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Titan's highly dynamic magnetic environment: A systematic survey of Cassini magnetometer observations from flybys TA–T62

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ABSTRACT

We analyze the variability of the ambient magnetic field near Titan during Cassini encounters TA–T62 (October 2004–October 2009). Cassini magnetometer (MAG) data show that the moon's magnetic environment is strongly affected by its proximity to Saturn's warped and highly dynamic magnetodisk. In the nightside sector of Saturn's magnetosphere, the magnetic field near Titan is controlled by intense vertical flapping motions of the magnetodisk current sheet, alternately exposing the moon to radially stretched lobe-type fields and to more dipolar, but highly distorted current sheet fields. In southern summer, when most of the Cassini encounters took place, the magnetodisk current sheet was on average located above Titan's orbital plane. However, around equinox in August 2009, the distortions of Titan's magnetic environment due to the rapidly moving current sheet reached a maximum, thus suggesting that the equilibrium position of the sheet at that time was significantly closer to the moon's orbital plane. In the dayside magnetosphere, the formation of the magnetodisk lobes is partially suppressed due to the proximity of the magnetopause. Therefore, during most encounters that took place near noon, Titan was embedded in highly distorted current sheet fields. Within the framework of this study, we not only provide a systematic classification of all Titan flybys between October 2004 and October 2009 as lobe-type or current sheet scenarios, but we also calculate the magnetospheric background field near Titan's orbit whenever possible. Our results show that so far, there is not a single Cassini flyby that matches the frequently applied picture of Titan's plasma interaction from the pre-Cassini era (background field homogeneous, stationary and perpendicular to the moon's orbital plane). The time scales upon which the ambient magnetospheric field close to Titan undergoes significant changes range between only a few minutes and up to several hours. The implications for the development of numerical models for Titan's local plasma interaction are discussed as well.

1. Introduction

Saturn's largest satellite Titan orbits its parent planet in the outer magnetosphere at a distance of about $20.3R_S$ (R_S=60 268 km). Due to the absence of a noteworthy intrinsic magnetic field (Ness et al., 1982; Neubauer et al., 1984; Backes et al., 2005), Titan's atmosphere and ionosphere are directly exposed to a flow of at least partially corotating magnetospheric plasma with a relative velocity of about 120 km/s. For more than two decades, our understanding of the resulting interaction process was based on the plasma and magnetic field data collected during a single close flyby of Voyager 1 in November 1980. During the Voyager 1 encounter, the undisturbed magnetospheric field $\underline{B}_0$ upstream of Titan was observed to be perpendicular to the moon's orbital plane. Plasma spectrometer data from this encounter were interpreted to indicate an upstream flow velocity vector $\underline{u}_0$ that is parallel to Titan's orbital plane (Neubauer et al., 1984). Nearly every available model of Titan's plasma interaction from the pre-Cassini era (see, e.g. Nagy et al., 2001; Kallio et al., 2004) assumes the characteristic length and time scales, upon which $\underline{B}_0$ and $\underline{u}_0$ undergo significant changes, to clearly exceed any length and time scale involved in the local plasma interaction process. These local scales are defined by, e.g. the pick-up ion gyroradii (several Titan radii, cf. Simon et al., 2007b) and periods or the convection time of a magnetic flux tube through the interaction region (up to several hours, cf. Bertucci et al., 2008).

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In such a geometry, Titan's orbital plane coincides with the plane defined by the corotation velocity $\underline{u}_0$ of the impinging magnetospheric flow and the undisturbed convective electric field $\underline{E}_0 = -\underline{u}_0 \times \underline{B}_0$. The interaction gives rise to the formation of a bipolar magnetotail, whose large-scale features should be symmetric with respect to Titan's orbital plane (cf. for instance Neubauer et al., 2006; Simon et al., 2006). Furthermore, simulations have shown that in this scenario, Titan's pick-up tail exhibits a "flat" structure, in such a way that the magnetic lobes prevent it from expanding significantly into the regions above and below the orbital plane (Simon et al., 2007a; Simon and Motschmann, 2009). For this reason, the Voyager 1 scenario permits easy and straightforward access to many physical processes involved in Titan's plasma interaction. However, more than 5 years of Cassini magnetic field measurements suggest that the highly idealized picture constructed from the Voyager 1 snapshot is far from complete.

Cassini observations indicate that the orientation of the magnetic field near Titan's orbit exhibits significant deviations from an ideal dipolar configuration. Titan's magnetic environment is strongly affected by the presence of Saturn's magnetodisk (Arridge et al., 2008b). At Saturn, synchronous orbit is located at a distance of only $1.8R_S$. This value is smaller than the radial distance of Enceladus ($3.9R_S$), which was found to be the major plasma source in Saturn's magnetosphere (see, e.g. Dougherty et al., 2006; Tokar et al., 2006). Since the centrifugal force acting on the newly injected plasma exceeds the gravitational force by a large factor, magnetic forces are required to confine the plasma. The equatorial, quasi-dipolar field cannot maintain stress balance with the plasma stresses. Therefore, the field lines become more and more stretched in radial direction (Gombosi et al., 2009). The resulting highly stretched magnetic field configuration and the corresponding magnetically confined plasma population make up the magnetodisk. Due to the disk's solar wind-induced asymmetry (Arridge et al., 2008c), the radial and the north–south magnetic field component also exhibits strong spatial variations between different local time sectors of the magnetosphere. Especially in the dayside magnetosphere, a radially stretched magnetic field configuration was found only at times of low solar wind dynamic pressure, i.e. when the stand-off distance of Saturn's magnetopause was larger than $23R_S$. Otherwise, the formation of the magnetodisk lobes is partially suppressed and a more dipolar field configuration is encountered at the dayside (Arridge et al., 2008c).

As discussed above, the stretching of the magnetic field lines due to centrifugal forces and pressure gradients (Arridge et al., 2007) leads to the formation of the magnetodisk lobes. Moreover, deviation from full corotation leads to an additional magnetic field component along the corotational flow direction: when the equatorial plasma moves outward, its angular velocity diminishes since Saturn's magnetosphere–ionosphere coupling cannot maintain full corotation any more. The plasma in the equatorial plasma sheet therefore tends to sub-corotate, i.e. the equatorial part of the magnetic field lines is bent back with respect to a strictly corotating meridional plane. As discussed by Bertucci (2009), these swept-back fields have already been detected along Titan's orbit in the dawn, dusk and midnight sectors of Saturn's magnetosphere.

Furthermore, seasonal effects exert some level of control on the configuration of the magnetodisk. The Cassini prime mission took place in southern summer. During this time, the current sheet was bent above the magnetic equator beyond radial distances of $15R_S$ (Arridge et al., 2008b). Overall, the magnetodisk was found to exhibit a bowl-like shape. In such a configuration, Titan's orbit is no longer located within Saturn's magnetic equator, but typically below the central magnetodisk current sheet. In northern summer, which commenced in August 2009, the situation should be reversed, with the current sheet being bent southward and Titan being located above the magnetic equator. Only close to the equinoxes, this warping of the magnetodisk should vanish and Titan's orbit should therefore coincide with Saturn's magnetic equatorial plane. Since Saturn was close to equinox during the Voyager 1 encounter, seasonal effects were relatively weak at that time and had not been included in the pre-Cassini picture of Titan's magnetic environment.

At a given orbital position inside Saturn's magnetosphere (as defined by the Saturn local time, SLT), Titan's distance to the magnetodisk current sheet is not only modified by long-term seasonal variations, but it also exhibits a strong dependency on the solar wind dynamic pressure and on the phase of Saturn's kilometric radiation (SKR). Despite being dominant in the noon sector of Saturn's magnetosphere, the influence of the solar wind has shown to be present at all local times, whereas at least in the dawn sector, the SKR modulation also has noteworthy impact on the magnetic field around Titan (Bertucci, 2009). This finding is confirmed by Arridge et al. (2008a) who studied the properties of thermal electrons around Titan's orbit at $20R_S$. These authors identified a modulation of the electron density in the moon's orbital plane that arises from periodic motion of the current sheet.

In addition, Titan's magnetic environment is affected by short-scale fluctuations of the current sheet, causing it to "flap", i.e. to move up and down, relative to the satellite's orbital plane with a period of about 10–20 min (Arridge et al., 2007, 2008b). This time scale is of the same order as the duration of a Titan encounter. Superimposed on these fluctuations may be large-scale vertical oscillatory motions of the current sheet around Titan's orbital plane with a characteristic duration of several hours (Arridge et al., 2008a).

Several recently published studies suggest that Titan itself may play a key role in controlling the large-scale dynamics of Saturn's magnetosphere. Russell et al. (2008) showed that the possibility of substorm occurrence is increased when Titan is located near midnight local time, since the moon locally injects additional plasma into the magnetosphere. By analyzing Cassini magnetometer and electron spectrometer data from June 2004 to December 2008, Wei et al. (2009) demonstrated that Titan also exerts a certain level of control on the location of the dayside magnetopause at Saturn. Near noon, Saturn's magnetopause seems to be more frequently inside Titan's orbit with the moon absent than with it present. These authors suggest that Titan's presence near noon locally enhances the total pressure by mass-loading, thereby reducing the magnetospheric compressibility.

Recently, Bertucci et al. (2009) presented a first attempt to characterize the variability of Saturn's magnetic field near Titan's orbit from a global perspective. Based on Cassini magnetic field observations accumulated during the first 3.5 years of the prime mission, the authors identified characteristic types of magnetic field regimes to which Titan may be exposed along its orbit around Saturn. In different local time sectors, Cassini encountered either a magnetodisk lobe regime where the fields are radially stretched and the plasma betas are low, or a current sheet regime with quasi-dipolar fields and high values of the plasma beta. Bertucci et al. (2009) considered magnetic field data that had been collected in the immediate vicinity of Titan as well as during orbit crossings that took place when Titan was far away. However, although they succeeded in characterizing the global features of Saturn's magnetospheric field at a distance of $20.3R_S$, they did not specify their findings to classify Titan's magnetic environment during the more than 50 Cassini flybys that had already taken place. Especially, Bertucci et al. (2009) did not investigate whether on the (rather small) length and time scales upon which Titan's local plasma interaction takes place, the picture of the moon's ionosphere interacting with a quiet and homogeneous magnetospheric background field is in principle applicable. Within the framework of the present study, we aim to fill this gap.

The primary purpose of this study is to characterize the ambient magnetospheric fields near Titan's orbit during the first 62 Cassini encounters (TA–T62 between October 2004 and October 2009, see also Fig. 1) as either magnetodisk lobe fields or current sheet fields. Our survey is based upon magnetic field observations made by the Cassini magnetometer (MAG) instrument (Dougherty et al., 2004). Specifically, we shall address the following questions:

- *Magnetodisk current sheet vs. lobes*: Which of the existing Titan flybys took place in the current sheet, and which flybys have to be assigned to the magnetodisk lobe category?
- *Dynamics of Titan's magnetic environment*: How significant is the imprint that vertical flapping motions of the current sheet leave on the observed magnetic fields during the Titan encounters? In other words: Is it even possible to assign a certain flyby scenario to a single category, or do transitions between different magnetic field regimes during the encounters play a key role?
- *Titan's local plasma interaction*: To what degree does the idealized picture of Titan's ionosphere interacting with a constant magnetospheric background field reflect the real situation? If such homogeneous ambient magnetic field conditions were indeed observed during certain flybys, how strong did the field orientation deviate from being perpendicular to the corotational flow direction? This information is of particular interest for the development of numerical models of Titan's local plasma interaction.
- *Time scales for variability of the ambient magnetospheric field*: Do the magnetic field data allow to estimate the length of the time windows during which Titan is exposed to a quasi-stationary magnetospheric background field? How do these time scales compare to the lifetime of fossil magnetic fields (Neubauer et al., 2006) in the moon's ionosphere?
- *Local time effects*: Can flybys that took place at the same orbital position be assigned to the same magnetic field category (sheet vs. lobe)?
- *Seasonal effects*: Do the magnetic field data collected in the same SLT sector show hints of seasonal variations in Titan's magnetic environment?

This paper is organized as follows: In Section 2, we specify the characteristics of the magnetic field data that have been analyzed. A criterion that allows a discrimination between magnetodisk current sheet fields and lobe-type fields is presented. We also introduce two parameters that are helpful for quantifying the deviation of the ambient magnetic field from "ideal" orientation: the stretch angle and the sweepback angle. In Sections 3–5, a systematic classification of the ambient field conditions during all available Titan flybys is presented and discussed in detail. Whenever possible, the magnitude and direction of the background field are derived from the data sets. Moreover, the results

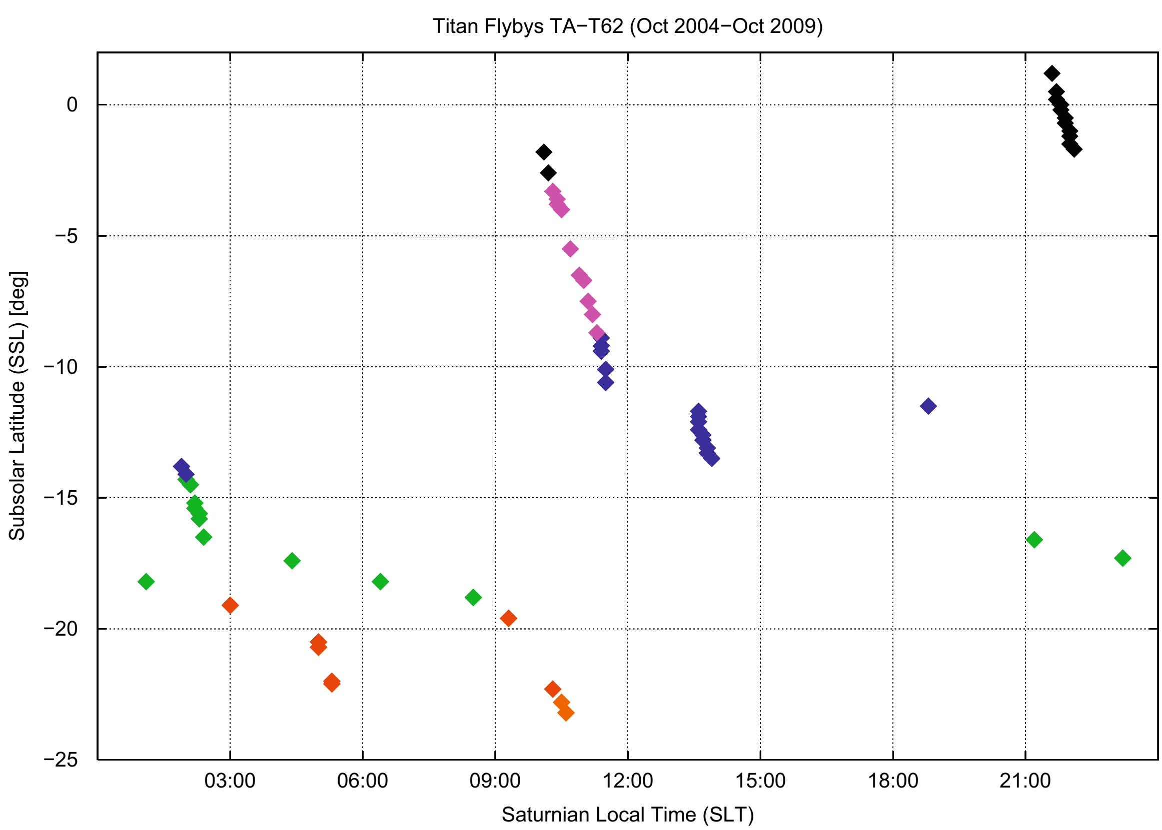

Fig. 1. Titan flybys TA–T62: Saturnian local time (SLT) vs. subsolar latitude (SSL). The figure illustrates the correlation between Titan's orbital position and the latitude of the moon's subsolar point for the encounters that took place in 2004 (TA and TB, orange), in 2005 (T3–T9, red), in 2006 (T10–T22, green), in 2007 (T23–T39, blue), in 2008 (T40–T49, magenta) and between January and October 2009 (T50–T62, black). Most of the Titan flybys took place in southern summer (i.e. SSL negative). During the encounters that occurred around equinox in August 2009, the latitude of the subsolar point was close to zero. The figure also illustrates that several series of flybys were carried out at nearly the same orbital position, with the subsolar latitude differing only insignificantly between consecutive passages. Details will be discussed in Section 5. So far, only a single Titan encounter (T34 on 19 July 2007) took place in the dusk sector (18:00–21:00) of Saturn's magnetosphere. The Voyager 1 flyby on 12 November 1980 (not included in the figure) occurred around equinox at about 13:30 SLT and a subsolar latitude of +3.9°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of our classification are compared with the findings of Rymer et al. (2009), who recently accomplished a categorization of the existing Titan flybys by employing data from the Cassini electron detectors. In Section 7, we discuss the implications of our findings for the characteristic time scales involved in shaping Titan's magnetic environment and the development of numerical models for the moon's local magnetospheric interaction. The paper concludes with a brief summary of our major results and an outlook to future projects.

