Planetary and Space Science 57 (2009) 1813–1820

Contents lists available at ScienceDirect

Planetary and Space Science

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

The variability of Titan's magnetic environment

C. Bertucci [a,b,*], B. Sinclair [a], N. Achilleos [c,d], P. Hunt [a], M.K. Dougherty [a], C.S. Arridge [d,e]

[a] Space & Atmospheric Physics Group, Imperial College London, SW72BZ, London, United Kingdom
[b] Institute for Astronomy and Space Physics, CONICET/University of Buenos Aires, Ciudad Universitaria, Buenos Aires, Argentina
[c] Atmospheric Physics Laboratory, University College London, London, United Kingdom
[d] The Centre for Planetary Sciences, UCL/Birkbeck
[e] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey, United Kingdom

ARTICLE INFO

Article history:
Received 14 November 2008
Received in revised form
12 February 2009
Accepted 18 February 2009
Available online 4 March 2009

Keywords:
Planetary magnetospheres
Magnetodisk
Titan
Plasma interactions with unmagnetized bodies

ABSTRACT

With a mean orbital radius of 20.2 Saturnian radii (1 Saturn radius $R_S = 60{,}330$ km), Titan is usually located within the kronian magnetosphere. 3.5 years of Cassini magnetometer observations in the vicinity of Titan's orbit reveal that the moon's magnetic environment is strongly affected by the presence of Saturn's magnetodisk. As a result of the disk's solar–wind-induced asymmetry, Titan is exposed to quasi-dipolar fields in the noon sector, and planetward, swept-back fields in the dawn, dusk and midnight sectors. These magnetic properties indicate that the moon is, on average, south of the central current sheet and immersed in Saturn's rotating magnetospheric plasma for all local times (SLT). At a given SLT, Titan's distance from the central current sheet associated with the magnetodisk depends on the solar wind pressure and on the phase of the Saturn's kilometric radiation (SKR). The influence of the solar wind is present at all SLT (although dominant in the noon sector), whereas the SKR modulation seems to affect the magnetic field to first-order at least in the dawn sector. Near dawn local times, Titan tends to be farther from the disk at SKR longitudes around $\sim 140^\circ$ and closer to it for longitudes around $\sim 320^\circ$. Depending on these factors, Titan is exposed to either: (i) a 'magnetodisk lobe' regime where the plasma beta is low and fields are radially 'stretched' and usually stronger or (ii) a 'current sheet' regime—characterized by quasi-dipolar, relatively weak fields and a high-beta plasma.

1. Introduction

The absence of an intrinsic magnetic field at Titan makes its atmosphere a site of direct interaction with the external plasma to which it is exposed, generating a 'flow-induced magnetosphere' (Ness et al., 1982; Neubauer et al., 1984). The external conditions largely determine the properties of the induced magnetosphere. In particular, the upstream magnetic field controls the orientation of the magnetotail's draped fields (e.g., Neubauer et al., 2006), the dynamics of both external (e.g., Sergis et al., 2007) and local charged particles (e.g., Hartle and Sittler, 2007; Garnier et al., 2007), as well as the geometry of external ionizing particle fluxes and ionospheric current systems (Cravens et al., 2008; Rosenqvist et al., this issue).

With a kronocentric apoapsis not exceeding 21 Saturn radii (1 Saturn radius $R_S = 60{,}330$ km), Titan is usually located in the confines of Saturn's magnetosphere, whose average magnetopause stand-off distance is $\sim 23\ R_S$ (Achilleos et al., 2008). This means that most of the time, Titan is immersed in Saturn's plasma environment. That was the case during the first close flyby of the moon by Voyager 1 around 1330 h Saturn local time (SLT). However, it was clear even then that the location and dynamics of Saturn's nearby magnetopause could strongly affect Titan's environment (Wolf and Neubauer, 1982).

During the Voyager flyby, Titan was embedded in quasi-dipolar kronian magnetospheric fields (Ness et al., 1982) and a hot ($\beta = 11$) plasma (Neubauer et al., 1984). In the absence of additional flybys, pre-Cassini studies used Voyager plasma conditions as typical of the magnetospheric interaction (e.g., Kallio et al., 2004). However, Pioneer 11 magnetic field measurements obtained on the dawn flank (Smith et al., 1980) of Saturn's magnetosphere raised the possibility that, far from the subsolar region, Titan could be exposed to tail/disk-type, non-dipolar fields.

