Planetary and Space Science 58 (2010) 1625–1635

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Dynamics of Saturn's magnetodisk near Titan's orbit: Comparison of Cassini magnetometer observations from real and virtual Titan flybys

Sven Simon [a,*], Alexandre Wennmacher [a], Fritz M. Neubauer [a], Cesar L. Bertucci [b,c], Hendrik Kriegel [d], Christopher T. Russell [e], Michele K. Dougherty [c]

[a] Institute of Geophysics and Meteorology, University of Cologne, Germany
[b] Institute for Astronomy and Space Physics, CONICET/University of Buenos Aires, Ciudad Universitaria, Buenos Aires, Argentina
[c] Space and Atmospheric Physics Group, The Blackett Laboratory, Imperial College London, UK
[d] Institute for Theoretical Physics, TU Braunschweig, Germany
[e] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, USA

ARTICLE INFO

Article history:
Received 10 May 2010
Received in revised form
20 July 2010
Accepted 2 August 2010
Available online 5 August 2010

Keywords:
Titan
Saturn's magnetosphere
Magnetodisk current sheet and lobes
Cassini flybys
Plasma interaction with unmagnetized bodies

ABSTRACT

We analyze the variability of the ambient magnetospheric field along Titan's orbit at 20.3 Saturn radii. However, while our preceding study (Simon et al., 2010) focused on Cassini magnetometer observations from the 62 Titan flybys (TA–T62) between October 2004 and October 2009, the present work discusses magnetic field data that were collected near Titan's orbit when the moon was far away. In analogy to the observations during TA–T62, the magnetospheric fields detected during these 79 "virtual" Titan flybys are strongly affected by the presence of Saturn's bowl-shaped and highly dynamic magnetodisk current sheet. We therefore provide a systematic classification of the magnetic field observations as magnetodisk current sheet or lobe-type scenarios. Among the 141 (62 real+79 virtual) crossings of Titan's orbit between July 2004 and December 2009, only 17 encounters (9 real+8 virtual) took place within quiet, magnetodisk lobe-type fields. During another 50 encounters (21 real+29 virtual), rapid transitions between current sheet and lobe fields were observed around the moon's orbital plane. Most of the encounters (54=22 real+32 virtual) occurred when Titan's orbit was embedded in highly distorted current sheet fields, thereby invalidating the frequently applied idealized picture of Titan interacting with a homogeneous and stationary magnetospheric background field. The locations of real and virtual Titan flybys are correlated to each other. Each of the 62 real Titan flybys possesses at least one virtual counterpart that occurred shortly before or after the real encounter and at nearly the same orbital position. A systematic comparison between Cassini magnetometer observations from the real Titan flybys and their virtual companions suggests that there is no clear evidence of Titan exerting a significant level of control on the vertical oscillatory motion of the magnetodisk near its orbit.

1. Introduction

Titan, Saturn's largest satellite, orbits its parent planet at a distance of about $20.3R_S$ (R_S=60 268 km). The absence of a noteworthy intrinsic magnetic field (Neubauer et al., 1984; Backes et al., 2005) leads to a direct exposure of Titan's dense atmosphere and ionosphere to the plasma in Saturn's outer magnetosphere. In the pre-Cassini era, most available studies of the interaction between Titan's ionosphere and Saturn's magnetospheric plasma were based on several highly idealized assumptions: the ambient magnetospheric field was considered to be nearly perpendicular to the moon's orbital plane, and – what is even more important – to be constant on any length and time scale involved in the local interaction process, e.g. the gyroradii and periods of the involved ion species or the convection time of a magnetic flux tube through the interaction region (see e.g. Nagy et al., 2001; Kallio et al., 2004; Ledvina et al., 2004). However, the ongoing Cassini mission has greatly improved our knowledge on the characteristics of the ambient magnetic field near Titan's orbit, one of the major results being that this idealized description may not reflect the real situation at all.

Titan's immediate magnetic environment is strongly affected by the proximity of its orbital plane to Saturn's warped and highly dynamic magnetodisk current sheet (Arridge et al., 2007, 2008b,c; Simon et al., 2010). Cassini arrived at Saturn shortly after southern summer solstice, i.e. during all Titan flybys of the prime mission (2004–2008), Saturn's dipole magnetic equatorial plane was strongly tilted with respect to the Sun–Saturn-line. Arridge et al. (2008b) showed that during this time, the magnetodisk current sheet did not coincide with the equatorial plane, but due to solar wind forcing, it was deformed into a bowl-like configuration. For this reason, Titan's orbit was no longer located within

---

[*] Corresponding author. Tel.: +49 221 4702556.
E-mail address: simon@geo.uni-koeln.de (S. Simon).

0032-0633/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2010.08.006

the dipole magnetic equator, but the moon could on average be found within the highly stretched field lines of the southern magnetodisk lobe. The magnetodisk current sheet has also shown to be a highly dynamic structure: On the one hand, it frequently performs vertical oscillations on characteristic time scales between about 10–20 min and up to several hours (Arridge et al., 2007, 2008b; Simon et al., 2010). On the other hand, it possesses a strong day–night asymmetry induced by the solar wind: near noon local time, the field lines are stretched into a disk-like configuration only in times of low solar wind dynamic pressure, i.e. when the stand-off distance of Saturn's magnetopause is larger than $23R_S$. Otherwise, the formation of the dayside magnetodisk is at least partially suppressed by the Chapman–Ferraro currents, thereby yielding a dipolarization of the magnetic field around noon. Of course, this high variability of the large-scale magnetospheric configuration also has significant impact on Titan's immediate magnetic environment.

Recently, Bertucci et al. (2009) confirmed that depending on Saturnian Local Time (SLT), Titan's orbit is either located within a regime of radially stretched, lobe-type field lines or a more dipolar current sheet regime. Simon et al. (2010) provided a systematic classification of Titan's magnetic environment during the first 62 Cassini encounters (TA–T62 between July 2004 and December 2009) as current sheet or lobe-type scenarios. These authors showed that the dynamics of the magnetodisk play a key role for the structure of the ambient magnetic field near Titan. Especially in the nightside magnetosphere, the current sheet carries out intense vertical oscillations on a characteristic time scale of up to several hours, alternately exposing Titan to lobe-type fields of different polarity and to highly perturbed current sheet fields. Simon et al. (2010) showed that in southern summer, the center of these current sheet oscillations was located above Titan's orbital plane. Around equinox in August 2009, however, the moon could be found directly within the center of vertical current sheet motion, yielding a significant intensification of the perturbations in its magnetic environment. The study of Simon et al. (2010) also showed that until late 2009, nearly every Titan flyby in the dayside magnetosphere took place within highly distorted current sheet fields, thereby amplifying the findings of Bertucci et al. (2009). Overall, Simon et al. (2010) demonstrated that there is not a single Titan flyby in the TA–T62 series which matches the idealized pre-Cassini picture of a constant and homogeneous magnetospheric background field, being perpendicular to the moon's orbital plane. A major consequence of this high variability is a nearly permanent "contamination" of Titan's ionosphere with fossil magnetic fields (Neubauer et al., 2006; Bertucci et al., 2008), recording the moon's frequent encounters with different field regimes. The classification of the magnetic field regimes near Titan provided by Simon et al. (2010) is in good agreement with the results of Rymer et al. (2009). These authors classified the ambient plasma conditions during Titan flybys TA–T55 by analyzing Cassini electron data.

The set of 62 close Titan encounters between Saturn Orbit Insertion (SOI) and late 2009 is accompanied by an even larger number of Cassini passages near Titan's orbit at $20.3R_S$ that occurred when the moon and the spacecraft were located in completely different sectors of the magnetosphere. The locations of these 79 "virtual" Titan flybys are illustrated in Fig. 1, displaying the tilt of Saturn's dipole axis with respect to the Sun–Saturn-line (equivalent to the latitude of Titan's/Saturn's subsolar point, SSL) and the Saturnian local time (SLT) of closest approach to Titan's orbital path. As can be seen from the figure, the locations of real and virtual Titan flybys are correlated. Each real Titan flyby possesses at least one virtual counterpart that occurred at nearly the same location in SSL–SLT space, i.e. at almost the same orbital position and very close in time before/after the real encounter. Thus, for each Titan flyby, at least one other sample of the magnetic field conditions at practically the same point in SSL–SLT space is available. The purpose of the present study is to analyze the magnetic field observations during these 79 virtual Titan flybys and to compare them with the classification provided for their 62 real counterparts (Simon et al., 2010). In particular, the following questions and problems shall be addressed:

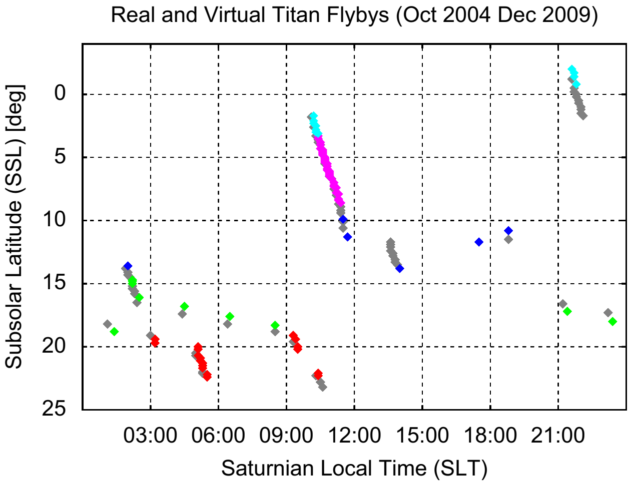

Fig. 1. Crossings of Titan's orbit at $20.3R_S$ between SOI 2004 and December 2009: Saturnian Local Time (SLT) versus Subsolar Latitude (SSL). The figure displays the correlation between the orbital position of closest approach and the latitude of Titan's/Saturn's subsolar point for the virtual Titan flybys that took place in 2005 (red), in 2006 (green), in 2007 (dark blue), in 2008 (magenta) and in 2009 (light blue). The locations of the real Titan encounters between October 2004 and October 2009 (TA–T62) are shown in gray. As can be seen from the figure, each real Titan flyby possesses at least one virtual counterpart, taking place at nearly the same position in SSL–SLT space. The series of virtual flybys in 2008 (magenta) completely overlaps with the corresponding sequence of real encounters (T35–T51). Therefore, only the virtual flybys are visible in the figure. A color-coded illustration of the real Titan flybys can be found in our companion paper (Simon et al., 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- *Current sheet versus magnetodisk lobes*: A classification of the 79 virtual Titan encounters between SOI and December 2009 as magnetodisk current sheet or lobe-type scenarios will be provided. This classification is based on the same technique as applied in our companion study of the real Titan flybys (Simon et al., 2010).
- *Real versus virtual Titan flybys*: Do magnetic field data from the virtual Titan flybys show a similarly high level of variability as observed during the set of 62 real encounters? How do Cassini MAG data from the virtual Titan flybys compare to observations from their real counterparts in the same local time sectors?
- *Titan's influence on magnetodisk dynamics*: Are there significant differences in magnetodisk dynamics observed during real and virtual Titan flybys? Previous studies of magnetic field observations at $20.3R_S$ have revealed that Titan may exert a certain level of control on large-scale magnetospheric processes in its neighborhood. For instance, Wei et al. (2009) showed that the presence of Titan appears to affect the location of Saturn's magnetopause. Near noon, the magnetopause was found more frequently inside Titan's orbit with the moon absent than with it present. Russell et al. (2008) suggested that the occurrence of reconnection events in Saturn's magnetotail is controlled by the orbital phase of Titan as well. It is therefore of appreciable interest to look for a possible influence of Titan on the vertical oscillatory/flapping

motion of Saturn's magnetodisk (Arridge et al., 2008b; Simon et al., 2010) near its orbit.

- *Overall statistics of Cassini magnetic field observations at* $20.3R_S$: Finally, our results for the real and virtual Titan flybys will be combined to provide a global characterization of the moon's magnetic environment within the first five years of the Cassini mission.

This paper is organized as follows: In Section 2, we will substantiate our definition of a "virtual" Titan flyby. The classification scheme that is applied to discriminate between magnetodisk current sheet and lobe-type fields is also briefly discussed. The classification of the magnetic field conditions during the virtual Titan encounters is presented in Section 3, along with a comparative discussion of the observations during real and virtual encounters. The paper concludes with a brief summary of our major findings in Section 4.

2. Data description and analysis method

2.1. Virtual titan flybys

We have conducted a systematic search of Cassini's trajectory for crossings of Titan's orbit beginning at Saturn Orbit Insertion (SOI) in July 2004 and ending in December 2009. The SPICE (Acton, 1996) library routines were used to perform the orbit and geometry calculations and the data kernels containing the reconstructed Cassini trajectory plus Saturn's and Titan's ephemerides provided by the Cassini navigation team were used.

In a first step, Titan's orbit with respect to Saturn's barycenter was scanned to locate the pericenter $\underline{p}$ and the apocenter $\underline{q}$, from which the semimajor axis, the eccentricity, and the center of the trajectory ellipse can be computed. The plane of the ellipse is spanned by $\underline{p}-\underline{q}$ and the difference in velocities at pericenter and apocenter, $\underline{v}_p-\underline{v}_q$.

The Titan orbit is subject to perturbations by other moons and to secular variations. Therefore, Titan's true orbit deviates from the idealized ellipse derived by the algorithm described above. The maximum deviation between the true Titan orbit and the idealized ellipse is found to be less than 300 km within one year.

In a next step, the Cassini trajectory was scanned for approaches of Titan's orbit ellipse, i.e. for intervals during which Cassini came closer than $1R_S$ to Titan's orbit (see also Wei et al., 2009).

Two kinds of approaches were retrieved: The "real" flybys at Titan, TA–T62, and Titan orbit crossings during which the moon was far away (at least 2 h of local time and more than $10R_S$). The latter events are referred to as "virtual" flybys. The terms "distance of closest approach" and "time of closest approach" can be defined for these virtual flybys; they refer to the point of minimum distance to the idealized trajectory ellipse (and not to the actual position of the moon itself) and the corresponding time. The Saturnian Local Time (SLT) of virtual closest approach thus may significantly differ from Titan's SLT. It should also be noted that the closest approach distance of a real Titan flyby usually refers to the distance between Cassini and the *surface* of the moon. Hence, for a real flyby this term is not defined with respect to Titan's trajectory ellipse.

By applying this method, we have found a total number of 79 virtual Titan flybys that occurred between SOI and the T63 encounter on 12 December 2009. The parameters of the flybys in different local time sectors are listed in Tables 2–6. Our nomenclature for the virtual flybys contains the number of the revolution during which the flyby took place as well as a distinction between inbound and outbound passages. For instance, "15oTI" refers to the virtual Titan (TI) encounter that occurred during the outbound (o) path of Cassini's Rev 15 orbit around Saturn. In the same way, the abbreviation "15iTI" would refer to a virtual flyby that took place during the inbound path (i) of the same orbit. There are two virtual Titan flybys which are deliberately ignored by this study: 119oTI on 16 October 2009 and 120oTI on 03 November 2009. Both flybys occurred in the dusk magnetosphere at about 17:00 SLT. As can be seen from Fig. 1, the data point density in the dusk magnetosphere (15:00–21:00 SLT) is currently very low, and the situation would not be significantly improved by the inclusion of two additional virtual flybys in this sector. These virtual encounters will therefore be discussed in a later paper, along with MAG data from the first series of close Titan flybys in the dusk magnetosphere (T63–T70 between December 2009 and July 2010).

As discussed in the preceding section (see also Fig. 1), each of the real Titan encounters is accompanied by at least one virtual counterpart. An overview of these real/virtual pairs is provided in Table 7. Appendix A provides a short discussion of the characteristics of Cassini's orbit during real and virtual Titan flybys.

2.2. Classification scheme for Cassini MAG observations

For this study, we have analyzed data from the Cassini magnetometer (MAG) instrument (Dougherty et al., 2004) with a time resolution of 10 s. For each encounter, a time interval of ± 8 h around closest approach to Titan's orbital trajectory is considered. As discussed in our preceding paper (Simon et al., 2010), applying such a large time window is helpful for fully understanding the dynamics of Saturn's magnetodisk near Titan's orbit.

The magnetic field data are given with respect to the cylindrical KSMAG coordinate system (at the position of Cassini) also applied by Bertucci (2009): The unit vector in z direction ($\underline{e}_z$) is aligned with Saturn's magnetic moment/rotation axis, whereas $\underline{e}_\rho$ is perpendicular to the z axis, pointing in radial direction. When the magnetic field $\underline{B}$ points away from the spin axis (northern magnetodisk lobe), the B_ρ component is positive, while below the magnetic equator (southern magnetodisk lobe), B_ρ has a negative sign. The unit vector $\underline{e}_\phi$ completes the locally orthogonal coordinate system and points eastward. It should be noted that for a real Titan flyby, this coordinate system would coincide with the corresponding Titan-centered Titan Interaction System TIIS (Backes, 2005; Backes et al., 2005).

In our companion paper (Simon et al., 2010), we have introduced a set of criteria that permit an unbiased discrimination between current sheet and lobe-type fields. In the present study, these criteria are applied in exactly the same way: the magnetic field data from the ± 8 h window are segmented in time intervals of 1 h length. For each segment, we compute the average magnetic field components $\langle B_i \rangle$ $(i=\rho,\phi,z)$ as well as their standard deviations δB_i. For each of the 360 data points from the 1 h binning intervals, the total magnetic field is calculated as well. Averaging these values over the 1 h time window yields an average field magnitude $\langle B \rangle$, which is required as a normalization value.

In the magnetodisk lobes (L^N: northern lobe, L^S: southern lobe), the field is stretched radially away from (or towards) Saturn's rotation axis and is rather quiet. This field regime is characterized by

$$\frac{|\langle B_\rho \rangle|}{\langle B \rangle} > 0.6 \quad \text{and} \quad \frac{\delta B_\rho}{\langle B \rangle} < 0.05. \tag{1}$$

Usually, there is no sharp boundary between current sheet and lobe-type field regimes. The Cassini magnetometer frequently observed fields that were mainly of the lobe-type, but nonetheless slightly distorted by short-scale intrusions of the magnetodisk current sheet (Arridge et al., 2007, 2008b). In this regime, the field strength criterion still holds, while the fluctuation level is slightly increased:

$$\frac{|\langle B_\rho \rangle|}{\langle B \rangle} > 0.6 \quad \text{and} \quad 0.05 \le \frac{\delta B_\rho}{\langle B \rangle} < 0.2. \tag{2}$$

In the following, this field regime is denoted by the symbols L_{Sh}^N for the northern lobe and L_{Sh}^S for the southern lobe, respectively.

The current sheet itself (symbol Sh) is identified by a breakdown of either the first or the second or both criteria in condition (2). If only the fluctuation criterion breaks down (i.e. $\delta B_\rho / \langle B \rangle \ge 0.2$), but the field strength criterion still holds (i.e. $|\langle B_\rho \rangle| / \langle B \rangle > 0.6$), this is denoted by an additional subscript (Sh_{L^N} for $\langle B_\rho \rangle > 0$ and Sh_{L^S} for $\langle B_\rho \rangle < 0$). The applied set of classification symbols is summarized in Table 1. A more detailed discussion of this classification procedure is provided in our companion study of the real Titan encounters.