2. Data description and analysis method

For this study, a systematic survey of Cassini magnetic field observations (Dougherty et al., 2004) has been carried out for Titan flybys TA–T62. In this section, the analysis method is presented and subsequently applied to a set of examples in Section 3.

2.1. Length of analyzed time intervals

For each Titan flyby, we have analyzed magnetic field data which were collected within a window of ± 8 h around closest approach. This interval is about more than a factor of two longer than the segments of ± 3 h considered in the companion studies by Rymer et al. (2009) and Wei et al. (2009). In the following, we shall discuss our reasons for applying an enlarged analysis window.

An important characteristic time scale of Titan's local plasma interaction is defined by the lifetime of fossil magnetic fields in the moon's ionosphere. As suggested by Neubauer et al. (2006), the slow and dense heavy ion plasma below altitudes of about 1700 km exhibits some kind of magnetic memory effect. The convection speeds of these newly generated pick-up ions may be reduced to as low as 100 m/s in this region. A magnetic flux tube which enters this region may therefore remain trapped there for a duration of several hours, in contrast to flux tubes passing Titan only peripherally within a few minutes. Thus, after a temporal change in the ambient magnetic field conditions near Titan, flux tubes from previously encountered field regimes may still be stored in the moon's ionosphere.

The first observational confirmation for the existence of fossil magnetic fields came from MAG data collected during the T32 encounter, as discussed by Bertucci et al. (2008). During T32, Titan left the magnetosphere of its parent planet near noon local time and became exposed to the shocked solar wind plasma in Saturn's magnetosheath. Magnetic field observations near closest approach revealed the presence of a bundle of trapped flux tubes, which Titan had carried from the magnetosphere into the magnetosheath. However, even when being continuously located inside the magnetosphere, Titan's ionosphere may experience a "contamination" by fossil magnetic fields. In this case, the variability of the ambient magnetic field conditions arises from partial or complete passages of the magnetodisk current sheet through the moon's orbital plane, as reported by Arridge et al. (2007, 2008a).

Based on in situ data from the T32 magnetopause passage and corresponding MHD simulations, Bertucci et al. (2008) and Ma et al. (2009) suggest the lifetime of fossil magnetic fields in Titan's ionosphere to range between $T_L = 20$ min and about $T_L = 3$ h. After this time, Titan's immediate magnetic environment would be devoid of fossil magnetic fields, if the upstream conditions had remained constant. We would like to point out that the lifetime of fossil magnetic fields may even clearly exceed the 3 h window estimated from the analysis of the T32 magnetosheath excursion. Physically, the longest possible time of residence for fossil magnetic fields near Titan is given by the longest possible convection time through its plasma environment. This residence time is probably prolonged by the magnetic diffusion time through Titan's inner, diffusion-dominated region for those field lines intercepted by the diffusion region as they move towards Titan. The transition altitude, based on the corresponding magnetic Reynolds number, depends on the epoch of the flyby, but is generally located just above an altitude of 1000 km (see, e.g. Backes, 2005). A famous case with the diffusion effect being predominant is the lunar one, where during the Apollo era the magnetic transients due to the electrodynamic interaction with the lunar interior have been studied (Dyal et al., 1974).

As indicated above, the lifetime of the fossil field signatures depends significantly on the location relative to Titan, with a maximum expected in the central wake. However, Titan's wake where fossil fields may prevail much longer than 3 h had not been sampled during the T32 magnetosheath excursion. Global modelling results that include a sufficiently accurate description of the physics occurring in the diffusion region were not available at the time of this writing either. Therefore, the time window obtained for T32 can therefore only be taken as a rough estimate for any other flyby scenario. In this sense, we adopt the $T_L = 3$ h value deduced from the T32 observations as an upper limit for the lifetime of fossil fields during any other flyby scenario as well.

Consequently, any kind of variability that Titan had encountered more than 3 h before closest approach would not be "remembered" by the moon's ionosphere any more. On the other hand, fossil magnetic fields observed near closest approach (C/A) could be completely ascribed to changes in the ambient field conditions that had occurred within the last 3 h. Our results for the magnetic field classification obtained within a ± 3 h window around closest approach will therefore receive special attention.

Nevertheless, this study considers an enlarged time interval of ± 8 h around closest approach of each Titan flyby. We note first that in many cases, magnetic field variability observed in such a rather large sampling window can be directly correlated to field variations that would be experienced at the position of Titan as well. Indeed, field variations detected outside the ± 3 h segment frequently provide a valuable diagnostic tool for estimating the length of the time windows during which Titan may be embedded in a quasi-stationary magnetospheric background. We would like to point out, however, that determining the length of these large-scale time windows is an additional purpose of our data survey and independent of whether the magnetic field observations near C/A are contaminated by fossil fields.

As implied by the results of Bertucci et al. (2009) and Arridge et al. (2008a), Titan's magnetospheric environment may experience frequent transitions between current sheet and lobe-type fields. Each passage of the current sheet through Titan's orbital plane goes along with a contamination of the moon's ionosphere by fossil fields. Therefore, such a passage marks the beginning of an interval during which the idealized picture of stationary upstream conditions in the absence of fossil magnetic fields is not applicable. If no further current sheet passages through Titan's orbital plane occur, a time window with "ideal conditions" (quasi-stationary background field, no fossil fields) is opened at $\delta t = T_L$ after the sheet passage. But how long does this time window last?

In the following, we introduce a method for estimating the maximum length of the "ideal" time window at the position of Titan by considering two subsequent current sheet crossings detected by Cassini, even if these observations occurred at large distances above or below the moon's orbital plane. The points in time at which the two sheet crossings were observed by the spacecraft are denoted by $t = t_1$ and $t = t_2 (> t_1)$, respectively. As an example, we consider a southbound flyby trajectory, i.e. Cassini crosses Titan's orbital plane from above to below.

Near Titan's orbit, the velocity of the Cassini spacecraft is typically of the order of 6 km/s. Therefore, within a ± 8 h interval around closest approach, the spacecraft may travel a maximum distance of about $\pm 2.8R_S$ in vertical direction, assuming a pure north–south motion. The current sheet itself, however, possesses a finite thickness of at least $4R_S$, cf. for instance Arridge et al. (2008b) or Giampieri and Dougherty (2004). Let us assume Cassini to be located, say, at $z=2R_S$ above Titan's orbital plane and to be embedded in the southern magnetodisk lobe regime (which is possible in the case of a warped current sheet). If the spacecraft now detects a transition from southern to northern lobe-type fields, i.e. if the sheet sweeps over Cassini from above to below, we can be sure that this variability is experienced at the position of Titan as well. Due to the finite thickness of the sheet, Titan will definitely be in contact with its lower boundary once it has passed Cassini from above to below. The point in time at which Cassini leaves the sheet at its upper side and becomes exposed to the northern lobe is denoted by $t=t_1$. If, for instance, a subsequent encounter with the current sheet is detected a few hours later near C/A to Titan at $z(t=t_2)=0$, these data allow to roughly determine the maximum length δT of the time interval during which ideal conditions (quasi-stationary background fields, no fossil fields) prevailed at the position of Titan:

$$\delta T = t_2 - t_1 - T_L. \quad (1)$$

As will be demonstrated in Section 5, the scenario discussed above is far from being hypothetical. There are numerous high-inclination Cassini flybys during which multiple current sheet crossings were observed (many of them outside the ± 3 h interval around C/A), thereby allowing to roughly estimate the length of the time windows during which Titan was exposed to a stationary background field.

Another important reason for the application of an extended ± 8 h interval is that data from a shorter ± 3 h window have frequently shown to contain only very little information on the mechanisms that are responsible for causing variability of the magnetic field conditions near closest approach to Titan. As will be discussed in more detail in Section 5, some of these effects operate on large spatial and time scales. Data from a reduced ± 3 h window have therefore shown to frequently contain an incomplete and maybe even misleading snapshot of the large-scale magnetospheric processes involved in shaping Titan's magnetic environment. Although—based on the 3 h limit for the lifetime of fossil fields adopted from T32—only data from a reduced ± 3 h window would be relevant for magnetic field observations near C/A, another major purpose of this study is to provide some basic understanding of the global magnetospheric processes that are responsible for causing the variabilities near Titan.

For instance, a periodic vertical oscillation of the current sheet around Titan's orbit (see, e.g. Arridge et al., 2008a) on a time scale of several hours may affect the field observations within a ± 3 h interval only once, thereby possibly leading to the wrong conclusion that such a sheet crossing through the orbital plane is a singular event and that the position of the sheet is otherwise stationary on large time scales. Of course, such a sheet passage through the orbital plane is only relevant for magnetic field observations near Titan, if it occurs within a time window of length T_L before Cassini's closest approach to the moon.

However, we would also like to point out that an exhaustive discussion of all the different effects involved in magnetospheric dynamics at $20.3R_S$ is far beyond the scope of the present study.

To sum up, there are several important reasons for considering an enlarged ± 8 h interval around C/A of each Titan encounter. First and foremost, such a time window allows to study the spatial and temporal evolution of the disturbances finally interacting with Titan up to almost the rotation period of Saturn. Besides, when assuming a predominantly vertical flapping motion of the current sheet, crossings observed far above or below the moon's orbital plane can be directly related to field variability that is also experienced at the position of Titan. Since the thickness of the sheet clearly exceeds the vertical distance that Cassini travels within 8 h, the spacecraft and the moon are often located nearly simultaneously in the current sheet. A survey of current sheet crossings observed at large distances therefore allows to draw additional conclusions on the time scales involved in shaping Titan's magnetospheric environment. Finally, there are good physical reasons to also expect residence times of fossil fields that clearly exceed the $T_L = 20\,\text{min} \ldots 3\,\text{h}$ window, although this remains to be confirmed by observations and modelling.

2.2. Classification scheme

The high-resolution (up to 32 vectors per second) magnetic field data have been averaged to 10 s. The magnetic field components are defined with respect to the Titan Interaction System (TIIS, cf. Backes, 2005), whose origin coincides with the center of Titan. The (x,y) plane of this coordinate frame is identical to Titan's orbital plane, with the $(+x)$ axis being aligned with the direction of ideal corotation and the $(+y)$ axis pointing from Titan to Saturn. The positive z axis is directed perpendicular to the moon's orbital plane and completes the right-handed coordinate system. In the idealized picture frequently applied in the pre-Cassini era, the ambient magnetic field $\underline{B}_0$ is antiparallel to the z axis. It should be noted that for a specific flyby scenario, the magnitudes of the magnetic field components obtained in this coordinate system are practically identical to the components with respect to the KSMAG cylindrical coordinate system applied by Bertucci et al. (2009). Only the sign of the radial field component (B_y in TIIS coordinates) is opposite in both coordinate frames.

Since we are mainly interested in the properties of the ambient magnetospheric field, the segment of each flyby trajectory where the field is distorted by the local interaction between Titan's ionosphere and the rotating magnetospheric plasma has not been considered in our analysis. Of course, the extension of the local interaction region (the "C/A segment") slightly differs from flyby to flyby. As will be discussed below, for several flybys it has been difficult to identify an outer boundary of the near-Titan interaction region in the data sets.

For the first step of the analysis, the magnetic field data before and after the C/A segment of each Titan encounter have been binned into time intervals of 1 h. For each binning interval, the average magnetic field components

$$B_j \equiv \langle B_j \rangle = \frac{1}{N}\sum_{i=1}^{N} B_j^i, \quad j = x,y,z, \quad (2)$$

as well as the standard deviations

$$\delta B_j = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(B_j^i - \langle B_j \rangle)^2}, \quad j = x,y,z, \quad (3)$$

have been computed, where $N=360$ is the typical number of data points in each 1 h time interval and B_j^i denote the measured magnetic field values. For normalization purposes, the average total magnetic field magnitude in each binning interval is required as well:

$$B \equiv \langle B \rangle = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\sum_{j=x,y,z}(B_j^i)^2}. \quad (4)$$

Alternatively, the magnitude of the average magnetic field

$$\langle \tilde{B} \rangle = \sqrt{\sum_{j=x,y,z} \langle B_j \rangle^2} \quad (5)$$

could be used for normalization. It should be noted that for the classification concept introduced in the following, $\langle B \rangle$ and $\langle \tilde{B} \rangle$ have been tested as normalization values, yielding no changes in the obtained classification of the flyby scenarios. The normalization values required for the following classification are obtained from Eq. (4).

In the magnetodisk lobes, the field is strongly stretched in radial direction (cf. Fig. 2), i.e. the B_y component should be the predominant one (Bertucci et al., 2009). Only in the immediate vicinity of the magnetodisk, the sweep-back of the magnetic field lines is expected to be so large that B_x can make the major contribution to the total magnetic field. For this reason, the first criterion that we apply to identify magnetodisk lobe-type fields (classification symbol L) is

$$\frac{|B_y|}{B} > 0.6. \quad (6)$$

By averaging magnetic field data collected near $20.3R_S$ during the first 3.5 years of the Cassini prime mission, Bertucci et al. (2009) came to the conclusion that the radial component (in KSMAG coordinates, i.e. perpendicular to Saturn's spin axis) usually makes up 60% of the total field near Titan ($\langle B \rangle = 5$ nT vs. $\langle B_y \rangle = 3$ nT). Within the time interval considered by these authors, Titan was on average located below the magnetodisk. However, the more dipolar current sheet fields observed during this period contributed to the above average value as well. Therefore, the B_y component in the magnetodisk lobes may indeed be larger than $0.6\langle B \rangle$. When applying our classification scheme, we found that at least in the nightside magnetosphere (18:00–06:00 SLT), the lobe-type fields that were identified by means of condition (6) without any exception fulfill an even stronger restriction:

$$\frac{|B_y|}{B} > 0.75. \quad (7)$$

Our second criterion for a lobe-type field is that in this regime, B_y is not distorted by the proximity to the current sheet. For this reason, the fluctuations of B_y within each binning interval should be rather small. Thus, the second criterion that has to be fulfilled by lobe-type fields is

$$\frac{\delta B_y}{B} \leq 0.05. \quad (8)$$

There is no sharp boundary between current sheet and lobe-type fields. Specifically, Cassini MAG data quite frequently show predominantly lobe-type fields (i.e. criterion (6) fulfilled) that are distorted by short-time encounters with the flapping current sheet (i.e. criterion (8) not fulfilled). These fields (classification symbol L_{Sh}) are identified by means of (6) and

$$0.05 < \frac{\delta B_y}{B} \leq 0.2. \quad (9)$$

When passing through the current sheet from above (north) to below (south), the radial magnetic field component reverses its direction. At the equinoxes, this means that the B_y component transits from $B_y < 0$ above the current sheet to $B_y > 0$ below the sheet. In any case, in the immediate vicinity of the sheet, the magnitude of the B_y component should be clearly smaller than in the magnetodisk lobe regime (cf. Fig. 2). Therefore, the first criterion that is applied to identify current sheet fields (classification symbol Sh) is

$$\frac{|B_y|}{B} < 0.6. \quad (10)$$

The second criterion characterizes again the fluctuations of the magnetic field within the 1 h binning intervals:

$$0.2 < \frac{\delta B_y}{B}. \quad (11)$$

The magnetic fields in the current sheet are expected to fulfill either condition (10) or (11) or both of them. Based on this scheme, all 62 Titan flybys that were available at the time of this writing have been sorted into the categories listed in Table 1. A series of examples will be provided in the next section.

