Titan at the edge: 2. A global simulation of Titan exiting and reentering Saturn's magnetosphere at 13:16 Saturn local time

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[1] We use a multifluid/multiscale model of Titan inside Saturn's magnetosphere to examine how Titan's induced magnetosphere and ion tail are affected when Titan crosses Saturn's magnetopause at 13:16 Saturn local time (SLT). During the simulation Titan crosses Saturn's magnetopause twice, exiting and reentering Saturn's magnetosphere. The magnetic field in Saturn's magnetosheath is predominately northward. Once inside Saturn's magnetosheath, Titan's connection to Saturn's magnetosphere is removed by slow ionospheric convection. Evidence for reconnection at Titan is not seen. Inside the magnetosheath the plasma flow is not perpendicular to the magnetic field, and magnetic field lines do not strongly drape around Titan. Titan's ionosphere is extended in the magnetosheath because Titan's ionospheric plasma is not stripped away by convecting magnetic field at high altitudes. After Titan crosses back into Saturn's magnetosphere, the magnetospheric plasma and field removes Titan's extended ionosphere, and Titan's induced magnetosphere returns to a "typical" configuration. The simulation is used to determine the time scale of Titan's connection to Saturn's magnetic field lines or magnetosheath magnetic field lines after a magnetopause crossing. In the magnetosheath, slow (~3 km/s) ionospheric convection removes Titan's connection to Saturn's magnetosphere in ~1.8 h. After Titan crosses back into Saturn's rapidly rotating magnetosphere, Titan's connection to magnetosheath magnetic field lines is removed through ionospheric convection in ~50 min. The results of the simulation are also compared to data from Cassini's T32 flyby.

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1. Introduction

[2] Typically, Titan orbits within Saturn's magnetosphere. However, Saturn's dayside magnetosphere is highly compressible. *Achilleos et al.* [2008] found that the subsolar distance of Saturn's magnetopause has a bimodal distribution with peaks at 22 and 27 R_S and a range from about 18 to 29 Saturn radii (R_S, 1 RS = 60,268 km). The data of *Achilleos et al.* [2008] suggest that at 12:00 Saturn local time (SLT) Titan's orbit is outside of Saturn's magnetosphere ~5% of the time. Therefore, Titan should occasionally interact with the solar wind and interplanetary magnetic field (IMF). In fact, Titan was observed outside of Saturn's magnetopause during Cassini's T32 flyby on 13 June 2007 when Titan was located at 13:16 SLT [*Bertucci et al.*, 2008]. Cassini was on an outbound trajectory and crossed magnetopause at 17:35 UT, just 20 min before closest approach [*Bertucci et al.*, 2008; *Garnier et al.*, 2009].

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[3] During the T32 flyby fossil magnetic field lines were detected within Titan's ionosphere [*Bertucci et al.*, 2008]. The direction of magnetic field observed by Cassini at low altitudes in Titan's ionosphere corresponded to a draped field that was initially southward. However, the interplanetary magnetic field (IMF) direction in the magnetosheath was northward. *Bertucci et al.* [2008] proposed that magnetic field lines at lower altitudes were frozen into Titan's ionosphere when Titan was still inside Saturn's magnetosphere and were preserved within Titan's ionosphere even after Titan crossed Saturn's magnetopause and entered Saturn's magnetosheath. *Bertucci et al.* [2008] estimated that the lifetime of the frozen in fields was between 20 min and 3 h. *Neubauer et al.* [2006] first suggested such fossil fields should exist in Titan's ionosphere and it is likely that fossil fields are observed frequently by Cassini, since the magnetic field configuration is highly variable near Titan [*Bertucci et al.*, 2009; *Simon et al.*, 2010a]. During the T32 flyby the presence of fossil fields was particularly obvious because the IMF was oriented northward, opposite to Saturn's magnetic field.

[4] Several models have been used to simulate how crossing Saturn's magnetopause affects Titan's magnetospheric interaction. *Ma et al.* [2009] simulated Titan cross-

Table 1. Summary of Noted Events in the Simulation

Event	Time (h)	B_{IMF} (nT)	P_{SW} (nPa)	R_{SW} (R_S)
Titan placed in simulation	48.0	[0, 0, 0.05]	0.008	25
Arrival of SW pressure pulse	51.7	[0, 0, 0.2]	0.022	25
Titan crosses into magnetosheath	52.4	[0, 0, 0.2]	0.022	18.75
Titan sheds Kronian magnetic field	54.2	[0, 0, 0.2]	0.022	18.75
Titan crosses into magnetosphere	55.3	[0, 0, 0.2]	0.022	22
Titan sheds magnetosheath field	56.1	[0, 0, 0.2]	0.022	22
SW pressure is reduced	57.0	[0, 0, 0.1]	0.008	27

ing the magnetopause into northward IMF using two MHD simulations. In the first simulation, only the magnetic field was changed, it was rotated from −8 to 8 nT. In the second simulation, the magnetic field was rotated from −8 to 8 nT and, simultaneously, the plasma density was increased and temperature was decreased. Real-time magnetic profiles along Cassini's T32 trajectory in both simulations were equivalent and able to reproduce the fossil field signatures in the T32 magnetometer data. The simulations of *Ma et al.* [2009] predicted reconnection of field lines downstream of Titan and a detachment of Titan's ion tail after Titan crossed into the magnetosheath. *Ma et al.*'s [2009] simulations determined that the lifetime of fossil field lines in Titan's ionosphere was slightly less than 2 h.

[5] *Simon et al.* [2009] also simulated Titan crossing a simplified magnetopause using a hybrid model. The resolution of the ionosphere in *Simon et al.*'s [2009] hybrid model was not sufficient to simulate fossil magnetic field lines within Titan's ionosphere, therefore their simulations could not address the lifetime of fossil fields. Although the upstream parameters were similar to the parameters used in the models of *Ma et al.* [2009], *Simon et al.*'s [2009] simulation did not result in a large-scale detachment of Titan's ion tail.

[6] *Müller et al.* [2010] simulated Titan crossing Saturn's magnetopause using a hybrid model that had better resolution than the *Simon et al.* [2009] model and a more physically correct treatment of the conductivity of Titan's ionosphere and interior. They simulated two cases: Titan crossing into a magnetosheath flow oriented parallel to the magnetospheric flow and Titan crossing into a magnetosheath flow oriented antiparallel to the magnetospheric flow. *Müller et al.* [2010] found the lifetime of Kronian fossil fields in Titan's ionosphere to be about 25 min. *Müller et al.* [2010] suggested that the treatment of magnetic diffusion through Titan's interior caused the large difference between the lifetime of fossil fields in their simulation and the simulations of *Ma et al.* [2009]. However, *Müller et al.* [2010] also noted since ion-neutral collisions that slow the convections of fossil fields to lower altitudes were not included their results should be regarded as a lower limit for the lifetime of fossil fields. Similar to the results of *Simon et al.* [2009], *Müller et al.*'s [2010] results also included no large-scale reconnection and detachment of Titan's ion tail.

[7] Interestingly, the results of *Müller et al.* [2010] and *Ma et al.* [2009] indicate that changing the ambient plasma density, temperature, and velocity does not affect the lifetime of fossil fields in the lower ionosphere. These simulations show that the lifetime of fossil fields is determined by the conductivity of the lower ionosphere rather than the ambient space environment because Titan's upper ionosphere shields the lower ionosphere from changes in ambient conditions. Therefore, the properties of fossil magnetic fields are best addressed with local simulations with good resolution inside the ionosphere.

[8] The focus of this paper is on large-scale features of Titan's induced magnetosphere instead of fossil fields within Titan's ionosphere. In particular, a multifluid/multiscale simulation of Titan embedded in Saturn's magnetosphere is used to determine how crossing Saturn's magnetopause affects Titan's ion tail and induced magnetosphere. During the simulation Titan crosses Saturn's magnetopause and enters the magnetosheath, and after a few hours crosses back into Saturn's magnetosphere. The results of the simulation describe how the plasma and field conditions upstream of Titan change as Titan crosses the magnetopause and how those changes affect the properties of Titan's ion tail and induced magnetosphere. The simulation is also used to determine the time scales for Titan's detachment from Saturn's magnetosphere after crossing into the magnetosheath, as well as the time scale for Titan's detachment from magnetosheath fields after Titan crosses back into Saturn's magnetosphere. The simulation results will also be compared with magnetic field and electron density data from Cassini's T32 flyby.

