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Morphology of the magnetic field near Titan: Hybrid model study of the Cassini T9 flyby

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[1] We study the deformation and morphology of the magnetic field near Titan by a three-dimensional numerical quasi-neutral hybrid model (HYB-Titan). We analyze two runs, one in which the sub-rotating plasma consists of oxygen (O^+) ions and protons (H^+) and another with only protons. We find that both cases result in the generation of Alfvén wing-like flux tubes. In comparison with the proton-only case, the direction and magnitude of the magnetic field in the oxygen-rich flow case are in better agreement with Cassini magnetic field observations during its Titan T9 flyby on Dec. 26, 2006, suggesting that the sub-rotating plasma contained heavy ions. The oxygen-rich run also supports the hypotheses that (1) the sub-rotating flow direction was offset by $\sim 30^\circ - 40^\circ$ from the ideal rotating flow direction and that (2) the spacecraft was magnetically connected to the sunlit side of near-Titan space in the tail when it approached Titan on the T9 flyby. **Citation:** Kallio, E., I. Sillanpää, R. Jarvinen, P. Janhunen, M. Dougherty, C. Bertucci, and F. Neubauer (2007), Morphology of the magnetic field near Titan: Hybrid model study of the Cassini T9 flyby, *Geophys. Res. Lett.*, *34*, L24S09, doi:10.1029/2007GL030827.

1. Introduction

[2] Saturn's moon Titan is a unique object for studying how a surrounding magnetized plasma flow interacts with a non-magnetized object with a dense atmosphere. Titan does not have a significant global intrinsic magnetic field. In that respect, Titan resembles Mars and Venus and these three objects can be expected to have similarities in the way they interact with the flowing plasma. However, Titan is most of the time embedded in Saturn's magnetosphere where the properties of the flowing plasma differ remarkably from the properties of the solar wind, especially in terms of composition and temperature of the plasma. The direction of the flow and the direction of the EUV source, the Sun, also vary periodically as Titan orbits Saturn.

[3] Understanding the Titan-Kronian magnetospheric plasma interaction is one of the science objectives of Cassini mission. The ion, electron and the magnetic field instruments onboard have made it possible to measure in detail the ram and wake sides of Titan in various EUV illumination conditions. The T9 flyby, that took place on Dec. 26, 2006, is especially interesting for studying the formed interaction region globally. During this flyby the Cassini spacecraft crossed Titan's plasma wake at a reasonable distance, several R_T (R_T = 2575 km), from Titan.

[4] In this paper the deformation and morphology of the magnetic field near Titan are studied by a global numerical three-dimensional (3D) quasi-neutral hybrid (QNH) model, which provides a global view to local in situ measurements. We analyze in detail two runs, one made with and another made without oxygen ions (O^+) in the sub-rotating flow. In addition, we study the resulting magnetic field line pattern during the T9 flyby. The measurements have shown a substantial enhancement of the electron density [*Modolo et al.*, 2007], a change in the electron energy spectra [*Coates et al.*, 2007] and an appearance of cold heavy ions [*Szego et al.*, 2007] during the ingress. These observations have been suggested to be a manifestation of the magnetic connection between the spacecraft and Titan's sunlit hemisphere [*Coates et al.*, 2007; *Wei et al.*, 2007].

[5] The paper is organized as follows. We first introduce some of the main characteristics of the numerical model. Then we compare the magnetic morphology in two runs made for different compositions of the sub-rotating flow. Finally, we analyze the magnetic connection of the spacecraft to Titan during the T9 flyby.

2. Description of the Model

[6] In this paper the Kronian magnetospheric plasma-Titan interaction is analyzed by a three-dimensional self-consistent quasi-neutral hybrid (QNH) model (HYB-Titan). In the HYB-Titan model ions are treated as particles while electrons form a massless charge-neutralizing fluid. The model was developed for studying the solar wind interaction with Mars, but it has thereafter been extended to other solar system objects, most recently Titan [*Kallio et al.*, 2004; *Sillanpää et al.*, 2007]. The model is described in detail in the literature (see, aforementioned references) and here we list only those features that are the most relevant for the present study.