However, we would like to point out that in strong analogy to our findings for the real Titan flybys (cf. Section 2.2 of Simon et al., 2010), the results of our magnetic field classification for the virtual encounters remain unaffected when the length of the binning intervals is reduced from 1 h to e.g. 30 min. Usually the magnetic field conditions near Titan's orbit change on time scales of above 1 h. Therefore, when applying a binning interval of 1 h, one does not risk to "miss" e.g. a passage through the current sheet from northern to southern lobe fields.

Table 1
Classification categories for Titan's magnetic environment.

Symbol	Explanation
Sh	Magnetodisk current sheet
L^N	Northern magnetodisk lobe ($B_\rho > 0$)
L^S	Southern magnetodisk lobe ($B_\rho < 0$)
L_{Sh}^N	Northern lobe ($B_\rho > 0$), brief occurrences of current sheet fields
L_{Sh}^S	Southern lobe ($B_\rho < 0$), brief occurrences of current sheet fields
Sh_{L^N}	Current sheet, brief occurrences of northern lobe ($B_\rho > 0$)
Sh_{L^S}	Current sheet, brief occurrences of southern lobe ($B_\rho < 0$)
Msh	Magnetosheath

3. Results

Our classification of Cassini MAG observations during the virtual Titan flybys is provided in Tables 2–6. In order to allow a straightforward comparison to the results for TA–T62, the data are arranged in exactly the same way as in our companion study (Simon et al., 2010): the classification scheme discriminates between the inbound and outbound region of each encounter. If a transition between different magnetic field regimes was observed, this is denoted by a sequence of classification symbols, listed in the order of time. Hence, the situation around closest approach to Titan's orbital path is characterized by the last symbol in the "inbound" column and the first symbol in the "outbound" column. Each table contains the classification results for a certain local time sector of the magnetosphere.

In the following, we compare these results to our findings for the real Titan flybys and discuss their implications for magnetodisk dynamics in different local time sectors. All information on the characteristics of the magnetic field during the real Titan flybys (TA–T62) have been taken from our preceding paper (Simon et al., 2010).

3.1. Post-midnight magnetosphere (00:00–03:00 SLT)

Titan's magnetic environment at about 02:00 SLT had been sampled during encounters T16–T24 which occurred between July 2006 and January 2007, i.e. long before equinox in August 2009. As can be seen from Table 7, these flybys are accompanied by a set of five virtual passages near Titan's orbit: 27iTI, 32iTI, 33iTI, 34iTI and 39iTI occurred around the same location in SSL–SLT space. In the order of time, the sequence of flybys is T16, 27iTI, T17, T18, T19, T20, 32iTI, 33iTI, 34iTI, T21, T22, T23, T24, 39iTI. During all of these encounters, Cassini crossed Titan's orbital

Table 2
Classification of Cassini MAG observations during virtual flybys in the 12:00–03:00 SLT sector.

Flyby	C/A	SLT	SSL	C/A distance (km)	z range [R_T]	Class. inb.	Class outb.
38oTI	04 February 07, 01:03	14.0 (10.7)	−13.8	5681.5 (2.2R_T)	−55.1…+54.2 (nb.)	Sh	Sh, Msh, Sh
47iTI	26 June 07, 07:18	17.5 (8.4)	−11.7	36250.4 (14.1R_T)	+16.9 …+14.5 (sb.)	Sh	Sh
49iTI	27 August 07, 17:43	18.8 (6.2)	−10.8	384.6 (0.1R_T)	+2.8 …+2.0 (sb.)	Sh, L_{Sh}^S	Sh
22oTI	22 March 06, 17:02	23.4 (12.4)	−18.0	258.3 (0.1R_T)	+2.8 …+3.5(nb.)	L_{Sh}^S	L_{Sh}^S
24oTI	24 May 06, 05:16	21.4 (10.2)	−17.2	1195.0 (0.5R_T)	+3.0 …+4.2 (nb.)	Sh, L_{Sh}^S, Sh	Sh, L_{Sh}^S
118iTI	18 September 09, 12:13	21.8 (9.8)	0.8	86.1 (0.0R_T)	-data gap-	-data gap-	-data gap-
120iTI	31 October 09, 07:58	21.7 (2.1)	1.4	1296.9 (0.5R_T)	2.6…1.7 (sb.)	L_{Sh}^N, Sh, L_{Sh}^S	L_{Sh}^S, Sh, L_{Sh}^N, Sh
121iTI	19 November 09, 08:35	21.7 (6.7)	1.7	1255.7 (0.5R_T)	2.6…1.7 (sb.)	L_{Sh}^N, Sh_{L^S}, L_{Sh}^N	L_{Sh}^N, Sh
122iTI	08 December 09, 09:25	21.6 (11.5)	2.0	1486.7 (0.6R_T)	2.5…1.6 (sb.)	L_{Sh}^N, Sh, L_{Sh}^S	L_{Sh}^S, Sh, L_{Sh}^N
20oTI	19 January 06, 04:25	1.4 (14.5)	−18.8	95.4 (0.0R_T)	+2.2…+2.5 (nb.)	L_{Sh}^S, Sh, L_{Sh}^S	Sh_{L^S}, L_{Sh}^S
27iTI	14 August 06, 23:33	2.5 (14.8)	−16.1	5509.0 (2.2R_T)	+13.3… −6.6 (sb.)	L_{Sh}^S, Sh	Sh, L_{Sh}^S, Sh
32iTI	06 November 06, 15:34	2.2 (20.7)	−15.0	552.0 (0.2R_T)	+32.7… −29.8 (sb.)	Sh, L_{Sh}^S	L_{Sh}^S
33iTI	18 November 06, 14:40	2.2 (14.6)	−14.8	2364.1 (0.9R_T)	+33.3… −29.4 (sb.)	Sh, L_{Sh}^N, Sh, L^S	L^S, L_{Sh}^S, Sh
34iTI	30 November 06, 13:14	2.2 (8.2)	−14.7	2423.9 (0.9R_T)	+33.3… −29.4 (sb.)	Sh, L^S, L_{Sh}^S	L_{Sh}^S, L^S
39iTI	16 February 07, 09:26	2.0 (5.2)	−13.6	6213.9 (2.4R_T)	+53.9… −49.9 (sb.)	L_{Sh}^N, Sh, L_{Sh}^S	L_{Sh}^S

The number of the flyby is given in the first column, whereas the second column contains the date and time of closest approach to Titan's orbital path. Cassini's orbital position at the time of C/A is characterized by the Saturnian Local Time (SLT, third column). In order to demonstrate that Cassini was indeed far away from Titan during the virtual encounters, the moon's orbital position (defined by its SLT value) is provided in brackets. It is very important to notice that neither the C/A time nor the SLT value are correlated to the actual position of Titan during the passage, but they refer to the point at which the distance between the spacecraft and the moon's orbital path achieved its minimum. The value of this minimum distance can be found in the fourth column. The fifth column provides the z coordinate of Cassini's position at the beginning and the end of the ± 8 h analysis window around C/A. For a northbound ("nb.") encounter, z increases during the passage, while a southbound ("sb.") passage is characterized by a transition from positive to negative z values. The classification of the magnetic fields observed before ("inb.") and after ("outb.") closest approach can be found in the final two columns, with the classification symbols listed in the order of time.

Table 3
Classification of Cassini MAG observations during virtual flybys in the 03:00–06:00 SLT sector.

Flyby	C/A	SLT	SSL	C/A distance (km)	z range [R_T]	Class. inb.	Class outb.
03oTI	18 February 05, 21:20	5.5 (16.2)	−22.4	5377.5 (2.1R_T)	+1.9,…,+1.9 (nb.)	Sh, L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}
04oTI	11 March 05, 08:02	5.5 (23.0)	−22.2	2095.9 (0.8R_T)	+0.7,…,+0.6 (sb.)	L^S_{Sh}	L^S_{Sh}, L^S, Sh_{L^S}
07oTI	04 May 05, 23:32	5.3 (8.8)	−21.7	11185.5 (4.3R_T)	+16.5,…, −8.5 (sb.)	Sh_{L^S}, L^S_{Sh}	L^S_{Sh}
08oTI	23 May 05, 03:48	5.3 (12.2)	−21.5	8577.7 (3.3R_T)	+15.6,…,−9.6 (sb.)	L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}, Sh
09oTI	10 June 05, 08:18	5.3 (15.7)	−21.3	4051.4 (1.6R_T)	+14.1,…,−11.4 (sb.)	Sh_{L^S}, L^S_{Sh}	L^S_{Sh}, Sh
10oTI	28 June 05, 13:22	5.2 (19.2)	−21.1	2048.9 (0.8R_T)	+13.4,…,−12.3 (sb.)	L^S, L^S_{Sh}	L^S
11oTI	16 July 05, 19:48	5.2 (22.6)	−20.9	130.4 (0.1R_T)	+12.8,…,−13.1 (sb.)	Sh_{L^S}, L^S_{Sh}, L^S	L^S, L^S_{Sh}, L^S
12oTI	04 August 05, 03:25	5.1 (2.0)	−20.7	2791.6 (1.1R_T)	+11.8,…,−14.3 (sb.)	Sh, L^S_{Sh}	L^S_{Sh}
15oTI	25 September 05, 17:32	5.1 (8.8)	−20.2	3543.4 (1.4R_T)	−1.3,…,−2.0 (sb.)	L^S_{Sh}	L^S, L^S_{Sh}, Sh
16oTI	13 October 05, 21:35	5.1 (12.2)	−20.0	5218.5 (2.0R_T)	−1.9,…,−2.8 (sb.)	Sh_{L^S}, L^S	L^S, L^S_{Sh}
17oTI	31 October 05, 20:01	3.2 (15.3)	−19.7	893.4 (0.3R_T)	+1.5,…,+1.4 (sb.)	L^S_{Sh}, Sh_{L^S}	Sh_{L^S}, L^S_{Sh}
18oTI	29 November 05, 08:43	3.2 (9.9)	−19.4	119.8 (0.0R_T)	+1.3,…,+1.0 (sb.)	L^S, L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}, L^S
25iTI	28 June 06, 16:28	4.5 (15.8)	−16.8	1761.5 (0.7R_T)	+0.8,…,0.0 (sb.)	L^S_{Sh}	L^S, L^S_{Sh}

Cassini's orbital position at the time of C/A is characterized by the Saturnian Local Time (SLT, third column). In order to demonstrate that Cassini was indeed far away from Titan during the virtual encounters, the moon's orbital position (defined by its SLT value) is provided in brackets.