2. Model

[9] A detailed description of the multifluid modeling method and initial conditions can be found in work by *Snowden et al.* [2011, hereinafter part 1]. The main difference between the simulation described in part 1 and this simulation is the location of Titan. In this simulation, Titan is placed in the xy plane at [18.11, 8.48, 0.0] R_S corresponding to 13:16 SLT. In the model's coordinate system, the *x* axis is in the orbital plane and points positively toward the solar direction, the *z* axis is aligned with the rotational/magnetic axes, and the *y* axis completes the set. The boundary conditions for Saturn's and Titan's ionosphere are the same as in part 1. Again, Titan is placed in the global Saturn simulation after 48 h of simulated time, after the Saturn simulation has reached quasi steady state. The IMF varies as described in Table 1. The solar wind density is 0.05 cm^{-3} when Titan is placed in the simulation but rises to 0.14 cm^{-3}, which increases the solar wind dynamic pressure and causes Saturn's magnetopause to move inward of Titan. The solar wind density is then reduced to 0.04 cm^{-3} which causes Saturn's magnetopause to move radially outward of Titan. The resulting solar wind pressure for each portion of the simulation are listed in Table 1. In order to simulate the tilting of Saturn's rotation and magnetic axis relative to the ecliptic the solar wind is tilted northward by 27°.

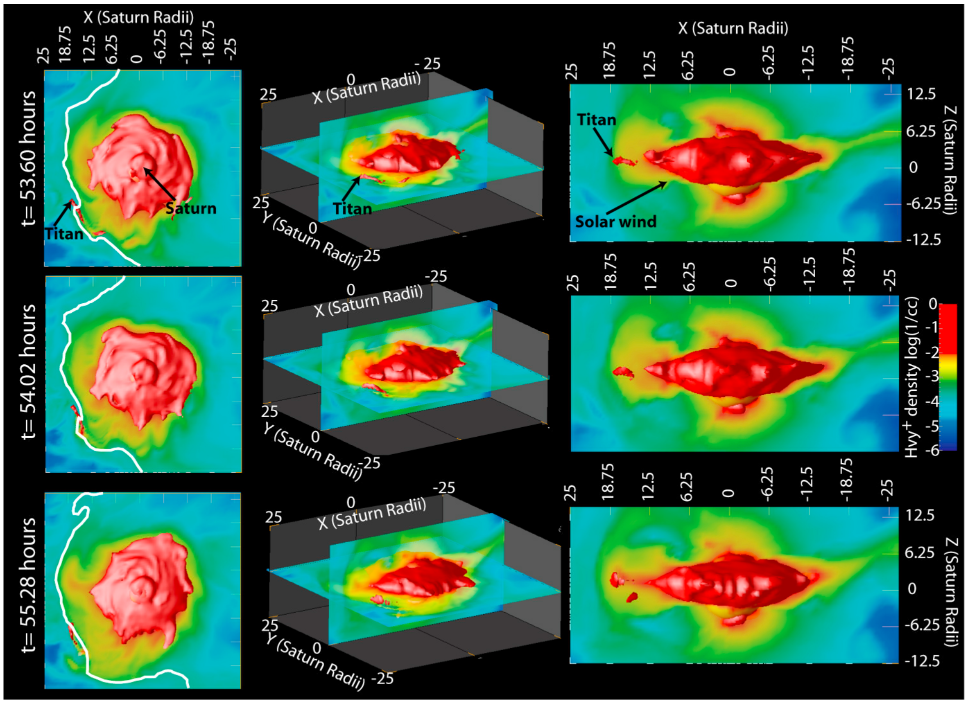

Figure 1. Titan in Saturn's magnetosheath at 13:16 SLT. Titan's ion tail is depicted with a red isosurface of constant Hvy$^+$ density equal to 0.01 cm^{-3} and Hvy$^+$ density in the orbital plane. The white line indicates the location of the magnetopause.

[10] As noted by *Müller et al.* [2010] and *Ma et al.* [2009] the resistance at and below the inner boundary will have an effect on the lifetime of magnetic field calculated by the simulation. In this simulation, a resistive term is set at and below the inner boundary in order to account for the diffusion of magnetic field within Titan's dense neutral atmosphere. The resistivity is set to 55 Ω-m at the inner boundary at an altitude of 1500 km. Inside the boundary the resistivity is increased until it reaches 435 Ω-m at 500 km altitude. Inside of ~1000 km altitude the bulk plasma velocity is set to zero but the magnetic field is not. Therefore, the magnetic field should be removed from the interior in a time period similar to the diffusion time scale on the order of several hours.

3. Results

3.1. Summary of Simulated Parameters

[11] The following sections describe the evolution of Saturn's magnetosphere, Titan's space environment and Titan's induced magnetosphere and ion tail during an increase, and then a decrease, in the solar wind dynamic pressure. Significant events in the simulation are listed in Table 1, where B_{SW} is the magnitude of the IMF, P_{SW} is the dynamic pressure of the solar wind, and R_{MP} is the subsolar distance of the magnetopause. Titan is placed in the simulation at 48 h after the Saturn model has reached equilibrium. The IMF is northward (antiparallel to Saturn's magnetic field) and the initial solar wind pressure at Saturn is 0.008 nPa. The magnetopause distance is ~25 R_S at the subsolar point. At 51.72 h, a pulse of increased solar wind pressure (.022 nPa) arrives at Saturn's magnetosphere and the magnetopause begins to compress. At 52.40 h Titan crosses into the magnetosheath. At its most compressed, the subsolar distance of Saturn's magnetopause is ~18.75 R_S.

[12] At 55.30 h Titan crosses back into the magnetosphere when the magnetopause expands outward. At 57 h, Saturn's magnetopause expands further until the subsolar distance of the magnetopause is more than 25 R_S due to the reduced solar wind pressure upstream of Saturn. At the end of the simulation Titan is located well inside Saturn's magnetosphere.

3.2. Titan's Exit and Slow Disconnection From Saturn's Magnetosphere

[13] Around 52.4 h, Titan crosses Saturn's magnetopause when the magnetopause compresses due to the increase in solar wind dynamic pressure (from 0.008 nPa to 0.022 nPa). Figure 1 shows the three-dimensional changes in Titan's ion tail after Titan has exited the magnetosphere from 3 different perspectives. Titan's ion tail is imaged by a red surface (isosurface) of constant Hvy$^+$ density equal to 0.01 cm^{-3}. At 53.6 h, a full hour after Titan crossed the magnetopause, Titan's ion tail is still inside the magnetosphere. The magnetopause current layer is punched out adjacent to Titan's ion tail, indicating that Titan's ion tail is preventing the inward motion of the magnetopause. This is in agreement with the findings of part 1, where Titan's magnetotail appeared to slow the inward motion of the magnetotail. Titan's ion tail may be able to keep Titan inside the magnetosphere in the prenoon sector, but Figure 1 shows that Titan's ion tail does not prevent Titan from crossing the magnetopause in the postnoon sector.

[14] At 54.44 h, about 2 h after Titan crossed into the magnetosheath, Titan's ion tail has split into two at the

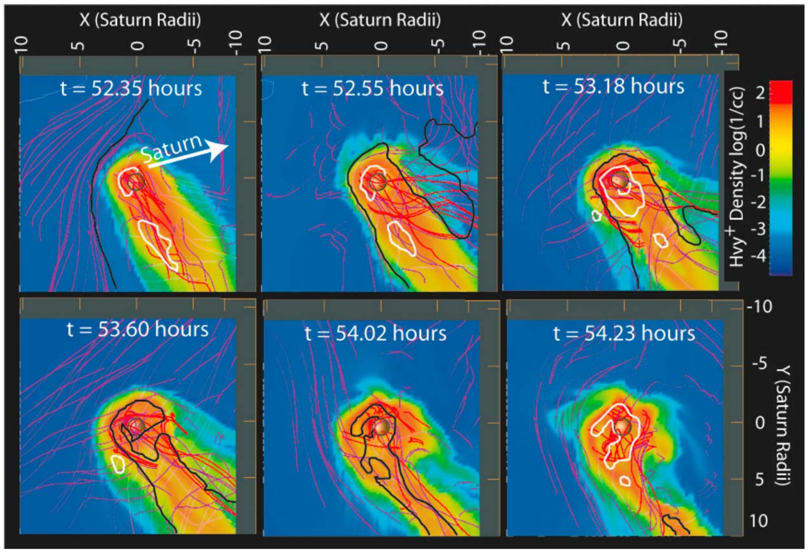

Figure 2. Close-up of Titan crossing Saturn's magnetopause at 13:16 SLT. Hvy^+ density in the orbital plane near Titan. Titan is located in the center of the plot, and Saturn is located toward the right. The thick white line indicates where B_Z is equal to zero, and the black line indicates the location of the magnetopause. Both the purple and red lines are magnetic field lines; the red lines go through Titan's ionosphere.

location of the magnetopause. Some of the ion tail plasma stays inside Saturn's magnetosphere and some of it appears as a short ion tail inside the magnetosheath. The portion of Titan's ion tail that crossed into the magnetosheath is deformed by the plasma flow in the magnetosheath, as will be discussed further in section 3.5. At 55.28 h, a disconnected clump of plasma from Titan's ion tail moves southward along Saturn's magnetopause. The southward motion of this plasma is due to coupling with southward moving reconnected magnetic field lines at Saturn's magnetopause. Reconnection occurs because the IMF in the simulation is northward, which is antiparallel to Saturn's magnetic field.