After the arrival of Cassini at the Saturnian system, magnetometer (MAG) measurements (Dougherty et al., 2005) confirmed the presence of a Jovian-type equatorial magnetodisk. This field geometry was shown to be consistent with the centrifugal force of the planet's subcorotating plasma dominating the stress balance beyond distances of $\sim 20\ R_S$ (Arridge et al., 2007). Follow-up studies (Bunce et al., 2008; Arridge et al., 2008a) showed that the

* Corresponding author at: Institute for Astronomy and Space Physics, CONICET/University of Buenos Aires, Ciudad Universitaria, Buenos Aires, Argentina. Tel.: +54 11 47890179; fax: +54 11 47868114.

E-mail addresses: cbertucci@iafe.uba.ar (C. Bertucci), benjamin.sinclair@imperial.ac.uk (B. Sinclair), nick@apl.ucl.ac.uk (N. Achilleos), peter.hunt@imperial.ac.uk (P. Hunt), m.dougherty@imperial.ac.uk (M.K. Dougherty), csa@mssl.ucl.ac.uk (C.S. Arridge).

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doi:10.1016/j.pss.2009.02.009

azimuthal symmetry of Saturn's magnetodisk (whose inner edge is as close as 16.2 R_S) breaks down during periods of high solar wind dynamic pressure, when the field in the noon sector field becomes quasi-dipolar and the magnetodisk structure remains in the magnetosphere's flanks and nightside. The dynamics of the magnetodisk were also studied from brief (of the order of a few tens of minutes) encounters by Cassini with the magnetodisk's central current sheet during the first mission sequence of equatorial orbits (Arridge et al., 2008a).

In addition to the influence of the solar wind, the magnetic field is modulated by the period of Saturn's kilometric radiation (SKR) emissions (Desch and Kaiser, 1981). The origin of these quasi-periodic signals (associated with the planet's rotation) has been discussed in several works (e.g., Espinosa et al., 2003; Southwood and Kivelson, 2007). This modulation also affects both thermal and energetic plasma measurements (e.g., Arridge et al., 2008b; Carbary et al., 2007) and a recently proposed longitude system based on the SKR emissions (Kurth et al., 2007, Kurth et al., 2008) efficiently organizes all plasma observations.

Based on Cassini magnetometer (Dougherty et al., 2004) observations accumulated during the first 3.5 years of the mission describing Saturn's outer magnetosphere on a global scale, it is the purpose of this paper to focus on the influence of the different sources of variability on Titan's magnetic environment. By studying the changes in the magnetic field properties near Titan's orbit, we are also able to identify the different types of plasma regimes to which the moon is exposed when residing within the kronian magnetosphere (the usual case).

The paper is organized as follows: Section 2 describes the type of data analyzed as well as the data selection based on Cassini's spatial coverage within the period of study. Section 3 addresses the large-scale structure of the magnetic field in the vicinity of Titan, as well as the structure in the immediate surroundings of the moon and the role of the quasi-periodic magnetic perturbations associated with the SKR emissions. Finally, Section 4 discusses these results and compares them with other Cassini plasma observations.

2. Cassini observations

Titan has an equatorial, slightly elliptical orbit with an apoapsis distance of 20.8 R_S and periapsis at 19.7 R_S. In the noon Saturn local time sector, the moon's orbit is very close to Saturn's magnetopause, whose stand-off distance (R_{MP}) – mainly controlled by a combination of solar wind dynamic pressure and internal magnetospheric reconfiguration – displays a bimodal distribution with mean values at ~22 and ~27 R_S (Achilleos et al., 2008). The resulting probability of Titan being outside Saturn's magnetopause peaks at 5.5% around 12 SLT (Fig. 1) and decreases symmetrically towards dawn and dusk sectors due to the symmetric magnetopause model (Arridge et al., 2006) used to obtain the bimodal distribution. Out of 44 flybys during Cassini's nominal mission (2004–2008), only one (T32) occurred outside Saturn's magnetosphere (Bertucci et al., 2008).

To study Saturn's magnetic field in the vicinity of Titan we employed Cassini fluxgate magnetometer data over the period 2004 Day-of-Year (DOY) 180 – 2007 DOY 325, (i.e., the first 52 orbits since Saturn insertion), which includes all the Titan flybys from TA through T37 (in mission nomenclature). The vectors are expressed in the Saturn-centered KSMAG cylindrical coordinate system (ρ, φ, Z), where the Z-axis is parallel to the planet's dipole (rotation) axis, ρ is the perpendicular radial distance from the Z-axis to the point in question, and φ is the azimuth measured positive eastwards from the subsolar meridian.