2.1. QNH Model and QNH-Coordinate System ($\mathbf{e}_x^{QNH}$, $\mathbf{e}_y^{QNH}$, $\mathbf{e}_z^{QNH}$)

[7] The base of the coordinate system used in the QNH runs is the following. The sub-rotating plasma flows to $\mathbf{e}_x^{QNH}$ direction, $\mathbf{e}_z^{QNH}$ gives the direction of the $+z_{QNH}$ axis and $\mathbf{e}_y^{QNH}$ completes the right-handed coordinate system.

[8] In both runs, the size of the simulation box is -24720 km (-9.6 R_T) < x_{QNH} < 30900 km (12 R_T), -30900 km (-12 R_T) < y_{QNH} < 30900 km (12 R_T), and

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-24720 km (-9.6 R_T) < z_{QNH} < 24720 km (9.6 R_T) where R_T = 2575 km is the radius of Titan. The simulations contain three grid sizes: 2060 km (=0.8 R_T), 1030 km (=0.4 R_T), and 515 km (=0.2 R_T) and the smallest grid size is used near Titan. The average number of ions in a grid cell is 40 and the used time step is 0.4 s. The inner boundary of the model is a spherical shell at r = 3500 km (r = $(x^2_{QNH} + y^2_{QNH} + z^2_{QNH})^{1/2}$) $\sim$ 1.36 R_T which mimics the exobase. Consequently, HYB-Titan does not include a self-consistently modeled ionosphere. Finally, ions are removed from the simulation when they cross the inner boundary.

2.2. TIIS Coordinate System ($\mathbf{e}_x^{TIIS}$, $\mathbf{e}_y^{TIIS}$, $\mathbf{e}_z^{TIIS}$)

[9] The trajectory of Cassini and magnetic field measurements are commonly presented in Titan-interaction coordinates (TIIS) in which the unit base vector $\mathbf{e}_z^{TIIS}$ points to North of Saturn, $\mathbf{e}_x^{TIIS}$ (=$\mathbf{e}_z^{TIIS}$ x $\mathbf{r}_{Titan}/|\mathbf{r}_{Titan}|$, where $\mathbf{r}_{Titan}$ is the vector from the center of Saturn to Titan) is the direction of the ideal rotating flow around Saturn. The unit vector e_y^{TIIS} completes the right-handed coordinate system and points to Saturn.

[10] The TIIS coordinates differs from the QNH coordinates if the sub-rotating plasma does not flow along $\mathbf{e}_x^{TIIS}$. The relation between the two coordinate systems can be expressed by a rotation matrix $\mathbf{R}$:

$$\mathbf{e}_i^{TIIS} = \mathbf{R}(\alpha,\beta,\gamma)\mathbf{e}_i^{QNH}, \quad i = x, y, z \tag{1}$$

[11] Here $\mathbf{R}(\alpha,\beta,\gamma) = \mathbf{R}_z(\gamma)*\mathbf{R}_y(\beta)*\mathbf{R}_x(\alpha)$, where $\mathbf{R}_x(\alpha)$ = [1 0 0; 0 cos(α) $-$sin(α); 0 sin(α) cos(α)], $\mathbf{R}_y(\beta)$ = [cos(β) 0 sin(β); 0 1 0; $-$sin(β) 0 cos(β)], and $\mathbf{R}_z(\gamma)$ = [cos(γ) $-$sin(γ) 0; sin(γ) cos(γ) 0; 0 0 1] are the rotation matrices that rotate the coordinate system counterclockwise the angles α, β and γ about the vectors $\mathbf{e}_x^{QNH}$, $\mathbf{e}_y^{QNH}$ and $\mathbf{e}_z^{QNH}$, respectively. The coordinate transformations between QNH and TIIS coordinates are therefore

$$[v_x, v_y, v_z]_{QNH} = \mathbf{R}(-\alpha,-\beta,-\gamma) \times [v_x, v_y, v_z]_{TIIS} \tag{2a}$$

$$[v_x, v_y, v_z]_{TIIS} = \mathbf{R}(\alpha,\beta,\gamma) \times [v_x, v_y, v_z]_{QNH} \tag{2b}$$

where $[v_x, v_y, v_z]_{QNH}$ and $[v_x, v_y, v_z]_{TIIS}$ are vectors in QNH and TIIS coordinates, respectively. In this paper the trajectory of Cassini and the result of QNH model run are presented in QNH coordinates.