Table 4
Classification of Cassini MAG observations during virtual flybys in the 06:00–12:00 SLT sector (part 1).

Flyby	C/A	SLT	SSL	C/A distance (km)	z range [R_T]	Class. inb.	Class outb.
21iTI	23 February 06, 15:43	8.5 (20.0)	−18.3	188.1 (0.1R_T)	−2.9,…, −2.4 (nb.)	Msh	Sh
23iTI	27 April 06, 04:05	6.5 (17.9)	−17.6	519.4 (0.2R_T)	−1.5,…,−1.6 (sb.)	-data gap-, L^S_{Sh}, L^S	L^S, L^S_{Sh}
04iTI	07 March 05, 17:33	10.4 (17.6)	−22.3	4390.1 (1.7R_T)	−1.4,…,−1.2 (nb.)	Sh	Sh, L^S_{Sh}
05iTI	28 March 05, 05:34	10.4 (0.4)	−22.1	3492.8 (1.4R_T)	−1.8,…,−1.5 (nb.)	Msh	Sh
15iTI	22 September 05, 03:47	9.5 (3.5)	−20.2	1265.0 (0.5R_T)	−2.8,…,−2.0 (nb.)	Sh	Sh, L^S_{Sh}, Sh
16iTI	10 October 05, 07:40	9.5 (6.7)	−20.0	1554.2 (0.6R_T)	−2.7,…,−1.9 (nb.)	Msh, Sh, Msh	Msh, Sh
18iTI	25 November 05, 16:36	9.4 (4.4)	−19.4	480.2 (0.2R_T)	−3.0,…,−2.5 (nb.)	Sh, L^S_{Sh}, Sh	Sh
19iTI	23 December 05, 02:31	9.3 (22.0)	−19.1	109.7 (0.0R_T)	−3.3,…,−2.6 (nb.)	Sh	Sh
48oTI	22 July 07, 13:57	11.7 (0.1)	−11.3	5392.2 (2.1R_T)	−0.6,…,−0.1 (nb.)	Sh	Sh
51oTI	26 October 07, 00:48	11.5 (23.6)	−9.9	2675.6 (1.0R_T)	−6.2,…,−0.6 (nb.)	Sh	Sh
56oTI	17 January 08, 20:36	11.4 (5.4)	−8.6	1058.3 (0.4R_T)	-data gap-	-data gap-	-data gap-
57oTI	29 January 08, 18:41	11.3 (23.5)	−8.4	2709.0 (1.1R_T)	−26.3,…,+23.4 (nb.)	L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}, Sh
58oTI	10 February 08, 17:36	11.3 (17.7)	−8.3	6166.3 (2.4R_T)	−29.2,…,+20.3 (nb.)	Sh,-data gap-	-data gap-, Sh
60oTI	04 March 08, 07:21	11.3 (3.2)	−7.9	6562.1 (2.5R_T)	−34.1,…,+25.4 (nb.)	Sh, Msh	Sh, Msh, Sh
61oTI	14 March 08, 23:13	11.2 (19.6)	−7.8	4772.1 (1.9R_T)	−33.7,…,+26.1 (nb.)	Sh, L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}, Sh
63oTI	04 April 08, 04:06	11.2 (1.7)	−7.4	4235.9 (1.6R_T)	−37.4,…,+30.4 (nb.)	Sh, L^S_{Sh}	Sh

Table 5
Classification of Cassini MAG observations during virtual flybys in the 06:00–12:00 SLT sector (part 2).

Flyby	C/A	SLT	SSL	C/A distance (km)	z range [R_T]	Class. inb.	Class outb.
64oTI	13 April 08, 18:01	11.1 (16.4)	−7.3	2410.3 (0.9R_T)	−37.0,…,+31.0 (nb.)	L^S_{Sh}, Sh	Sh
65oTI	23 April 08, 07:24	11.1 (6.3)	−7.2	1802.3 (0.7R_T)	−36.9,…,+31.2 (nb.)	Sh	Sh
66oTI	02 May 08, 20:33	11.1 (21.1)	−7.0	2017.9 (0.8R_T)	−36.9,…,+31.1 (nb.)	Sh, Msh, Sh	Sh, Msh, Sh
68oTI	20 May 08, 08:57	11.0 (23.3)	−6.7	2352.1 (0.9R_T)	−34.2,…,+28.3 (nb.)	Sh	Sh
70oTI	04 June 08, 11:28	10.9 (22.1)	−6.5	4957.8 (1.9R_T)	−33.2,…,+26.3 (nb.)	L^S_{Sh}, Sh, L^S_{Sh}	L^S_{Sh}, Sh
71oTI	11 June 08, 14:57	10.9 (8.6)	−6.4	5553.6 (2.2R_T)	-data gap-	-data gap-	-data gap-
72oTI	18 June 08, 18:06	10.9 (19.7)	−6.3	6898.2 (2.7R_T)	−33.5,…,+25.7 (nb.)	L^S_{Sh}, Sh	Sh, L^N_{Sh}
73oTI	25 June 08, 21:07	10.9 (6.0)	−6.2	1963.3 (0.8R_T)	−31.9,…,+27.8 (nb.)	Sh	Sh
74oTI	02 July 08, 22:07	10.9 (17.0)	−6.1	743.7 (0.3R_T)	−32.1,…,+27.5 (nb.)	L^S_{Sh}, Sh	Sh, L^S_{Sh}, Sh, L^N_{Sh}
75oTI	09 July 08, 23:05	10.8 (3.2)	−6.0	592.4 (0.2R_T)	−32.3,…,+27.2 (nb.)	Msh, Sh	Sh, Msh
76oTI	17 July 08, 00:06	10.8 (14.1)	−5.9	1775.0 (0.7R_T)	−32.5,…,+26.9 (nb.)	L^S_{Sh}	L^S_{Sh}, Sh, L^N_{Sh}
77oTI	24 July 08, 01:10	10.8 (0.5)	−5.7	3620.0 (1.4R_T)	−32.8,…,+26.5 (nb.)	Sh, L^S_{Sh}, Sh	Sh
79oTI	07 August 08, 11:40	10.8 (22.3)	−5.5	4096.8 (1.6R_T)	−37.9,…,+32.0 (nb.)	Sh	Sh
80oTI	14 August 08, 20:54	10.7 (9.2)	−5.4	2177.9 (0.8R_T)	−37.7,…,+32.2 (nb.)	Sh	Sh
81oTI	22 August 08, 05:29	10.7 (20.5)	−5.3	2917.3 (1.1R_T)	−37.7,…,+32.0 (nb.)	Sh	Sh
82oTI	29 August 08, 14:39	10.7 (7.3)	−5.2	3194.2(1.2R_T)	−37.8,…,+32.2 (nb.)	Sh	Sh, Msh
83oTI	05 September 08, 23:36	10.7 (18.8)	−5.1	3724.2 (1.4R_T)	−37.9,…,+32.1 (nb.)	L^S_{Sh}	L^S_{Sh}, Sh, L^N_{Sh}

plane ($z=0$) from north to south. The tilt of the flyby trajectory with respect to the ($z=0$) plane continuously increased during the series: Within the ±8 h interval around closest approach, T16 covered a range of $z=1.4R_T\ldots-8.1R_T$ (radius of Titan: $R_T=2575$ km). During the final 39iTI encounter, a distance of $z=53.9R_T\ldots-49.9R_T$ was covered in vertical direction.

Cassini magnetic field data collected during the real flybys did not only show that Titan was located in the immediate vicinity of the current sheet, but they also confirmed that in southern summer, the magnetic equator was on average displaced to above the moon's orbital plane (cf. Arridge et al., 2008b). The magnetic fields detected above Titan's orbit were dominated by frequent

Table 6
Classification of Cassini MAG observations during virtual flybys in the 06:00–12:00 SLT sector (part 3).