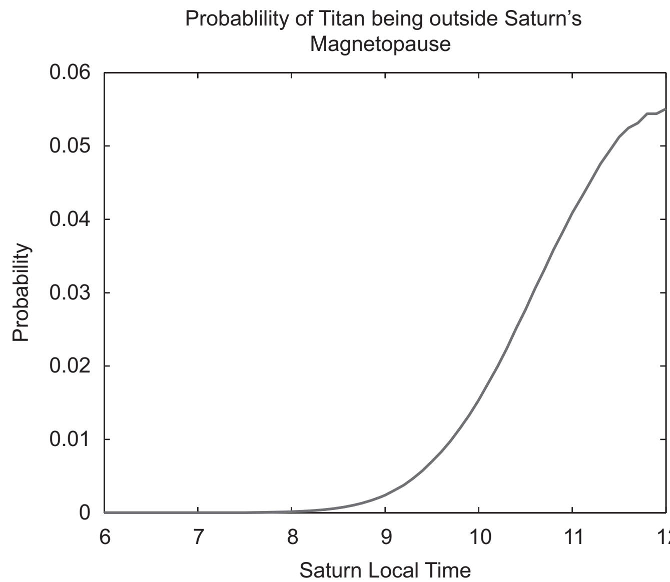

Fig. 1. Probability of Titan being outside Saturn's magnetopause as a function of Saturn local time based on the stand-off distance distribution published in Achilleos et al. (2008).

To study the large-scale structure of the kronian field in the vicinity of Titan, we initially considered measurements in the range $15<\rho<25$ R_S, and $-1<Z<1$ R_S, which was later reduced to the range $19<\rho<21$ R_S, and $-0.5<Z<0.5$ R_S. Data obtained within the magnetosheath and Titan's induced magnetosphere were removed.

Apart from the consideration of the magnetic field components in the KSMAG system, we studied the deviations of the magnetic field from a pure north/south orientation (equivalent to the magnetic equator) by using two angles: the stretch and the sweepback angles.

$$\text{Stretch} = \operatorname{atan}(-B_\rho/B_Z) \quad (1)$$

$$\text{Sweepback} = \operatorname{atan}(B_\varphi/B_\rho) \quad (2)$$

The stretch angle measures the deviation of the meridional component of the field from a pure north–south direction. Thus, a zero stretch angle will identify the magnetic equator (current sheet center) whereas large positive (and respectively negative) values for this angle imply regions outside and above (below) the current sheet. The sweepback angle (Khurana and Kivelson, 1993) measures the degree to which a field line is swept out of the meridional plane in a direction parallel (positive sweepback) or antiparallel (negative sweepback) to planetary rotation. The way it is defined, the sweepback angle is actually independent of the orientation of the planetary dipole (i.e., whether the field lines run north to south, or south to north).

3. Results

3.1. Saturn's magnetodisk and solar wind influence

The location of Titan with respect to Saturn's magnetic equator (or equivalently the planet's magnetodisk current sheet) characterized by $B_\rho=0$, near-zero fields, can be assessed by studying the vertical distribution of B_ρ across the moon's orbital plane. As Fig. 2 shows, the radial component of the ambient magnetic field at Titan's orbit ($Z=0$) is generally negative, indicating that during the interval of study Titan is usually below (south of) Saturn's magnetodisk. In other words, MAG measurements clearly show

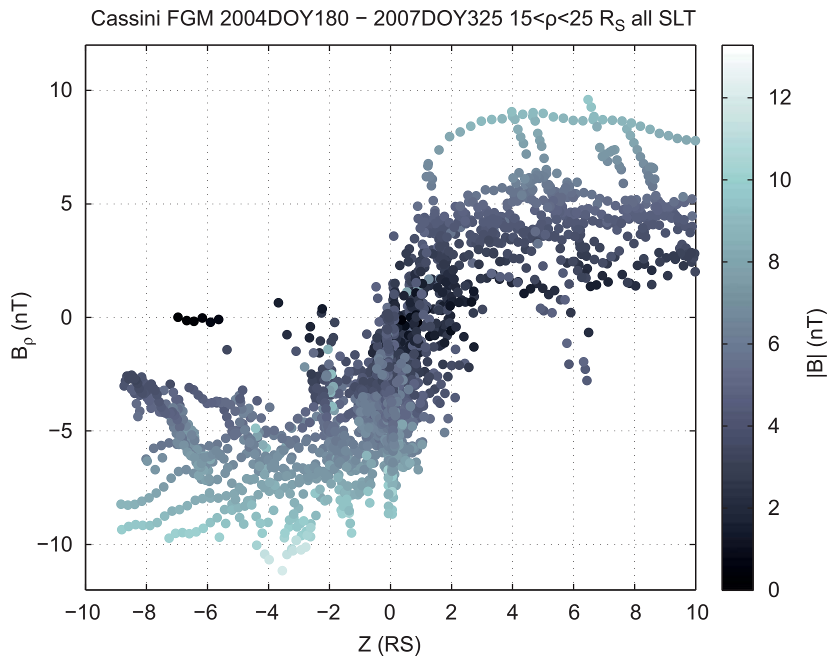

Fig. 2. One-hour resolution distribution of the radial component of the magnetic field (B_ρ) versus the vertical distance from the kronographic equator (Z) and the magnetic field strength within the ring $15<\rho<25$ R_S.

