

Characteristics and variability of Titan's magnetic environment

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The structure and variability of Saturn's magnetic field in the vicinity of Titan's orbit is studied. In the dawn magnetosphere, the magnetic field presents a significant radial component directed towards Saturn, suggesting that Titan is usually located below the planet's warped and dynamic magnetodisc. Also, a non-negligible component along the co-rotation direction suggests that Saturn's magnetic field lines close to the magnetodisc are being swept back from their respective magnetic meridians. In the noon sector, Titan seems to be closer to the magnetodisc central current sheet, as the field lines in this region seem to be more dipolar. The distance between the central current sheet and Titan depends mainly on the solar wind pressure. Also, $\delta|B|/|B| \sim 0.5$ amplitude waveforms at periods close to Saturn's kilometric radiation period are present in the background magnetic field. This modulation in the field is ubiquitous in Saturn's magnetosphere and associated with the presence of a rotating asymmetry in the planet's magnetic field.

Keywords: Titan; plasma interactions; planetary magnetospheres; Saturn

1. Introduction

Titan is perhaps one of the most interesting examples of the interaction of the atmosphere of a weakly magnetized body with a wind of flowing plasma. As a result of the absence of a significant intrinsic magnetic field (Neubauer *et al.* 1984), the atmosphere and exosphere of Titan are exposed to the direct interaction with its plasma environment. Photoionization, electron impact and charge exchange act as catalysts of the interaction by generating an ionosphere that becomes the ultimate obstacle to the external plasma, but also by creating a corona of cold light and heavy ions beyond the ionosphere (Hartle *et al.* 2006), which is responsible for the mass loading of the external plasma. As a consequence of the conservation of linear momentum, the mass-loaded external plasma decelerates near Titan. The virtual absence of collisions causes the magnetic field lines frozen into the external plasma to pile up near the sub-flow point, drape around the Moon's ionosphere and stretch along the direction of the flow, defining an induced magnetosphere and magnetotail. The magnetotail

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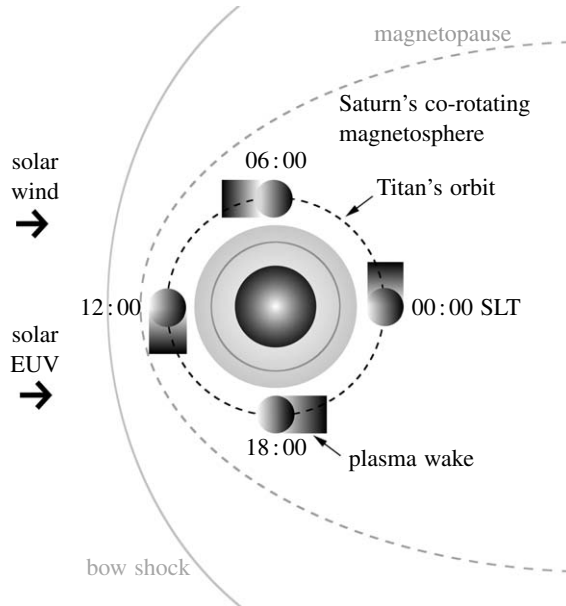


Figure 1. Schematic describing the dependence of the Titan–Saturn interaction on Saturn local time (SLT). When Titan is inside Saturn’s rotating magnetosphere, the angle between the solar EUV photon wake and the plasma wake is a function of Titan’s SLT. Assuming a purely azimuthal magnetospheric flow, SLT is zero when Titan is located in the anti-solar direction with respect to its parent planet.

consists of two lobes containing draped field lines parallel and antiparallel to the external flow. This interaction has been shown to lead to the removal of ionized atmospheric constituents as they receive via collision-less processes (Szego *et al.* 2007) the linear momentum lost by the external flow.

The orientation of an induced magnetosphere strongly depends on the direction of the external plasma flow and that of the ambient magnetic field frozen into it. In a simplified case, where the direction of the external flow coincides with that of the EUV photons and the magnetic field is perpendicular to them, the plane of the current sheet separating the tail lobes is perpendicular to the plane containing the field and the plasma wind vectors (Israelevich *et al.* 1994). As a result, the induced magnetosphere rotates with the upstream field around the plasma velocity vector.