Flyby	C/A	SLT	SSL	C/A distance (km)	z range [R_T]	Class. inb.	Class outb.
84oTI	13 September 08, 08:33	10.7 (5.4)	-5.0	3752.8 (1.5R_T)	$-37.9,\ldots,+32.1$ (nb.)	Sh, L^S_{Sh}, Sh	Sh
85oTI	20 September 08, 17:28	10.6 (16.9)	-4.8	4233.7 (1.6R_T)	$-37.9,\ldots,+32.0$ (nb.)	L^S_{Sh}, Sh	Sh
86oTI	28 September 08, 02:23	10.6 (3.6)	-4.7	4649.7 (1.8R_T)	$-38.0,\ldots,+31.9$ (nb.)	Sh	Sh
87oTI	05 October 08, 11:13	10.6 (15.0)	-4.6	2006.1 (0.8R_T)	$-37.7,\ldots,+32.3$ (nb.)	Msh	Sh, Msh
88oTI	12 October 08, 19:30	10.6 (1.8)	-4.5	1100.3 (0.4R_T)	$-37.6,\ldots,+32.4$ (nb.)	L^S_{Sh}, Sh, L^S_{Sh}	Sh
89oTI	20 October 08, 03:20	10.6 (13.0)	-4.4	3053.4 (1.2R_T)	$-37.2,\ldots,+33.1$ (nb.)	Sh	Sh
90oTI	27 October 08, 10:32	10.5 (23.9)	-4.3	1866.5 (0.7R_T)	$-37.4,\ldots,+32.9$ (nb.)	Sh	Sh
92oTI	11 November 08, 16:03	10.5 (22.8)	-4.0	4570.2 (1.8R_T)	$-38.8,\ldots,+32.1$ (nb.)	Sh	Sh
94oTI	27 November 08, 15:09	10.5 (22.8)	-3.8	4636.5 (1.8R_T)	$-41.7,\ldots,+35.8$ (nb.)	Sh, L^S_{Sh}, Sh	Sh, L^S_{Sh}
96oTI	13 December 08, 13:54	10.4 (22.8)	-3.5	2684.9 (1.04R_T)	$-42.9,\ldots,+37.9$ (nb.)	Sh	Sh, L^N_{Sh}, Sh
98iTI	31 December 08, 02:49	10.4 (0.9)	-3.3	2654.1 (1.0R_T)	$-49.1,\ldots,+44.2$ (nb.)	L^S_{Sh}	L^S_{Sh}, Sh
99iTI	09 January 09, 16:39	10.4 (15.6)	-3.1	2013.3 (0.8R_T)	$-49.1,\ldots,+44.2$ (nb.)	Sh	Sh
100iTI	19 January 09, 06:26	10.3 (5.6)	-3.0	2002.7 (0.8R_T)	$-49.1,\ldots,+44.2$ (nb.)	L^S_{Sh}	L^S_{Sh}, Sh
101iTI	28 January 09, 19:59	10.3 (20.4)	-2.8	844.1 (0.3R_T)	$-49.3,\ldots,+44.3$ (nb.)	L^S_{Sh}, Sh	Sh, L^N_{Sh}, Sh
103oTI	19 February 09, 07:28	10.3 (4.2)	-2.5	1312.9 (0.5R_T)	$-54.2,\ldots,+49.3$ (nb.)	L^S_{Sh}, Sh	Sh, Sh_{L^N}
104oTI	03 March 09, 06:16	10.2 (22.5)	-2.3	36.5 (0.0R_T)	$-54.2,\ldots,+49.3$ (nb.)	Sh, Msh, Sh	Sh
105oTI	15 March 09, 05:32	10.2 (16.6)	-2.1	2765.4 (1.1R_T)	-data gap-	-data gap-	-data gap-
108oTI	11 April 09, 08:40	10.2 (9.0)	-1.7	16785.9 (6.5R_T)	$-58.9,\ldots,+54.8$ (nb.)	L^S_{Sh}, Sh	Sh, L^N_{Sh}

Table 7
Real and virtual Titan flybys.

Local time sector	Real flybys	Virtual flybys
00:00–03:00	T11	20oTI
03:00–06:00	T9	17oTI, 18oTI
03:00–06:00	T14	25iTI
06:00–09:00	T12	23iTI
06:00–09:00	T10	21iTI
18:00–21:00	T34	49iTI
21:00–00:00	T15	24oTI
21:00–00:00	T13	22oTI
00:00–03:00	T16–T24	27iTI, 32iTI, 33iTI, 34iTI, 39iTI
03:00–06:00	T4, T5, T6, T7	03oTI, 04oTI, 07oTI, 08oTI, 09oTI, 10oTI, 11oTI, 12oTI, 15oTI, 16oTI
09:00–12:00	TA, TB, T3	04iTI, 05iTI
09:00–12:00	T8	15iTI, 16iTI, 18iTI, 19iTI
09:00–12:00	T35–T51	48oTI,…,108oTI
12:00–15:00	T25–T33	38oTI
21:00–00:00	T52–T62	118iTI, 120iTI, 121iTI, 122iTI

Each of the 62 Titan encounters between October 2004 and December 2009 (TA–T62) possesses at least one virtual counterpart that occurred at nearly the same position in SSL–SLT space. The table provides an overview of these pairs of real/virtual encounters. The local time sector where the flybys took place is given in the first column. The upper half of the table contains those Titan encounters which are accompanied by only one or two virtual passages. The pairs listed in the lower half correspond to complete series of multiple flybys which took place at nearly the same position in SSL–SLT space. During the time interval considered in this study, 47iTI is the only virtual Titan encounter which does not possess a real counterpart.

transitions between lobe-type regimes of different polarity, separated by passages through the magnetodisk current sheet that occurred on a time scale of 1–2 h. Below the orbital plane, Cassini was mainly embedded in southern lobe-type fields that were only slightly distorted by the proximity to the flapping current sheet.

As can be seen from Table 2, Cassini magnetometer observations from the corresponding set of virtual flybys completely match this overall picture. As an example, MAG observations from the 39iTI encounter are shown in Fig. 2. About $2R_S$ above Titan's orbital plane, Cassini crossed the magnetodisk current sheet from north to south, as indicated by the reversal in the sign of the B_ρ component. Although the fields detected subsequently could clearly be assigned to the southern magnetodisk lobe category, they were nonetheless still slightly distorted by the proximity to the current sheet. Especially during the companion flybys 27iTI and 33iTI, the distortions caused by the flapping current sheet below Titan's orbital plane were a lot stronger. On several occasions, Cassini left the rather quiet lobe-type regime and became completely embedded in the current sheet.

In general, comparing data from the real flybys to their virtual counterparts implies that it is impossible to provide a definite characterization of the magnetic fields near Titan's orbit at a certain point in SSL–SLT space. For instance, even if quiet, unperturbed lobe-type fields were observed near Titan during a certain encounter, observations from a subsequent (virtual) passage at the same point in SSL–SLT space may reveal a completely different picture. This shows that Titan's magnetic environment is not only affected by large-scale seasonal changes in the overall shape of the magnetodisk (Arridge et al., 2008b), but due to short-scale variations in the current sheet position, there is only a single pair of consecutive real/virtual flybys in this local time sector (34iTI and T21, see also Table 6 in Simon et al., 2010) during which the same magnetic field conditions were observed in the immediate vicinity of closest approach.

In our companion study of the real Titan flybys, we identified three encounters in the post-midnight sector (T17, T20 and T24) during which a sharp transition from highly perturbed current sheet fields to quiet magnetodisk lobe-type fields (L^S) practically coincided with Cassini's closest approach to Titan. It was argued

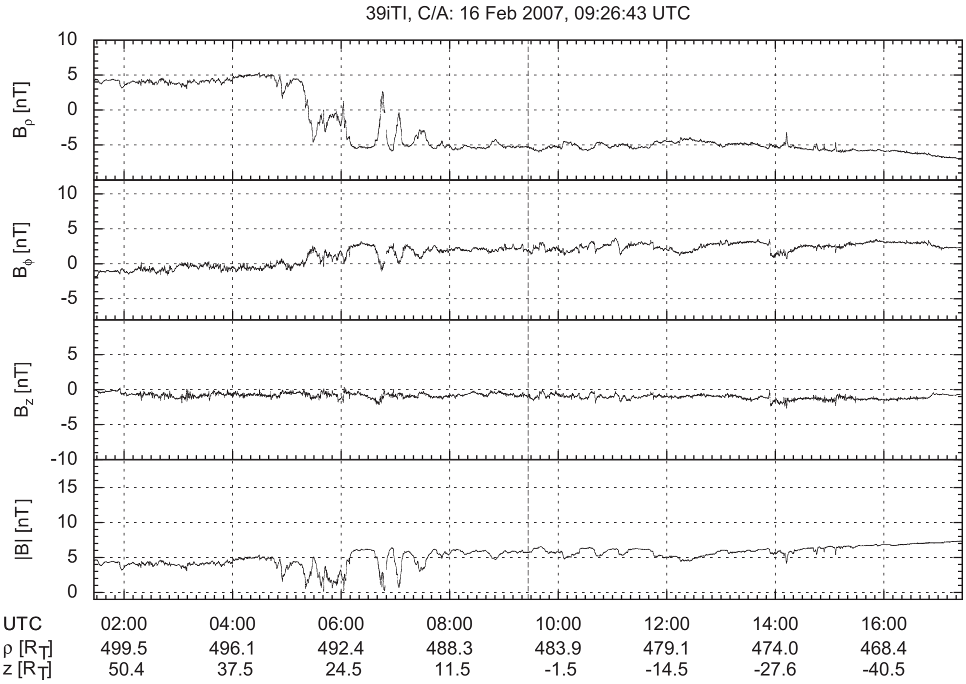

Fig. 2. Cassini magnetic field observations during virtual Titan flyby 39iTI in cylindrical KSMAG coordinates. The closest approach of this flyby took place in the pre-midnight magnetosphere (2.0 SLT) on 16 February 2007 at 09:26. The figure displays the magnetic field data collected in a ±8 h interval around closest approach (C/A, dashed line).

that at least in the nightside magnetosphere, where the influence of the solar wind is rather weak (Bertucci et al., 2009), Titan itself might exert some level of control on the vertical motion of the current sheet. Based on the limited number of available datasets in this sector, it is of course still impossible to decide whether this observation was just by coincidence. It should nevertheless be noted that during the series of virtual flybys which overlapped with T16–T24, transitions between lobe-type regimes of different polarity were only observed far above or below Titan's orbital plane, but not in the immediate vicinity of $z=0$.