that Saturn's magnetic equator ($B_\rho=0$) occurs, on average, above (north of) Titan's orbital plane (between $Z=0$ and $Z=2$ R_S). In spite of the lack of a uniform azimuthal coverage, this behavior holds for all observed SLTs. In agreement with the idea that the magnetodisk is in stress balance, the magnetic fields far from the central current sheet (high $|Z|$) are significantly more stretched and stronger. These regions are referred to as the lobes of the magnetodisk. Near Titan's orbit ($Z{\sim}0$), the average magnetic field strength is ~5 nT with a radial component of around −3 nT. The dispersion observed around $B_\rho{\sim}0$ can be attributed to short-term variations in solar wind pressure that moves vertically the center of the disk at a particular radial distance, contributing to the dispersion along Z (Arridge et al., 2008c).

The distribution of the stretch angle measurements upon SLT can be observed in Fig. 3. There is a good coverage in SLT except the region 1400–1700 h. The field is more stretched in the dusk, midnight and dawn magnetospheric sectors and more dipolar near noon. A slight asymmetry is observed with respect to noon with the dusk sector showing a higher variability than the pre-dawn and dawn sectors. Measurements between 0400 and 0500 show a few positive stretch measurements. As the figure shows, these measurements occur between $Z=0.84$ and 1 R_S and do not reflect the general trend. If these measurements are ignored, the dawn sector shows the strongest negative stretch with the least variability (see Table 1). These values show that in this sector Titan rarely encounters Saturn magnetodisk current sheet.

In the noon sector, the stronger variability reveals the higher sensitivity of the disk's structure to the changes in solar wind pressure. Table 1 summarizes the average magnetic field strength, stretch and sweepback angles and their standard deviations per 6-h sector.

The higher variability in the late dusk (1800–2000) SLT sector is a real feature since in that sector, Cassini is situated neither at a particularly high Z, nor at a particularly low ρ. The midnight sector displays similar properties to the dawn sector, with a slightly higher variability for passes with similar Z.

Fig. 4 shows the distribution of sweepback angles versus SLT. The first feature to note is the weaker dependence on local time when compared to that of the stretch angle. Outside the range 1800–2000 SLT, the sweepback angle is on average around −20°, indicating a field swept out of the meridional plane antiparallel to corotation. Another distinct feature is that the sweepback angle is not symmetric about 1200 SLT. The most readily apparent demonstration of this aspect is the differing values around 1900 and 0500 SLT. This is similar to the degree of local-time asymmetry observed in the stretch angle. As in the case of the stretch angle, the lowest standard deviation in the sweepback occurs in the pre-dawn region 0400 < SLT < 0600.

The observations are incompatible with the possibility that in the midnight sector Titan may interact with the magnetotail of Saturn. If that situation occurred, one would expect a stretch angle near 90° and a sweepback angle near 0°. The sweepback angle in the region 2300 < SLT < 0100 is persistently negative almost within a standard deviation $-20^\circ \pm 24^\circ$, which strongly suggests that the region 15 $R_S<\rho<25$ R_S (encompassing Titan's orbital region) is situated, even at midnight, within a magnetodisk field geometry.

Finally, the near-zero values in the noon sector suggest that here Cassini encounters more frequently the central current sheet, in agreement with the stretch angle observations. A higher variability in sweepback is observed in dusk sector, similar to the behavior for the stretch angle.

The spatial range of the study was reduced to $19<\rho<21$ R_S and $-0.5<Z<0.5$ R_S to reduce variations associated with large-scale trends in the field, but still taking into consideration Titan's variable orbital distance. As Figs. 5 and 6 show, the dispersion in the field angle data is significantly reduced in the dusk and midnight sectors, but not so much in the dawn and noon sectors. The reduction of the range in Z has removed numerous positive stretch measurements associated with fields above the magnetodisk, restoring the symmetry across 1200 SLT as initially expected. Also, a more distinct pattern seems to have emerged in the sweepback angle, which clearly increases between 0800 and 1400, and reduces between 1800 and 2400. Reducing the spatial range further was found to degrade the results as not only the variability observed in Figs. 5 and 6 remains, but also because the SLT coverage is severely affected.