[15] The fact that Titan's ion tail remains intact for several hours after Titan crosses the magnetopause implies that Saturn's draped magnetic field lines stay frozen into Titan's ionosphere. This can be seen in Figure 2, which shows Hvy^+ ion density near Titan in the orbital plane. The red and purple lines are magnetic field lines; the red magnetic field lines are draped within ~2000 km of Titan's surface. The white lines indicate where B_Z is equal to zero and the black line indicates the location of the magnetopause current sheet. As Titan crosses the magnetopause current sheet, shown in black, the current sheet wraps around Titan and Titan's ion tail. The red field lines, which are connected to Titan's ionosphere, appear to swing toward Saturn because Titan is still magnetically connected to Saturn and Titan's ionospheric plasma outflows in the direction of the shifted magnetic field lines.

[16] Red magnetic field lines near Titan appear magnetically connected to Saturn until about 54.2 h, about 1.8 h after Titan crossed the magnetopause. Titan does not disconnect from Saturn's magnetic field through reconnection of field lines in Titan's tail, as predicted by *Ma et al.* [2009], as no magnetic null is observed in the tail. Rather the separation from Saturn's magnetic field appears to be controlled by plasma convection at high altitudes in Titan's ionosphere. In the simulation the curvature force ($\vec{J} \times \vec{B}$) of the frozen in magnetic field causes Titan's ionospheric plasma to convect at the Alfvén speed (~3 km/s) from the ramside (relative to the magnetospheric flow) to the wakeside of Titan's ionosphere. The distance a field line has to convect from the ramside of Titan's ionosphere to the wakeside, where it can disconnect from Titan's ionosphere, is ~5 R_T. Therefore, the time scale for Titan to disconnect from Saturn's magnetosphere through convection would be ~1.2 h, which is similar to the disconnection time scale predicted by the simulation.

[17] The connection between Titan and Saturn's magnetosphere is slowly eroded away at the edges of Titan's ion tail, until southward oriented field lines are isolated from Titan's dense ionosphere. This is shown in Figure 3. In Figure 3 the B_Z component of the magnetic field is mapped onto the field lines near Titan. Purple field lines have southward B_Z and are Kronian magnetic field and red field lines have northward B_Z and are magnetosheath field lines. To indicate the location of Titan's ionosphere and ion tail there is a translucent isosurface of constant Hvy^+ density equal to 0.01 cm^{-3}. Saturn is located out of the plane. At 51.09 h, Saturn's magnetic field (in purple) is draped around Titan. At 53.18 h, Titan has crossed the magnetopause current layer but is very close to the boundary. In this region the magnetic field is not well organized. Magnetosheath field lines (red) are present near Titan but Titan is still draped in Kronian field lines (purple). At 53.39 h, on the Saturn side of Titan's ionosphere, a large bundle of magnetic field lines can be seen. The magnetosheath field eventually piles up on the bundle of field lines causing the bundle to slowly flow away from Titan, finally breaking free at 54.23 h. Once free, this bundle of Kronian magnetic field moves southward taking a clump of Hvy^+ plasma from Titan's ion tail along with it, as seen in the global view in Figure 1.

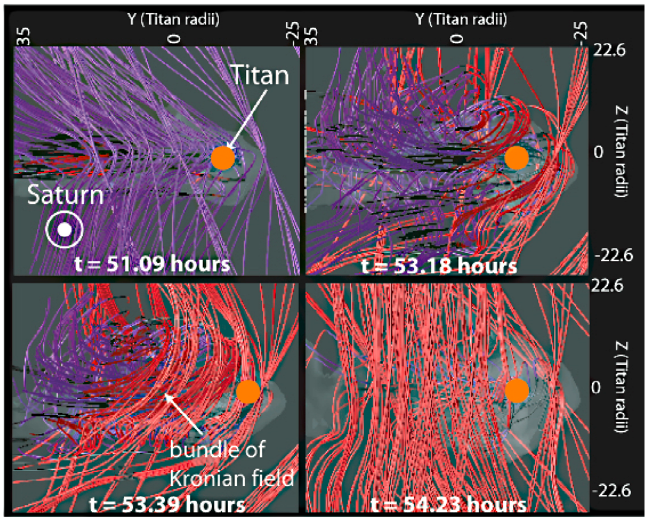

Figure 3. Magnetic field lines located near Titan. The purple field lines have $B_Z < 0$ and indicate southward Kronian magnetic field. The red field lines have $B_Z > 0$ and indicate northward IMF magnetic field lines. Plasma near Titan is imaged with grey translucent isosurface of constant Hvy^+ density equal to 10.0 cm^{-3}.

[18] Even after Titan has disconnected from Saturn's global field, the white line inside Titan's ionosphere in Figure 2 indicates southward oriented field remain deep within Titan's ionosphere for more than 3 h. This time period is similar to analytical estimates of the lifetime of fossil fields in Titan's ionosphere [*Cravens et al.*, 2009] and the lifetime of fossil fields deep in Titan's ionosphere found by *Ma et al.* [2009]. It is larger than the lifetime found by *Müller et al.* [2010], but that lifetime was stated to be a lower limit. However, this time should not be taken as indicative of the lifetime of fossil fields deep in Titan's ionosphere. The lifetime of magnetic field lines below Titan's exobase is controlled by magnetic diffusion terms which depend on ion-neutral and electron-neutral interaction rates. This model is not well suited to make a precise determination of the lifetime of fossil fields below Titan's exobase (altitudes less than ~1400 km altitude) because the model does not finely resolve Titan's ionosphere or include all the proper diffusion terms.

3.3. Titan's Reentry Into Saturn's Magnetosphere and Shedding of an Expanded Ionosphere and Northward IMF

[19] At 55.30 h Titan reenters Saturn's magnetosphere. As indicated in Table 1, Titan reenters Saturn's magnetosphere before the solar wind pressure is reduced upstream of Saturn's magnetopause. The rotation of features at the edge of Saturn's plasma disk causes Saturn's magnetopause to expand. As shown by *Kidder et al.* [2009] centrifugal interchange in Saturn's magnetosphere causes large features, called fingers, to arise at the edges of Saturn's plasma disk. These fingers can extend into Saturn's outer magnetosphere and sweep over Titan [*Winglee et al.*, 2009]. Figure 4 shows a finger (indicated by an arrow) as it moves from the dawn to dusk side of Saturn's dayside magnetosphere, pushing Saturn's magnetopause radially outward. The rotation of this finger causes Titan to reenter Saturn's magnetosphere. Again this is in agreement with the result of the simulation described in part 1 where the plasma disk was shown to have a large influence on the location of the magnetopause when it is compressed.

[20] Figure 5 shows the global view of Titan and Titan's ion tail, after Titan has reentered Saturn's magnetosphere. At 56.11 h, Titan and a relatively short ion tail are very close to the inside of Saturn's magnetopause and portions of Titan's ion tail are outside of the magnetosphere. The three-dimensional view shows that by 56.95 h Titan appears to be detached from the portion of Titan's ion tail that was left outside of the magnetosphere. The side view of Saturn's magnetosphere (third column) shows how the broken off portion of Titan's tail begins to spread northward along Saturn's magnetopause.

[21] When Titan enters the magnetosphere it is going from a low-pressure environment to a high-pressure environment with a rotational flow that is perpendicular to the magnetic field. Figure 6 shows a high-resolution view of Titan's reentry into Saturn's magnetosphere with the same convention as Figure 2. The color contour shows Hvy^+ ion density near Titan. The white line indicates where B_Z is equal to zero and the black line indicates the location of the magnetopause current sheet. As the magnetopause moves

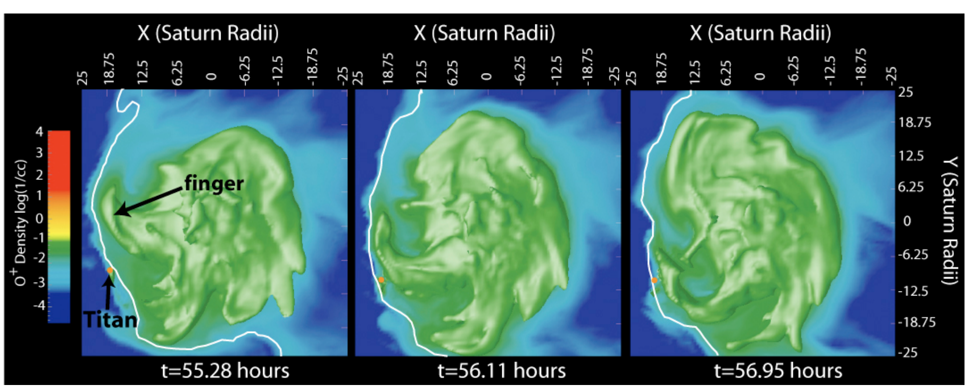

Figure 4. Saturn's plasma disk is depicted with a green isosurface of constant O^+ density equal to 0.03 cm^{-3} and O^+ density in the orbital plane. The white line marks the location of the magnetopause.