2.3. Upstream Parameters

[12] In the first study of this paper we analyze the response of the morphology of the magnetic field to two flow cases which are referred to as the H-run and the O-run. The macroscopic properties (density, bulk velocity, temperature) of different ion species in the sub-rotating plasma are not well-establish but the total magnetospheric electron density based on ELS measurements is estimated to be about 10^{-1} cm^{-3} [*Coates et al.*, 2007]. In the O-run the sub-rotating plasma was assumed to consists of two ion species, H^+ and O^+ ions, and in the H-run H^+ and H_2^+ ions. In the O-run the upstream densities are set to n(O^+) = 0.2 cm^{-3}, n(H^+) = 0.1 cm^{-3}, and in the H-run they are n(H^+) = 0.3 cm^{-3}, n(H_2^+) = 0.1 cm^{-3}. The ion bulk velocities are also parameters that we can only use estimates for the T9 flyby. In both simulation cases the bulk velocities are set to $\mathbf{U}_{corot}$ = $[U_x, U_y, U_z]_{QNH}$ = $[120, 0, 0]_{QNH}$ km s^{-1} and the sound speed, c_s, is assumed to be 164 km s^{-1}, close to the situation during Voyager 1 flyby in 1980 [*Neubauer et al.*, 1984]. The analyzed cases are therefore subsonic with a sonic Mach number M_s ($\equiv U_{corot}/U_{sound}$) = 0.73. The Alfvén Mach number M_A ($\equiv U_{corot}/(B/(4\pi \times 10^{-7} \times \rho)^{-1/2})$ where ρ is the total mass density) in the H-run is 0.54 and in the O-run 1.40.

[13] Both runs contain also methane (CH_4^+) photoions which are generated from a Chamberlain density profile (see *Sillanpää et al.* [2007] for details of the neutral profiles). The total CH_4^+ production rate within the simulation box in the O-run is 5.1×10^{24} s^{-1} and 1.7×10^{25} s^{-1} in the H-run corresponding a solar photoionization rate of $\sim 10^{-7}$ s^{-1}–10^{-8} s^{-1} [see *Sillanpää et al.*, 2007]. Because of the small scale height of nitrogen compared to the grid size, nitrogen ions (N_2^+) are generated differently from methane ions in the HYB-Titan model: In the H-run, 2.0×10^{25} s^{-1} N_2^+ ions are emitted from the exobase with a small velocity ($\sim$2 km s^{-1}) away from Titan. In the O-run no N_2^+ ions were used. The extreme ultraviolet (EUV) radiation source, the Sun, is in the direction which corresponds to the Saturn local time (SLT) during the T9 flyby (SLT = 3.03 h) and the subsolar latitude of $-20°$.

[14] In the analyzed runs $\mathbf{B}_{corot}$ is assumed to be $[3.7368, 5.7010, -2.1546]_{TIIS}$ nT, very close as observed by MAG magnetometer onboard Cassini [see *Bertucci et al.*, 2007]. However, the direction and magnitude of $\mathbf{U}_{corot}$ have not been accurately determined. The location of the polarity reversal layer of the magnetic tail suggests that the velocity vector points about 30° away from $\mathbf{e}_x^{TIIS}$ towards the anti-Saturn direction (i.e. towards $-\mathbf{e}_y^{TIIS}$). In this study we assume about 30° angle between $\mathbf{B}_{corot}$ and $\mathbf{U}_{corot}$ vectors and use $\mathbf{B}_{corot}$ = $[-0.47, 6.91, -1.78]_{QNH}$ nT.