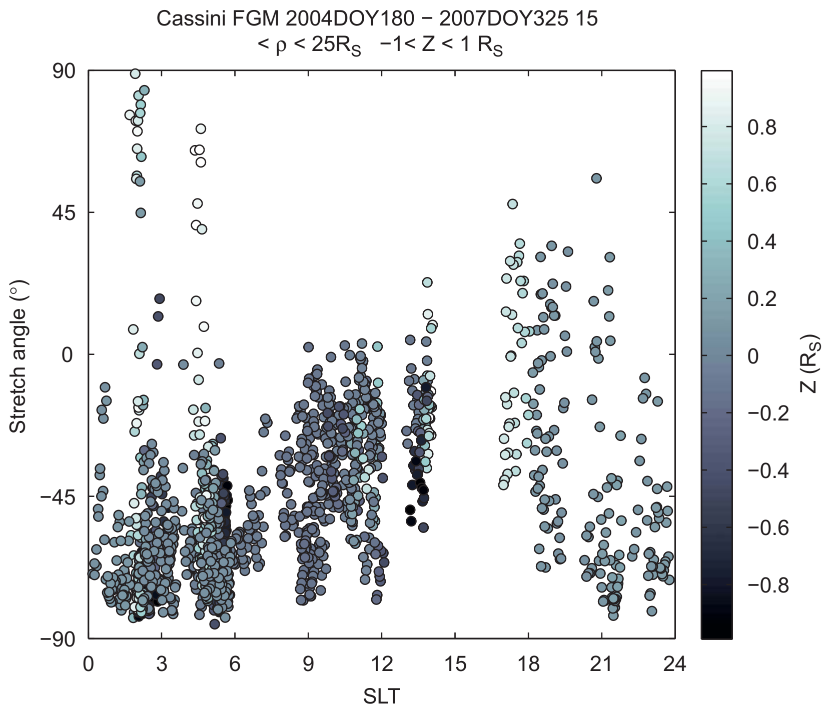

Fig. 3. One-hour resolution distribution of the stretch angle versus SLT and Z within the sector $15<\rho<25$ R_S, $-1<Z<1$ R_S.

Table 1
Average field strength, stretch and sweepback angle per SLT sector.

	Dawn (3–9 SLT)	Noon (9–15 SLT)	Dusk (15–21 SLT)	Midnight (21–3 SLT)
Field strength (nT)	5.3 ± 1.7	4.4 ± 1.6	3.7 ± 1.4	4.8 ± 1.8
Stretch angle (deg.)	-58 ± 20[a]	-32 ± 19	-18 ± 32	-56 ± 33
Sweepback angle (deg.)	-24 ± 16	-10 ± 25	-7 ± 41	-18 ± 23

[a] Without outliers the results are: $-60\pm15°$.

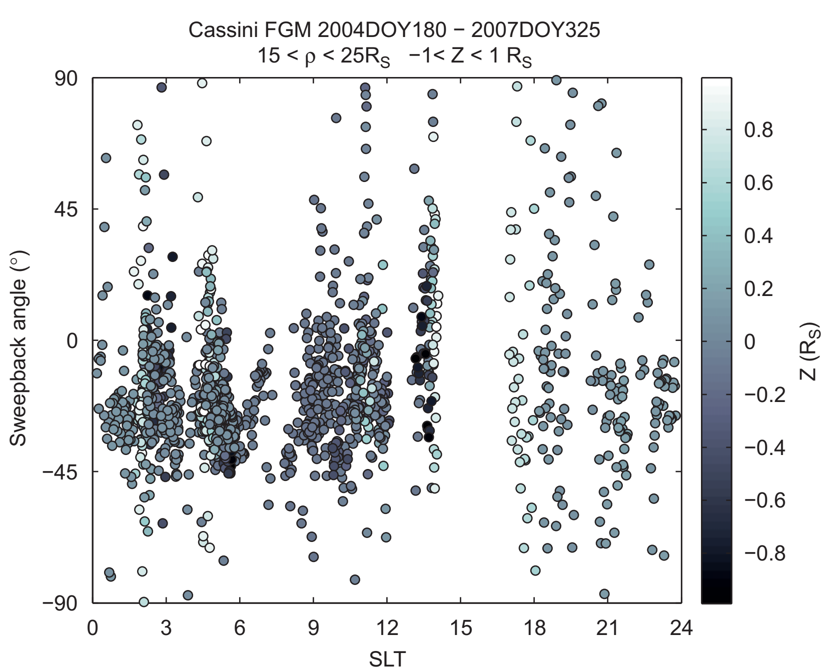

Fig. 4. One-hour resolution distribution of the sweepback angle versus SLT and Z within the sector $15<\rho<25$ R_S, $-1<Z<1$ R_S.