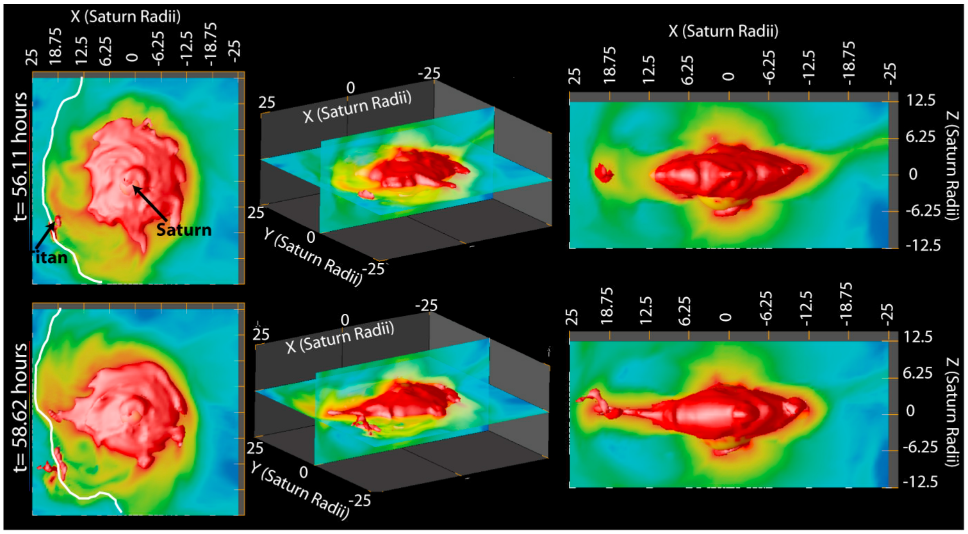

Figure 5. Titan crossing back into Saturn's magnetosphere at 13:16 SLT. Titan's ion tail is depicted with a red isosurface of constant Hvy^+ density equal to 0.01 cm^{-3} and Hvy^+ density in the orbital plane. The white line indicates the location of the magnetopause.

toward Titan, the magnetosheath plasma is pushed radially away from Saturn and the IMF field lines drape around Titan. Similar to Titan's first crossing of the magnetopause, at 55.49 h the magnetopause current layer wraps around Titan and Titan's ion tail.

[22] Plasma convection controls the time scale of Titan's connection to magnetosheath fields, similar to what was observed when Titan crossed into the magnetosheath. In this case, the rapidly rotating plasma and perpendicular field inside Saturn's magnetosphere cause plasma convection to occur much more rapidly. Over the next ~50 min the high-altitude northward field is eroded away through convection in Titan's ionosphere and, starting around 56.12 h a clump of northward field moves downstream. Along with the northward field Titan also sheds the extended ionosphere it obtained inside the magnetosheath.

[23] The time scale of Titan's connection to magnetosheath field above Titan's exobase from Titan's excursion into Saturn's magnetosheath is shorter (~50 min compared to ~1.8 h) after Titan crosses back into Saturn's magnetosphere than the timescale of Titan's connection to Kronian fields within Saturn's magnetosheath. The main reason for

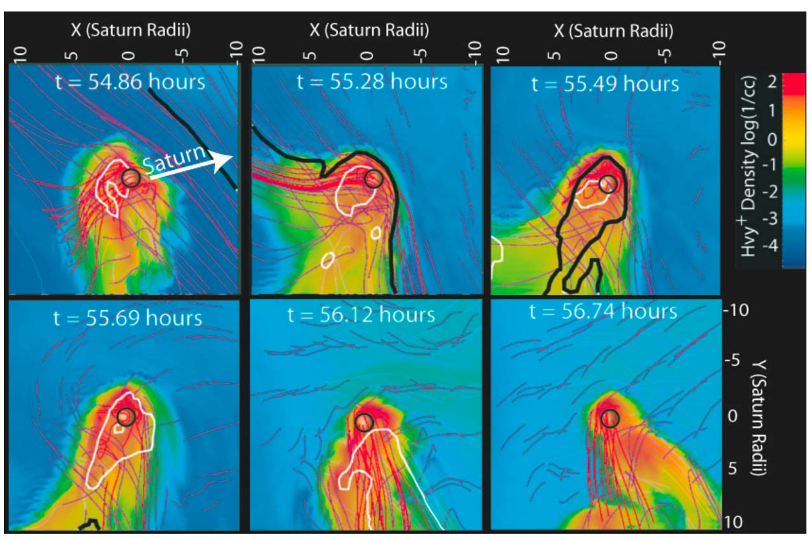

Figure 6. Close-up of Titan crossing back into Saturn's magnetosphere at 13:16 SLT. The color contour is Hvy^+ density in the orbital plane near Titan. Titan is located in the center of the plot, and Saturn is located toward the right. The thick white line indicates where B_Z is equal to zero, and the black line indicates the location of the magnetopause. Both the purple and red lines are magnetic field lines; the red lines go through Titan's ionosphere.

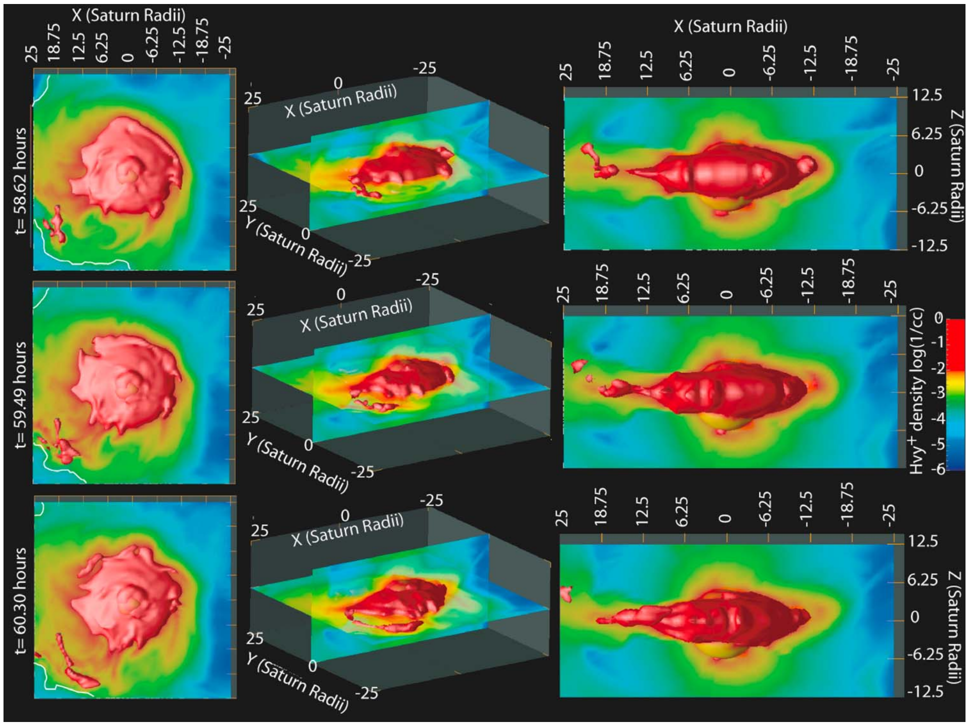

Figure 7. Titan's ion tail is depicted with a red isosurface of constant Hvy^+ density equal to 0.01 cm^{-3} and Hvy^+ density in the orbital plane. The white line indicates the location of the magnetopause.

this is that Titan's ionosphere is extended inside the magnetosheath and the magnetosheath magnetic field is mostly frozen into this extended region, which is rapidly stripped off by magnetospheric plasma and field.

[24] Titan's induced magnetosphere and ion tail eventually return to a configuration that is much closer to the ideal state. Figure 7 shows the large-scale evolution of Titan's ion tail after Titan has crossed back into the magnetosphere. At 58.62 h, a large clump of plasma near Titan's ion tail can be seen outside of the magnetopause spreading northward. By 60.30 h, Titan has recovered an ion tail similar to the ion tail simulated before Titan exited Saturn's magnetosphere.