So far, there is only one other flyby pair in the post-midnight magnetosphere: T11 and its virtual counterpart 20oTI. During both passages, Cassini's trajectory was practically parallel to Titan's orbital plane and hence, to the dipole magnetic equator. The height of the spacecraft above the ($z=0$) plane changed by less than $0.3R_T$ within the ±8 h interval around closest approach. For T11, the average distance between the spacecraft and Titan's orbital plane was $z=0.05R_T$, whereas the 20oTI passage occurred at an altitude of about $z=2.4R_T$. T11 was among the very few encounters of the TA–T62 series during which only slightly distorted southern lobe-type fields were observed on both sides of C/A, implying that during this passage, the current sheet was located far above Titan's orbital plane. The overall picture obtained during the 20oTI encounter is not too dissimilar from this. The radial magnetic field component remained continuously negative within the ±8 h segment around closest approach, implying that the spacecraft was continuously located below the sheet. However, the intensity of the distortions caused by the proximity to the lower side of the current sheet was significantly stronger than during the T11 flyby. Around C/A, Cassini was exposed to current sheet fields which were identified by a breakdown of the fluctuation criterion for the lobe-type regime.

Due to the apparently quiet ambient magnetic field conditions during T11, a global numerical model (based on the assumption of stationary upstream conditions) was successfully applied to reproduce the key features of Cassini MAG observations from this encounter (Simon, 2007). However, a comparison between MAG data from T11 and its virtual counterpart clearly shows that the results of this kind of numerical flyby study can by no means be generalized to a definite picture of Titan's magnetic environment at a certain point in SSL–SLT space.

3.2. *Pre-midnight magnetosphere (21:00–00:00 SLT)*

In 2006, Titan's magnetic environment in the pre-midnight magnetosphere was sampled during two wakeside flybys: T13 and T15. During both encounters, the spacecraft trajectory remained practically confined to the moon's orbital plane within the ±8 h analysis window around closest approach. The ambient magnetic field during T13 and T15 was dominated by Titan's proximity to the lower side of the current sheet: during both encounters, C/A occurred while Titan was embedded in highly distorted current sheet fields. Moderately distorted southern lobe-type fields were detected only at large distances to Titan, i.e. outside a ±3 h interval around C/A.

As can be seen from Table 7, each of these flybys is accompanied by one virtual counterpart. The 22oTI passage took place at nearly the same point in SSL–SLT space as T13, whereas 24oTI is the virtual counterpart of T15. Despite the inclination of the virtual flyby trajectories being slightly larger than during T13 and T15, Cassini moved practically parallel to Titan's orbital plane in the time interval under consideration. The trajectories were located at an altitude of $z \approx 3.1R_T$ (22oTI) and $z \approx 3.6R_T$ (24oTI), respectively. As can be seen from Table 2, MAG data obtained during 22oTI and 24oTI fully confirm the picture obtained during their real counterparts. During both passages, the observed lobe-type fields were frequently perturbed by short-scale intrusions of the lower side of the current sheet into Cassini's path. In correspondence to the real encounters, Cassini's closest approach to Titan's orbit during 24oTI occurred within the current sheet.

With regard to current sheet dynamics, the most striking observations in the pre-midnight magnetosphere were made during the T52–T62 flyby series, taking place around equinox in August 2009. During this sequence of encounters, the average location of the sheet nearly coincided with Titan's orbital plane, thereby placing the moon within the center of vertical current sheet motion. Near equinox, the distortions of Titan's magnetic environment by the flapping current sheet were therefore more intense than during any other period of the Cassini mission.

The T52–T62 flyby series is accompanied by four virtual encounters: 118iTI, 120iTI, 121iTI and 122iTI (cf. Table 7). Due to a data gap, no magnetic field observations are available for 118iTI. During the other three encounters, Cassini's trajectory was practically parallel to Titan's orbital plane, with the spacecraft being located between $z = 2.6R_T$ and $z = 1.6R_T$ within the entire ± 8 h analysis interval. In other words, Cassini's distance to the dipole magnetic equator and thus, to the average current sheet location around equinox (Arridge et al., 2008b) was practically constant within the entire observation interval. As an example, magnetic field from 122iTI are shown in Fig. 3.

Cassini magnetic field observations during all three virtual encounters are dominated by frequent transitions between current sheet and lobe-type fields of different polarity, i.e. the sheet continuously swept over Titan's orbital plane from above to below, then reversed its direction and crossed the moon's orbit again from south to north. For each encounter, the spacecraft traveled a distance of about $4.7R_S$ in $\underline{e}_\rho$ direction within the ± 8 h interval around closest approach. Assuming that all points in the $4.7R_S$ interval are crossed by the oscillating sheet almost simultaneously, MAG data from these flybys permit an at least rough estimation for the characteristic duration of the sheet oscillations: during 122iTI, the spacecraft observed a steady transition from northern to southern magnetodisk lobe fields around 05:30. The spacecraft then detected moderately distorted southern lobe-type fields, before the current sheet again swept over Cassini at 12:00. Based on the above assumption of an idealized geometry, this would yield a time window of about 6 h between two subsequent current sheet crossings through Titan's orbital plane. Observations from 120iTI and 121iTI suggest the time window between consecutive current sheet encounters to range between 4 and 7 h as well.

Given that a current sheet crossing always leaves a bundle of fossil fields (Neubauer et al., 2006) in Titan's ionosphere that can persist for up to 3 h, there is only a small window of a few hours during which the upstream conditions at Titan may be stationary and the ionosphere is devoid of fossil fields. These estimations are fully consistent with our analysis of magnetic field data collected during the close Titan encounters TA–T62. Overall, a comparison between the dynamical features in the magnetic field observations from real and virtual Titan flybys strongly implies that Titan does not exert a significant level of control on the vertical motion of the current sheet. In this context, the term "control" means that the presence of Titan may be the reason/trigger for local oscillatory motion of the current sheet near its orbit, i.e. that the intensity of these features would be different with Titan present or absent. Our results indicate that if there is any influence of Titan on magnetodisk dynamics at $20.3R_S$, it will be so weak that it is completely obscured by the constantly changing (global) magnetospheric dynamics of Saturn. The field perturbations arising from the omnipresent current sheet motion on planetary rotation scales (see e.g. Arridge et al., 2008a) determine the ambient magnetic field conditions near Titan's orbit, but the presence of Titan affects neither the period nor the magnitude of these perturbations on a measurable scale.

3.3. *Dawn magnetosphere (03:00–09:00 SLT) and dusk magnetosphere (15:00–21:00 SLT)*

The Titan encounters T4, T5 and T6 took place in Saturn's dawn magnetosphere. This series of encounters took place in southern summer, with Cassini remaining inside a $|z| < 0.5R_S$ interval

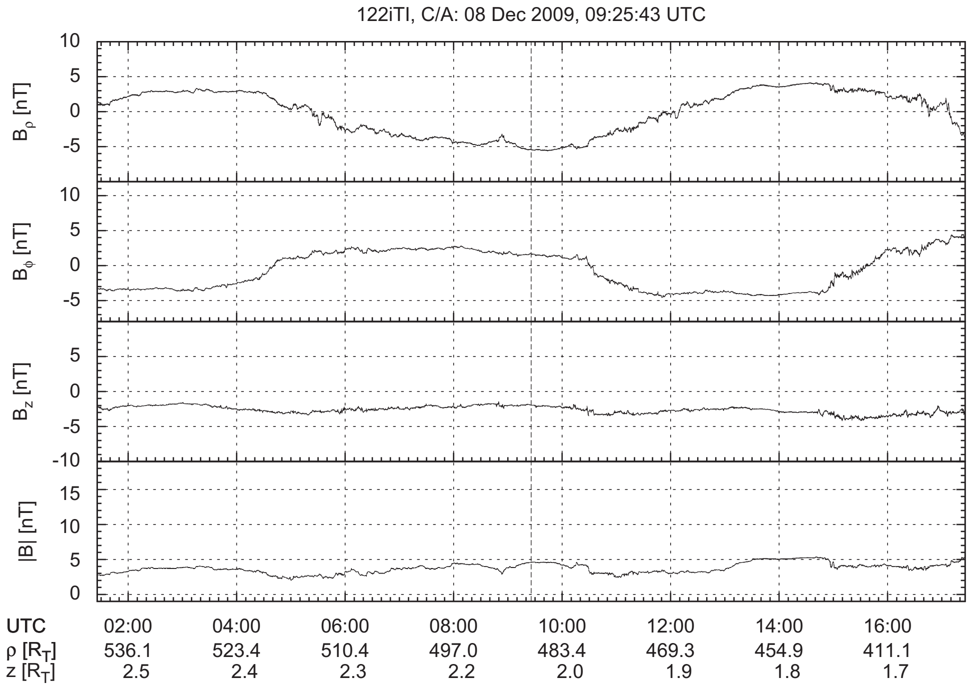

Fig. 3. Cassini magnetic field observations during virtual Titan flyby 122iTI in cylindrical KSMAG coordinates. The closest approach of this flyby took place in the pre-midnight magnetosphere (21.6 SLT) on 08 December 2009 at 09:25. The figure displays the magnetic field data collected in a ± 8 h interval around closest approach (dashed line). The radius of Titan is $R_T = 2575$ km.

around Titan's orbital plane. The picture of Titan's magnetic environment obtained during these flybys strongly resembles the observations made in the nightside magnetosphere in southern summer. On the one hand, no sign of northern lobe-type fields was detected during these flybys. On the other hand, Cassini data show that the southern lobe-type regime was frequently perturbed by intrusions of the current sheet into the spacecraft path.

In this sector of SSL–SLT space, the real Titan flybys constitute a minority: as can be seen from Table 7, T4–T6 are accompanied by 10 virtual encounters which can be classified into two different categories. As presented in Table 3, during passages 03oTI, 04oTI, 15oTI and 16oTI, Cassini remained very close to Titan's orbital plane, i.e. there should be no significant change in the vertical distance between the spacecraft and the average position of the current sheet within the $\pm 8\,\mathrm{h}$ analysis windows. The flyby geometries are therefore essentially the same as during T4, T5 and T6. MAG data from these three virtual flybys show the same high level of variability as observed during their real counterparts: the magnetic field in Titan's orbital plane is dominated by current sheet intrusions of varying intensity.