2.4. Comparison Between the O-Run and the H-Run and the Used Coordinate Transformation

[15] The more accurately the model can reproduce the observed directions of the magnetic field, the more accurate the obtained field lines can be anticipated to be. In this work the direction of $\mathbf{U}_{corot}$ is studied by an automatic algorithm that rotates the trajectory of Cassini in QNH coordinates with a rotation matrix $\mathbf{R}(\alpha, \beta, \gamma)$ for α from $-40°$ to 40°, β from $-40°$ to 40° and γ from $-40°$ to 40° in 2.5° steps calculating the minimum average difference between the direction of $\mathbf{B}$ based on MAG data and the direction of $\mathbf{B}$ based on QNH model. The optimal rotation angles for the O-run were $\alpha = -5°$, $\beta = -10°$ and $\gamma = -30°$, with the average difference of 10.3° between the directions of the simulated and observed magnetic field vectors along the T9 trajectory. The optimal fit corresponds to an optimal $\mathbf{B}_{corot}$ = $\mathbf{R}(5°, 10°, 30°) \times [-0.47, 6.91, -1.78]_{QNH}$ nT = $[3.3207, 5.8523, -2.4210]_{TIIS}$ nT. The relatively small difference between the found optimal direction of $\mathbf{B}_{corot}$ and the observed direction supports the conclusion that the sub-rotating flow is offset by about 30°–40° from the TIIS x-axis. The optimal fit for the H-run is found at a relatively similar rotation angle ($\alpha = -17.5°$,

$\beta = -25°$ and $\gamma = -32.5°$). However, the H-run does not succeed in reproducing the observed change in the B_x component, a signature in the data that is discussed later in Section 3.2., implying that the morphology of the magnetic field of the O-run is better in agreement with magnetic field observations than that of the H-run. In this paper the transformation of the magnetic field from QNH coordinates to TIIS coordinates is carried out by using the optimal rotation matrix we have found: $\mathbf{R}(5°, 10°, 30°)$.

3. Morphology of the Magnetic Field

3.1. Alfvén Wing-Like Structure

[16] Figure 1 shows the magnetic field lines in the H-run. The field lines, the color planes and the trajectory of Cassini during its T9 flyby are presented in QNH coordinates. The TIIS coordinate axes are added to visualize the relation between the coordinates.

[17] In the H-run the magnetic field lines near Titan ($r < 2\ R_T$) form a narrow flux tube far away from Titan ($r > 5\ R_T$). The diameter of the cross cut of the flux tube is about the same as the diameter of the exobase. The flux tube is approximately on the plane which contains the center of Titan, $\mathbf{U}_{corot}$ and $\mathbf{B}_{corot}$ vectors (Figure 1c). It is worth noting that the Alfvén angle, $\alpha_{Alfvén}$ ($\equiv$ atan(M_A^{-1})), is 62°. This provides a good first order approximation for the angle between the flux tube and the x_{QNH} axis that is seen in Figure 1. Although a detailed analysis of the morphological properties of the magnetic field lines is beyond the scope of the present study, it is interesting to note that the field line bulge seen in Figure 1 resembles field lines associated with so-called Alfvén wings [see, e.g., *Neubauer*, 1998].

[18] Figure 2a displays the field lines in the O-run where the field line starting points are the same as in Figure 1. Compared with the H-run, the field lines are now spread in a larger volume in space. Some of the field lines are only slightly draped around Titan much like the field lines in the undisturbed sub-rotating flow, while some are highly draped. However, a clear flux tube like structure exists also in the O-run, as seen in Figure 2b, where the field