3.4. Plasma and Magnetic Field Conditions Upstream of Titan as Titan Crosses In and Out of Saturn's Magnetosphere

[25] Here line plots of the plasma and fields 20 R_T upstream of Titan are analyzed to determine how Titan's space environment is affected by crossing Saturn's magnetopause.

[26] Figure 8a shows the plasma density 20 R_T upstream of Titan. From 48 to ~52 h the plasma density is 0.03 cm^{-3}. The composition is mostly O^+ (~0.02 cm^{-3}) with slightly less H^+ (~0.01 cm^{-3}), which is indicative of Saturn's plasma disk. The plasma density increases to 0.2 cm^{-3} when Titan enters the magnetosheath around 52 h, consistent with the density observed in the magnetosheath by Cassini's Langmuir probe during the T32 flyby [*Garnier et al.*, 2009]. The density remains higher on average inside the magnetosheath (although it varies from ~0.1 cm^{-3} to ~1.0 cm^{-3}) until Titan reenters the magnetosphere around 55 h. As expected, the plasma is composed entirely of H^+ inside the magnetosheath.

[27] The temperature of the ambient H^+, shown in Figure 8b, increases to ~200 eV near the magnetopause, but inside the magnetosheath the H^+ temperature is similar to the temperature inside the magnetosphere (10–50 eV). It is important to note that the dominant plasma near Titan inside the magnetosphere, O^+, is much hotter (200–1000 eV) than the plasma inside the magnetosheath and, in general, the plasma disk inside Saturn's magnetosphere is a higher-pressure environment than Saturn's magnetosheath.

[28] Plasma velocity upstream of Titan is complex, as seen in Figure 8c. The velocity and magnetic field are shown in the Titan-centered TIIS coordinate system and the x axis points in the direction of corotation, the y axis is directed from Titan toward Saturn, and the z axis points upward perpendicular to the orbital plane. Inside the magnetosphere (48–52.4 h and 55.5–60 h) the plasma velocity is ~150 km/s in the orbital plane.

[29] In the magnetosheath the plasma velocity is much more variable. At first there is a strong decrease in plasma velocity (down from 150 km/s to about 50 km/s) coincident with Titan crossing the magnetopause current layer. Then the plasma velocity sharply increases to about 200 km/s. Finally, the plasma velocity in the magnetosheath settles at ~150 km/s and is oriented primarily in the positive z direction. Velocity in the positive z direction inside the magnetosheath is not unexpected because the solar wind flow in the simulation has a positive v_Z component, which simulates the tilt of Saturn's magnetic axis relative to the solar wind (as depicted in Figure 1). The strong vertical plasma flow observed in this simulation may also be due to Titan's location close to 12:00 SLT. Closer to the flanks of Saturn's magnetosphere the flow direction has a stronger horizontal component, flowing in the corotation direction on the dusk side and anticorotation direction on the dusk side. For example, Figure 7 of part 1 shows that the flow on the

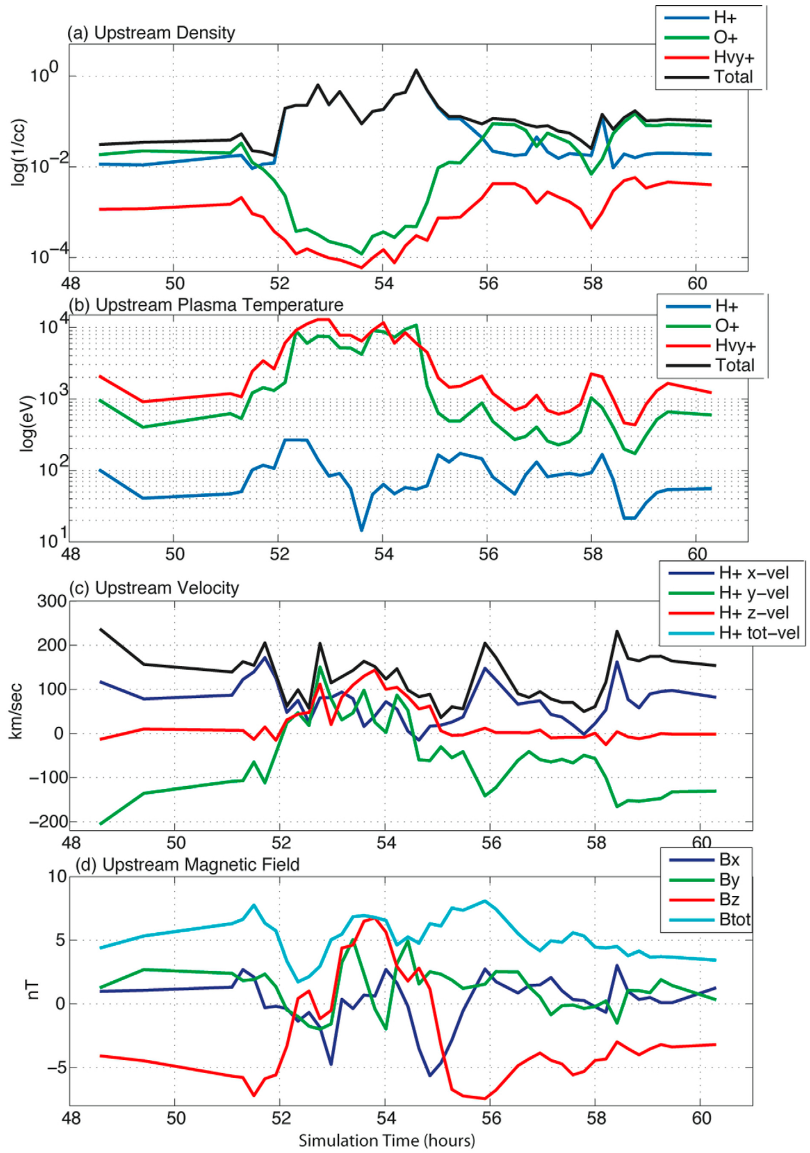

Figure 8. Plasma and magnetic field characteristics 20 R_T upstream of Titan in Titan-centered (TIIS) coordinates. In the TIIS coordinate system the x axis is in the direction of corotation, the y axis is directed from Titan toward Saturn, and the z axis is perpendicular to the orbital plane.

other side of the magnetopause around 09:00 SLT has both a strong vertical component and strong counterclockwise component. Therefore, the direction of the plasma flow encountered by Titan in the magnetosheath appears to be affected by both the obliquity of Saturn and by the location of Titan within Saturn's magnetosphere. The following section will show how the direction of plasma flow in the magnetosheath causes Titan's induced magnetosphere to be highly irregular.

[30] Figure 8d describes the magnetic field magnitude and direction 20 R_T upstream of Titan. Inside Saturn's magnetosphere the magnetic field is mostly in the B_Z direction with some radial stretching indicated by the significant B_Y component. The magnitude of the magnetic field is about 5 nT. The magnetic field makes a slow transition (over the period of 1 h) from southward ($B_Z \sim -5$ nT) to northward ($B_Z \sim 5$ nT) and back when Titan crosses Saturn's magnetopause.

3.5. Titan's Induced Magnetosphere Inside and Outside of Saturn's Magnetosphere

[31] The characteristics of Titan's ionosphere and induced magnetosphere are highly irregular inside Saturn's magnetosheath. Figure 9 shows two views of Titan's induced magnetosphere at two different times in the simulation. Figures 9a and 9b show Titan's ion tail with a magenta surface of constant density equal to 1.0 cm^{-3} and the color contour shows the plasma velocity in the z direction. Figures 9c and 9d show Hvy$^+$ density in the vertical and orbital plane and the white lines are magnetic field lines. In Figures 9a and 9c Titan's is inside Saturn's magnetosphere, and in Figures 9b and 9d Titan is inside Saturn's magnetosheath.