With an orbital apoapsis that does not exceed 21 planetary radii ($R_S=60\,268$ km), Titan is located in the confines of Saturn’s magnetosphere. Saturn’s magnetopause’s position is mainly controlled by the solar wind (Achilleos *et al.* in press) and follows a bimodal distribution with means at 21 and 27 R_S . While inside Saturn’s magnetosphere, Titan interacts with Saturn’s partially co-rotating magnetospheric flow. This flow consists of charged particles from the E-ring and Enceladus (Kivelson 2006) that transport Saturn’s magnetic field and encounters Titan at speeds of approximately 100 km s^{-1} (Hartle *et al.* 1982). The angle between the co-rotating magnetospheric flow and the solar photons responsible for the ionization of Titan’s atmosphere varies along its orbit according to the Moon’s local time with respect to Saturn (SLT). Assuming ideal co-rotation, i.e. the flow is tangential to Titan’s orbit, this angle is zero when Titan is located at 18.00 SLT and 180° at an SLT of 06.00 (figure 1).

For SLT near noon, Titan can also interact with the shocked solar wind and the interplanetary magnetic field during periods of high solar wind dynamic pressure, as the pressure balance at the magnetopause occurs at lower kronocentric distances, leaving Titan in the magnetosheath (Bertucci *et al.* 2008).

During the Voyager 1 flyby (approx. 13.30 SLT), Titan was found within Saturn's magnetosphere and immersed in a typical southward magnetic field (Ness *et al.* 1982). Consistently, an induced magnetic tail consisting of draped Kronian field lines was observed downstream from the moon; with a lobe of field lines antiparallel to the flow downstream from the moon's Northern Hemisphere ('north lobe') and a lobe of parallel field lines downstream from the Southern Hemisphere ('south lobe').

Based on Voyager 1 observations, it was expected that Cassini could find Titan immersed in a field that would always be perpendicular to the moon's orbital plane (Blanc *et al.* 2002). However, measurements from Cassini's magnetometer MAG (Dougherty *et al.* 2004) in Saturn's outer magnetosphere showed that the field near the planet's equatorial plane was influenced by the presence of a magnetodisc extending from $15 R_S$ (Arridge *et al.* 2008a), and formed by the centrifugal outflow of plasma originated in Saturn's E-ring and the icy satellites (Kivelson 2006), which stretches Saturn's magnetic field lines on the equatorial plane. In addition, Saturn's magnetic field is strongly modulated by the planet's rotation period. These oscillations seem to be in phase with the enhancements in the Saturn kilometric radiation emissions (Kurth *et al.* 2007), and their origin is discussed in several works (e.g. Espinosa *et al.* 2003; Cowley *et al.* 2006).

In this paper, the properties of the magnetic field measured by Cassini in the vicinity of Titan's orbit during the first 20 orbits around Saturn (July 2004–December 2005) is examined in an attempt to characterize the moon's magnetic environment in the noon and dawn sectors of Saturn's magnetosphere. Then, the implications for different interaction scenarios based on the magnetic field and plasma properties are briefly discussed.

2. Characterization of Titan's magnetic environment from Cassini data

The topology of Saturn's magnetic field was studied using MAG data in magnetic cylindrical coordinates (ρ, φ, Z) , where the Z -axis is aligned with Saturn's magnetic axis, ρ is the perpendicular distance from this axis, and azimuthal angle φ is measured positive in the direction of planetary rotation ($\varphi=0$ corresponds to the noon meridian). The time resolution of the data used in this work is 1 hour. The orientation of the magnetic field was studied using two angles: the 'stretch' angle = $\arctan(-B_\rho/B_Z)$ and the 'sweepback' angle = $\arctan(B_\varphi/B_\rho)$. As negative (positive) values of stretch angle indicate a field pointing towards (away from) Saturn, the stretch angle indicates Cassini's location with respect to the planet's magnetodisc (north and south, respectively). Negative (positive) values of sweepback angle indicate field lines being swept out of the meridian plane (ρ, Z) in a direction antiparallel (parallel) to the local co-rotation direction.