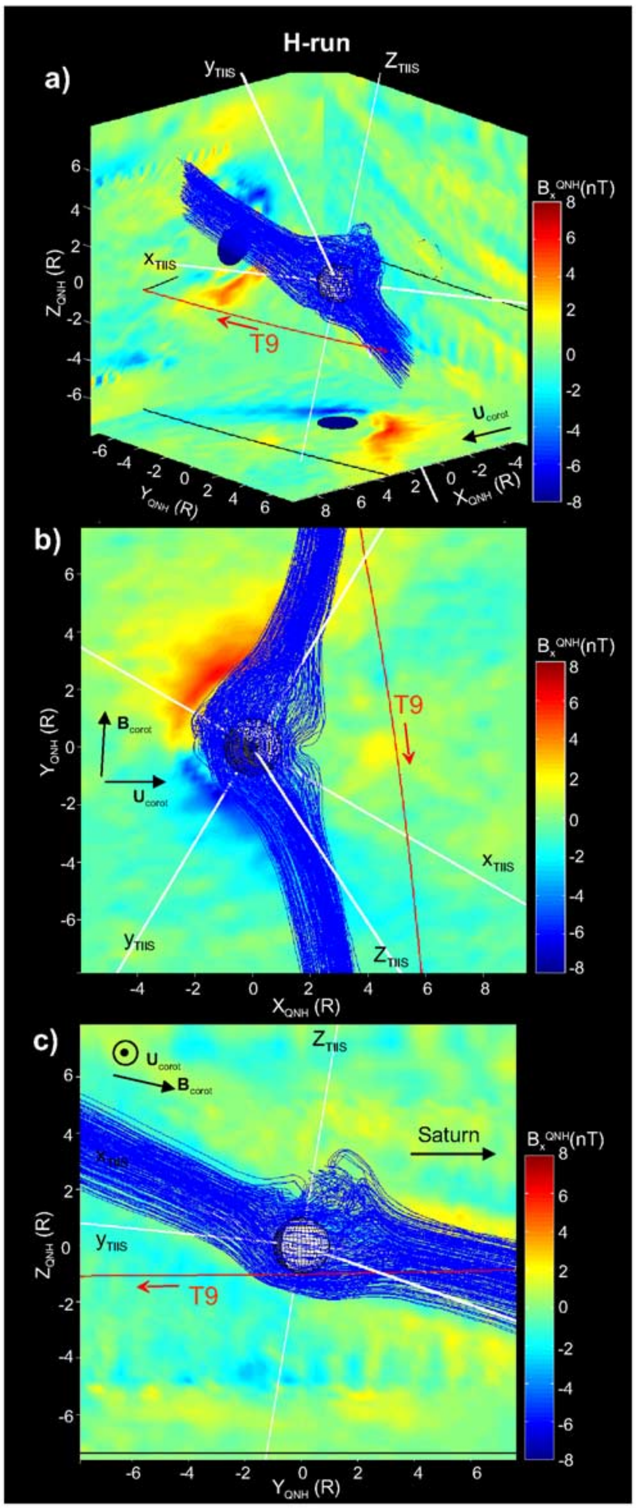

Figure 1. The morphology of the magnetic field lines (blue lines) in the H-run in which the dominating ion species in the sub-rotating flow is H^+ ions viewed in (a) 3-D, (b) along the z_{QNH} axis, and (c) along the x_{QNH} axis. The magnetic field line tracing is started on a surface of a spherical shell at 4350 km ($\sim$1.7 R_T) from the center of Titan. The red line shows the trajectory of Cassini during its T9 flyby. The black lines present the trajectory of Cassini projected along the QNH coordinate axes on the XY_{QNH}, XZ_{QNH}, and YZ_{QNH} planes. The color on the three perpendicular planes show B_x in QNH coordinates at $x_{QNH} = 5\ R_T$, $y_{QNH} = 0$, and $z_{QNH} = 0$ planes which are moved to $x_{QNH} = -5\ R_T$, $y_{QNH} = -8\ R_T$, and $z_{QNH} = -8\ R_T$ so that they do not hide the field lines. The magnetic field lines and the color planes are presented in the QNH coordinates in which the sub-rotating plasma flows to $+x_{QNH}$ direction. The three white lines show the x_{TIIS}, y_{TIIS}, and z_{TIIS} coordinate axis whose attitude is fixed to the Saturn-Titan system at a given position of Titan. The labels x_{TIIS}, y_{TIIS} and z_{TIIS} show the pointing directions of the TIIS axes, $\mathbf{U}_{corot}$ the direction of the ideal rotating flow, $\mathbf{B}_{corot}$ the direction of the magnetic field in the undisturbed sub-rotating flow, and T9 the trajectory of Cassini. The red arrows show the direction of the Cassini spacecraft on the T9 trajectory.