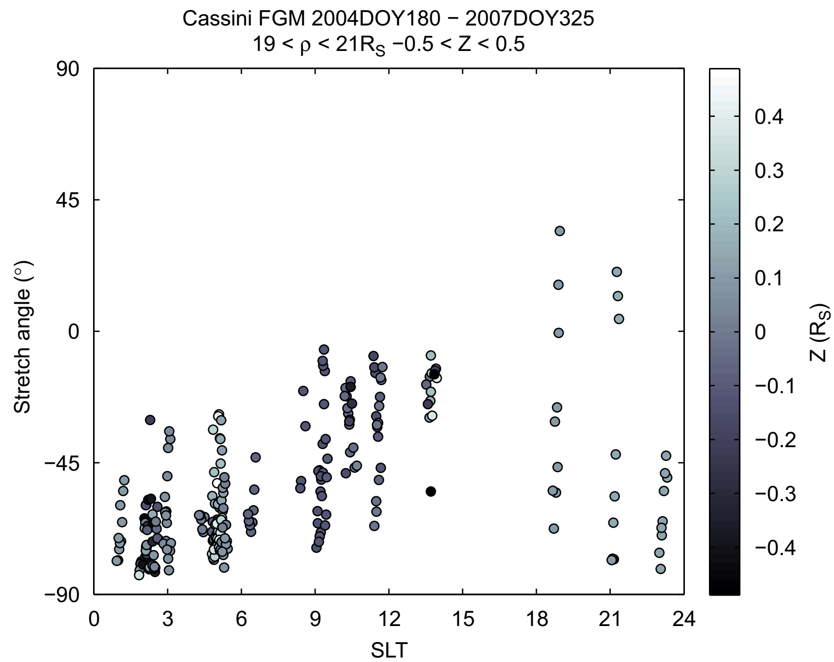

Fig. 5. One-hour resolution distribution of the stretch angle versus SLT and Z within the sector $19<\rho<21$ R_S, $-0.5<Z<0.5$ R_S.

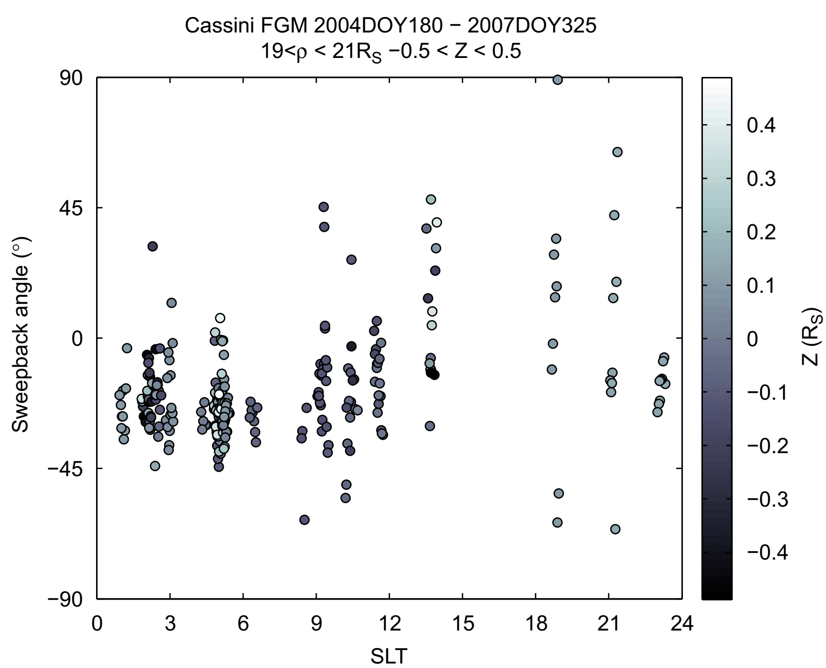

Fig. 6. One-hour resolution distribution of the sweepback angle versus SLT and Z within the sector $19<\rho<21$ R_S, $-0.5<Z<0.5$ R_S.

3.2. *Periodicities*

The motive in this work for studying periodicities is to determine to what degree they are responsible for the large variations in the orientation of the magnetic field in Titan's orbital region. The strategy for achieving this was to focus on a region which would be the least affected by the influences of the solar wind and where there would also be enough data to perform a statistically meaningful analysis. The region chosen for the analysis was then $0400<\mathrm{SLT}<0600$, $19<\rho<21$ R_S and $-0.5<Z<0.5$ R_S. To increase the number of measurements per sector, 1 min resolution data were employed.