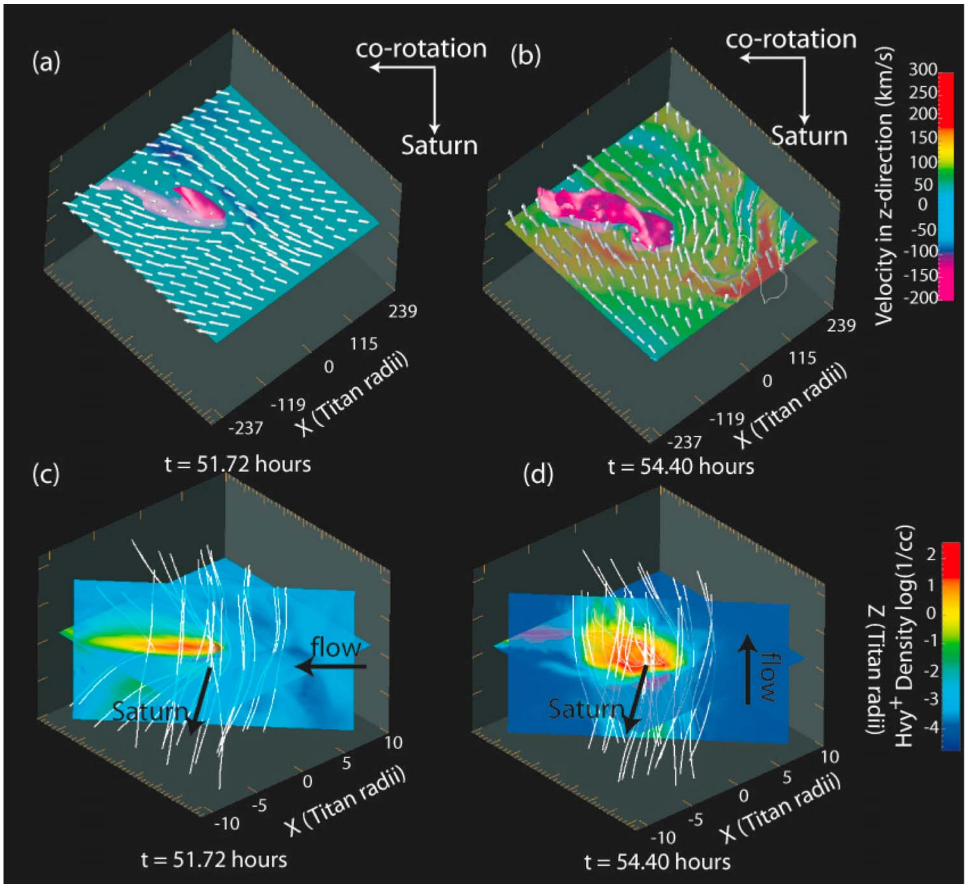

Figure 9. (a and b) Titan's ion tail is imaged with a magenta isosurface of constant Hvy^+ density equal to 1.0 cm^{-3}, and the background contour is the velocity in the z direction. The white arrows indicate the flow direction. (c and d) Hvy^+ density in the orbital plane and vertically along the corotation axis. White lines are magnetic field lines.

[32] Inside Saturn's magnetosphere (51.72 h) Titan's induced magnetosphere is close to the ideal configuration. The flow is perpendicular to the magnetic field and field lines wrap around Titan. The $\vec{J} \times \vec{B}$ force causes a narrow tail of Hvy^+ plasma to form in Titan's wake. In contrast, inside the magnetosheath (at 54.40 h) Titan's induced magnetosphere is nothing like the ideal configuration. Figure 9b shows that the plasma flow near Titan is in the positive z direction and Titan's ion tail is extended in the vertical direction (in agreement with the distortion of Titan's ion tail seen in Figure 1 at this time).

[33] Furthermore, in the magnetosheath the plasma flow is not perpendicular to the magnetic field and magnetic field lines do not drape around Titan. Since there is no strong draping of magnetic field, the $\vec{J} \times \vec{B}$ force is absent and no wake of ions forms behind Titan. Instead, Titan's ion tail is slowly eroded. Furthermore, because magnetic field lines do not flow through Titan's upper atmosphere, high-altitude ionospheric plasma is not stripped away, and Figure 9d shows that Titan's ionosphere is extended in Saturn's magnetosheath.

[34] Therefore, both the results in this simulation and the simulation presented in part 1 suggest that near Saturn's magnetopause Titan's flow environment is highly irregular and Titan may interact with plasma flowing vertically, out of the orbital plane. In both cases the flow direction was nearly parallel to the magnetic field and magnetic field lines did not drape around Titan, leading to significant changes in ion outflow. More investigation is necessary to determine whether Cassini data confirms this prediction and whether Titan has been observed in an environment with strong vertical plasma flow.

3.6. Comparison of a Synthetic Flyby and Data From Cassini's T32 Flyby

[35] In this section we compare the simulation results with Cassini magnetometer (MAG) data [*Bertucci et al.*, 2008], Cassini electron spectrometer data (CAPS-ELS), and Cassini Langmuir probe data (RPWS-LP) [*Ma et al.*, 2009; *Garnier et al.*, 2009]. Figure 10 shows the T32 trajectory. The plot on the left shows the trajectory in TIIS coordinates. The plot on the right shows the trajectory rotated into the model coordinates with the same orientation as Figures 2 and 6 for easy comparison. During the T32 flyby Cassini was initially inside of Saturn's magnetosphere. However, before encountering Titan Cassini entered a region with strong northward magnetic field identified as the magnetosheath or the magnetopause region. Cassini exited

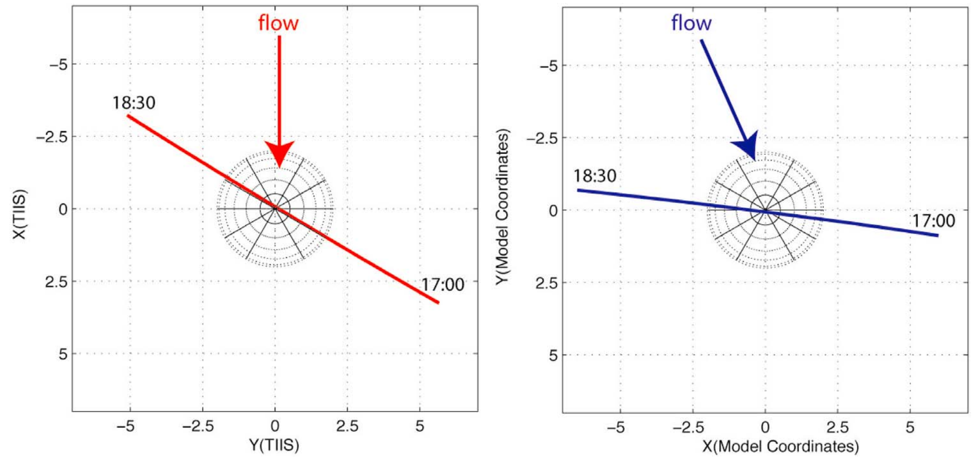

Figure 10. The trajectory of the T32 flyby. (left) The trajectory in TIIS coordinates. (right) The trajectory rotated into model coordinates with the same orientation as Figures 2 and 6.

into the magnetosheath during the outbound portion of the flyby [*Bertucci et al.*, 2008]. The closest approach occurred at 17:46 UTC and the altitude of the spacecraft was 975 km over Titan's north pole.

[36] Figures 11a–11c show Cassini MAG data and the simulated magnetic field in TIIS coordinates. The simulated magnetic field is sampled in real time starting at 51.25 h of simulated time and the closest approach occurred at 52.76 h simulated time. The simulation and the magnetic field do not show very good agreement. One of the drawbacks of this type of simulation is that we are not able to specify specific incident conditions (the ambient fields,

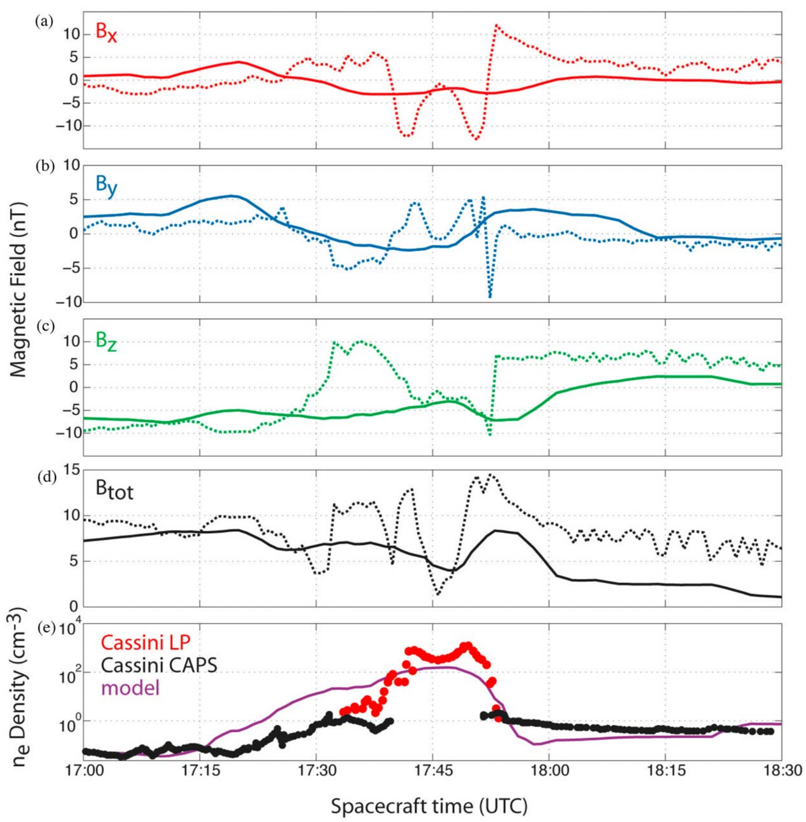

Figure 11. (a-d) Cassini MAG data (dotted) from the T32 flyby and simulation magnetic field (solid) in TIIS coordinates. (e) Electron density from Cassini CAPS-ELS and RPWS-LP and simulated electron density along the T32 trajectory. The simulated data is sampled in real time starting at 51.25 simulated hours. Closest approach occurred at 17:46 UTC and at 52.76 h of simulated time.