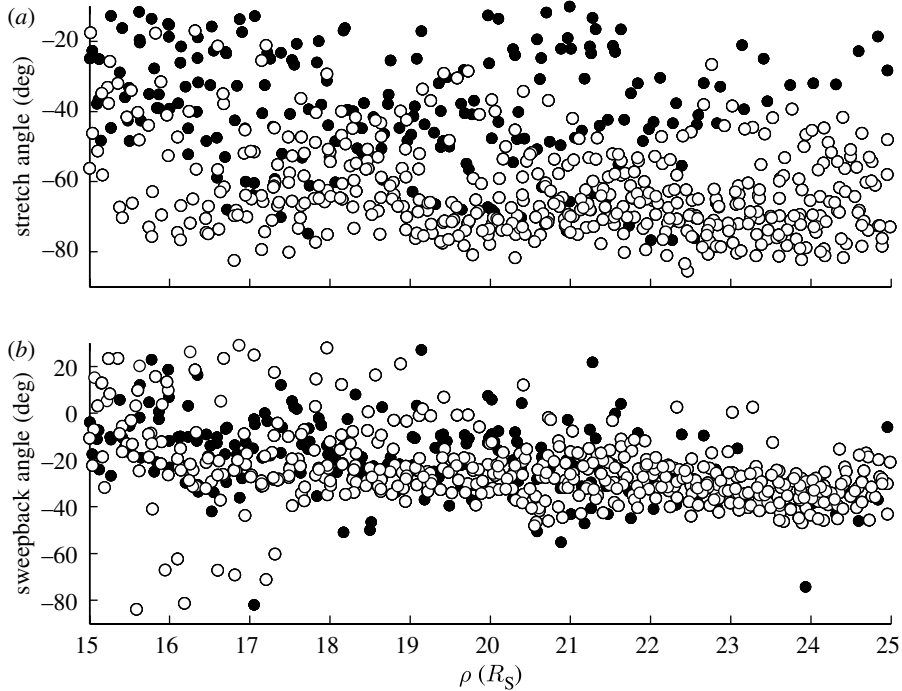


Figure 2. One-hour resolution (a) stretch and (b) sweepback angles as a function of radial cylindrical distance from Saturn in the vicinity of Titan’s orbit ($15 < \rho < 25 R_S$, $-1 < Z < 0.5 R_S$) from Cassini’s first 20 orbits. The measurements are divided into two SLT sectors: open circle, dawn ($03.00 < \text{SLT} < 08.00$); and filled circle, noon ($09.00 < \text{SLT} < 11.30$).

(a) Influence from Saturn’s magnetodisc

The behaviour of the stretch and sweepback angles was analysed in the vicinity of Titan’s orbit defined as the sector $15 < \rho < 25 R_S$, $-1 < |Z| < 0.5 R_S$. As a result of Cassini’s orbital geometry during the first 20 orbits, magnetic field measurements in this region occur within the sector $03.00 < \text{SLT} < 11.30$ of Saturn’s magnetosphere. Measurements in this sector occurring within the magnetosheath were removed.

The effect of SLT on the orientation of the ambient field near Titan was studied by dividing stretch and sweepback angle measurements into two sectors: (i) a ‘dawn’ sector ($03.00 < \text{SLT} < 08.00$) and (ii) a ‘noon’ sector ($09.00 < \text{SLT} < 11.30$). Figure 2a shows the stretch angle as a function of kronocentric equatorial distance, ρ . The first conclusion that can be drawn from this plot is that, in general, Titan is immersed in Kronian magnetic field lines showing negative stretch. However, the average values and the variability of the stretch angle in the two sectors clearly differ, as the field in the dawn sector is, on average, more stretched (-65°) than in the noon sector (-38°). Also, the standard deviation of the stretch angle is more pronounced in the noon sector ($\sigma_{\text{noon}} = 17^\circ$) than in the dawn sector ($\sigma_{\text{dawn}} = 11^\circ$). Consistent with these results is the fact that, whereas the dawn field never attains near-zero or positive values of stretch angle, the increase in the dispersion near noon leads to occasional

near-zero and marginally positive values. Owing to the small extent of the region of study along Z with respect to the estimation of the magnetodisc thickness (Arridge *et al.* 2008a), the stretch angle provides a good estimate of the distance between Cassini and the magnetodisc's central current sheet. Thus, the more negative and less variable stretch angle values in the dawn sector reveal that Titan only occasionally interacts with Saturn's central current sheet, where the field is north/south. Furthermore, these measurements show that the current sheet is displaced north of Titan's orbital plane. In the noon sector, the stronger variability suggests that the magnetodisc is more dynamic or that its thickness varies, allowing Titan to interact occasionally with the central current sheet.