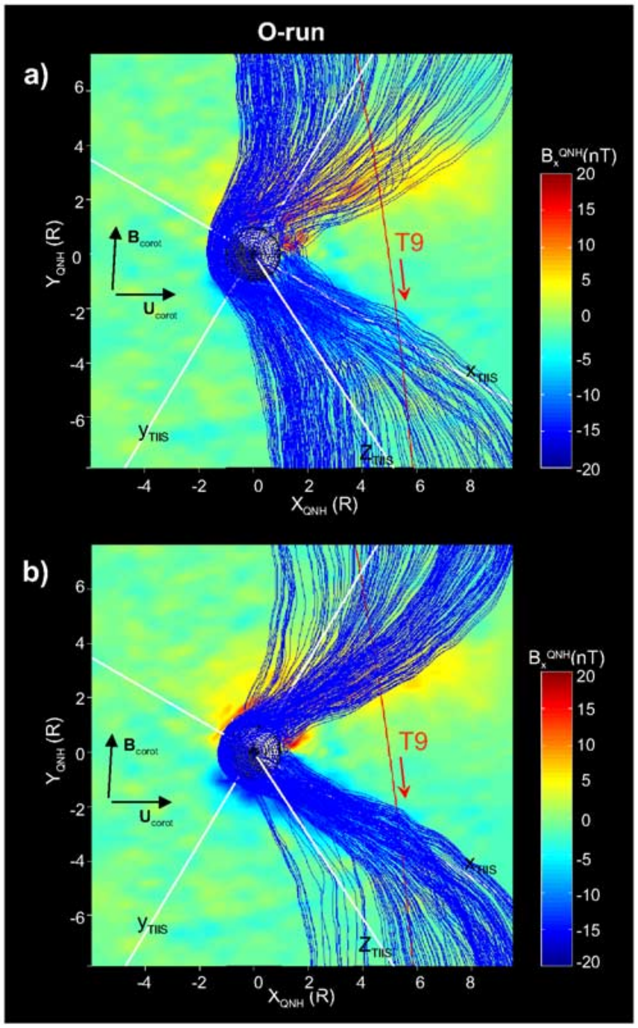

Figure 2. The morphology of the magnetic field lines in the O-run in which the dominating ion species is O^+ ions viewed along the $+z_{QNH}$ axis. (a) The magnetic field line tracing is started on a surface of a spherical shell at 1.7 R_T from the center of Titan as in Figure 1. (b) The magnetic field line tracing was started closer to Titan near the model exobase. Note that the color scale of B_x is from −20 nT to 20 nT while in Figure 1 in the H-run it was from −8 nT to 8 nT. See Figure 1 for the description of the lines and the color planes.

line tracing starts almost at the height of the exobase. In the O-run $\alpha_{\text{Alfvén}} = 36°$, that is, the draping angle is much smaller than in the H-run. The morphological difference of the magnetic field lines between the O-run (Figure 2a) and the H-run (Figure 1) is the consequence of the difference in spatial size of the interaction region near Titan, which is magnetically connected to Alfvén wing-like structure. The interaction region is closer to Titan in the O-run than in the H-run. It is also worth noting that in the O-run the B_x component differs more from its original value than in the H-run.

[19] The red lines in Figure 1 and Figure 2 show the trajectory T9 of Cassini. The spacecraft is approaching Titan from the $y_{QNH} > 0$ hemisphere, which is the Saturn-facing hemisphere. As seen especially in Figure 1b, the trajectory never connects to the flux tube within a simulation box in the H-run. In the O-run, on the contrary, the simulation suggests that on $y_{QNH} > 0$ (the Saturn-facing hemisphere) the spacecraft was magnetically connected to region near the exobase. The magnetic connection to the T9 trajectory will be studied in more detail in section 3.2.

3.2. Magnetic Connection of Cassini's Trajectory to Titan During the T9 Flyby

[20] The blue lines in Figure 3 show the magnetic field lines which are connected to the T9 trajectory in the O-run. The model suggests that the spacecraft was initially, at $y_{QNH} \sim 6\ R_T$, magnetically connected to the sunlit side near Titan. Near the closest approach, both before and after it, the spacecraft was, on the contrary, on the magnetic field lines that did not connect to regions near Titan. The simulation also suggests that methane ions, which are presented in Figure 3 as red dots, were escaping from Titan asymmetrically with respect to the direction of the convective electric field in the undisturbed flow, $\mathbf{E}_{corot}$ ($\equiv -\mathbf{U}_{corot} \times \mathbf{B}_{corot}$).

[21] A comparison between the direction of the magnetic field on MAG data and in the O-run during the T9 flyby can be seen in Figure 4. The three upper panels show a comparison between the direction of MAG data and QNH model, and the fourth panel displays the total magnetic field. The bottom panel gives the closest distance of the magnetic field line above the exobase that is magnetically connected to the trajectory of the spacecraft at a given time. The distances are derived from the magnetic field lines that are shown in Figure 3. The bottom panel shows that at UT ~ 18:10–18:30 h the spacecraft was magnetically connected to the regions very close ($r < 2R_T$) to Titan. On the other hand, at UT ~ 19:10–19:30 h, when a clear change in B_x takes place, the spacecraft was in a region where the magnetic field lines do not connect to close Titan's exobase.