velocity, and density) on Titan, and therefore we will not always be able to find good agreement with data from specific flybys. Figure 11 shows that we do not simulate a very strong magnetic field rotation near Titan. This is due to the relatively course (927 km) resolution of the simulation and also due to the fact that we do not predict strong magnetic field draping when Titan is in the magnetosheath. Most of the structure in the magnetic field near closest approach is due to the fossil fields detected in Titan's ionosphere [*Bertucci et al.*, 2008] that are frozen in near or below the exobase. This simulation does not resolve this region well enough to detect the layering of magnetic fields in Titan's lower ionosphere. Therefore, local simulations [e.g., *Ma et al.*, 2009] are better tools for describing the structure of magnetic field in Titan's ionosphere.

[37] In Figure 11e, the electron density derived from CAPS-ELS and the RPWS-LP reported by *Ma et al.* [2009] is compared with the simulated electron density along the T32 trajectory. On the inbound leg, after about 17:30 UTC, Cassini detected cold and relatively dense plasma [*Garnier et al.*, 2009]. The density of this plasma increased steadily toward closest approach. *Garnier et al.* [2009] noted that the gradual increase of plasma before closest approach was very different than the rapid decrease in plasma density around 17:50 UT when Cassini exited Titan's ionosphere. At 17:30 UT, Cassini was at an altitude of 4249 km, too far away to detect Titan's exoionosphere. Furthermore, the flyby was not crossing downstream of Titan relative to the corotational flow direction. *Garnier et al.* [2009] noted that a significant shift in the flow direction may shift the orientation of the wake region downstream of Titan. This is what is observed in our simulation. Figure 11 shows that, similar to the Cassini data, there is a gradual increase in the plasma density before closest approach and a rapid decrease after closest approach. Figure 2 shows that, at 52.55 h, Titan's plasma is shifted toward Saturn as Titan crossed the magnetopause. In the simulation, the gradually increasing density before closest approach due to the detection of plasma outflowing from Titan. Therefore, it is likely that the cold plasma detected by Cassini on the inbound portion of T32 was Titan's plasma wake.

4. Discussion

[38] Unlike the simulations by *Ma et al.* [2009], we do not simulate rapid reconnection (<10 min) that disconnects Titan from Saturn's magnetosphere and results in a rapid loss of Titan's ion tail. Instead Titan disconnects from Saturn's magnetosphere through slow ionospheric convection with a time scale of ~1.8 h. The difference between our results and the results of *Ma et al.* [2009] is due to the flow direction in the magnetosheath and the treatment of ion dynamics. *Ma et al.* [2009] did not adjust the direction of flow as Titan crossed the magnetopause, so magnetosheath field lines draped directly over Kronian field lines, compressing the tail until an x point formed. In our model, northward oriented field lines do not drape over the southward oriented field lines in the same direction as corotation. Even if the magnetosheath field draped over Titan's induced magnetosphere, as it did in the simulation of *Ma et al.* [2009], our simulation may not have predicted rapid reconnection. In our multifluid simulation, the dynamics of several ion species are simulated with each ion having an individual mass. The multispecies, single-fluid treatment used by *Ma et al.* [2009] solves for the density of 7 different ion species and then adds the mass densities of the ion species to obtain a single-massed fluid with one momentum equation. Therefore, all ion fluids have the same velocity. This approach may lead to a different Alfvén speed, which would affect the time scales of reconnection. Heavy ions in Titan's ion tail significantly decrease the reconnection rate. The convection speed in Titan's upper ionosphere and ion tail is similar to the Alfvén speed, therefore, the time scale for Titan's tail to disconnect through reconnection is comparable to the time scales for convection, even with favorable field line geometry.

[39] The simulation results are similar to the erosion of Titan's ion tail simulated by the hybrid model of *Müller et al.* [2010]. In that simulation Titan's tail did not detach but "clouds" of plasma were removed from the tail as it adjusted to the new flow direction. If that simulation was run longer than ~25 min, Titan's ion tail may have been completely detached. The difference between our simulation results and the results of *Müller et al.* [2010] is that in the simulations by *Müller et al.* [2010] Titan's ion tail remains within the orbital plane because the magnetosheath plasma flow is assumed to be in the orbital plane. However, our Saturn simulation predicts a northward flow in the magnetosheath near the magnetopause. There have been no reported measurements of the plasma flow direction in Saturn's magnetosheath; however, a northward flow relative to the orbital plane near noon is physically in agreement with the tilt of Saturn's rotational axis relative to the Saturn-Sun axis during Saturn's northern spring season. Cassini arrived at Saturn about two years after Saturn's northern winter solstice, therefore during most of Cassini's prime and equinox missions the solar wind has been exerting a northward force. However, during Cassini's T32 flyby the tilt was only ~15° rather than ~27° simulated here.

[40] We also find that Titan's ionosphere is much more extended inside Saturn's magnetosheath because no typical induced magnetosphere forms which would strip off ionospheric plasma at high altitudes. This result has several implications. First, the lifetime of any fossilized IMF fields from Titan's excursion into Saturn's magnetosheath is shorter in Saturn's magnetosphere than the lifetime of Kronian fields within Saturn's magnetosheath. The main reason for this is that Titan's ionosphere is extended inside the magnetosheath and the IMF fields are mostly frozen into this extended region. Since the magnetic field is not perpendicular to the plasma flow, convection does not drive the magnetic field to low altitudes in Titan's ionosphere. Instead IMF fields mostly remain at high altitudes in Titan's extended ionosphere and are quickly stripped away when Titan enters Saturn's magnetosphere.

[41] The reconfiguration of Titan's induced magnetosphere inside Saturn's magnetosheath affects ionospheric plasma convection and ion outflow because the magnetic field is not strongly draped in Titan's ionosphere. The outflow rate from Titan was determined by calculating the flux of particles out of a box centered on Titan. We find that the average ion outflow rate (~1×10^{25} ions/s) is larger inside

Saturn's magnetosphere than in the magnetosheath (~6 to 8×10^{24} ions/s). Particle precipitation along magnetic field lines would also be strongly affected. In the future, it would be interesting to further investigate how the dynamics of Titan's ionosphere are affected when Titan is inside Saturn's magnetosheath with a higher-resolution model.

5. Conclusions

[42] Results of a simulation of Titan crossing Saturn's magnetopause at 13:16 SLT were presented. Titan is initially located inside Saturn's magnetosphere. When the solar wind pressure is increased, Saturn's magnetopause compresses and moves radially inward of Titan. After several hours, the rotation of cold, dense fingers at the outer edge of Saturn's plasma disk cause the magnetopause to expand past Titan.

[43] When Titan crosses the magnetopause current sheet it wraps around Titan's ionosphere and ion tail. Slow (~3 km/s) ionospheric convection removes Titan's connection to Saturn's magnetosphere in ~1.8 h, until Titan's ion tail is broken into two. The portion of Titan's ion tail that is left outside of Saturn's magnetosphere slowly moves away from Titan along the outside edge of Saturn's magnetosphere.

[44] When Titan crosses back into Saturn's rapidly rotating magnetosphere with relatively higher plasma pressure, Titan's connection to magnetosheath magnetic field lines is removed through ionospheric convection in ~50 min. Again, Titan's ion tail is split into two with a significant portion of Titan's tail remaining outside of Saturn's magnetosphere. The portion of Titan's ion tail which is left outside of Saturn's magnetosphere flows northward along the magnetopause. Plasma from Titan's ionosphere leaks out of Saturn's magnetosphere throughout the simulation. Therefore, both this simulation and the simulation in part 1 show that ions from Titan are lost from Saturn's dayside magnetosphere when the magnetopause is close to Titan's orbit. Results from a previous simulation with Titan at 21:00 SLT, showed that Titan's plasma is also lost from Saturn's magnetosphere when Titan is in Saturn's magnetotail. Therefore, each Saturn-Titan simulation run to date seems to confirm the idea that plasma from Titan is lost from Saturn's magnetosphere before a complete ion torus can form. Heavy plasma from Titan drifts outwards, to the edge of Saturn's magnetosphere, and escapes at the first opportunity.