The plot of the sweepback angle as a function of radial distance shown in figure 2b reveals that the noon magnetic field covers a much larger range than the dawn field, but, statistically speaking, dawn and noon sectors are not significantly different, with mean values of -26° and -19° , and standard deviations of 11° and 17° , respectively. The negative mean values indicate that, in general, the magnetospheric field lines encountering Titan are 'lagging' with respect to co-rotation. This results in a significant magnetic field component along the direction of the magnetospheric flow encountering Titan. Nevertheless, both local time sectors also display positive angles, revealing the presence of 'leading' magnetic field lines.

Cassini data obtained during the Rev 5 (periapsis: 29 March 2005) orbit provide a good illustration of how different Saturn's magnetosphere near Titan can look, depending on SLT and solar wind pressure. Figure 3 shows the field stretch and sweepback angles as a function of the cylindrical radial distance ρ . During the inbound leg (noon sector, $09.45 < \text{SLT} < 11.00$), Saturn's magnetosphere was compressed, the magnetopause stand-off distance (R_{MP}) being approximately $18.5 R_S$ according to the model by Arridge *et al.* (2006). Between 15 and $25 R_S$ radial distance, Cassini is on the equatorial plane ($Z \sim -0.06 R_S$), yet the magnetic field shows very little stretch (angle $\sim -20^\circ$). These two elements suggest that the magnetodisc could have been thickened by the compression and 'braced' by the solar wind pressure. This configuration would produce a relatively large magnetospheric field strength near Titan, and a field geometry thus capable of balancing the centrifugal force of the rotating magnetospheric plasma with less radial distortion.

In the outbound leg of Rev 5, the magnetosphere was expanded ($R_{\text{MP}} \sim 27 R_S$) and accordingly we see a negative sweepback, and a more stretched field with respect to the inbound leg, suggesting that the current sheet is displaced north of the planet's equatorial plane as a consequence of solar wind forcing.

(b) 10.8-hour modulations

The statistical properties of the stretch and sweepback angle measurements clearly show that the configuration of Saturn's magnetic field in the vicinity of Titan is strongly influenced by the proximity to Saturn's magnetodisc. However, a part of the dispersion observed in these angles is due to oscillations in the magnetic field at periods close to Saturn's rotation. Figure 4 shows the stretch and sweepback angles as functions of radial distance ρ for three consecutive

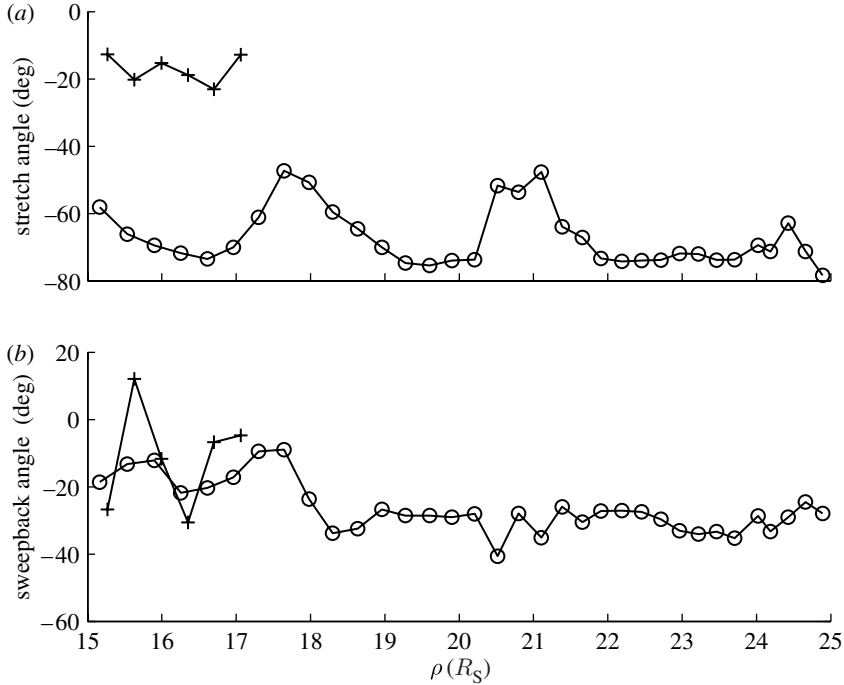


Figure 3. (a) Stretch and (b) sweepback angles as a function of radial cylindrical distance from Saturn for Cassini’s orbit Rev 5. The values of the magnetopause stand-off distance R_{MP} for the inbound (pluses; $R_{MP}=18.5 R_S$) and outbound (circles; $R_{MP}=27 R_S$) legs based on Arridge *et al.* (2006) are indicated.