We would like to note here that in very few cases fields were observed that fulfill the condition $0.2 \ll \delta B_y/B$, while simultaneously possessing a strong B_y component ($|B_y|/B \approx 0.95$). These fields are assigned to the current sheet regime (Sh) by our scheme. However, the unusually large B_y component is denoted by an additional subscript "L^N" ($B_y < 0$) or "L^S" ($B_y > 0$).

Of course, we have also tested the sensitivity of our classification procedure to the time resolution of the magnetic field data and the length of the binning intervals. When reducing the time resolution of the magnetic field data, e.g. to 1 s, the resulting classifications remain unaffected for all available flybys. However, increasing the data resolution to e.g. 1 min results in a loss of information, since on these time scales, distortions of lobe-type fields by short current sheet encounters are often not fully resolved. For this reason, lobe-type fields with minor current sheet features are wrongly characterized as purely lobe-type. On the other hand, we have tested different lengths for the binning intervals as well. When reducing the binning length from 1 h to 30 min, the transition regions between lobe-type fields and

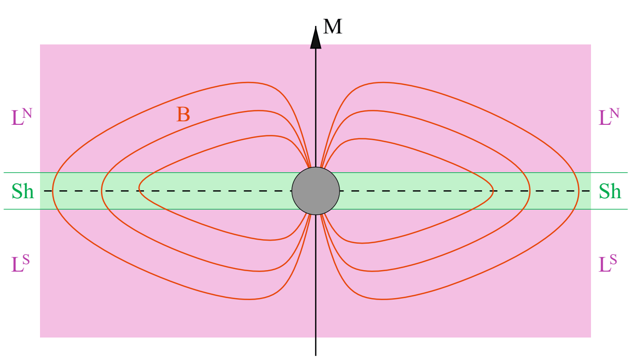

Fig. 2. Magnetodisk lobe vs. current sheet fields. For the case of the current sheet coinciding with Saturn's dipole magnetic equator (dipole moment M), the figure displays a schematic sketch of the field lines in the giant planet's magnetosphere. In the magnetodisk lobes (magenta), the field lines are radially stretched at large distances to Saturn. The symbol L^N denotes the northern magnetodisk lobe where the magnetic field points away from Saturn, while in the southern lobe (symbol L^S), the magnetic field is directed towards the planet. In the magnetodisk current sheet (green, symbol Sh), the radial magnetic field component reverses its direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Classification categories for Titan's magnetic environment.

Symbol	Explanation
Sh	Magnetodisk current sheet
L^N	Northern magnetodisk lobe ($B_y < 0$)
L^S	Southern magnetodisk lobe ($B_y > 0$)
L^N_{Sh}	Northern lobe, brief occurrences of current sheet fields
L^S_{Sh}	Southern lobe, brief occurrences of current sheet fields
Sh_{L^N}	Current sheet, brief occurrences of northern lobe
Sh_{L^S}	Current sheet, brief occurrences of southern lobe
Msh	Magnetosheath
(*)	Unclassified, maybe extended features from Titan interaction

current sheet fields are often slightly shifted, but the overall picture of Titan's magnetic environment during a certain flyby does not change at all. For many encounters, this is also still valid when the duration of the binning intervals is lengthened to 2 h. For the examples presented in the following section, results for 2 h binning intervals are shown whenever this did not yield a change of the classification.

Whenever Titan was embedded in quiet, lobe-type fields directly before or after closest approach, these fields have been used to calculate the average background magnetic field near the satellite's orbit. These average values have been computed from intervals of typically 2 h before and after the near-Titan segment of an encounter. In order to avoid any "contamination" of these background fields by Titan's local plasma interaction, the region of strongly draped field lines in the immediate vicinity of the moon has been omitted. In the few cases where extended features from the Titan interaction were observed in the inbound region (asterisk in the classification tables), the inbound field vector refers to the situation directly before entry into the distorted field regime.

2.3. Stretch angle and sweepback angle

As will be discussed in the following sections, we did not find a single flyby scenario during which the background magnetic field was oriented perpendicular to Titan's orbital plane. In order to characterize the deviation of the ambient field from "ideal" north–south orientation, two parameters are introduced: the stretch angle Str and the sweepback angle Sw (Bertucci et al., 2009; Khurana and Kivelson, 1993).

The stretch angle is defined as

$$\mathrm{Str} = \arctan\left(\frac{B_y}{B_z}\right). \tag{12}$$

This angle measures the degree to which a field line is stretched towards/away from Saturn. Fig. 3 illustrates the meaning of this quantity for the case of the current sheet coinciding with the magnetic equator. At the magnetic equatorial plane ($z=0$), the B_y component vanishes, leading to a stretch angle of Str=0. The region above the magnetic equator ($B_y<0$ and $B_z<0$) is characterized by positive values of the stretch angle, whereas below the sheet, Str assumes negative values. The sweepback angle, on the other hand, provides a measure of how strong a field line is bent back with respect to a strictly corotating meridional plane (Khurana and Kivelson, 1993). It is calculated from

$$\mathrm{Sw} = \arctan\left(-\frac{B_x}{B_y}\right). \tag{13}$$

In order to obtain the same sign of Sw regardless of the magnetic latitude, this definition includes a dependency on B_y. In Fig. 4, this is illustrated in more detail. Near the magnetic equator, the field lines shown in the figure are swept back with respect to ideal corotation. Consequentially, a negative value of the sweepback angle is obtained on both sides of the $z=0$ plane. If tan(Sw) had been introduced, e.g. as the ratio of B_x and B_z, positive values would be obtained above the equatorial plane, while below it, the sweepback angle would assume negative values. In other words, despite the field line being deformed in the same way above and below the equator, this behaviour would be characterized by different signs of the sweepback angle. It should be noted that whereas Sw < 0 characterizes sub-corotating field lines, magnetic field lines threading super-corotating plasma are denoted by positive values of the sweepback angle. Sporadically, such a situation has also been encountered at $20.3R_S$ (Bertucci et al., 2009).

The ratio $B_x/(-B_z)$, defining the tilt of the magnetic field against the vertical direction, can in principle be computed from the stretch and sweepback angles according to $\tan(\mathrm{Str})\cdot\tan(\mathrm{Sw})$. The stretch- and sweepback angles for magnetic field observations at $20.3R_S$ have also been computed by Bertucci et al. (2009) and Wei et al. (2009). However, neither of these studies contains an overview that assigns these parameters to specific Titan encounters, but only a general discussion for different local time sectors is provided.

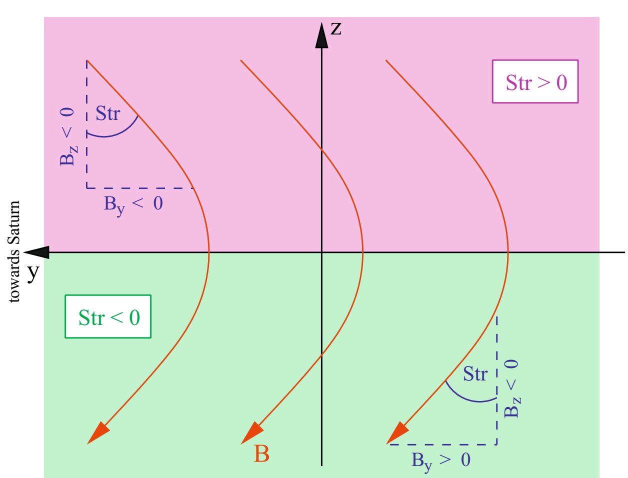

Fig. 3. Stretch angle. This angle provides a measure for the stretching of the magnetic field lines near Titan's orbit towards/away from Saturn. The figure illustrates this stretched field configuration in the (y,z) plane of the Titan interaction system at an arbitrary orbital position. The y axis points towards Saturn, whereas the z axis is antiparallel to Saturn's magnetic moment. Above the dipole magnetic equator ($z=0$), the B_y component is negative, yielding negative values of the stretch angle $\mathrm{Str}=\arctan(B_y/B_z)$. Below the magnetic equator, both the B_y component and the stretch angle are positive.

3. Examples

In this section, we demonstrate the application of our classification criteria to a set of three selected flybys: T20, T21 and T54. The trajectories of these encounters can be seen in Fig. 5, whereas the corresponding magnetic field data sets (± 8 h around C/A) are displayed in Figs. 6, 7 and 8, respectively. The T33 encounter, whose trajectory is also shown in the figure, will be discussed in Section 5.4.

The magnetic field data collected during these encounters contain frequent transitions between current sheet and lobe-type field regimes, thus providing an excellent opportunity to test our classification technique. A more systematic discussion of the physics seen in the data, along with a comparison to a companion study (Rymer et al., 2009), will be given in Sections 4–6.

3.1. Flybys T20 and T21

T20 and T21 were two consecutive encounters that took place at nearly the same orbital position of Titan (02:00 SLT). Closest approach during T20 occurred on 25 October 2006, whereas the subsequent visit to Titan was about seven weeks (i.e. three Titan revolution periods) later on 12 December 2006. As illustrated in Fig. 5, the trajectories were nearly identical: During both encounters, Cassini crossed Titan's orbital plane from north to south while moving from the anti-Saturn-facing to the Saturn-facing hemisphere of the moon. After closest approach, Cassini was located upstream of Titan (i.e. $x<0$) during both flybys.

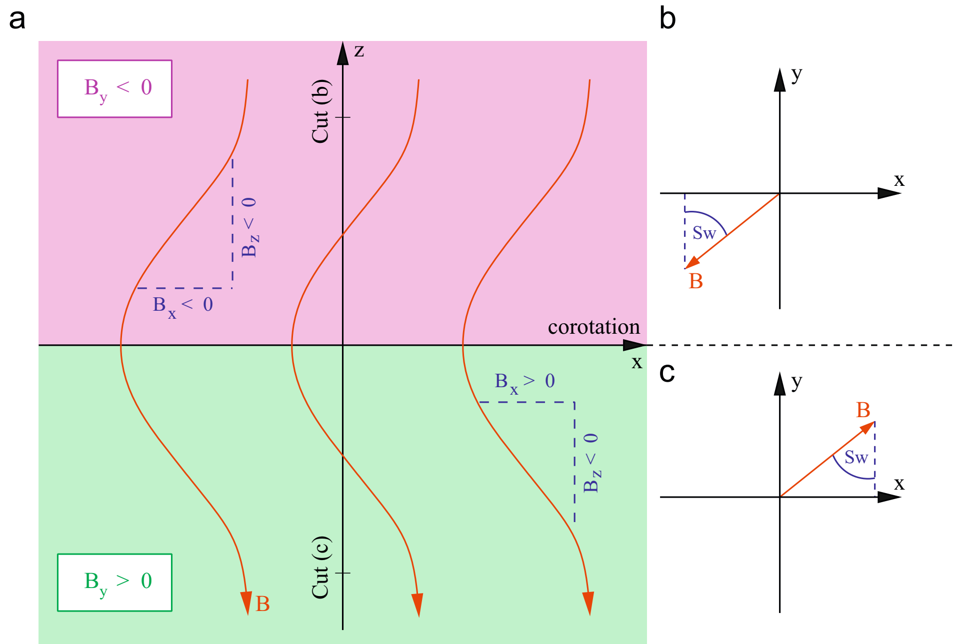

Fig. 4. Sweepback angle. This angle permits to measure how strong a magnetic field line is bent back with respect to a strictly corotating meridional plane. Plot (a) displays a cut through the (x,z) plane of the Titan interaction system, with the $(+x)$ axis being aligned with the direction of ideal corotation. Plot (b) shows a cut through a $(z>0)$ plane parallel to Titan's orbital plane, whereas a cut through a plane with $(z<0)$ can be seen in plot (c). The field lines shown in the sketches are bent back with respect to a $(x=\text{const})$ plane, since the magnetosphere–ionosphere coupling cannot supply the angular momentum required for full corotation. Above Titan's orbital plane (see plot (b)), both B_x and B_y are negative, yielding a negative value of the sweepback angle $\text{Sw}=\arctan(-B_x/B_y)$. For the segment of the field line that is located below the $(z=0)$ plane (cf. plot (c)), the directions of both field components are reversed, thus retaining the negative sign of the sweepback angle along the entire field line.

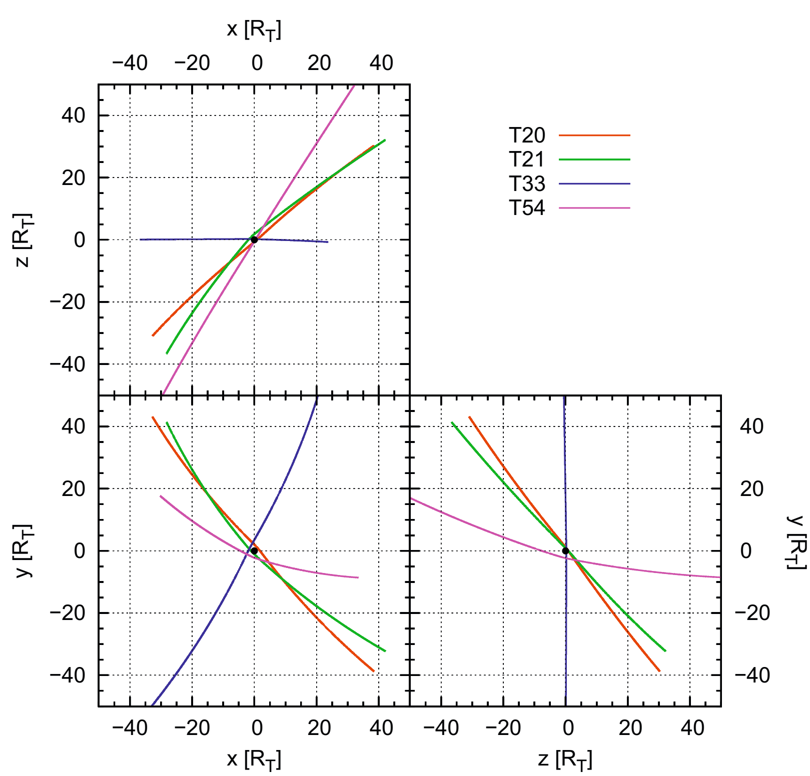

Fig. 5. Cassini's trajectory during Titan flybys T20, T21, T33 and T54, shown in Titan interaction (TIIS) coordinates. The radius of Titan is $R_T=2575$ km. During T20, T21 and T54, Cassini crossed Titan's orbital plane $(z=0)$ from north to south while moving in positive y direction, i.e. away from Saturn. T33 was an equatorial flyby $(z\approx 0)$, with the spacecraft moving antiparallel to the corotation direction and towards Saturn.

Despite the similarity of the flyby trajectories, there are nevertheless significant differences in the measured magnetic field signatures.