[45] At 13:16 SLT, inside Saturn's magnetosphere, Titan's space environment is characteristic of Saturn's plasma disk and the configuration of Titan's induced magnetosphere is similar to the "ideal" case. Inside the magnetosheath, the magnetosheath plasma flows northward and Titan's induced magnetosphere is highly irregular because the plasma flow is not perpendicular to the magnetic field. The magnetic field no longer drapes around Titan's ionosphere and ions do not outflow into Titan's wake due to the $\vec{J} \times \vec{B}$ force. The relatively low pressure and lack of Saturn's rapidly rotating magnetic field, which strips Titan's ionosphere at high altitudes, causes Titan's ionosphere to be expanded inside Saturn's magnetosheath. Once Titan crosses back inside Saturn's magnetosphere, the extended regions of plasma around Titan are rapidly stripped off until Titan's ionosphere and induced magnetosphere returns to a more typical state.

[46] Simulation results along Cassini's T32 trajectory were compared with Cassini MAG, CAPS, and RPWS data. The simulation was not able to reproduce the structure of the magnetic field in Titan's ionosphere due to its relatively course grid size. Therefore, local simulations are still the best tool for understanding the magnetic topology within Titan's ionosphere. However, the simulation results were comparable to the CAPS/RPWS electron density data and we showed that the asymmetry in electron density observed during the flyby could be due to a shift in the direction plasma outflowing from Titan's ionosphere as Titan crossed Saturn's magnetopause.

[47] Titan's plasma interaction is challenging to understand because not only is Titan's environment highly variable at one location in Saturn's magnetosphere, as shown by this simulation. Titan's environment is also expected to be significantly different in the various sectors (prenoon, postnoon, dawn, dusk, tail) of Saturn's magnetosphere. In these two papers we examined Titan's environment in the prenoon and postnoon sectors of Saturn's magnetosphere. In part 1, we showed that Titan's environment is strongly affected by the inward and outward motion of Saturn's magnetopause and by irregular plasma flows near the magnetopause on the dawn side of Saturn's magnetosphere. In this paper, we describe a simulation of Titan crossing into the magnetosheath and then, after a few hours, back into the magnetosphere and show that the movement of Saturn's magnetopause is also very important in the postnoon sector. The simulation results presented here are probably representative of Titan's environment from about 08:00 to 12:00 SLT and the simulation results presented in part 1 are probably representative of Titan's environment from about 12:00 to 16:00 SLT. The variability in Titan's environment is likely very different at 06:00 and 18:00 SLT because Titan is no longer interacting directly with Saturn's magnetopause because it is flared out, far from Titan's orbit [*Kanani et al.*, 2010].

[48] Titan orbits near the outer boundary of Saturn's magnetosphere where the plasma convection is still not well understood. On the flanks and the nightside of Saturn's magnetosphere the movement of Saturn's magnetopause may have a weaker effect on Titan's plasma environment, on the other hand reconnection events in Saturn's magnetotail may have a strong effect. Even if Titan is not near the magnetopause, Titan's environment can still be affected by external forcing of Saturn's magnetosphere because the solar wind pressure and IMF can affect the overall configuration Saturn's magnetic field and plasma disk as shown by *Winglee et al.* [2009]. More simulations and analysis of Cassini's data is needed to determine if the variability of Titan's plasma environment can be organized in terms of Titan's location within Saturn's magnetosphere. The characteristics of the magnetic field for many of Cassini's flybys have been described by *Bertucci et al.* [2009] and *Simon et al.* [2010b] as well as the plasma density [e.g., *Rymer et al.*, 2009]. Unfortunately, the ambient plasma velocity and flow direction are more difficult to determine [*Thomsen et al.*, 2010]. As seen in these simulations, the flow direction can have a strong effect on the morphology of Titan's induced magnetosphere and ion outflow. Until a more complete understanding can be obtained from the data, coupled Saturn-Titan simulations are useful for character-

izing the variability in the various sectors of Saturn's magnetosphere.

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References

Achilleos, N., C. S. Arridge, C. Bertucci, C. M. Jackman, M. K. Dougherty, K. K. Khurana, and C. T. Russell (2008), Large-scale dynamics of Saturn's magnetopause: Observations by Cassini, *J. Geophys. Res.*, *113*, A11209, doi:10.1029/2008JA013265.

Bertucci, C., et al. (2008), The magnetic memory of Titan's ionized atmosphere, *Science*, *321*, 1475–1478, doi:10.1126/science.1159780.

Bertucci, C., B. Sinclair, N. Achilleos, P. Hunt, M. K. Dougherty, and C. S. Arridge (2009), The variability of Titan's magnetic environment, *Planet. Space Sci.*, *57*, 1813–1820, doi:10.1016/j.pss.2009.02.009.

Cravens, T. E., et al. (2009), Model-data comparisons for Titan's nightside ionosphere, *Icarus*, *199*, 174–188, doi:10.1016/j.icarus.2008.09.005.

Garnier, P., et al. (2009), Titan's ionosphere in the magnetosheath: Cassini RPWS results during the T32 flyby, *Ann. Geophys.*, *27*, 4257–4272, doi:10.5194/angeo-27-4257-2009.

Kanani, S. J., et al. (2010), A new form of Saturn's magnetopause using a dynamic pressure balance model, based on in situ, multi-instrument Cassini measurements, *J. Geophys. Res.*, *115*, A06207, doi:10.1029/2009JA014262.

Kidder, A., R. M. Winglee, and E. M. Harnett (2009), Regulation of the centrifugal interchange cycle in Saturn's inner magnetosphere, *J. Geophys. Res.*, *114*, A02205, doi:10.1029/2008JA013100.

Ma, Y. J., et al. (2009), Time-dependent global MHD simulations of Cassini's T32 flyby: From magnetosphere to magnetosheath, *J. Geophys. Res.*, *114*, A03204, doi:10.1029/2008JA013676.

Müller, J., S. Simon, U. Motschmann, K.-H. Glassmeier, J. Saur, J. Schule, and G. J. Pringle (2010), Magnetic field fossilization and tail reconfiguration in Titan's plasma environment during a magnetopause passage: 3D adaptive hybrid code simulations, *Planet. Space Sci.*, *58*, 1526–1546, doi:10.1016/j.pss.2010.07.018.

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.

Rymer, A. M., H. T. Smith, A. Wellbrock, A. J. Coates, and D. T. Young (2009), Discrete classification and electron energy spectra of Titan's varied magnetospheric environment, *Geophys. Res. Lett.*, *36*, L15109, doi:10.1029/2009GL039427.

Simon, S., U. Motschmann, G. Kleindienst, J. Saur, C. L. Bertucci, M. K. Dougherty, C. S. Arridge, and A. J. Coates (2009), Titan's plasma environment during a magnetosheath excursion: Real-time scenarios for Cassini's T32 flyby from a hybrid simulation, *Ann. Geophys.*, *27*, 669–685, doi:0.5194/angeo-27-669-2009.

Simon, S., A. Wennmacher, F. M. Neubauer, C. L. Bertucci, H. Kriegel, J. Saur, C. T. Russell, and M. K. Dougherty (2010a), Titan's highly dynamic magnetic environment: A systematic survey of Cassini magnetometer observations from flybys TA-T62, *Planet. Space Sci.*, *58*, 1230–1251, doi:10.1016/j.pss.2010.04.021.

Simon, S., A. Wennmacher, F. M. Neubauer, C. L. Bertucci, H. Kriegel, C. T. Russell, and M. K. Dougherty (2010b), Dynamics of Saturn's magnetodisk near Titan's orbit: Comparison of Cassini magnetometer observations from real and virtual Titan flybys, *Planet. Space Sci.*, *58*, 1625–1635, doi:10.1016/j.pss.2010.08.006.

Snowden, D., R. Winglee, and A. Kidder (2011), Titan at the edge: 1. Titan's interaction with Saturn's magnetosphere in the prenoon sector, *J. Geophys. Res.*, *116*, A08229, doi:10.1029/2011JA016435.

Thomsen, M. F., D. B. Reisenfeld, D. M. Delapp, R. L. Tokar, D. T. Young, F. J. Crary, E. C. Sittler, M. A. McGraw, and J. D. Williams (2010), Survey of ion plasma parameters in Saturn's magnetosphere, *J. Geophys. Res.*, *115*, A10220, doi:10.1029/2010JA015267.

Winglee, R. M., D. Snowden, and A. Kidder (2009), Modification of Titan's ion tail and the Kronian magnetosphere: Coupled magnetospheric simulations, *J. Geophys. Res.*, *114*, A05215, doi:10.1029/2008JA013343.

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