During the remaining six virtual flybys, the inclination of Cassini's trajectory was significantly larger, covering a vertical range of $z = +16.5R_T \ldots -14.3R_T$. However, MAG observations from these flybys do not show any qualitative differences to the overall features observed during the low-inclination passages. Again, Cassini detected frequent transitions between moderately distorted southern lobe-type fields and current sheet field regimes. This implies that although in southern summer, the sheet may on average be located far above Titan's orbital plane (as implied by the nearly complete absence of northern lobe fields in the MAG data from the high-inclination encounters), there is a region with a vertical extension of at least $30R_T$ around the moon's orbit which is affected by the intense vertical motion of the sheet.

One might speculate that at least around solstice, the distance between Titan's orbit and the region affected by vertical current sheet motion may be large enough to apply the idealized picture of the moon's ionosphere interacting with a homogeneous and stationary magnetospheric background field. However, at solstice the angle between the Sun–Saturn line and the planet's magnetic moment/rotation axis is only about 5° larger than during the series of high-inclination passes discussed here (about 26.7°, cf. Arridge et al., 2008b). Thus, given the large vertical extension of the region where current sheet perturbations were detected during the high-inclination flybys, it seems unlikely that the situation at solstice will be substantially different. Although this hypothesis remains to be proven by in-situ data from Cassini's solstice mission (2010–2016), our current understanding is that even in the nightside magnetosphere, Titan's orbit may practically never be embedded in a quasi-stationary magnetospheric environment on long time scales of e.g. a day.

Another Titan encounter that occurred in the dawn sector of Saturn's magnetosphere is T9 at about 03:00 SLT. This flyby was of particular importance since so far, it is the only equatorial passage during which Cassini crossed Titan's induced magnetotail at a relatively large distance of more than $4R_T$ (see e.g. Ma et al., 2007; Kallio et al., 2007; Simon et al., 2007 for details). The T9 encounter was accompanied by a set of two additional passages, with the trajectories of all three flybys being confined to an interval of $0 < z < 1.5R_T$ around Titan's orbital plane. The magnetic field signatures observed during these encounters were very similar: the fields detected in Titan's orbital plane mainly belonged to the southern lobe-type regime, but they were distorted by frequent intrusions of the lower side of the current sheet. Thus, around the time of the T9 encounter, Titan's orbit near 03:00 SLT was apparently located in the immediate vicinity of the sheet, i.e. when moving through this region, the moon's ionosphere was most likely strongly contaminated by fossil magnetic fields. Only because T9 occurred far downstream of Titan, these signatures did not manifest in the magnetic field data obtained during the encounter.

So far, Titan's magnetic environment in the dusk magnetosphere (15:00–21:00 SLT) is largely unexplored. At the time of this writing, only a single close flyby (T34) and two virtual passages had taken place in this local time sector. Both T34 and its virtual counterpart 49iTI were equatorial passes, with the observed magnetic fields belonging mainly to the current sheet category. Magnetic field observations in the dawn magnetosphere (03:00–09:00 SLT) suggest that between midnight and noon, there is a steady transition between the large-scale current sheet oscillations in the nightside magnetosphere and the short-scale perturbations observed around 12:00 SLT. It remains to be seen whether magnetic field observations around dusk show a similarly steady connection between noon and midnight or whether the current sheet exhibits a pronounced asymmetry in local time. A complete series of Titan encounters in the dusk magnetosphere is scheduled for the first half of 2010 (flybys T63–T70). Analyzing the magnetic field observations from these flybys and their virtual counterparts will be a subject of our work in the near future.

3.4. *Dayside magnetosphere (09:00–15:00 SLT)*

So far, most of Cassini's passages through Saturn's orbital plane at $20.3R_S$ occurred in the pre-noon sector of the magnetosphere. The close Titan flybys T35–T51 in this sector make up a minority, since they are accompanied by a set of 49 virtual passages. As can be seen from Fig. 1, the trace of these virtual encounters in SSL–SLT space completely overlaps with the T35–T51 series. Again, the observations from the virtual flybys show very similar characteristics as the data collected during T35–T51. Independent of the inclination of Cassini's trajectory, the magnetic field observations are dominated by highly perturbed current sheet fields, showing that around noon local time, the sheet is significantly broader than around midnight (see also Sergis et al., 2009). As an example, Cassini MAG data from 92oTI are displayed in Fig. 4. During this encounter, both criteria for lobe-type fields break down within the entire $\pm 8\,\mathrm{h}$ window. In strong analogy to the encounters of the T35–T51 series, there is not a single virtual flyby in the pre-noon magnetosphere during which quiet lobe-type fields were observed on both sides of C/A to Titan's orbit. Overall, Cassini never remained within only moderately distorted lobe-type fields for more than 1 h. During very few virtual Titan flybys, short segments of moderately distorted northern lobe-type fields were observed at large distances to the moon. The observations from the real Titan flybys, on the other hand, do not show any sign at all of northern lobe fields. Most likely, this can be ascribed to the fact that we consider data from far more virtual than real encounters around noon.

The second flyby series in the noon magnetosphere (T25–T33) is accompanied by only a single virtual flyby (38oTI). In analogy to T25–T33, Cassini was embedded in highly distorted current sheet fields most of the time, except for a short excursion into the magnetosheath a few hours after C/A.

4. Summary and concluding remarks

Between October 2004 and December 2009, the Cassini spacecraft has accomplished a total number of 141 encounters with Titan's orbital path near $20.3R_S$. During 62 of these passages, Titan was located in the immediate vicinity of the spacecraft at

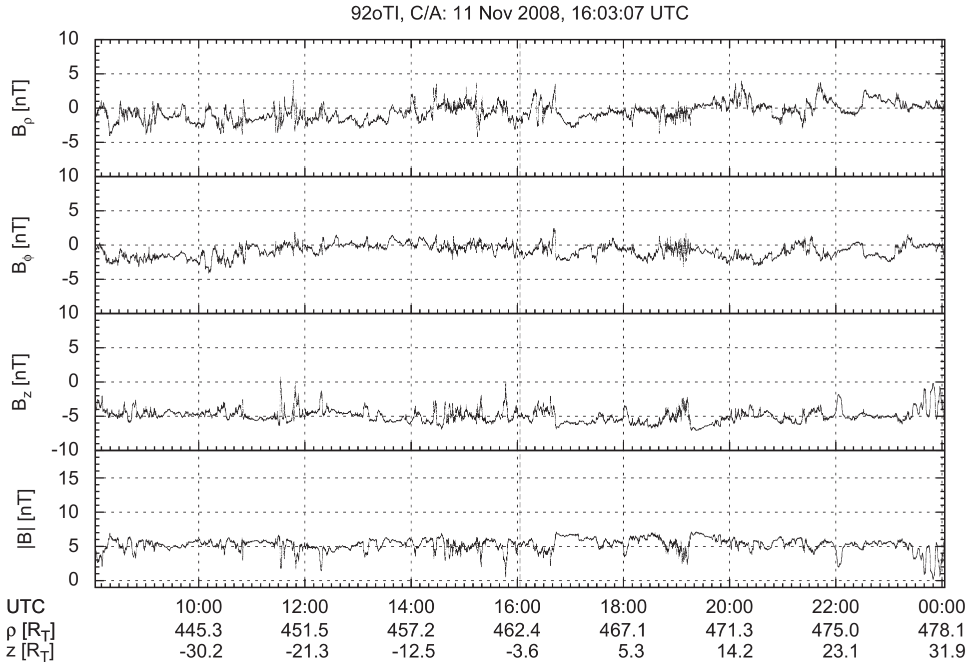

Fig. 4. Cassini magnetic field observations during virtual Titan flyby 92oTI in cylindrical KSMAG coordinates. The closest approach of this flyby occurred in the pre-noon magnetosphere (10.5 SLT) on 11 November 2008 at 16:03. The figure displays the magnetic field data collected in a ±8 h interval around closest approach (dashed line).

the point of closest approach, whereas the remaining 79 passages occurred with Titan being located in a completely different sector of the magnetosphere. The locations of real and virtual Titan flybys in SSL–SLT space are correlated: each of the real flybys is accompanied by at least one virtual counterpart.

A comparison between MAG data from the real Titan flybys and their virtual companions suggests that whether Titan is present or absent has no qualitative influence on the dynamics of the magnetodisk current sheet (i.e. its vertical oscillatory/flapping motion) at $20.3R_S$. Whether Titan is present or absent has no noticeable influence on the intensity of the perturbations in the ambient magnetospheric field, caused by oscillatory/flapping motion of the current sheet. All encounters in the nightside magnetosphere are dominated by intense vertical flapping motions of the sheet, going along with frequent transitions between current sheet and lobe-type fields in Titan's orbital plane. In the dayside magnetosphere, this effect is largely obscured by the increased thickness of the sheet, nearly permanently placing Titan's orbit in a highly perturbed current sheet regime.

Overall, the observations made during the virtual Titan flybys fully confirm our picture of the moon's magnetic environment from the TA–T62 encounters. In both the dayside and the nightside magnetosphere, Titan's orbit is embedded in a highly perturbed magnetic field regime most of the time. In the dayside magnetosphere, the time windows during which the ambient magnetospheric field can be considered constant have a duration of only a few minutes. In the nightside magnetosphere, the length of these windows is bounded by subsequent sweeps of the current sheet through Titan's orbital plane, yielding a duration of 3–6 h.

