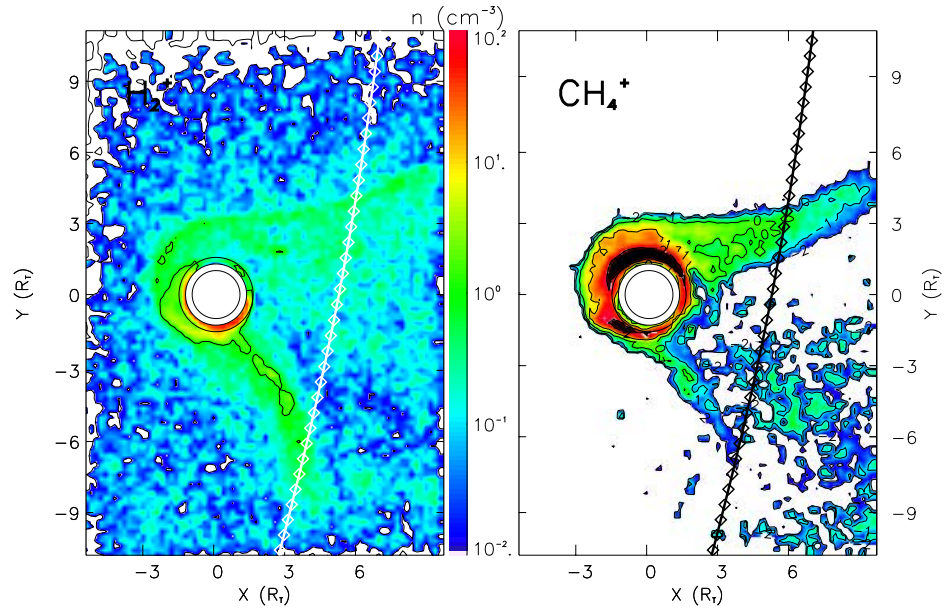


Figure 3. Density maps of (left) H_2^+ and (right) CH_4^+ in the XY plane of Titan. The trajectory of Cassini is indicated in the simulation coordinate system.

density maps of H_2^+ and CH_4^+ ions respectively, in the equatorial plane of Titan.

[18] Similar features are identified in the simulation (Figure 3, right), where only region 1 contains heavy ions, CH_4^+ (and N_2^+ ions not presented). The density map of light ions (Figure 3, left) gives a completely different picture. Due to the extended molecular hydrogen corona, the ionisation of the neutral corona leads to a significant plasma cloud of H_2^+ ions which extends far from Titan ($\geq$10 Titan radii). Note that the production rate of H_2^+ ions by charge exchange is relatively important far from Titan ($q_{H_2^+} \propto n(H_2)$) The H_2^+ production rate dominates above $\sim$2 R_T compared to the N_2^+ production rate. This plasma composition of the wake of Titan agrees very well with the observations reported by the CAPS and RPWS instruments [*Szego et al.*, 2007; *Modolo et al.*, 2007]. Photoionisation is the main ionisation source of CH_4 and N_2 while the extended corona of molecular hydrogen is essentially ionised by charge exchange reactions with the magnetospheric ions. On the Saturn-facing edge, also corresponding to the dayside hemisphere, heavy ions are produced and accelerated in the magnetic lobe by electric fields and are associated with the draping of the magnetic field lines around Titan. On the other hand, H_2^+ ions are formed on the ram-side and convected in the two magnetic lobes.

[19] One of the major loss mechanism of the neutral atmosphere can be described in terms of escaping plasma. Up to now, no significant cold plasma data set has been available to provide an accurate estimate of the escaping ion flux. Voyager 1 observations suggested a total plasma outflow of 1.2×10^{24} ions.s^{-1} from simple pressure balance considerations [*Gurnett et al.*, 1982] while the value given by the RPWS - Langmuir Probe measurements vary from 10^{25} ions/s for the Ta flyby [*Wahlund et al.*, 2005], to 2–7×10^{25} ions/s for this flyby [*Modolo et al.*, 2007]. Note that these estimates are given from observations along the path of the spacecraft and an assumption on the geometry of the escaping flux is mandatory, commonly a cylindrical geometry is used. Global simulation models are useful to set the observations in a global frame and provide an estimate of the total escaping flow without any assumptions on the morphology of the plasma outflow. MHD simulations computed with upstream plasma parameters similar to those encountered for Ta and Tb encounters, gave an estimate of the total ion escape fluxes of 5.1×10^{24} ions/s and 2.6×10^{24} ions/s respectively [*Ma et al.*, 2006]. Hybrid simulations performed by [*Sillanpää et al.*, 2006] indicate a net outflow of methane ions, of the order of 1.1×10^{25} ions/s, with different Titan's orbital positions. Our simulation model, performed with the T9 conditions, suggests a total escape flux of 5.6×10^{25} ions/s (with a contribution of 1.3, 2.4 and 1.9×10^{25} ions/s for N_2^+, CH_4^+ and H_2^+ respectively), in concordance with the Cassini's estimate. Since the presented simulation model does not include any loss term which can balance the ion production, the escaping flux estimated may be interpreted as a theoretical maximum total ion loss rates. Temperature and densities of neutral components in the range of 1200–2000 km control the extension of neutral coronae, and thus influence the ionic production rate; a better description of the upper atmosphere should improve the estimate of the ion escaping outflow. Moreover charge exchange cross sections used in the simulation model are assumed to be constant and do not vary with the energy. An energy dependance of the charge exchange cross-section might also affect the estimate of the escaping ion flux.

4. Conclusion

[20] Cassini observations have shown that Titan has a complex and dynamic plasma wake. Strong asymmetries on the electron number densities and in the plasma composition have been observed.