orbits of Cassini in the SLT sector where the T9 flyby took place (Bertucci *et al.* 2007): Rev 17 (periapsis: 29 October 2005), Rev 18 (27 November 2005) and Rev 19 (periapsis: 24 December 2005), during which the T9 flyby occurred. The stretch angle clearly shows oscillations with a period close to Saturn’s rotation period (10 hours 47 min 6 s \sim 10.8 hours, according to Giampieri *et al.* 2006). The Rev 19 ‘waveform’ in this representation does not repeat itself after 03.00 SLT, unlike those of the other orbits, because Cassini encounters Titan at 03.06 SLT. For all three orbits, the amplitude of these fluctuations in the angular parameters decreases with distance from the planet. The stretch angle is always negative, indicating that, as it is seen in the entire dawn sector, the spacecraft never crosses the centre of the current sheet, remaining south of this structure. The sweepback angle is also negative most of the time, indicating a field that corresponds to plasma that is ‘lagging’ the planet with respect to co-rotation. However, field with a positive ‘leading’ value of this angle is also observed, suggesting that at these times Cassini is immersed in plasma with angular velocity closer to, or exceeding, co-rotation. Furthermore, it is apparent that these changes in the azimuthal properties of the field lines are correlated with the particular ‘phase’ of approximately 10.8-hour oscillation. Finally, we note that Titan’s orbit ($\rho \sim 20.2 R_S$) intersects the oscillations at different phases, implying that a fixed SLT and a uniform distance from the magnetodisc is not enough to make sure that Saturn’s field near Titan will be the same at any time.

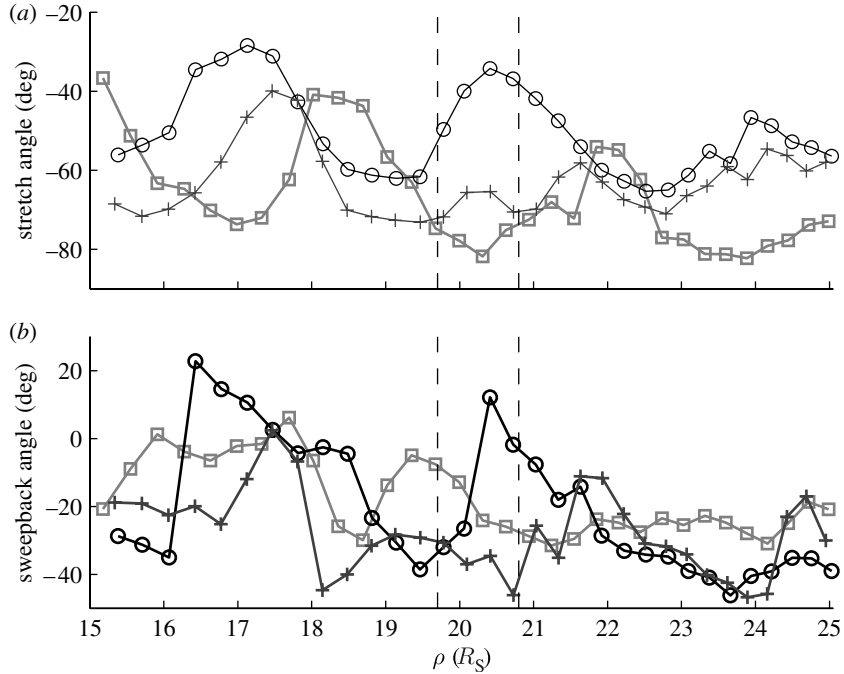


Figure 4. (a) Stretch and (b) sweepback angles as a function of radial cylindrical distance from Saturn for the outbound legs of orbits Rev 17 (squares), 18 (circles) and 19 (pluses). The vertical dashed lines at $\rho = 19.7$ and $20.8 R_S$ indicate, respectively, the periaapsis and apoapsis of Titan's elliptical orbit.