The strong fluctuations of the B_y component detected in the inbound part of T20 (cf. Fig. 6) suggest that Cassini was passing through a current sheet field regime. After C/A, however, these

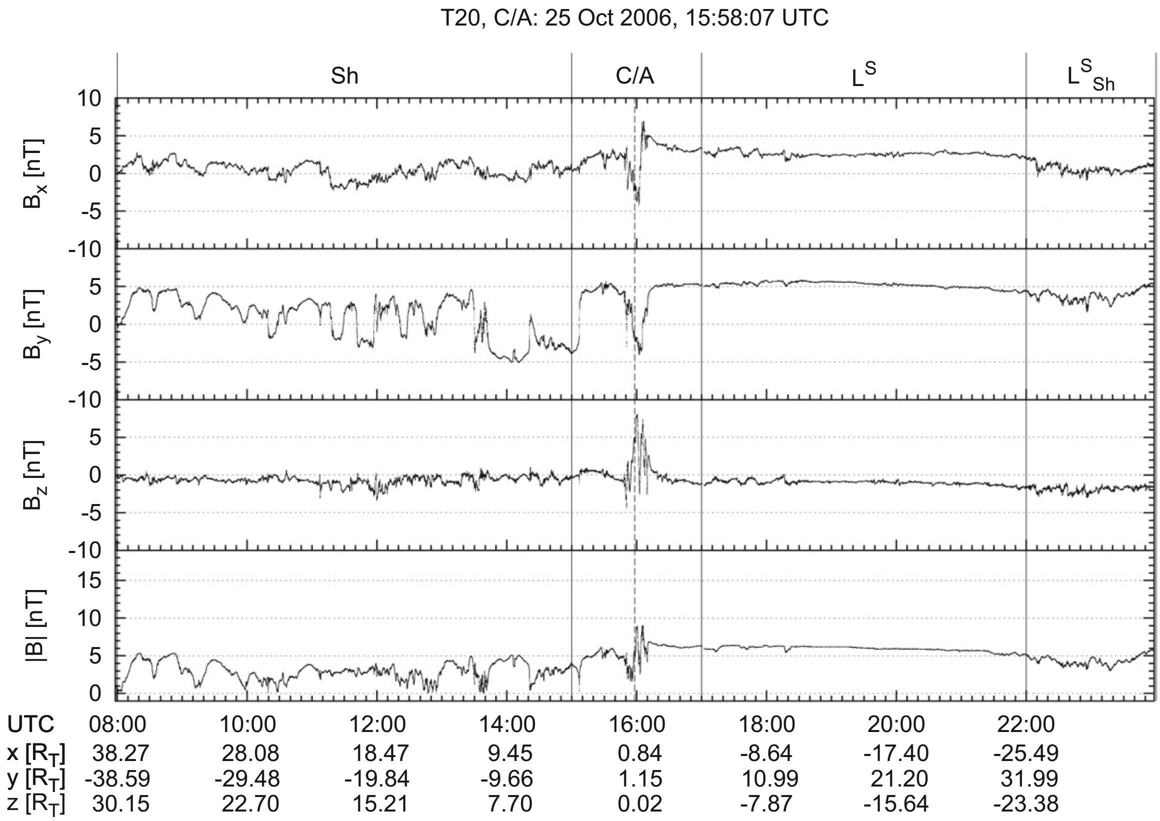

Fig. 6. Cassini magnetic field observations in a ± 8 h interval around closest approach of the T20 encounter. This flyby took place on 25 October 2006; the position of C/A is denoted by a dashed line.

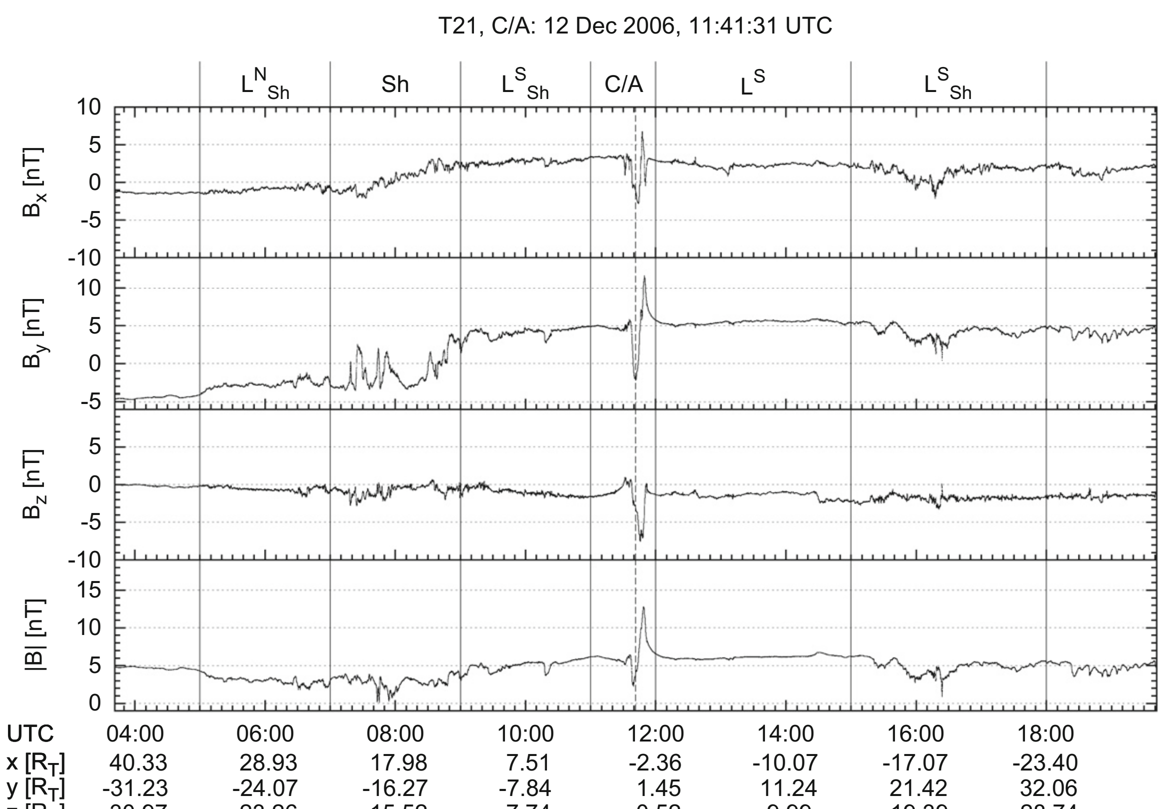

Fig. 7. Cassini magnetic field observations during T21. The closest approach (dashed line) of this encounter took place on 12 December 2006 at about 11:41. The magnetic field data are displayed for a ± 8 h interval around C/A.

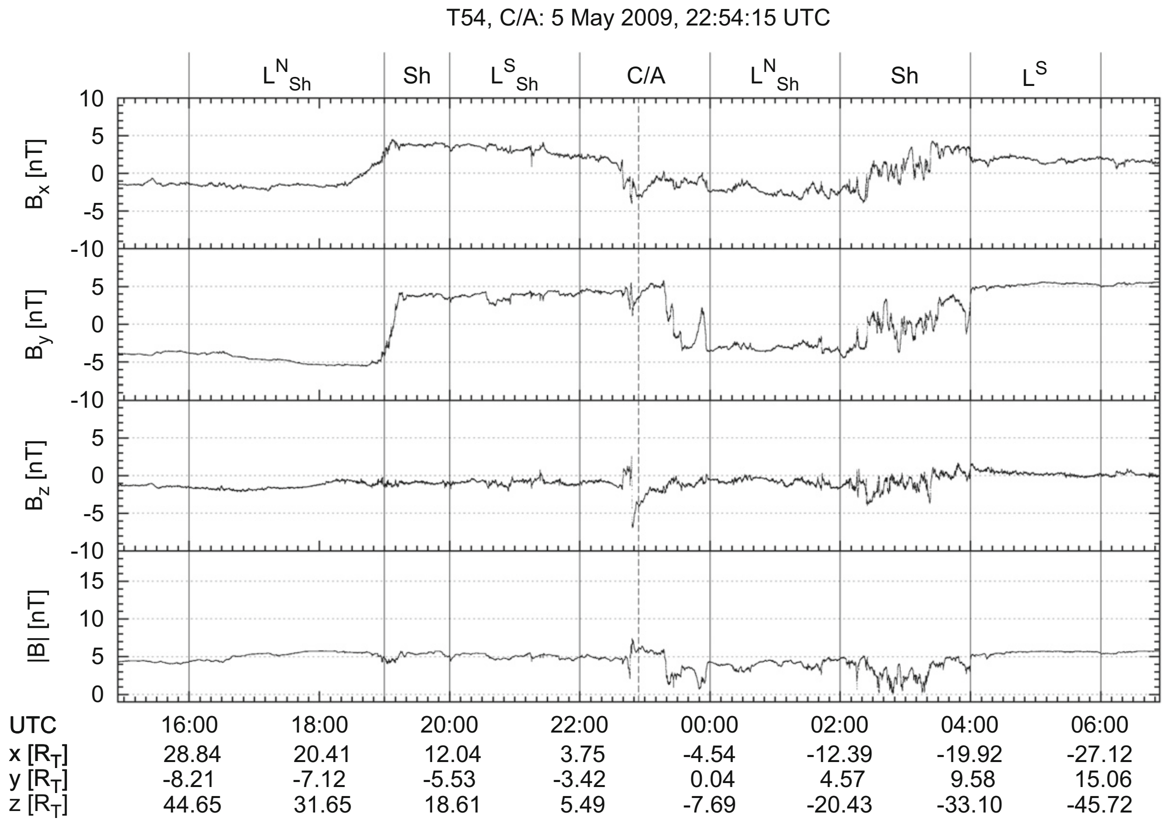

Fig. 8. Cassini magnetic field observations during the T54 flyby. The closest approach of this encounter took place on 05 May 2009 at about 22:54.

Table 2
Classification of the magnetic field near Titan during Cassini flyby T20 on 25 October 2006.

UTC	$\|B_y\|/B$	$\delta B_y/B$	Classification
08:00–10:00	0.90	0.42	*Sh*
10:00–12:00	0.37	0.77	*Sh*
12:00–14:00	0.29	0.95	*Sh*
14:00–15:00	0.92	0.40	*Sh*
17:00–18:00	0.87	0.03	L^S
18:00–20:00	0.90	0.03	L^S
20:00–22:00	0.86	0.05	L^S
22:00–00:00	0.87	0.16	L^S_{Sh}

Cassini achieved its closest approach altitude of 1029.5 km at about 15:58. The interval around closest approach (15:00–17:00) where the magnetic field was strongly affected by the local interaction with Titan's ionosphere has been omitted.

fluctuations were no longer observed and the spacecraft was immersed into quiet, magnetodisk lobe-type fields for about 6 h. The field was again distorted by current sheet signatures after 22:00. This classification by qualitative inspection of the data is fully confirmed by the quantitative approach introduced in the preceding section (cf. Table 2). In this case, the length of the binning intervals could be increased to 2 h without altering the results. An interval of about ± 1 h around closest approach has been omitted, since in this region, Cassini passed through the field distortions arising from the local interaction between the magnetospheric plasma and Titan's ionosphere. As can be seen from the upper half of Table 2, the magnetic fields in the inbound region are clearly classified as current sheet fields. Between 10:00 and 14:00, both criteria for lobe-type fields break down. In the other two segments (08:00–10:00 and 14:00–15:00), the B_y component fulfills the relation $|B_y|/B > 0.6$, which—if applied alone—would classify these fields as lobe-type. However, the fluctuation criterion (11) clearly assigns this field regime to the current sheet. Between 17:00 and 20:00, the classification indicates that Cassini passed through very quiet lobe-type fields with no hints of current sheet features. The $|B_y|/B$ and the $\delta B_y/B$ criteria for pure lobe-type fields are both fulfilled in this region. During the re-encounter with the current sheet after about 20:00, the $|B_y|/B$ condition for lobe fields still holds, but the distortions can clearly be identified by means of the fluctuation criterion. Since the fluctuations are fairly small ($|B_y|/B = 0.16$), this field regime is still classified as primary lobe-type. These results already illustrate that the current sheet is a highly dynamic structure whose motion can affect regions far below Titan's orbit, even in southern summer when the statistical center of the current sheet was slightly displaced above the orbital plane.

For the quiet lobe regime after C/A, the background magnetic field has been computed from the MAG data: $\underline{B}_0 = (2.64, 5.21, -0.99)$ nT. The values of the stretch and sweepback angles are $\mathrm{Str} = -79.2^\circ$ and $\mathrm{Sw} = -26.8^\circ$, respectively. Thus, the field lines below Titan's orbital plane were stretched towards Saturn, which is typical of the southern magnetodisk lobe regime. A negative value of the sweepback angle indicates that the plasma and the magnetic field lines threading it were sub-corotating. Therefore, the T20 scenario provides a first hint towards strong deviations from the idealized pre-Cassini picture. The proximity to the current sheet in the inbound region also suggests that, when attempting to characterize Titan's local plasma interaction during this flyby, the assumption of a constant magnetic background field would not be applicable.

During the T21 encounter, Cassini again passed through Titan's orbital plane from north to south. A qualitative inspection of the

B_y component suggests that before 07:00, Cassini was embedded in the northern magnetodisk lobe ($B_y < 0$) and subsequently passed through the current sheet between 07:00 and 09:00. Despite the similarity in the geometries of both encounters, Cassini's stay in the current sheet regime during T21 was about several hours shorter than during T20. On the one hand, this may imply that the thickness of the sheet near 02:00 SLT has diminished significantly between both encounters. However, the more likely explanation is that in the inbound region of T21, the current sheet was rapidly moving northward with a speed much larger than that of Cassini, yielding an only very short exposure of the spacecraft to the highly distorted $B_y \approx 0$ regime. About 2 h before C/A, the magnetometer detected a lobe-type field regime again, with B_y being positive. After C/A, Cassini remained in the rather undisturbed fields of the southern magnetodisk lobe ($B_y > 0$) for about another 3 h, before the perturbations associated with the current sheet increased again. In analogy to T20, these observations again imply that the magnetodisk current sheet apparently "flaps" around Titan's orbital plane in vertical direction quite frequently.

We will again show now that this rather intuitive interpretation is fully confirmed by our quantitative classification scheme (cf. Table 3). Before 07:00, the $|B_y|/B$ condition permits a clear identification of magnetodisk lobe fields, whereas the proximity to the current sheet already manifests in the increased level of fluctuations. The current sheet is again identified by means of the $\delta B_y/B$ condition. However, after 08:00, the field strength criterion for lobe-type fields breaks down as well. After entry into the southern magnetodisk lobe, the relative magnitude of B_y increased again to values far above 0.7B, while the level of fluctuations diminished as Cassini approached Titan. The quiet lobe-type fields in the outbound region fulfill both the field strength and the fluctuation criterion. After 15:00, the fluctuation level $\delta B_y/B$ increased again to values well above 0.05, corresponding to the slight distortion of the field signature by current sheet features.

For the T21 encounter, the ambient magnetic fields have been computed for both the inbound and the outbound segments of the trajectory. The values are provided in Table 6. What should be noted here is that while the stretch angle in the outbound region deviates by only about 6% from the inbound value, the sweepback angle shows a drop by more than a factor of 1.5. It is not clear to which degree this change has to be ascribed to the local interaction with Titan. In any case, the magnetic field observations show again that similar to T20, Titan's magnetic environment was strongly affected by the presence of the magnetodisk current sheet and that the assumption of spatially homogeneous background fields would not reflect the real situation.

Table 3
Classification of Titan's magnetic environment during Cassini flyby T21 on 12 December 2006.

UTC	$\lvert B_y\rvert/B$	$\delta B_y/B$	Classification
05:00–06:00	0.92	0.10	L_{Sh}^{N}
06:00–07:00	0.92	0.17	L_{Sh}^{N}
07:00–08:00	0.60	0.60	Sh
08:00–09:00	0.20	0.75	Sh
09:00–10:00	0.81	0.12	L_{Sh}^{S}
10:00–11:00	0.81	0.09	L_{Sh}^{S}
12:00–14:00	0.89	0.03	L^{S}
14:00–15:00	0.88	0.03	L^{S}
15:00–16:00	0.88	0.15	L_{Sh}^{S}
16:00–17:00	0.84	0.19	L_{Sh}^{S}
17:00–18:00	0.85	0.08	L_{Sh}^{S}

Again, the interval around closest approach (11:41, C/A altitude: 1000 km) is not considered for the classification. Since the segments before 11:00 and after 12:00 are apparently devoid of any features arising from Titan's local plasma interaction (cf. Fig. 7), an interval of only 1 h near C/A (11:00–12:00) has been omitted.

3.2. Flyby T54

The T54 encounter took place on 05 May 2009 when Titan was located at about 22:00 clock angle position on its orbit around Saturn. Again, Cassini crossed Titan's orbital plane from north to south (see Fig. 5). Since this encounter took place near equinox on 11 August 2009, one would expect the current sheet to be rather "flat" and thus, nearly coincide with Titan's orbital plane. In view of the finite thickness of the current sheet (several R_S, cf. Arridge et al., 2008b), Cassini should have been embedded in current sheet fields long before and after closest approach. However, as displayed in Fig. 8, the magnetic field observations reveal a completely different picture. We commence again with a qualitative inspection of the data set, followed by an application of our quantitative classification criteria.