Figs. 7 and 8 show, respectively, the stretch and the sweepback angle in the chosen region as a function of SKR longitude (SLS3, Kurth et al., 2008) and magnetic field strength. In spite of the increase in the time resolution, the dispersion of the stretch angle measurements does not increase significantly. Only one set of extreme measurements, five consecutive stretch angle readings ranging from -80° up to 80° and likely to be associated with brief encounters with the current sheet (Arridge et al., 2007), was removed from the data set. The cleaned plot reveals a clear dependence of the stretch angle upon the SKR longitude: this angle tends to be on average more negative and less variable at

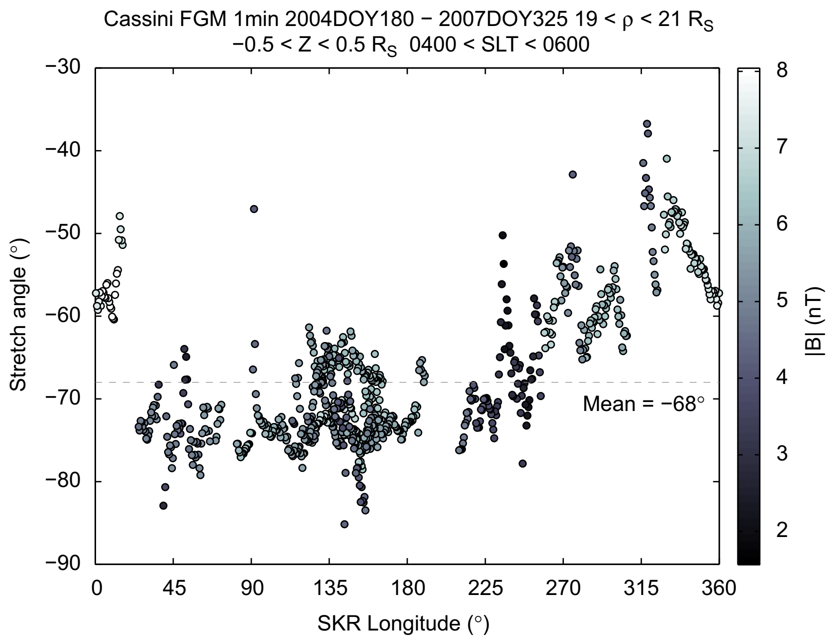

Fig. 7. One-minute resolution distribution of the stretch angle versus SLS3 SKR longitude and magnetic field strength in the region $0400<SLT<0600$, $19<\rho<21$ R_S, $-0.5<Z<0.5$ R_S.

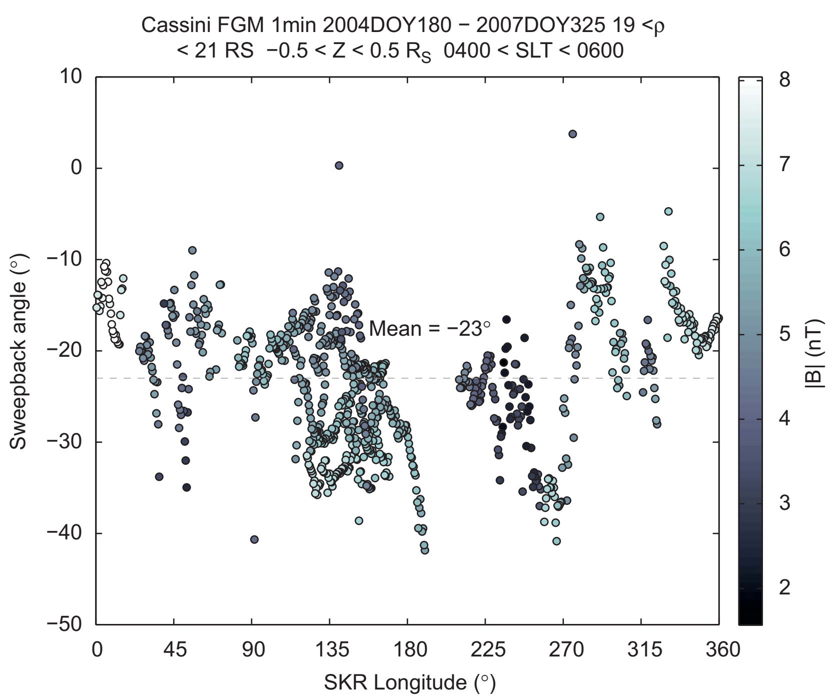

Fig. 8. One-minute resolution distribution of the sweepback angle versus SLS3 SKR longitude and magnetic field strength in the region $0400<SLT<0600$, $19<\rho<21$ R_S, $-0.5<Z<0.5$ R_S.

SKR longitudes around 140°. Conversely, less stretched fields are observed around 320°. This behavior remains as the spatial interval is further reduced. Also, a slight dependence is observed with respect to the magnetic field strength, as stronger stretch angles seem to correspond to higher field intensities.

Similar behaviors are also observed for other SLT sectors, but the higher dispersion makes this trend less evident. The SKR dependence is not as clear in the sweepback angle (Fig. 8). A slight decrease is observed around 200°, but this disappears when the spatial range is reduced. Also, no sweepback angle-$|B|$ correlation is observed.