Among the 141 real and virtual Titan flybys that had taken place at the time of this writing, C/A of only 17 (=9 real and 8 virtual, i.e. 12%) took place within quiet or moderately perturbed lobe-type fields. For about 40% of the available encounters (54=22 real and 32 virtual), the magnetometer detected highly perturbed current sheet fields around C/A. Frequent transitions between current sheet and lobe-type fields were observed near closest approach of another 50 flybys (21 real and 29 virtual, i.e. 35%). During 2 real (T32 and T42) and 5 virtual Titan flybys, closest approach occurred within Saturn's magnetosheath. A total number of 13 flybys could not be classified due to extended data gaps around C/A.

Acknowledgements

The authors are grateful to Joachim Saur for careful inspection of the manuscript and for valuable comments.

Appendix A. Cassini's orbit geometry during real and virtual titan flybys

Titan is the only moon in the Saturnian system that possesses a large enough mass to significantly change Cassini's orbit during a flyby. Therefore, the Cassini mission uses Titan to perform gravity assist maneuvers in order to realize gradual orbit changes. A fundamental requirement for such a gravity assist maneuver is that the resulting orbit of the spacecraft will eventually re-encounter Titan. Not only do the respective orbits of Cassini and Titan have to (almost) intersect, but also the respective periods of the orbits are required to have a common multiple.

For example, the 05oTI(T4) flyby on 31 March 2005 was performed in such way that the next flyby 06oTI(T5) on 16 April 2005 occurred in the subsequent Cassini orbit about one Titan orbit period (16 days) later. The latter flyby lead Cassini on an orbit that intersected the Titan orbit six times roughly every 18 days until the next Titan flyby 13oTI(T6) occurred on 22 August 2005. Thus, the T5 post-flyby orbit of Cassini was chosen in such way that seven of its orbit periods corresponded to eight orbit periods of Titan. In the above example, the T5 flyby occurred on orbit 06 outbound, and T6 occurred on orbit 13 outbound. The above-mentioned six virtual flybys in between took place on orbits 07 outbound, 08 outbound, 09 outbound, 10 outbound, 11 outbound, and 12 outbound, respectively.

If the post-flyby Cassini orbit is chosen in such way that it intersects the Titan orbit in two points, then the next flyby can be arranged to occur either on the inbound or the outbound leg of the orbit. Such orbits allow to go from Titan flybys on inbound legs to Titan flybys on outbound legs and vice versa. For example, Titan flyby 03iTI(T3) on 15 February 2005 occurred on the inbound leg of the Cassini orbit, while the subsequent Titan flyby 05oTI(T4) occurred on the outbound leg. Thus, the post-T3 orbit is an example for such an orbit. Between the real flybys T3 and T4, four virtual flybys took place with an alternation between inbound and outbound: 03oTI, 04iTI, 04oTI, and 05iTI. An alternative way to switch from Titan flybys on inbound legs to Titan flybys on outbound legs (or vice versa) is to place them right at the apocenter, as was done for e.g. 106oTI(T51) on 27 March 2009 and 108iTI(T52) on 04 April 2009.

References

Acton, C., 1996. Ancillary data services of NASA's navigation and ancillary information facility. Planet. Space Sci. 44 (1), 65–70.

Arridge, C.S., André, N., Achilleos, N., Khurana, K.K., Bertucci, C.L., Gilbert, L.K., Lewis, G.R., Coates, A.J., Dougherty, M.K., 2008a. Thermal electron periodicities at $20R_S$ in Saturn's magnetosphere. Geophys. Res. Lett. 35 (15), L15107. doi:10.1029/2008GL034132.

Arridge, C.S., Khurana, K.K., Russell, C.T., Southwood, D.J., Achilleos, N., Dougherty, M.K., Coates, A.J., Leinweber, H.K., 2008b. Warping of Saturn's magnetospheric and magnetotail current sheets. J. Geophys. Res. 113, A08217. doi:10.1029/2007JA012963.

Arridge, C.S., Russell, C.T., Khurana, K.K., Achilleos, N., André, N., Rymer, A.M., Dougherty, M.K., Coates, A.J., 2007. Mass of Saturn's magnetodisc: Cassini observations. Geophys. Res. Lett. 34, L09108. doi:10.1029/2006GL028921.

Arridge, C.S., Russell, C.T., Khurana, K.K., Achilleos, N., Cowley, S.W.H., Dougherty, M.K., Southwood, D.J., Bunce, E.J., 2008c. Saturn's magnetodisc current sheet. J. Geophys. Res. 113, A04214. doi:10.1029/2007JA012540.

Backes, H., 2005. Titan's Interaction with the Saturnian Magnetospheric Plasma. Ph.D. Thesis, Universität zu Köln.

Backes, H., Neubauer, F.M., Dougherty, M.K., Achilleos, N., André, N., Arridge, C.S., Bertucci, C., Jones, G.H., Khurana, K.K., Russell, C.T., Wennmacher, A., 2005. Titan's magnetic field signature during the first Cassini encounter. Science 308 (5724), 992–995.

Bertucci, C., Achilleos, N., Dougherty, M.K., Modolo, R., Coates, A.J., Szego, K., Masters, A., Ma, Y., Neubauer, F.M., Garnier, P., Wahlund, J.-E., Young, D.T., 2008. The magnetic memory of Titan's ionized atmosphere. Science 321 (5895), 1475–1478.

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

Bertucci, C.L., 2009. Characteristics and variability of Titan's magnetic environment. R. Soc. London Philos. Trans. Ser. A 367 (1889), 789–798.

Dougherty, M.K., Kellock, S., Southwood, D.J., Balogh, A., Smith, E.J., Tsurutani, B.T., Gerlach, B., Glassmeier, K.-H., Gleim, F., Russell, C.T., Erdos, G., Neubauer, F.M., Cowley, S.W.H., 2004. The Cassini magnetic field investigation. Space Sci. Rev. 114, 331–383. doi:10.1007/s11214-004-1432-2.

Kallio, E., Sillanpää, I., Janhunen, P., 2004. Titan in subsonic and supersonic flow. Geophys. Res. Lett. 31 (15), L15703. doi:10.1029/2004GL020344.

Kallio, E., Sillanpää, I., Jarvinen, R., Janhunen, P., Dougherty, M., Bertucci, C., Neubauer, F., 2007. Morphology of the magnetic field near Titan: hybrid model study of the Cassini T9 flyby. Geophys. Res. Lett. 34 (October), 24. doi:10.1029/2007GL030827.

Ledvina, S.A., Luhmann, J.G., Brecht, S.H., Cravens, T.E., 2004. Titan's induced magnetosphere. Adv. Space Res. 33 (11), 2092–2102.

Ma, Y.-J., Nagy, A.F., Toth, G., Cravens, T.E., Russell, C.T., Gombosi, T.I., Wahlund, J.-E., Crary, F.J., Coates, A.J., Bertucci, C.L., Neubauer, F.M., 2007. 3D global multi-species Hall-MHD simulation of the Cassini T9 flyby. Geophys. Res. Lett. 34 (December), L24S10. doi:10.1029/2007GL031627.

Nagy, A.F., Liu, Y., Hansen, K.C., Kabin, K., Gombosi, T.I., Combi, M.R., DeZeeuw, D.L., 2001. The interaction between the magnetosphere of Saturn and Titan's ionosphere. J. Geophys. Res. 106 (A4), 6151–6160.

Neubauer, F.M., Backes, H., Dougherty, M.K., Wennmacher, A., Russell, C.T., Coates, A., Young, D., Achilleos, N., Andre, N., Arridge, C.S., Bertucci, C., Jones, G.H., Khurana, K.K., Knetter, T., Law, A., Lewis, G.R., Saur, J., 2006. Titan's near magnetotail from magnetic field and plasma observations and modelling: Cassini flybys TA, TB and T3. J. Geophys. Res. 111, A10220. doi:10.1029/2006JA011676.

Neubauer, F.M., Gurnett, D.A., Scudder, J.D., Hartle, R.E., 1984. Titan's magnetospheric interaction. In: Gehrels, T., Matthews, M.S. (Eds.), Saturn. University of Arizona Press, Tucson, Arizona, pp. 760–787.

Russell, C.T., Jackman, C.M., Wei, H.Y., Bertucci, C., Dougherty, M.K., 2008. Titan's influence on Saturnian substorm occurrence. Geophys. Res. Lett. 35 (12), L12105. doi:10.1029/2008GL034080.

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

Sergis, N., Krimigis, S.M., Mitchell, D.G., Hamilton, D.C., Krupp, N., Mauk, B.H., Roelof, E.C., Dougherty, M.K., 2009. Energetic particle pressure in Saturn's magnetosphere measured with the magnetospheric imaging instrument on Cassini. J. Geophys. Res. 114, A02214. doi:10.1029/2008JA013774.

Simon, S., 2007. Titan's highly variable plasma environment: a 3d hybrid simulation study. Ph.D. Thesis, Technische Universität Braunschweig.

Simon, S., Kleindienst, G., Boesswetter, A., Bagdonat, T., Motschmann, U., Glassmeier, K.-H., Schuele, J., Bertucci, C., Dougherty, M.K., 2007. Hybrid simulation of Titan's magnetic field signature during the Cassini T9 flyby. Geophys. Res. Lett. 34, L24S08. doi:10.1029/2007GL029967.

Simon, S., Wennmacher, A., Neubauer, F., Bertucci, C., Kriegel, H., Saur, J., Russell, C., Dougherty, M., 2010. 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.

Wei, H.Y., Russell, C.T., Wellbrock, A., Dougherty, M.K., Coates, A.J., 2009. Plasma environment at Titan's orbit with Titan present and absent. Geophys. Res. Lett. 36 (23), L23202. doi:10.1029/2009GL041048.