The B_y component shows that Titan's magnetic environment in the ± 8 h interval around C/A was dominated by frequent encounters with the magnetodisk current sheet. Before about 19:00, fairly quiet lobe-type fields were detected. Then, the current sheet swept over Cassini from below to above and the spacecraft entered the southern magnetodisk lobe regime. Before C/A at 22:54, the magnetometer measured lobe-type fields, featuring a strong B_y component towards Saturn and being only moderately distorted by current sheet features. Nearly coincident with C/A, the spacecraft detected another current sheet encounter (23:00–00:00) and became again exposed to the stretched fields in the northern lobe. A subsequent current sheet crossing between 02:00 and 04:00 was followed by Cassini's re-entry into the southern magnetodisk lobe. It is most remarkable to notice that although the flyby took place near equinox, the measured magnetic field signature is not dominated by current sheet features. Instead, the data reveal segments of lobe-type fields that are interrupted by short-time passages from one side of the sheet to the other. As will be discussed in more detail in the next section, this seems to be a common feature of all Titan encounters that took place around equinox. The motion of the current sheet during the T54 encounter is also illustrated in Fig. 9, displaying the relative positions of Titan, Cassini and the sheet at several selected points in time.

Of course, the rather quiet lobe-type fields detected around closest approach allow the computation of background magnetic fields for the inbound and outbound regions (cf. Table 6). However, as illustrated in Fig. 8, the B_y component nearly reversed its direction during the encounter. The passage from the northern to the southern side of the current sheet coincides with Cassini's closest approach to Titan, i.e. with the region where the distortions caused by the moon's local plasma interaction manifest as well. Therefore, the structure of Titan's induced magnetosphere is expected to clearly differ from the idealized picture of homogeneous magnetic field lines being draped around a conducting obstacle.

Finally, we will demonstrate that our classification scheme is applicable to this kind of highly perturbed flyby scenario as well. In a first attempt, we again used binning intervals of 1 h. However, this length has subsequently been increased to 2 h in most segments of the flyby trajectory, since this did not yield any changes in the obtained field classification. The results of the quantitative analysis are provided in Table 4. The magnetic field between 16:00 and 19:00 is clearly identified as lobe-type, since B_y is significantly larger than 0.6B and the fluctuation level is small. During the current sheet passage between 19:00 and 20:00, both criteria for lobe-type fields break down. Subsequently, the B_y

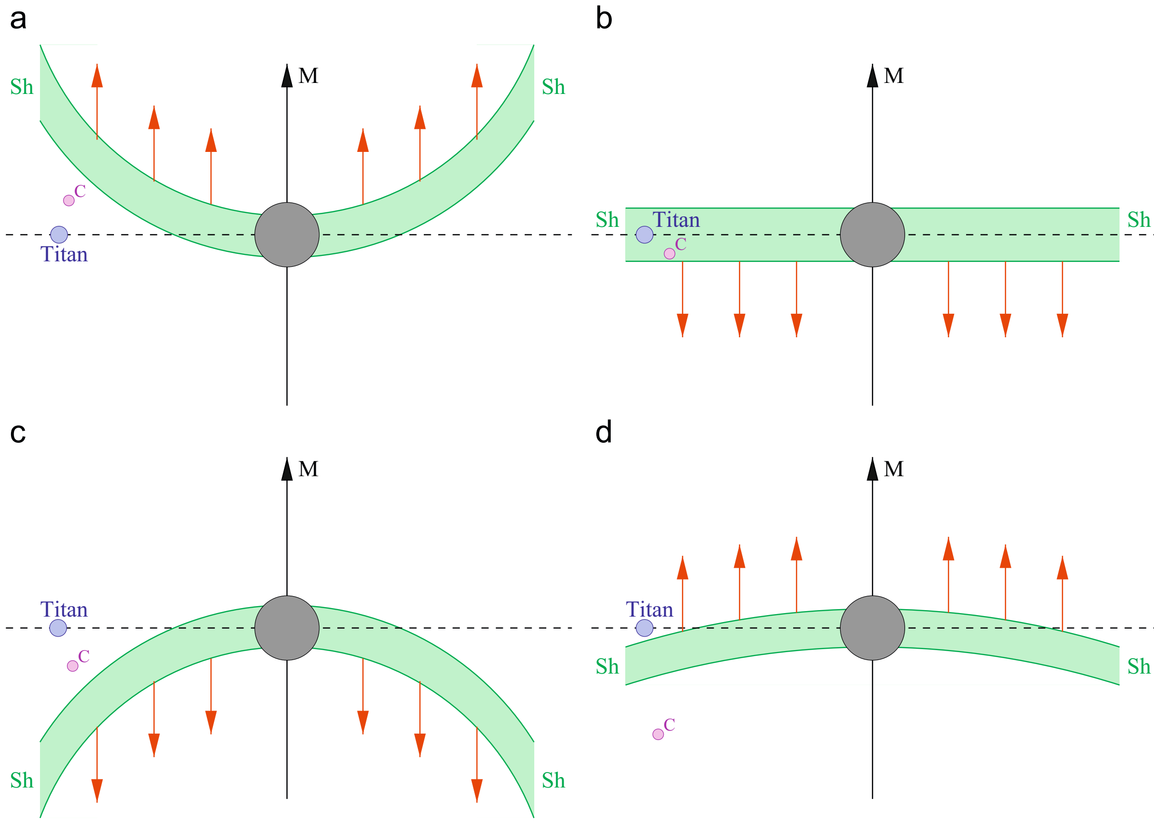

Fig. 9. Current sheet motion during the T54 encounter. In a series of snapshots, the figure illustrates the relative positions of Cassini (symbol C, magenta circle), Titan and the magnetodisk current sheet (symbol Sh, green). Cassini was moving from north to south, whereas the red arrows denote the vertical velocity of the current sheet. (a) Snapshot of the situation at about 20:00. The current sheet has just swept over Cassini from below to above, going along with a transition from northern to southern magnetodisk lobe fields at the position of the spacecraft. (b) Situation at about 23:30, i.e. short after C/A. The flapping current sheet has reversed its direction. At this point in time, Cassini's vertical distance to Titan's orbital plane was only about 0.2 R_S, which is clearly smaller than the estimated thickness of the sheet (Arridge et al., 2008b). For this reason, both Titan and Cassini are now exposed to current sheet fields. (c) Snapshot at about 01:00. The rapidly moving current sheet is now located below Titan's orbital plane and Cassini. Thus, the spacecraft as well as the moon are embedded in northern magnetodisk lobe fields. (d) Snapshot of the situation at about 05:00. The current sheet has reversed its direction again and is now located above Cassini. Probably, it passed Titan's orbital plane around the same time. In this situation, the spacecraft again detected southern lobe-type fields. It should be noted that for this illustration, we have assumed the flapping motion of the magnetodisk to be symmetric across the magnetosphere. Like a bird's wings, the current sheet synchronously moves up and down on the left and right side. While this is possible, it implies that the reason for the flapping is external to the magnetosphere (i.e. induced by the solar wind). Based on our current state of knowledge, however, we cannot exclude that the sheet perturbations seen by Titan have to be ascribed to internal effects (e.g. dynamics of Saturn's magnetotail) and are therefore localized near the moon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Classification of Titan's magnetic environment during Cassini flyby T54.

UTC	$\lvert B_y \rvert / B$	$\delta B_y/B$	Classification
16:00–18:00	0.88	0.10	L_{Sh}^N
18:00–19:00	0.95	0.06	L_{Sh}^N
19:00–20:00	0.54	0.40	Sh
20:00–22:00	0.75	0.08	L_{Sh}^S
00:00–02:00	0.77	0.09	L_{Sh}^N
02:00–04:00	0.03	0.69	Sh
04:00–06:00	0.94	0.05	L^S

The spacecraft achieved its closest approach altitude of 3242 km on 05 May 2009 at 22:54.

component nearly returns to its original strength, with the fluctuations dropping well below 0.2B. This combination of parameters is typical of lobe-type fields again. The current sheet passage around C/A has been omitted from the analysis, since in this region a proper discrimination between local (i.e. caused by Titan) and global magnetic field perturbations is not possible. Despite B_y being weaker than in the inbound region of the encounter (16:00–19:00), the northern lobe-type field regime between the two outbound current sheet passages fulfills both the field strength and the fluctuation criterion. Finally, it should be noted that although the lobe-type fields detected after 04:00 are again well identified, the relative magnitude of B_y in this segment clearly exceeds the strength detected during the inbound passage through the southern lobe.

4. Classification of Titan's magnetic environment during TA–T62

The classification procedure that has been introduced and tested in the preceding sections is now applied to Cassini MAG observations during all Titan flybys that were available at the time of this writing. The results are presented in Tables 5 and 6. The classification of the inbound and outbound magnetic fields during TA–T62 can be found in Table 5. A clear transition between different magnetic field regimes (as observed, e.g. during T54) is denoted by a sequence of classification symbols in the order of time. For each flyby, the last symbol in the inbound column and the first symbol in the outbound column thus characterize the situation around closest approach. These two symbols also characterize the magnetic field conditions that prevailed within a window of roughly ± 3 h around C/A. Therefore, they can be

Table 5
Classification of Titan's magnetic environment during the Cassini encounters that took place between 2004 and 2009.

Flyby	Date	SLT	SSL (deg)	Class. inb.	Class. outb.
TA	26 October 2004	10.6	−23.2	*Msh*, *Sh*	L_{Sh}^{S}, *Sh*
TB	13 December 2004	10.5	−22.8	*Sh*	L_{Sh}^{S}
T3	15 February 2005	10.3	−22.3	L_{Sh}^{S}	*Sh*
T4	31 March 2005	5.3	−22.1	L_{Sh}^{S}	L_{Sh}^{S}
T5	16 April 2005	5.3	−22.0	L_{Sh}^{S}, *Sh*	L_{Sh}^{S}
T6	22 August 2005	5.0	−20.7	L_{Sh}^{S}	Sh_{L^S}, L_{Sh}^{S}
T7	07 September 2005	5.0	−20.5	–data gap–	–data gap–
T8	28 October 2005	9.3	−19.6	L_{Sh}^{S}	L_{Sh}^{S}, *Sh*, L_{Sh}^{S}
T9	26 December 2005	3.0	−19.1	L_{Sh}^{S}, (∗)	L_{Sh}^{S}
T10	15 January 2006	8.5	−18.8	L_{Sh}^{S}	Sh_{L^S}
T11	27 February 2006	1.1	−18.2	L^{S}, (∗)	L^{S}
T12	19 March 2006	6.4	−18.2	*Sh*, L_{Sh}^{S}	L_{Sh}^{S}
T13	30 April 2006	23.2	−17.3	L_{Sh}^{S}, *Sh*	*Sh*, L^{S}
T14	20 May 2006	4.4	−17.4	L_{Sh}^{S}	L^{S}, L_{Sh}^{S}
T15	02 July 2006	21.2	−16.6	L_{Sh}^{S}, *Sh*	*Sh*, L_{Sh}^{S}
T16	22 July 2006	2.4	−16.5	(∗)	L_{Sh}^{S}
T17	07 September 2006	2.3	−15.8	*Sh*	L^{S}
T18	23 September 2006	2.3	−15.6	L_{Sh}^{N}, *Sh*, L^{S}	L_{Sh}^{S}
T19	09 October 2006	2.2	−15.4	L_{Sh}^{S}, (∗)	*Sh*, L_{Sh}^{S}
T20	25 October 2006	2.2	−15.2	*Sh*	L^{S}, L_{Sh}^{S}
T21	12 December 2006	2.1	−14.5	L_{Sh}^{N}, *Sh*, L_{Sh}^{S}	L^{S}, L_{Sh}^{S}
T22	28 December 2006	2.0	−14.3	L_{Sh}^{N}, *Sh*, L^{S}	*Sh*, L_{Sh}^{S}
T23	13 January 2007	2.0	−14.1	(∗)	L^{S}
T24	29 January 2007	1.9	−13.8	L_{Sh}^{N}, *Sh*	L_{Sh}^{S}
T25	22 February 2007	13.9	−13.5	–data gap–, *Sh*	*Sh*
T26	10 March 2007	13.8	−13.3	L_{Sh}^{S}	*Sh*
T27	26 March 2007	13.8	−13.1	L_{Sh}^{S}, *Sh*	*Sh*
T28	10 April 2007	13.7	−12.8	*Sh*	*Sh*
T29	26 April 2007	13.7	−12.6	*Sh*	*Sh*, *Msh*, *Sh*
T30	12 May 2007	13.6	−12.4	Sh_{L^S}, *Sh*	*Sh*
T31	28 May 2007	13.6	−12.1	*Sh*	*Sh*
T32	13 June 2007	13.6	−11.9	*Msh*, *Sh*	*Msh*
T33	29 June 2007	13.6	−11.7	*Sh*	*Sh*
T34	19 July 2007	18.8	−11.5	*Sh*	*Sh*
T35	31 August 2007	11.5	−10.6	*Sh*, L_{Sh}^{S}	*Sh*, L_{Sh}^{S}
T36	02 October 2007	11.5	−10.1	*Sh*	*Sh*
T37	19 November 2007	11.4	−9.4	*Sh*, L_{Sh}^{S}	–data gap–
T38	05 December 2007	11.4	−9.2	*Sh*	*Sh*
T39	20 December 2007	11.4	−8.9	*Sh*	*Sh*
T40	05 January 2008	11.3	−8.7	(∗)	*Sh*
T41	22 February 2008	11.2	−8.0	*Sh*, L_{Sh}^{S}	L_{Sh}^{S}, *Sh*,
T42	25 March 2008	11.1	−7.5	*Sh*, *Msh Sh*	*Msh*, *Sh*
T43	12 May 2008	11.0	−6.7	L_{Sh}^{S}	L_{Sh}^{S}, *Sh*
T44	28 May 2008	10.9	−6.5	*Sh*	*Sh*
T45	31 July 2008	10.7	−5.5	L_{Sh}^{S}	*Sh*
T46	03 November 2008	10.5	−4.0	L_{Sh}^{S}	*Sh*
T47	19 November 2008	10.4	−3.8	L_{Sh}^{S}, *Sh*	*Sh*
T48	05 December 2008	10.4	−3.6	L_{Sh}^{S}, *Sh*	*Sh*
T49	21 December 2008	10.3	−3.3	*Sh*	*Sh*
T50	07 February 2009	10.2	−2.6	L_{Sh}^{S}, *Sh*	*Sh*
T51	27 March 2009	10.1	−1.8	*Sh*	*Sh*
T52	04 April 2009	22.1	−1.7	L_{Sh}^{N}, *Sh*	*Sh*, L_{Sh}^{S}
T53	20 April 2009	22.0	−1.5	L_{Sh}^{N}, *Sh*	L_{Sh}^{S}, L^{S}
T54	05 May 2009	22.0	−1.2	L_{Sh}^{N}, *Sh*, L_{Sh}^{S}	L_{Sh}^{N}, *Sh*, L^{S}
T55	21 May 2009	22.0	−1.0	L_{Sh}^{N}, *Sh*	*Sh*, L_{Sh}^{S}, L^{S}
T56	06 June 2009	21.9	−0.7	L_{Sh}^{N}, *Sh*, L_{Sh}^{S}	*Sh*, L_{Sh}^{S}
T57	22 June 2009	21.9	−0.5	L^{N}, L_{Sh}^{N}, *Sh*	L_{Sh}^{S}
T58	08 July 2009	21.8	−0.2	L_{Sh}^{N}, *Sh*, L_{Sh}^{S}	*Sh*, L_{Sh}^{N}, *Sh*, L_{Sh}^{S}
T59	24 July 2009	21.8	0.0	L^{N}, *Sh*	L_{Sh}^{S}, *Sh*
T60	09 August 2009	21.7	0.2	*Sh*	*Sh*
T61	25 August 2009	21.7	0.5	*Sh*, L_{Sh}^{N}, *Sh*	L_{Sh}^{S}, *Sh*, L_{Sh}^{N}
T62	12 October 2009	21.6	1.2	L_{Sh}^{S}, *Sh*, L_{Sh}^{N}	*Sh*, L_{Sh}^{S}, *Sh*

The classification scheme discriminates between the inbound (inb.) and the outbound (outb.) regions of each flyby. For the classification, an interval of about ± 8 h around closest approach is considered. The table also includes the Saturnian local time (SLT) and the latitude of Titan's subsolar point (SSL) during each encounter. The asterisks in the classification tables refer to large-scale field perturbations in Titan's wake that are probably associated with the moon's local plasma interaction. There is a single Titan flyby in 2009 which has not been considered: T63 was scheduled for 12 December. After T34, this was the second encounter that took place in the dusk sector (17:00 SLT) of Saturn's magnetosphere. For an identification of overall trends in Titan's magnetic environment near dusk, significantly more flybys are required.