4. Discussion

[22] We have also studied the role of the mass of the sub-rotating plasma by making a pure H^+ run where the upstream flow consisted only of H^+ ions with the density of 3.3 cm^{-3} and where M_A is, consequently, 1.4 as in the O-run. The pure H^+ flow results in similar type of Alfvén wing-like structures as in the O-run, but in this case the cross section of the flux tube increases only slightly in the tail, causing an unrealistically large maximum magnetic field along T9 (about 14 nT, the figure not shown). This implies that the mass of sub-rotating plasma, not only M_A, affects the morphology of the magnetic field, and suggests that the sub-rotating plasma during the T9 flyby likely contained a substantial amount of heavier ions, as assumed in the analyzed O-run.

[23] Finally, our global view of the Cassini T9 flyby with our simulation results has many characteristic features similar to T9 runs that have also been reproduced using a 3D MHD model (Y. Ma et al., unpublished manuscript, 2007) and another 3D hybrid model [*Modolo et al.*, 2007]. The common features include the formation of a magnetotail or delta wing-like features in the anti–ram side region and asymmetric escape of methane ions. Our results are also

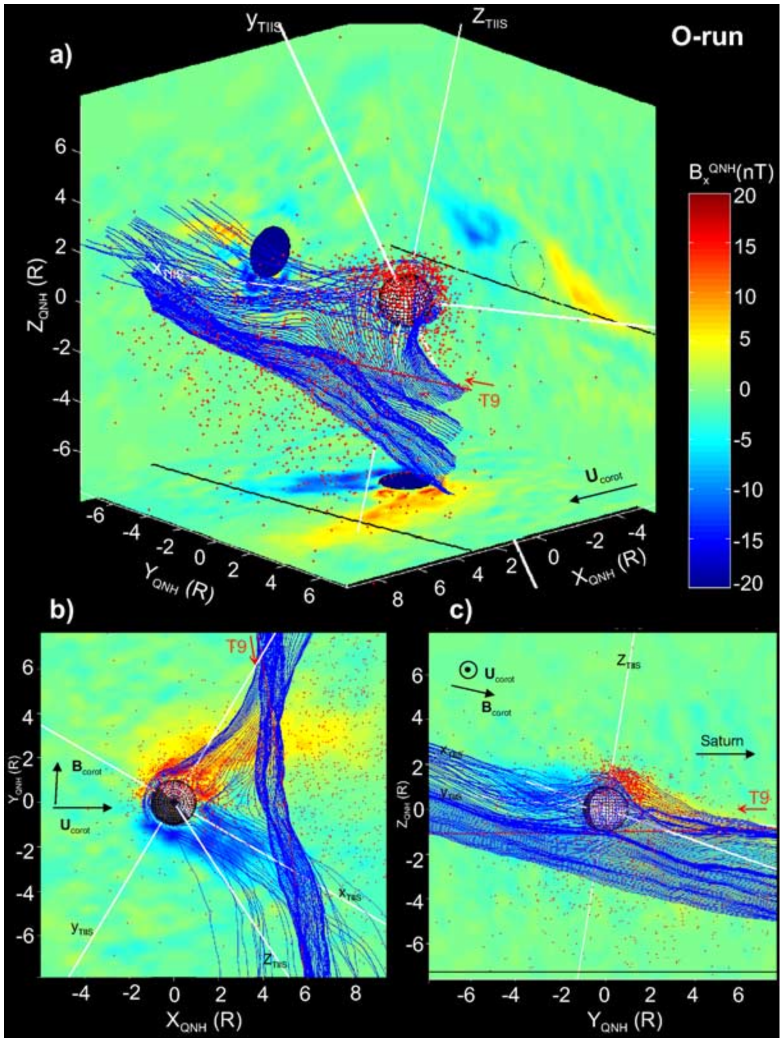

Figure 3. The magnetic connection of the trajectory T9 to Titan in the O-run. The magnetic field line tracing was started on the T9 trajectory. Two hundred red dots represent escaping CH_4^+ ions. Their positions are generated randomly to the simulation box from the density of CH_4^+ ions, based on the O-run. Note that the T9 trajectory and the field lines are in a 3D space and, therefore, some of the field lines are above and some below the T9 flyby trajectory at a given vantage point. See Figure 1 for the description of the lines and the color planes.