[21] Three-dimensional and multi-species hybrid simulations have been used to characterize the plasma wake of Titan using conditions similar to those encountered during

the T9 flyby. The simulations reproduce the main features observed in the electron number density derived by the RPWS measurements as well as plasma composition seen by the CAPS experiment. However, significant differences between computed and observed plasma parameters are still present. These differences may be due to some deficiencies in the simulation model, such as the coarse spatial resolution, or some temporal change in the upstream magnetospheric plasma conditions.

[22] We suggest that asymmetries observed during this flyby are a consequence of the asymmetry in the production, mainly the day/night asymmetry in the photoproduction rate in the ionosphere, and the upstream topology of the magnetic field. Observations plead in favour of an independent treatment of each ions species in order to reproduce self-consistently the different ion dynamic behaviour.

[23] **Acknowledgments.** R.M. and G.M.C. wish to acknowledge the International Space Science Institute (ISSI) in Bern for the support given to the International Team "Titan, a planetary scale laboratory: Preparing for the Cassini/Huygens exploration." They are also indebted to the Centre National d'Etude Spatiale (CNES) for their support.

References

Backes, H., et al. (2005), Titan's magnetic field signature during the first Cassini encounter, *Science*, *308*, 992–995, doi:10.1126/science.1109763.

Bertucci, C., F. M. Neubauer, K. Szego, J.-E. Wahlund, A. J. Coates, M. K. Dougherty, D. T. Young, and W. S. Kurth (2007), Structure of Titan's mid-range magnetic tail: Cassini magnetometer observations during the T9 flyby, *Geophys. Res. Lett.*, doi:10.1029/2007GL030865, in press.

Gurnett, D. A., F. L. Scarf, and W. S. Kurth (1982), The structure of Titan's wake from plasma wave observations, *J. Geophys. Res.*, *87*, 1395–1403.

Hartle, R. E., et al. (2006), Preliminary interpretation of Titan plasma interaction as observed by the Cassini Plasma Spectrometer: Comparisons with Voyager 1, *Geophys. Res. Lett.*, *33*, L08201, doi:10.1029/2005GL024817.

Ma, Y., A. F. Nagy, T. E. Cravens, I. V. Sokolov, K. C. Hansen, J.-E. Wahlund, F. J. Crary, A. J. Coates, and M. K. Dougherty (2006), Comparisons between MHD model calculations and observations of Cassini flybys of Titan, *J. Geophys. Res.*, *111*, A05207, doi:10.1029/2005JA011481.

Modolo, R., and G. M. Chanteur (2007), A global hybrid model for Titan's interaction with the kronian plasma: Application to the Cassini Ta flyby, *J. Geophys. Res.*, doi:10.1029/2007JA012453, in press.

Modolo, R., G. M. Chanteur, E. Dubinin, and A. P. Matthews (2005), Influence of the solar EUV flux on the Martian plasma environment, *Ann. Geophys.*, *23*, 433–444.

Modolo, R., J.-E. Wahlund, R. Boström, P. Canu, W. S. Kurth, D. Gurnett, G. R. Lewis, and A. J. Coates (2007), Far plasma wake of Titan from the RPWS observations: A case study, *Geophys. Res. Lett.*, *34*, L24S04, doi:10.1029/2007GL030482.

Neubauer, F. M., D. A. Gurnett, J. D. Scudder, and R. E. Hartle (1984), Titan's magnetospheric interaction, in *Saturn*, edited by T. Gehrels and M. S. Matthews, pp. 760–787, Univ. of Ariz. Press, Tucson.

Neubauer, F. M., et al. (2006), Titan's near magnetotail from magnetic field and electron plasma observations and modeling: Cassini flybys TA, TB, and T3, *J. Geophys. Res.*, *111*, A10220, doi:10.1029/2006JA011676.

Sillanpää, I., E. Kallio, P. Janhunen, W. Schmidt, K. Mursula, J. Vilpolla, and P. Tanskanen (2006), Hybrid simulation study of ion escape at Titan for different orbital positions, *Adv. Space Res.*, *38*, 799–805.

Szego, K., Z. Bebesi, C. Bertucci, A. J. Coates, F. Crary, G. Erdos, R. Hartle, E. C. Sittler, and D. T. Young (2007), Charged particle environment of Titan during the T9 flyby, *Geophys. Res. Lett.*, doi:10.1029/2007GL030677, in press.

Wahlund, J.-E., et al. (2005), Cassini measurements of cold plasma in the ionosphere of Titan, *Science*, *308*, 986–989, doi:10.1126/science.1109807.

Waite, J. H., et al. (2005), Ion neutral mass spectrometer results from the first flyby of Titan, *Science*, *308*, 982–986, doi:10.1126/science.1110652.

Yelle, R. V., N. Borggren, V. de La Haye, W. T. Kasprzak, H. B. Niemann, I. Müller-Wodarg, and J. H. Waite (2006), The vertical structure of Titan's upper atmosphere from Cassini Ion Neutral Mass Spectrometer measurements, *Icarus*, *182*, 567–576, doi:10.1016/j.icarus.2005.10.029.

C. Bertucci, Space and Atmospheric Physics Group, Imperial College London, Exhibition Road, London SW7 2BZ, UK.

P. Canu and G. M. Chanteur, Centre d'Etudes des Environnements Terrestre et Planétaires, Institut Pierre Simon Laplace, 10-12 avenue de l'Europe, F-78140 Vélizy, France.

D. Gurnett and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA.

A. P. Matthews, School of Physics, University of KwaZulu-Natal, Durban 4041, South Africa.

R. Modolo and J.-E. Wahlund, Swedish Institute of Space Physics, Uppsala Division, Box 537, SE-75121 Uppsala, Sweden. (modolo@irfu.se)