Table 6
Whenever Titan was embedded in undistorted, lobe-type fields around C/A, the background field $\underline{B}_0$ and the stretch (Str) and sweepback (Sw) angles have been computed.

Flyby	Date	SLT	$\underline{B}_0$ inb. (nT)	Str inb. (deg)	Sw inb. (deg)	$\underline{B}_0$ outb. (nT)	Str outb. (deg)	Sw outb. (deg)
TA	26 October 2004	10.6				(2.04,3.88,−3.88)	−45.0	−27.8
TB	13 December 2004	10.5				(1.63,3.66,−3.23)	−48.6	−24.0
T3	15 February 2005	10.3	(1.20,2.69,−2.67)	−45.2	−24.0			
T4	31 March 2005	5.3	(2.65,5.16,−1.40)	−74.8	−27.2	(2.59,4.16,−1.24)	−73.4	−32.0
T5	16 April 2005	5.3				(2.05, 3.51,−1.46)	−67.4	−30.3
T6	22 August 2005	5.0	(1.42,4.27,−0.98)	−77.0	−18.4	(2.02,4.38,−0.83)	−79.2	−24.7
T7	07 September 2005	5.0						
T8	28 October 2005	9.3	(1.51, 2.80,−1.45)	−62.6	−28.4	(1.17,3.84,−1.71)	−66.0	−16.9
T9	26 December 2005	3.0	(3.81,7.23,−2.25)	−72.7	−27.8	(3.47,5.30,−1.95)	−69.8	−33.2
T10	15 January 2006	8.5	(1.55, 3.48,−2.72)	−52.0	−24.1			
T11	27 February 2006	1.1	(2.36,6.55,−1.42)	−77.8	−19.8	(2.34,5.01,−1.14)	−77.2	−25.1
T12	19 March 2006	6.4	(1.44,4.74,−2.59)	−61.4	−16.9	(3.37,5.05,−2.94)	−59.8	−33.8
T13	30 April 2006	23.2						
T14	20 May 2006	4.4	(1.97,3.79,−1.47)	−68.8	−27.4	(2.51,5.17,−1.62)	−72.6	−25.9
T15	02 July 2006	21.2						
T16	22 July 2006	2.4				(2.83,5.65,−2.23)	−68.5	−26.6
T17	07 September 2006	2.3				(1.94,5.43,−0.84)	−81.2	−19.7
T18	23 September 2006	2.3	(1.75,4.56,−0.97)	−78.0	−21.0	(1.61,3.71,−0.85)	−77.1	−23.4
T19	09 October 2006	2.2	(−0.30,4.55,−2.67)	−59.6	3.8			
T20	25 October 2006	2.2				(2.64, 5.21,−0.99)	−79.2	−26.8
T21	12 December 2006	2.1	(2.72,4.09,−1.02)	−76.0	−33.6	(1.85, 4.70,−1.61)	−71.1	−21.5
T22	28 December 2006	2.0	(2.89,4.44,−1.43)	−72.1	−33.0			
T23	13 January 2007	2.0				(2.97,5.33,−0.92)	−80.2	−29.2
T24	29 January 2007	1.9				(1.95, 4.15,−1.02)	−76.3	−25.2
T25	22 February 2007	13.9						
T26	10 March 2007	13.8	(1.59, 2.56,−2.76)	−42.8	−31.8			
T27	26 March 2007	13.8						
T28	10 April 2007	13.7						
T29	26 April 2007	13.7						
T30	12 May 2007	13.6						
T31	28 May 2007	13.6						
T32	13 June 2007	13.6						
T33	29 June 2007	13.6						
T34	19 July 2007	18.8						
T35	31 August 2007	11.5	(1.00,3.02,−1.18)	−68.7	−18.3			
T36	02 October 2007	11.5						
T37	19 November 2007	11.4	(1.64, 3.15,−1.53)	−64.1	−27.5			
T38	05 December 2007	11.4						
T39	20 December 2007	11.4						
T40	05 January 2008	11.3						
T41	22 February 2008	11.2	(1.52, 3.50,−2.55)	−53.8	−23.5	(0.82, 3.58,−2.42)	−56.0	−12.8
T42	25 March 2008	11.1						
T43	12 May 2008	11.0	(1.12, 2.35,−2.94)	−38.6	−25.6	(0.80, 2.04,−2.22)	−42.5	−21.5
T44	28 May 2008	10.9						
T45	31 July 2008	10.7	(1.61,3.28,−2.08)	−57.9	−26.2			
T46	03 November 2008	10.5	(1.11, 3.66,−1.05)	−73.9	−16.9			
T47	19 November 2008	10.4						
T48	05 December 2008	10.4						
T49	21 December 2008	10.3						
T50	07 February 2009	10.2						
T51	27 March 2009	10.1						
T52	04 April 2009	22.1						
T53	20 April 2009	22.0				(2.29, 4.56,−0.99)	−77.7	−26.7
T54	05 May 2009	22.0	(3.12,3.79,−0.89)	−76.8	−39.5	(−2.35,−3.08,−0.78)	75.8	−37.4
T55	21 May 2009	22.0						
T56	06 June 2009	21.9	(0.95, 5.18, −1.25)	−76.4	−10.4			
T57	22 June 2009	21.9				(2.27,4.77,−1.05)	−77.6	−25.4
T58	08 July 2009	21.8	(0.78, 5.24,−0.44)	−85.2	−8.4			
T59	24 July 2009	21.8				(2.59,4.77,−1.06)	−77.5	−28.5
T60	09 August 2009	21.7						
T61	25 August 2009	21.7				(1.27,4.80,−1.07)	−77.5	−14.8
T62	12 October 2009	21.6						

The table provides these background magnetic field data for the inbound (inb.) and outbound (outb.) regions of the Titan encounters that took place between 2004 and 2009 (except for T63).

directly compared to the findings of Rymer et al. (2009). A detailed comparison will be provided in Section 6.

The background magnetic fields that have been computed whenever Titan was embedded in lobe-type fields around C/A can be found in Table 6. If a computation of the background fields was not possible (especially when $\delta B_j \gg B$ for all three components), no entry has been made in the tables. In the following sections, the conclusions that can be drawn from this classification scheme are discussed.

In general, we expect the detailed data provided in Tables 5 and 6 to be of major importance for Titan science within the next years. On the one hand, the characteristics of the background magnetic field are required as input parameters for any kind of model for Titan's local plasma interaction. The classification of the ambient magnetic field conditions will also be very helpful for deciding whether the application of a local model is suitable at all for a certain flyby scenario. On the other hand, since both the orientation of Titan's pick-up tail and the local ion gyroradii are controlled by the ambient magnetic field conditions, the material provided in this paper is likely to support interpretation of data collected by other Cassini investigations addressing the moon's upper atmosphere or plasma environment—such as the Cassini plasma spectrometer (CAPS)—as well.

5. Local time and seasonal effects

The midnight (21:00–03:00 SLT) and noon (09:00–15:00 SLT) sectors of Saturn's magnetosphere are well covered by the available flybys. However, so far only eight flybys have taken place in the dawn sector (03:00–09:00 SLT). In the dusk sector (15:00–21:00 SLT), only a single Titan encounter (T34) had been accomplished by the time of this writing.

As can be seen from the classification tables and Fig. 1, Cassini has already completed several series of successional Titan encounters in the midnight, dawn and noon magnetosphere. Within these series, Titan's orbital position at C/A changed only insignificantly from flyby to flyby. Titan's magnetic environment at about 02:00 SLT has been investigated during a sequence of nine encounters from July 2006 until January 2007 (T16–T24). Another series of flybys, T52–T62, took place between April and October 2009. During these encounters, Titan was located at about 22:00 SLT on its orbit around Saturn. Thus, comparing the observations made during the T16–T24 series to data from T52 to T62 will be of special interest. On the one hand, both flyby series occurred in the nightside magnetosphere where the influence of the solar wind should be weak. On the other hand, the T16–T24 series took place in southern summer, whereas T52–T62 cover the time around equinox.

During another series of nine flybys between February and July 2007 (T25–T33), Titan was on each occasion located in the noon sector of Saturn's magnetosphere at about 13:30 SLT. It should be noted that the Voyager 1 encounter took place near the same orbital position (Neubauer et al., 1984), but under conditions closer to those of equinox. During T35–T51 which occurred between August 2007 and March 2009, Titan was located between 10:00 SLT and 11:30 SLT. This sequence of flybys therefore provides another opportunity to identify seasonal tendencies in Titan's magnetic environment.

The satellite's plasma interaction around 05:00 SLT was planned to be analyzed during a sequence of encounters in 2005 (T4, T5, T6 and T7). Unfortunately, the observational data of the T7 flyby were lost due to both, problems with Cassini's on-board data recorder and a ground station error. Therefore, only three of these flybys are actually considered for our analysis. In the following sections, we systematically discuss the magnetic field observations from each of these flyby series. In order to gain some insight in the large-scale magnetospheric processes that are responsible for shaping Titan's magnetic environment during the encounters, our discussion focuses on data from the extended ± 8 h interval around C/A of each flyby. The implications for Titan's local magnetospheric interaction will be discussed in Section 7.

5.1. *Flyby series T16–T24: post-midnight magnetosphere*

First we shall focus on T16–T24, which took place on the nightside of Saturn's magnetosphere. The trajectories of all these encounters were qualitatively similar to Cassini's path during T20 and T21, as displayed in Fig. 5. During all encounters, Cassini crossed the magnetic equatorial plane from north to south. As can be seen from Table. 5, Titan's magnetic environment during this series of flybys was dominated by frequent current sheet encounters, often denoting transitions from the northern to the southern magnetodisk lobe.

Magnetometer data from T18, T21 (cf. Fig. 7) and T22 show that during these flybys, Cassini was initially embedded in the northern magnetodisk lobe and crossed the current sheet to enter the southern lobe only a few hours before closest approach. For T17, T20 and T24, the transition from highly perturbed current sheet fields to the southern magnetodisk lobe regime even coincided with the spacecraft's closest approach to Titan. Comparison of these flybys also provides evidence for high variability in current sheet dynamics: For T18, T21, T22 and T24, the inbound current sheet passages were detected during time intervals of only about 2 h, whereas for T17 and T20, Cassini was immersed in the current sheet during the entire inbound segments of the encounters, beginning 8 h before C/A.

Assuming that the vertical thickness of the current sheet did not vary significantly during this series of encounters, the magnetic field observations suggest strong changes in the vertical velocity pattern of the sheet: During T18, T21, T22 and T24, the current sheet was moving rapidly northward when Cassini approached Titan from above, whereas such a motion of the current sheet seems to have been absent during other flybys like T17 and T20. Despite not being as prominent as in the inbound region, the lobe-type fields detected southward of Titan's orbital plane were frequently distorted by current sheet features as well. This observation suggests that the flapping current sheet—which was found to move upward in the inbound regions of T18, T21, T22 and T24—may reverse its direction and come close to Cassini again when the spacecraft is already located far below Titan's orbital plane.

Overall, MAG observations during flybys T16–T24 show that above Titan's orbital plane, Cassini was typically embedded in a combination of current sheet and lobe-type fields, whereas the fields detected southward of the moon mainly belonged to the magnetodisk lobe category. This finding is consistent with the idea that the current sheet possesses a bowl-like shape: In southern summer, when this flyby series took place, the sheet was on average displaced to above Titan's orbital plane. In the picture of a rapidly flapping/oscillating current sheet, however, only the equilibrium position of the sheet would coincide with the bowl-like geometry introduced by Arridge et al. (2008b).

The unperturbed lobe-type fields detected in the outbound regions of T16–T24 have been used to compute the background values provided in Table 6. As can be seen from the exemplary T20 and T21 flyby trajectories in Fig. 5, these values also characterize the ambient magnetic fields upstream of Titan. However, only during two flybys of this series (T18 and T21), Cassini encountered nearly unperturbed southern lobe fields directly before closest approach as well. The inbound and outbound field magnitudes measured during these encounters are nonetheless not the same, but at least for T18, the ambient field orientation (as defined by the stretch and sweepback angle) did not undergo significant changes. The characteristics of the lobe-type fields detected below Titan's orbital plane are qualitatively similar for all encounters: The field lines are stretched towards Saturn, with the stretch angle ranging between -68° and -82°. The values of the sweepback angle are negative in all cases and only cover a narrow interval as well ($-20^\circ \ldots -30^\circ$). Thus, the overall properties of the magnetodisk lobe fields below Titan's orbit remained practically constant during the flyby series under consideration. Although only very few field values have been computed for the inbound region of this series (T18, T19, T21 and T22), the general tendency is the same as observed outbound: The field lines are stretched towards Saturn and (except for T19) swept back with respect to rigid corotation.

5.2. Flyby series T52–T62: pre-midnight magnetosphere

The second sequence of flybys that took place in the night sector of Saturn's magnetosphere is T52–T62. The flyby trajectories of this series are very similar to those of T16–T24: Cassini crossed Titan's orbital plane from above (north) to below (south) while moving towards Saturn. During all flybys of this sequence, the spacecraft reached the region upstream of Titan (i.e. $x<0$) after closest approach.[1]

As an example, the trajectory of T54 is shown in Fig. 5. This flyby series occurred around equinox in August 2009. Thus, according to the current sheet model developed by Arridge et al. (2008b), one would expect the sheet to be "flat" at this time and hence, the magnetic field near Titan to be dominated by current sheet features. Especially, the B_y component of the magnetic field should nearly vanish near Titan's orbit. However, as already discussed in the analysis of T54 (cf. Section 3), Cassini magnetic field data reveal a completely different behaviour, showing that the picture of a quasi-stationary magnetodisk is not suitable for understanding Titan's magnetic environment near equinox.

As can be seen from Table 5, the entire series of flybys is dominated by frequent transitions from current sheet to northern and southern magnetodisk lobe fields. An extreme example for this behaviour is T58: Within the ± 8 h interval around closest approach, three passages through the current sheet were detected by Cassini. In contrast to the T16–T24 flyby series, the region below Titan's orbital plane was not only distorted by frequent intrusions of the current sheet, but Cassini even detected long intervals of undisturbed $B_y<0$ that can be ascribed to passages through the northern magnetodisk lobe. During T16–T24, the field below Titan's orbital plane was also slightly distorted by encounters with the lower side of the current sheet. However, data collected in the outbound regions of these flybys show no hint of a complete current sheet crossing below Titan's orbital plane and a re-entry into the northern magnetodisk lobe regime. The general trend from T16 to T24 was that typically, Cassini left the northern magnetodisk lobe regime long before intersecting Titan's orbital plane.

Assuming the magnetodisk current sheet to "flap" vertically around a certain equilibrium position, magnetic field observations during T52–T62 clearly imply that this equilibrium location was closer to Titan's orbital plane than during the T16–T24 series. This confirms the general picture of a bowl-shaped current sheet whose radius of curvature diminishes when the angle between Saturn's magnetic dipole axis and the Sun–Saturn-line is increased (Arridge et al., 2008b). However, this does not yield a permanent embedment of Titan's orbit in a quasi-stationary current sheet, in such a way that—due to the finite thickness of the sheet—the highly stretched fields in the magnetodisk lobes do no longer play a role for the moon's local plasma interaction. In fact, the descent of the average current sheet position into Titan's orbital plane increases the influence of rapid flapping/oscillation motions on the satellite's plasma interaction, alternately exposing it to lobe-type fields of different polarity that are separated by current sheet passages. It should be noted that during only a single flyby of this series (T60, cf. Table 5), Titan's magnetic environment was completely dominated by current sheet fields. However, due to a data gap, only a shortened ± 4 h interval of magnetic field data was available around closest approach of this encounter.