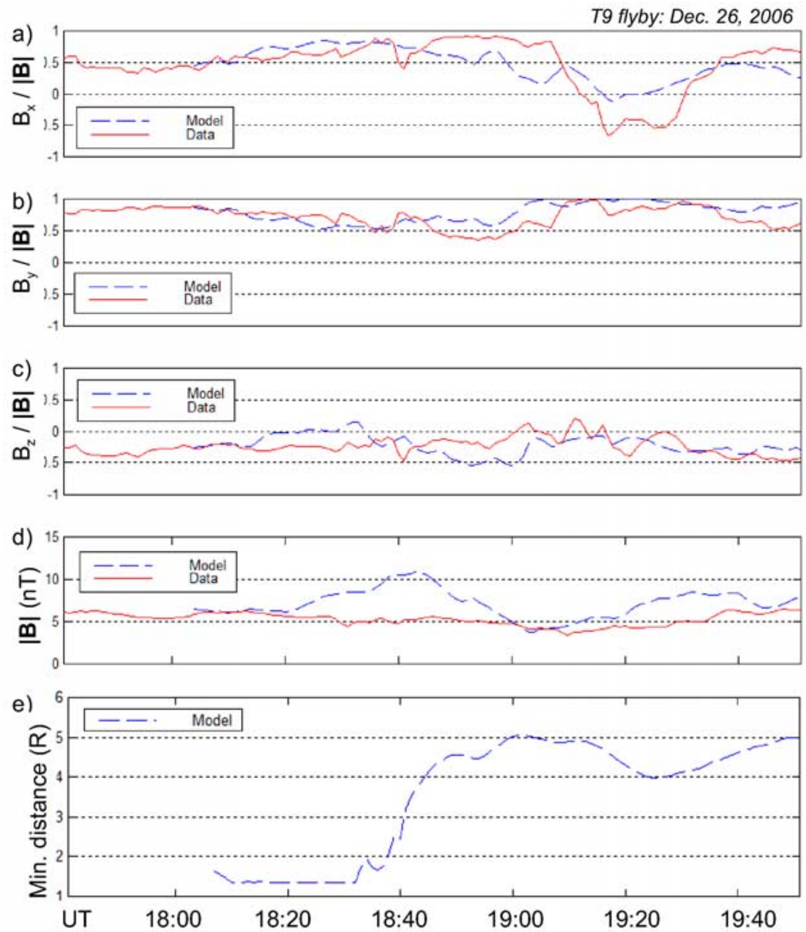

Figure 4. Comparison of (a, b, c) the direction and (d) the magnitude of the magnetic field in the hybrid mode in the O-run and MAG/CASSINI measurements on the T9 flyby on Dec. 26, 2006. (e) The minimum distances of the field lines that are shown in Figure 3 from the center of Titan at a given time along the T9 flyby trajectory.

in line with election and ion measurements during the T9 flyby, which have shown a clear composition difference between the region before and after the closest approach and which has been suggested to be a manifestation of the change of the magnetic connection between the spacecraft and Titan [*Szego et al.*, 2007; *Coates et al.*, 2007].

5. Summary

[24] A global numerical model is used to study the morphology of the magnetic field lines near Titan in two cases: (1) when the sub-rotating flow contains heavy O^+ ions, and (2) when oxygen ions are absent. Both cases are found to result in Alfvén wing-like magnetic morphology. The draping of the field lines around Titan, as well as the change of the magnetic field from the undisturbed values, however, are very different between the analyzed cases. A comparison between the runs suggests that the sub-rotating flow contained substantial amount of heavy ions during Cassini's T9 flyby, and that the spacecraft was magnetically connected to the sunlit hemisphere during the ingress phase of the flyby. These results are in line with *in situ* particle measurements [*Wei et al.*, 2007; *Coates et al.*, 2007].

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