Cold ionospheric plasma in Titan’s magnetotail


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The interaction between Titan and the corotating Saturnian plasma forms an induced magnetosphere with an elongated Alfven-wing-style magnetotail. On 26 December 2005, the Cassini spacecraft flew through Titan’s magnetotail, providing the first distant tail observation, over 5 Titan radii downstream. We examine measurements observed by the magnetometer and Langmuir probe during this pass. We use the direction of the magnetic field along the trajectory to identify the source regions of plasma reaching the spacecraft. Cold plasma, with a density of about 10 cm⁻³, is found magnetically connected to the ionosphere. Titan’s ionosphere appears to be escaping along field lines down the tail, leading to particle loss from the atmosphere.


1. Introduction

Titan is firmly embedded in the flowing plasma in Saturn’s outer magnetosphere at a distance of 20 Saturn radii (Rₛ). Our present understanding is based on observations with Voyager and Cassini [Ness et al., 1982; Kivelson and Russell, 1983; Backes et al., 2005; Wahlund et al., 2005]. The sub-corotating plasma encountering Titan is submagnetosonic, and thus there is no standing bow shock in front of Titan. While there is no evidence at present for the existence of an intrinsic field at Titan, the ionosphere of Titan acts as a barrier to the plasma flow and produces an induced magnetosphere. The plasma flow slows down in front of Titan and largely diverts around it. This is in many aspects similar to the picture of the supersonic solar wind interacting with an unmagnetized planet such as Venus where field lines are compressed (at a shock) and drape around its ionosphere [e.g., Luhmann et al., 2004].

2. Measurements

The magnetometers onboard Cassini spacecraft measure the magnetic field vector [Dougherty et al., 2004] and the raw data are averaged to 1 s resolution to be used for analysis in this paper. The data are in Titan Interaction System (TIIS) coordinates, in which x-axis is in the nominal corotation direction, y-axis points from Titan to Saturn, and z-axis completes the right-handed coordinate system. The Langmuir Probe measures, among other cold plasma parameters, the electron density and temperature [Gurnett et al., 2004; Wahlund et al., 2005]. By combining both data sets, we can study the plasma environment from both field and particle aspects.

During the Titan flyby T9, the spacecraft passed Titan’s orbital plane with the closest approach (CA) of 5 Rₜ at 1900 UT. A detailed analysis of the plasma environment in Titan’s induced magnetosphere during this flyby is given by Bertucci et al. [2007]. Our analysis rises from a different perspective of the interaction by focusing on how the flux tubes and plasma in distant tail connect to the flow terminator magnetically. Figure 1 shows a general picture of the interaction during 1500~2300 UT. Panels a and b show the spacecraft trajectory and the magnetic field vector during this 8-hour interval. As the spacecraft approaches from downstream to upstream, the field orientation does not change very much until the spacecraft gets into Titan’s tail region at about 6 Rₜ, where a strongly draped field is encountered at 1910~1940 UT that appears to be accompanied by a current sheet crossing. Panel a exhibits a large scale draping pattern away from Titan in...
which there appears to be a bending of the field across the upstream side of Titan over the entire 60 Titan radii path shown here except in the wake. There is a slight asymmetry in the angle of the field vectors to the x-axis on either side of Titan, but this asymmetry is consistent with an outward flow of the plasma from Saturn that we discuss below. In panel c and d, the flux tubes observed on the trajectory are traced back to the YZ-plane (the nominal flow terminator) to show where these flux tubes are connected near Titan. Letters A to O in panel c show positions along spacecraft trajectory, and by projecting the field lines from those letter-designated positions back to the YZ-plane, the positions where the flux tubes cross the nominal flow terminator are obtained and shown in panel d. The black line in panel d denotes the direction of the sunlight during the middle of this interval. This analysis assumes that the field lines are nearly straight, which is a good approximation for the situations in Titan’s distant tail where the magnetic field dominates the pressure. In general, the flux tubes connect to regions not very far from Titan in the nominal flow terminator. The flux tube denoted by the letter H connects to the region closest to Titan, and this flux tube, defined by its plasma content, is observed for about 15 minutes around 1830 UT. It will be shown in the later part of this paper that this is also the interval when the cold dense plasma is observed.