Whenever homogeneous lobe-type fields were detected around C/A, the average field values have been computed and are listed in Table 6. Whereas the sweepback angle shows stronger variations, the stretch angles obtained for the southern lobe regime cover only a narrow range around -77°. Only for T58, the stretch angle for the inbound encounter with the southern lobe is significantly larger. Table 6 also shows that on both sides of Titan's orbital plane, the fields were bent back with respect to corotation.

5.3. Flyby series T4–T7: dawn magnetosphere

Titan's magnetic environment around 05:00 clock angle position has been sampled during a series of flybys in 2005: T4, T5 and T6. The trajectories of these encounters all remained within $0.5R_S$ around the moon's orbital plane, with the spacecraft mainly moving in $(-y)$ direction from the Saturn-facing to the anti-Saturn-facing hemisphere. As can be seen from Table 5, Cassini MAG data from the ± 8 h intervals show no hint of northern magnetodisk lobe fields. All encounters with the southern lobe were quite frequently distorted by current sheet features. Since during T4, T5 and T6, Cassini did not move significantly in vertical direction, these flybys confirm that the current sheet was on average located above Titan's orbital plane. On the other hand, the sheet quite frequently intruded into the moon's immediate environment due to vertical motion. It should also be noted that T4 is among the very few encounters during which homogeneous, lobe-type fields were detected on both sides of C/A.

5.4. Flyby series T25–T33: post-noon magnetosphere

So far, two complete sequences of Titan flybys have been carried out in the dayside magnetosphere: T25–T33 around 13:30 SLT and T35–T51 around 11:00 SLT. Of these flybys, T32 and T42 took place outside the magnetosphere of Saturn. Since the case of Titan being outside the magnetosphere is very rare (probability of 5.5% near noon, cf. Bertucci et al., 2009), we have not defined an additional criterion for the identification of magnetosheath-type fields. Instead, we have adopted the classification of these flybys from Bertucci et al. (2008) and Rymer et al. (2009).

During the encounters of the T25–T33 series, Cassini was moving away from Saturn while crossing Titan's orbital plane from south to north. The inclination of the spacecraft trajectory with respect to the orbital plane continuously decreased within the flyby series: While Cassini passed from $z \approx -50R_T$ to $z \approx +50R_T$ (radius of Titan: $R_T = 2575$ km) during the ± 8 h interval around closest approach of T25 and T26, the spacecraft trajectory remained practically confined to Titan's equatorial plane during T33. In general, Titan's magnetic environment in the dayside magnetosphere has already shown to be strongly affected by the solar wind. Specifically, as discussed by Arridge et al. (2008c), the formation of the magnetodisk lobes can be partially suppressed in times of high solar wind dynamic pressure. The overall evaluation of the magnetic field near Titan's orbital plane by Bertucci et al.

[1] This is indeed valid for all flybys of the TA–T62 series.

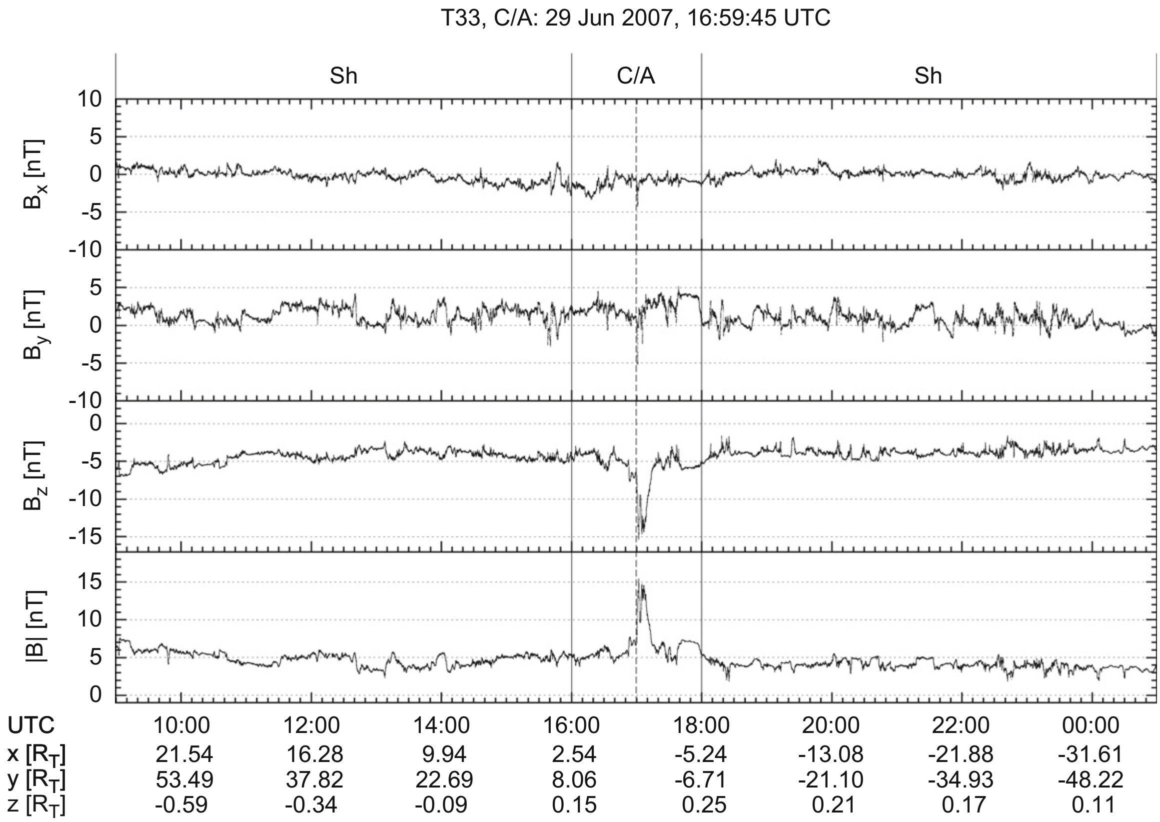

Fig. 10. Magnetic field observations along Cassini's trajectory during the T33 flyby. The figure displays a ± 8 h interval around closest approach on 29 June 2007 at 16:59 (dashed line).

Table 7
Classification of the magnetic field along Cassini's trajectory during the T33 flyby.

UTC	$\lvert B_y\rvert/B$	$\delta B_y/B$	Classification
10:00–12:00	0.25	0.19	*Sh*
12:00–14:00	0.32	0.25	*Sh*
14:00–16:00	0.31	0.21	*Sh*
18:00–20:00	0.21	0.21	*Sh*
20:00–22:00	0.22	0.25	*Sh*
22:00–00:00	0.22	0.22	*Sh*

An interval of ± 1 h around closest approach (29 June 2007, 17:00 UTC) has been omitted.

(2009) has shown that both the stretch and the sweepback angle are significantly smaller than in the nightside sector of the magnetosphere, with the sweepback angle often assuming values close to zero. In other words, the tendency suggested by this companion study is that in the noon magnetosphere, Titan is immersed into the central current sheet more frequently.

As can be seen from Table 5, this general trend is in complete agreement with our classification of flybys T25–T33. Titan's magnetic environment during this series was dominated by highly perturbed current sheet fields; only a single encounter (T26) shows a noteworthy segment of unperturbed lobe-type fields (longer than 2.5 h) in the inbound region. As an example, the trajectory and the magnetic field signature of the T33 encounter are displayed in Figs. 5 and 10. The corresponding classification is provided in Table 7. As can be seen, the $\lvert B_y\rvert/B$ criterion for lobe-type fields breaks down along the entire flyby trajectory. The normalized fluctuation level $\delta B_y/B$ is comparable to, or even larger than, $\lvert B_y\rvert/B$. Such a strong violation of our criteria for lobe-type fields has shown to be characteristic of nearly the entire magnetic field data set acquired during Titan flybys in the noon magnetosphere, thus confirming the findings of Bertucci et al. (2009).

Overall, Titan's magnetic environment around noon local time is completely different from the situation found in the nightside magnetosphere. Although the fields encountered near noon are clearly more dipolar than at the nightside, the picture of Titan being embedded in a constant, dipole-like magnetic background is not valid at all due to the high level of variability. We would also like to note that such a predominance of current sheet fields is exactly what one would have expected for the near-equinox flyby series T52–T62.

Finally, it should be noted that the decreasing inclination of Cassini's trajectory within the T25–T33 flyby series has only very weak impact on the observed magnetic field regimes. During the high-inclination flybys, Cassini detected moderately distorted southern lobe-type fields at the beginning of the analysis interval (i.e. far below Titan's orbital plane) before entering highly perturbed current sheet fields. During the remaining encounters of this series, no sign of southern lobe-type fields was detected at all. Moreover, there is not a single flyby in the T25–T33 series during which Cassini penetrated into the northern magnetodisk lobe when being located far above Titan's orbital plane. This also implies that in the dayside magnetosphere, the thickness of the current sheet may be significantly larger than on the nightside. Based on data from Cassini's Magnetospheric Imaging Instrument (MIMI), Sergis et al. (2009) came to the same conclusion.

5.5. *Flyby series T35–T51: Pre-noon magnetosphere*

The first Titan encounters in 2004 and early 2005 (TA, TB, T3) took place in the pre-noon sector of Saturn's magnetosphere. Later, Titan's plasma interaction in this sector was explored

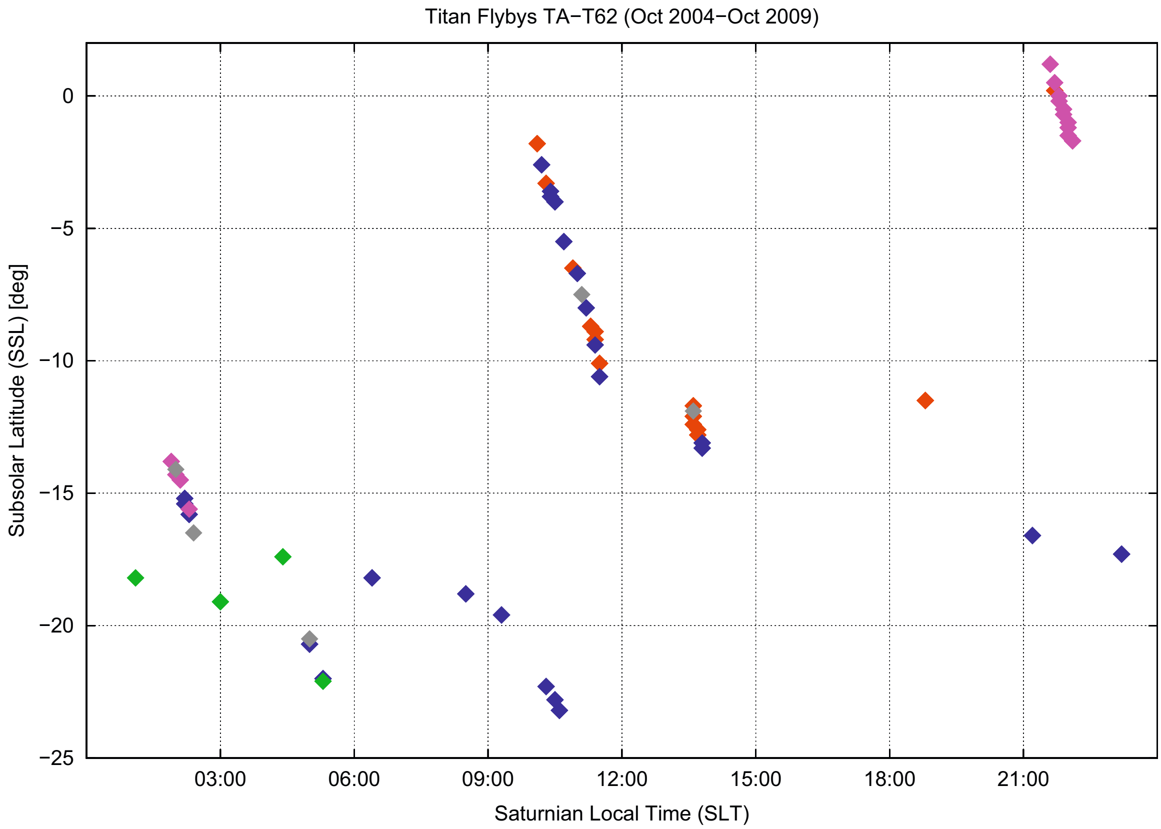

Fig. 11. Classification of Titan's magnetic environment during Cassini encounters TA–T62. The figure provides a color-coded illustration of the magnetic field regimes observed in different sectors of SSL-vs.-SLT space. Flybys during which highly distorted current sheet fields were observed within the entire ± 8 h interval around C/A are denoted in red. During many encounters, a "mixture" of current sheet and southern lobe-type fields was observed (blue), with the current sheet features in the dayside magnetosphere being by far more prominent than on the nightside. Due to vertical flapping motion of the current sheet, rapid transitions between current sheet and lobe-type fields of different polarity (magenta) were observed during the T16–T24 and T52–T62 flybys series. Only during very few encounters, quiet or moderately distorted southern lobe-type fields (green) were observed in the entire time window. The flybys which occurred mainly outside of Saturn's magnetosphere (T32 and T42) or which could not be classified due to extended data gaps are denoted in gray. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during a sequence of flybys (T35–T51) that commenced in August 2007 and ended in March 2009. All these flybys took place between 10:00 and 11:30 SLT. During the flybys of the T35–T51 series, Cassini moved away from Saturn. Except for T35, T36 and T37, the spacecraft always crossed Titan's orbital plane from below to above. During the T35, T36 and T37 encounters, Cassini moved nearly parallel to Titan's orbital plane within the ± 8 h time window around C/A. From T38 to T51, the inclination of the spacecraft trajectory with respect to Titan's orbit continuously increased, with the trajectory covering a range from $z \approx -50R_T$ to $z \approx +50R_T$ during the final flybys of the series.

Again, strongly distorted current sheet fields make up the major feature of the magnetic field observations during this flyby sequence. Whereas all detections of southern magnetic lobe fields near Titan were at least moderately distorted by the proximity to the magnetodisk current sheet, there are again no hints of penetrations into the northern lobe within the ± 8 h intervals around closest approach. Only for two flybys of this series (T41 and T43), the ambient magnetic field fluctuations around C/A were so small that a computation of the background field makes sense.

Even though the T35–T51 flyby series covers a time interval of more than 18 months, the magnetic field data acquired during these encounters do not allow the identification of seasonal tendencies in the structure of Titan's magnetic environment. From the available flyby data, a clear impact of the changing magnetospheric tilt (with respect to the Sun–Saturn-line) on the magnetic fields near Titan's orbit could only be identified in the nightside magnetosphere. The earlier flybys in the pre-noon sector (TA, TB, T3) completely match the picture from the T35 to T51 series as well.

The increasing inclination of Cassini's trajectory during the flyby series has again no significant impact on the magnetic field observations. During the first encounters of the sequence and the final high-inclination flybys, Cassini was mainly embedded in current sheet fields within the analyzed ± 8 h intervals. The spacecraft never penetrated into the northern magnetodisk lobe.

5.6. Comparison between flyby series

The T16–T24 and T52–T62 encounter series both occurred in Saturn's nightside magnetosphere. Cassini's strongly inclined trajectory during these series allowed to identify the impact of seasonal changes in the overall magnetospheric configuration on Titan's immediate environment: magnetic field observations from both series reveal strong vertical fluctuations in the location of the current sheet, with the average sheet position being displaced to far above Titan's orbit during the southern summer flybys T16–T24. At the time of the equinox flyby series T52–T62, the average sheet position had descended into Titan's orbital plane. A comparison between observations from these flyby series shows no hints of local time asymmetries in the nightside magnetic field conditions near Titan. Besides, given the short duration of most current sheet passages, the sheet seems to be significantly thinner than in the dayside magnetosphere.

In contrast to this, the high-inclination encounters from the dayside flyby series (T25–T33 and T35–T51) showed Titan to be embedded in a broad, highly perturbed current sheet regime. Lobe-type fields were mostly observed only at large distances below Titan's orbit. Although the characteristics of the dayside magnetic field may undergo seasonal changes as well, these effects do not have a noteworthy impact on Titan's immediate magnetic environment. In analogy to the nightside magnetosphere, a comparison between data from T25–T33 and T35–T51 reveals no obvious local-time asymmetry with respect to the noon-midnight plane. The results of our flyby classification are summarized in Fig. 11.