3. Discussion and conclusions

The observations reported in this paper reveal that Titan encounters an ambient Kronian magnetic field that is not always dipolar (associated with Saturn's internal dynamo). Two non-dipolar contributions are identified: (i) a recurrent Saturnward, lagging field consistent with the proximity of the planet's magnetodisc; and (ii) a ubiquitous, oscillating field with a period of approximately 10.8 hours.

As for the first contribution, the negative stretch angles indicate that Titan is systematically south of Saturn's magnetodisc current sheet. The northward displacement of the magnetodisc with respect to Titan's orbit seems to be a seasonal effect produced by the forcing of the solar wind whose sub-flow point, during the period of the observations described here, is located at southern magnetic latitudes (Arridge *et al.* 2008a). This situation is expected to be reversed in the Northern Hemisphere summer, when the magnetodisc would be displaced southwards, leaving Titan north of the central current sheet.

The observations obtained during Cassini's Rev 5 orbit also show that Saturn's magnetodisc is a dynamic structure whose central current sheet moves with respect to Titan in response to changes in the solar wind dynamic pressure. Whereas a compression of the magnetopause is associated with a decrease in the stretch angle, exposing Titan to a more dipolar field typical of the magnetodisc centre, an expansion of the magnetosphere leads to more stretched field lines, typical of the magnetodisc lobes. Initial analysis of Cassini Plasma Spectrometer (CAPS; Young *et al.* 2004) data indicates that the centre of Saturn's magnetodisc

is populated by denser, hotter and probably heavier plasma than the magnetodisc lobes (Arridge *et al.* 2008*b*). As a result, Titan is exposed to plasma whose properties range between: (i) a ‘current sheet’ regime with less stretched fields and denser and hotter (and therefore more energetic) plasma; and (ii) a ‘lobe-type’ regime characterized by stretched fields and low-density and low-temperature plasma. The former scenario would lead to high-energy and high-pressure inputs to Titan’s ionosphere and atmosphere, with probably a more compressed induced magnetosphere; whereas, in the latter scenario, a lower-energy input would lead to a more expanded induced magnetosphere. These different energy input regimes are being studied in more detail, as processes such as magnetospheric plasma ion and electron precipitation (e.g. Garnier *et al.* 2007; Cravens *et al.* 2008) might be subject to strong variabilities associated with them.

Initial analyses indicate that Voyager 1 flyby (approx. 13.30 SLT) is an example of Titan’s interaction under a current sheet regime. The quasi-dipolar field and the high plasma beta of the ambient plasma (Neubauer *et al.* 1984) indicate that Titan is immersed in the centre of a probably thick current sheet as a result of the effect of the Chapman–Ferraro currents that are important in the near noon sector. An example of lobe-type regime is the T9 flyby (Bertucci *et al.* 2007), where a significant deflection of the external flow from co-rotation was observed on the orbital plane (Szego *et al.* 2007). The strong Saturn-ward component resulted in a southward convective electric field that may have led to a north–south asymmetry in Titan’s induced magnetosphere.

The 10.8-hour oscillations observed in the magnetic field also affect the configuration of the magnetic field near Titan. The origin of this feature is still unknown, but it is likely to be associated with the presence of a rotating asymmetry in Saturn’s magnetic field (Southwood & Kivelson 2006). Near Titan’s orbit, these oscillations have an amplitude of typically a few nanoteslas ($\delta|B|/|B| \sim 0.5$), which is very close to the magnetic field magnitude measured by Cassini in Titan’s induced magnetosphere (Backes *et al.* 2005). Recently, Arridge *et al.* (2008*b*) have reported similar time-scale variations in CAPS data and showed an anticorrelation with the stretch angle of the magnetic field. The interpretation given was that Titan would move in to and out of Saturn’s magnetodisc current sheet as a consequence of a periodic vertical motion that follows the phase of Saturn’s rotating asymmetry.

In summary, Cassini MAG observations reveal that Titan’s magnetic environment is strongly controlled by the proximity of Saturn’s magnetodisc and the presence of a rotating asymmetry in its magnetic field. As a result, the ambient magnetic field near Titan is not strictly dipolar, as Voyager 1 observations led us to think, but radially stretched and lagging with respect to co-rotation. To date, no study on the global properties of the Kronian flow velocity near Titan and their relations with the magnetic field orientation remains has been done. Hopefully, existing collaborations with other Cassini teams will produce such combined analyses in the near future.

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