The magnetometer data during the tail crossing is shown in Figure 2. The time series of magnetic field and spacecraft position are given for a two-hour interval centered at CA. The spacecraft position is shown in TIIS coordinates, while the magnetic field is in local REN coordinates in which $B_R$ (radial) is in the radial direction, $B_N$ (northward) is in direction of $R \times Z$ in TIIS, and $B_E$ (eastward) is in the direction of $N \times R$. We see that the radial component of magnetic field reverses orientation across a current sheet between two tail lobes at 1910 UT. In TIIS coordinates, the background magnetic field is estimated as $(3.68, 4.69, -2.36)$ nT [Bertucci et al., 2007], thus the plane of the two lobes’ center should be oblique to the XY-plane and the intersection of the two planes should be along the flow direction (under assumption that the flow is in the XY-plane). Since the trajectory is nearly in the XY-plane, the location of the center between lobes in the XY-plane indicates that the tail is not along the corotation direction but deviates $34^\circ$ from it and is outward from Saturn. The CAPS observations are also consistent with an outward deflection of $65 \pm 30^\circ$ [Szegö et al., 2007]. The analysis by Bertucci et al. [2007] indicates the upstream flow is $36^\circ$ outward from the corotation direction by
Figure 2. Magnetometer data during a two hour interval around the closest approach (1900 UT). The spacecraft position is shown in TIIS coordinates, while the magnetic field is in local REN coordinates in which $B_r$ (radial) is in the radial direction, $B_n$ (northward) is in direction of $R \times Z$ in TIIS, and $B_e$ (eastward) is in the direction of $N \times R$.

Figure 3. The magnetic pressure ($B^2$/2 solid line in the upper panel), the sum of magnetic pressure and electron thermal pressure (dots in the upper panel), the electron density (dots in the middle panel), the electron temperature (dots in the lower panel), and estimated ion temperature (circles in the lower panel) during the interval 1800–2000 UT. The ion temperature is calculated by using the electron density and assuming the total pressure is at the value of the dash line in the upper panel between 1827 and 1840 UT.
independent study of the MAG data. All three estimates indicate a strong flow component away from Titan during the encounter.

In Figure 3, we combine both magnetometer data and Langmuir Probe data to understand the magnetic features and particle behavior in the distant tail region. The magnetic pressure, the electron density, the electron temperature, and estimated ion temperature are shown during the interval 1800–2000 UT. The ion temperature is calculated by assuming the total pressure is at the value of the dashed line in the upper panel between 1827 and 1840 UT. By ignoring the dynamic pressure within the flux tube and curvature force in the magnetic configuration of the tail, the estimated ion temperature should be close to the real value and be a lower-limit estimate. During 1825–1842 UT, the Langmuir Probe detected cold dense plasma with an electron density of about 10 cm$^{-3}$. This plasma region is located in one lobe of Titan’s induced magnetotail about 6 R$_{\text{T}}$ away and about 1.7 R$_{\text{T}}$ across. In the dense plasma region, the electron and ion temperatures are similar and of the same order of magnitude as those in Titan’s ionosphere (of the order of 1 eV), and the plasma density is much lower than that in the ionosphere. The boundary where density rises and falls is very sharp.