6. Comparison with Cassini electron data (CAPS and MIMI)

Based on data from the Cassini electron spectrometers, Rymer et al. (2009) recently presented a classification of Titan's plasma environment during flybys TA–T55. These authors have grouped the electron background observed around the Titan encounters into four broad categories: current sheet, magnetodisk lobe, magnetosheath and bimodal (i.e. a mixture of two easily identifiable, distinct electron populations). The results presented by these authors show that Titan's electron background exhibits a high level of variability: only 34 encounters from the TA–T55 series are clearly associated with one of the categories listed above, whereas the remaining ones need to be characterized by a combination of different environments. Among these 34 flybys, 19 occurred within the current sheet and eight in the magnetodisk lobe regime. During another two encounters (T32 and T42), Titan was found in Saturn's magnetosheath at the time of closest approach. The remaining five flybys are characterized by predominantly bi-modal electron signatures. However, in contrast to our study, an interval of only ± 3 h around closest approach has been considered. Although Rymer et al. (2009) provide a chronological list of different environment types observed during each Titan encounter, they do not discriminate between features seen in the inbound and outbound regions.

As stated above, since our scheme does not include a criterion for magnetosheath fields, the classification of the only two Titan encounters that have so far taken place in the immediate vicinity of Saturn's magnetopause (T32 and T42) has been adopted from the studies of Rymer et al. (2009) and Bertucci et al. (2008). Of course, a classification scheme for the magnetic field also does not include a category corresponding to bimodal electron populations. However, it should be noted here that for numerous flybys, our classification of Titan's magnetic environment during a ± 3 h interval around closest approach is in very good agreement with the results of Rymer et al. (2009). Specifically, during the following encounters, both the CAPS and the MAG classification suggest that Titan was located in the current sheet around closest approach: TA, T5, T13, T15, T19, T29, T33, T34, T36, T39, T44, T49, T50, T51, T52, T53 and T55. The Titan flybys T4, T8, T14, T18, T41, T43 and T54 are classified as lobe-type by both studies. Clear transitions between magnetodisk lobes and current sheet have been detected by the electron spectrometer and the magnetometer during encounters TB, T12, T20, T21, T22 and T24.

7. Discussion

In this section, we discuss the implications of our findings for Titan's local plasma interaction. We also derive an estimate for the length of the time window during which the idealized picture of Titan interacting with a stationary magnetospheric background in the absence of fossil fields may be applicable.

7.1. Titan's local magnetospheric interaction

Independent of whether one considers a ± 8 h window or only a reduced ± 3 h interval, Titan's magnetospheric environment exhibits a high degree of variability. When considering a ± 3 h interval around closest approach, i.e. the last symbol in the inbound column and the first symbol in the outbound column of Table 5, the overall statistics of our magnetic field classification looks as follows: So far, there are fewer than 10 Titan flybys during which quiet, lobe-type fields were detected in both the inbound and the outbound regions. Our analysis shows that among the 62 available Titan encounters, closest approach of 22 flybys took place when the moon was embedded in Saturn's magnetodisk current sheet. During another 21 flybys, the near-Titan region was characterized by transitions between current sheet and lobe-type fields. Between October 2004 and October 2009, there have been only nine encounters during which quiet, lobe-type fields of the same polarity were observed on both sides of closest approach. Two Titan encounters (T32 and T42) have taken place close to Saturn's magnetopause. For eight flybys, our classification procedure could not be applied near C/A, either due to data gaps or because of difficulties in isolating the magnetic field features that need to be ascribed to Titan's local plasma interaction. We again emphasize that this overall picture of high magnetic field variability is completely independent of whether a ± 8 h or only a ± 3 h window is considered.

These findings have severe consequences for the application of simulation models (e.g. MHD or hybrid codes) to the local interaction between Titan's ionosphere and Saturn's magnetospheric plasma. There are only very few Titan flybys during which quiet magnetic field conditions were observed on both sides of closest approach. Indeed, the ± 3 h segment around C/A is frequently dominated by highly perturbed current sheet fields, exhibiting short-scale fluctuations on time scales of only a few minutes (see for instance Fig. 10). In many cases, current sheet fields were observed on one side of C/A, whereas the magnetic fields observed on the other side were of the moderately distorted lobe-type. In such highly variable scenarios, fossil magnetic fields will be omnipresent in the MAG data collected near closest approach. Besides, the large-scale features of Titan's pick-up tail are also strongly disrupted by such an inhomogeneous magnetospheric environment. As discussed in Section 2.1, there are also good physical reasons to expect lifetimes for fossil fields that are even longer than 3 h. For this reason, even the magnetic field data from the nine flybys during which lobe-type fields were observed within the ± 3 h segment may still contain remnants of previously encountered field regimes.

For the numerous flybys during which highly perturbed field conditions prevailed near C/A, a simulation model that assumes the background magnetospheric fields to be constant in space and time may still be very useful for providing some general insights in the physics of Titan's local plasma interaction. However, it is not suitable at all for quantitatively explaining Cassini plasma and magnetic field observations in the vicinity of the moon. Recently, Simon et al. (2008) and Simon and Motschmann (2009) therefore presented a first series of "local" hybrid simulations, exposing Titan to a non-stationary magnetospheric environment. An alternative approach has been presented by Winglee et al. (2009) who developed a combined two-body simulation of Saturn's (global) magnetospheric interaction with the solar wind and Titan's (local) interaction with the magnetospheric plasma of its parent planet. In any case, a lot of work still remains to be done on this field.

7.2. Influence of large-scale magnetospheric fluctuations

Basically, Titan's local magnetospheric interaction is controlled by three different time scales. The first of these scales is defined by the lifetime of fossil magnetic fields in the moon's ionosphere, which—due to lack of sufficiently accurate data and modelling results—we assume to be roughly represented by the 20 min…3 h window from T32. The other two scales refer to the times in which the ambient magnetospheric field conditions near Titan undergo significant changes. On the one hand, the current sheet carries out frequent vertical "flapping" oscillations with a characteristic duration of about 10–20 min. These signatures are omnipresent in the MAG data collected near Titan's orbit and continually resupply newly fossilized flux tubes to the moon's ionosphere.

On the other hand, considering a large ± 8 h window around C/A reveals hints of a second, significantly longer time scale that also plays a key role for Titan's magnetic environment. The data from these extended sampling intervals imply that the picture of constant magnetospheric background fields at Titan is never applicable for longer than about 5 h.

Let us again have a look at the MAG data from T20 (cf. Fig. 6). During this highly inclined encounter, Cassini crossed Titan's orbital plane from north to south. Above the orbital plane, the magnetometer detected strongly perturbed current sheet fields until about 1 h before C/A. At this point, the spacecraft was located at an altitude of about $4R_T$ above the orbital plane and had a distance of less than $8R_T$ to Titan. These length scales are comparable to the size of Titan's local plasma interaction region, as inferred from numerical simulations (see, e.g. Simon et al., 2007b; Simon and Motschmann, 2009). In other words, the highly perturbed current sheet fields observed above Titan's orbit had immediate impact on the moon's local magnetospheric interaction. After C/A, Cassini detected quiet lobe-type fields for about 6 h. Subsequently, the spacecraft came again into contact with the lower side of the oscillating current sheet. Since at the time of this re-encounter, Cassini was already located far below Titan's orbital plane, the current sheet has swept over Titan from above to below at some point within the 6 h interval. Thus, the time window during which Titan may have been embedded in quiet lobe-type fields is bounded by Cassini's two encounters with the current sheet, i.e. its duration was clearly less than 6 h.

Cassini magnetic field observations from the T54 encounter can be interpreted in a similar way. At C/A, the current sheet swept over the spacecraft from north to south. After this point, the sheet was located below both the spacecraft and the moon (see Fig. 9 for illustration). Cassini then observed quiet, nearly unperturbed southern lobe-type fields for about 3 h. However, about 3 h after C/A and less than $1R_S$ below Titan's orbital plane, the sheet again swept over the spacecraft from below to above. At about 04:00, i.e. 5 h after closest approach, Cassini left the current sheet at its lower side and became again embedded in the southern lobe. Given the finite thickness of the sheet (see Section 2.1), it is reasonable to assume that this sheet crossing had immediate impact on the magnetic fields close to Titan as well. At 04:00, Cassini was located at the lower side of the current sheet at about $z=-1.4R_S$ below the orbital plane. The thickness of the sheet, however, is of the order of $4R_S$. Thus, there was again a time window of at maximum 5 h during which Titan might have been exposed to a quasi-stationary magnetospheric background.

Magnetometer data from virtually every flyby in the nightside magnetosphere provide strong evidence of large-scale vertical motions of the current sheet around Titan's orbital plane. Exploring these effects in detail, i.e. incorporating a time-dependency in the Arridge et al. (2008b) model and determining the period of the sheet oscillations, is far beyond the scope of the present study. However, in analogy to T20 and T54, we have searched the entire data set from the nightside flyby series (T16–T24 and T52–T62) for multiple current sheet crossings. This survey has shown that an interval of roughly 5 h provides a reasonable estimate for the time between subsequent sheet sweeps through Titan's orbital plane. Of course, this result so far characterizes only the situation during these two sequences of nightside encounters. We note that this period is about a factor of 2 smaller than Saturn's radio period of about 10.7 h. Assuming a periodic vertical oscillation of the current sheet around Titan's orbital plane with the period of Saturn's kilometric radiation (see, e.g. Khurana et al., 2009), Titan would experience a "zero-crossing" approximately every 5 h, which is in good agreement with our estimate.

We would also like to point out that the exact period of these large-scale current sheet sweeps experienced by Titan may undergo seasonal variations. Around equinox (flybys T52–T62), Titan's orbital plane coincided with the average position of the current sheet. Therefore, the sheet might sweep over Titan approximately every 10.7 h/2. In southern summer, however, the equilibrium position of the sheet oscillations is displaced above the moon's orbital plane. In this situation (consider a horizontal cut through a sine wave below its symmetry plane), Titan might experience large-scale magnetic field oscillations on two different time scales, one of them being shorter and the other one being longer than 10.7 h/2. In an extreme case near southern summer solstice, Titan might experience only the "minima" of the sheet oscillation in intervals of 10.7 h. The average sheet position might even be displaced so far above Titan's orbital plane that the moon does not experience the oscillations at all. However, data from the available Titan flybys do not allow to draw further conclusions on whether these scenarios may indeed occur. Besides, the length of the time interval between subsequent sheet passages may be "smeared": due to the finite thickness of the sheet, such a passage does not occur instantaneously. As suggested, e.g. by MAG data from T54, a passage of the sheet through a certain $z=$const. plane may require up to a few hours. Stationary magnetospheric background conditions may prevail at Titan only after the moon has completely left the sheet. Therefore, this effect may lead to an additional shortening of the time window during which the picture of quasi-stationary background fields is applicable.

To sum up, when the current sheet sweeps over Titan at $t_1=0$, the moon's ionosphere is contaminated by fossil magnetic fields. Assuming that the lifetime deduced for T32 can be adopted as a rough estimate for any other flyby as well, these fields have practically vanished at $t=T_L=20\,\text{min}\ldots3\,\text{h}$ after the sheet encounter. Thus, this point marks the beginning of a time window during which the ionosphere is devoid of fossil fields and the ambient magnetospheric conditions can be considered quasi-stationary. The window is closed at $t=t_2=5$ h by the subsequent passage of the current sheet through Titan's orbital plane, i.e. its length is of the order of $\delta T \approx 2\,\text{h}\ldots4.5\,\text{h}$. We would like to point out that even the mere existence of an upper limit for the length of this time window cannot be deduced from the data, if only a reduced time interval of ± 3 h around closest approach is considered. Only if C/A of a Titan encounter takes place within such a time window δT, the magnetic fields observed near closest approach can be purely ascribed to the interaction with the momentary background field. Lifetimes for fossil fields in excess of 3 h would yield $\delta T \approx 0$, i.e. the magnetic memory of the moon's ionosphere would never be completely empty.

So far, we have only discussed the situation in the nightside magnetosphere (flyby series T16–T24 and T52–T62). Considering an extended ± 8 h window around C/A of the high-inclination Titan flybys in the dayside magnetosphere reveals that in this region, no effect on a large time scale of several hours is involved in shaping Titan's magnetic environment. The vertical oscillatory motion of the current sheet may be present in this region as well, but it is most likely obscured by the increased thickness of the sheet or by variations on shorter scales caused by the solar wind.

8. Summary and concluding remarks

Even in the sixth year of the Cassini mission, most available discussions of Titan's plasma interaction still rely on the picture constructed after the Voyager 1 flyby in 1980. In the idealized description upon which most modelling attempts are based, the ambient magnetospheric field is assumed to be perpendicular to the moon's orbital plane, and—what is even more important—to be constant on length and time scales that significantly exceed the characteristic scales of the local plasma interaction process. In this study, we have conducted a systematic analysis of Cassini magnetic field observations during Titan encounters TA–T62, the major purpose being to update the still frequently applied description of the ambient magnetic field from the pre-Cassini era.

Our results clearly indicate that so far, there is not a single Titan encounter that matches the idealized picture of a stationary background field that is perpendicular to the orbital plane. Titan's immediate magnetic environment is strongly affected by the proximity to Saturn's warped and highly dynamic magnetodisk current sheet. During southern summer when most of the Titan encounters took place, the moon was on average located below Saturn's magnetodisk. Therefore, the field lines encountered by Titan were stretched in radial direction. Simultaneously, the deviation from full corotation in the rotating magnetodisk plasma requires the field lines to bent back with respect to a strictly corotating meridional plane.

Besides, the magnetodisk current sheet has shown to be a highly dynamic structure, carrying out intense vertical flapping/oscillatory motions around Titan's orbital plane. Thus, the moon is alternately exposed to quasi-dipolar—but nonetheless highly distorted—sheet fields and to radially stretched lobe-type fields. Near equinox in late 2009, the average position of the oscillating current sheet coincided with Titan's orbital plane, making the satellite's magnetic environment even more susceptible to rapid changes between lobe-type and sheet fields than in southern summer. So far, these effects have mainly been observed in the nightside magnetosphere of Saturn. Around noon local time, the formation of the magnetodisk lobes is partially suppressed by the proximity to the magnetopause, thus assigning the magnetic field near Titan's orbit a more dipolar character than in the nightside magnetosphere. However, this magnetic background is continuously distorted by strong fluctuations in all three field components. In general, the time scales upon which Titan's immediate magnetic environment is distorted by the oscillating current sheet range between only a few minutes and about 5 h.

Among the 62 available Titan flybys between October 2004 and October 2009, there are only nine encounters during which quiet, lobe-type fields were observed within a ± 3 h interval around closest approach. During most other flybys, this region was dominated either by highly perturbed current sheet fields or by rapid transitions between current sheet and lobe-type fields. Every change in the ambient magnetic field conditions leaves an imprint in the "magnetic memory" of Titan's ionosphere that can persist there for up to several hours. Thus, when Titan is embedded in such a distorted magnetospheric environment, one needs to keep in mind that magnetic field signatures observed during close flybys cannot be purely ascribed to the interaction with the momentary background field, but they may frequently be contaminated by fossil fields from previously encountered field regimes. For many flybys, the often applied modelling assumption of constant magnetospheric background conditions is therefore not applicable. For these cases, simulation models of Titan's local magnetospheric interaction are required to be fully time-dependent and also need to consider the history of the background field.

An important aspect that shall be addressed by future work is whether Titan itself may exert some level of control on the vertical motion of the current sheet. During encounters T17, T20 (cf. Fig. 6) and T24, the ambient magnetic field conditions detected by Cassini suddenly "switched" from highly distorted sheet fields to quiet lobe-type fields just at the spacecraft's closest approach to Titan. Is this just a coincidence? Based on the available flyby data, it seems so since there is also a large number of southbound encounters during which the sheet passage took place long before closest approach. However, this question definitely deserves further attention as well.

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