These plasmas are identified as ionospheric plasma transported along flux tube from Titan’s ionosphere, because of the temperature values and the sharp boundary. This interpretation is consistent with the study of the CAPS data by Coates et al. [2007], who observe ionospheric electrons and ions from 1824–1844 UT. To allow ionospheric plasma be observed at 6 R$_{\text{T}}$ in the downstream tail, the flux tube containing this plasma should connect to the ionosphere. To test this interpretation, the field lines are projected back to the flow terminator during 1830–1846 UT, assuming a 34° outflow away from corotation direction. Figure 4 shows the result of this analysis and each panel is in the same format as in Figure 1. In panel d, we see that the flux tubes denoted by F and H come closest to the ionosphere in the wake terminator plane at altitude of about 2 R$_{\text{T}}$, using a straight line extrapolation. The closest approaches of the field lines to Titan on the upstream side are certainly much closer than their intersection in the terminator plane. The spacecraft crossed these flux tubes from 1835–1838 UT, in the middle of the interval in which the dense plasma is observed. If we perform the analysis for flow direction in the corotation direction, we can also get the flux tubes during that interval connecting closest to the ionosphere with altitude about 2000 km. If we extrapolate the magnetic field backward with the MHD model [Ma et al., 2006], we obtain a lower altitude for the flux tube, about 800 km. The plasma at Cassini must originate in Titan’s ionosphere and move along flux tubes into the distant tail.

Figure 4. In a new coordinate system with x axis in the flow direction 34° outward from Saturn (a, b) shows spacecraft trajectory and magnetic field vector in the XY-plane/YZ-plane during 1830–1846 UT; (c) shows the flux tube starting points along the trajectory; (d) shows the end of the flux tube on the nominal flow terminator; the black line in Figure 4d shows the sunlight direction.
region. During the transport, the cross-section of the flux tube expands as the field gets weaker and the plasma density decreases. By assuming the cross section of the flux tube is round and 1.7 \( R_{\text{Ti}} \) is the diameter, the magnetic flux contained in the flux tube is about \( 7.5 \times 10^4 \) \( T \cdot m^2 \). If we assume constant magnetic flux along the flux tube and its cross-section in the ionosphere covers a whole forward hemisphere of Titan, then \( B_{\text{ionosphere}} \pi R_{\text{Ti}}^2 h = 7.5 \times 10^4 \) \( T \cdot m^2 \) leads to a height of 930 km assuming ionospheric field \( B_{\text{ionosphere}} \) is 10 nT. This estimate indicates that the flux tube contains much of the magnetic flux in the lower ionosphere. The sunlight direction is shown as a black line in panel d, which suggests that the field lines enter the nightside ionosphere close to Titan and wrap around the planet. We note that at the Saturn local time of these observations (about 3 LT) the sunlit side of Titan is principally in the flow wake region.

3. Discussion and Conclusions

Titan has a thick ionosphere that stands off the upstream plasma flow; however, it is not strong enough to keep the magnetosheath field from penetrating into the lower atmosphere. The ionopause is located at an altitude between 1000 and 1500 km in the sunlit ionosphere from INMS data (J. G. Luhmann, personal communication, 2006), and magnetic field (observed between 1 nT to over 10 nT) is observed at regions below the ionopause on low altitude flybys not illustrated here. The Langmuir Probe data indicate the ionopause to be commonly above and around 2000 km. On a flux tube with one end penetrating in the lower ionosphere and the other end stretching into the distant magnetotail, the dense plasma in the ionosphere and the dilute plasma in the tail would lead to a pressure gradient along the flux tube, accelerating the ionospheric plasma and transporting it to the distant tail. When the spacecraft crossed a portion of such a flux tube in the distant tail, it observed plasma originating from Titan’s ionosphere, which could be much denser than the ambient plasma in the tail. The field lines appear to connect to the ionosphere at low altitudes near the flow terminator.

In conclusion, we combined the magnetometer data and plasma data to study Titan’s distant magnetotail. We find that there is cold dense plasma observed in the distant magnetotail. The cold dense plasma is in flux tubes connecting to the nightside Titan ionosphere at low altitudes, and the tube has magnetic flux content sufficient to contain much of the magnetic flux in the magnetized upstream ionosphere. These flux tubes appear to be strongly rooted low in the upstream ionosphere allowing the ionospheric plasma to move along field lines to the spacecraft in the distant tail, and leading to loss of the atmosphere.

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References


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