At Titan's orbit, the SKR related periodicities manifest themselves as compressive fluctuations of the order of $|\Delta B|/B \sim 0.5$ (Bertucci, 2009) which account for the difference in the magnetic field measured inbound and outbound from Titan reported in several works (Backes et al., 2005, Neubauer et al., 2006).

4. Discussion and conclusions

The magnetic field measurements obtained by Cassini in the vicinity of Titan's orbit reveal that the moon's plasma environment is strongly influenced by Saturn's dynamic magnetodisk. The general trend observed in the stretch angle confirms that the magnetodisk's center is usually located north of the moon's orbit, in agreement with the observed seasonal northward displacement observed by Arridge et al. (2008c). This means that for most of its orbit, Titan is embedded in fields typical of the southern magnetodisk lobe, which are relatively depleted of thermal plasma when compared to the typical population of the central current sheet. Exceptions to this general behavior are observed in the noon and the late dusk sectors. In the noon sector, the solar wind pressure contributes to the dipolarization of the kronian field and Titan is more likely to be immersed in a thicker plasma sheet. In the late dusk sector, the available data corresponds to only two orbits occurring at similar kronographic latitudes ($Z\sim0.1\ R_S$). Along these two orbits, Cassini measures monotonically increasing stretch angles (going from negative to positive values), whereas the sweepback angle first increases displaying positive values and then decreases back to negative values. This suggests that Cassini crosses the center of Saturn's magnetodisk from south to north probing, respectively, supercorotating fields and lagging fields. This intriguing feature is not associated with Titan flybys and significantly complicates the interpretation of the moon's interaction, especially if concurrent changes in the plasma flow are observed.

When Titan interacts with the center of Saturn's magnetodisk (the current sheet) the field to which it is exposed is closer to the north–south direction (typical of the magnetic equator) and the thermal plasma density is higher (Arridge et al., 2008b). The energetic particles participating in the ring current also concentrate around the magnetic equator leading to plasma beta values of the order 10–100 (Sergis et al., 2007). Therefore, the presence of Titan inside Saturn's magnetodisk current sheet would lead to a 'high-energy particle input' scenario in opposition to a 'low-energy particle input' scenario when the moon is located within the magnetodisk's lobes. With its high-beta plasma and quasi-dipolar ambient field, the Voyager 1 flyby is an example of the first type of scenario, as the magnetodisk current sheet seems to be thicker around the noon sector. A classification of 'high energy' and 'low energy' plasma environments for the Cassini Titan flybys is currently underway and will be addressed in a future work.

In addition to the strong changes in the plasma pressure observed with distance from the magnetic equator, the Cassini Plasma Spectrometer (CAPS) (Young et al., 2004) measurements reveal a clear vertical gradient in plasma composition with heavy ions confined to the magnetic equator and light (H^+) ions dominating the magnetodisk lobe population (Sittler et al., this issue).

The results just presented imply that there is a strong dependence between the mass and the dynamic properties of these particles and the orientation of the background magnetic field. The amount of energy capable of being deposited into Titan's atmosphere by particle precipitation will depend on the particular configuration of the field, which will range from a high-energy scenario in the case of a quasi-dipolar field to a low-energy scenario, when Titan is exposed to fields typical of the magnetodisk lobes. The probability of Titan being exposed to either particular plasma/field configuration depends on SLT because of the asymmetrical average shape of Saturn's magnetodisk (Arridge et al., 2008a) and on the factors controlling its dynamics: (1) the solar wind pressure and (2) the SKR longitude. The solar wind pressure strongly controls the structure of the disk, which virtually disappears in the noon sector when magnetopause stand-off distance $R_{MP}\sim<20\ R_S$ (Arridge et al., 2008a). Changes in the solar wind dynamic pressure also affect the kronographic latitude of the magnetodisk's current sheet by pushing it northwards as the pressure increases (Bertucci, 2009).

In spite of the greater variability observed in the sweepback angle distribution with SLT, Cassini magnetometer data strongly suggests that in the midnight sector, Titan interacts with a rotation dominated plasma flow. This interpretation is independently confirmed by CAPS plasma velocity measurements in the nightside magnetosphere (McAndrews et al., 2008, 2009).

Titan magnetic environment also depends on the SKR phase. This is a second-order effect in the noon sector, but it is of first-order in sectors less sensitive to solar wind pressure, such as the dawn or pre-dawn sectors. In these sectors, Titan is exposed to more stretched fields at SKR longitudes around 140° and less stretched around 320°. These results are compatible with the studies by Arridge et al. (2008b) (in Saturn's outer magnetosphere) and Gurnett et al., (2007) (in the inner magnetosphere). In both works plasma density minima and maxima are found to occur around 150° and 330°, respectively. In particular, our observations are compatible with the interpretation given by Arridge et al. (2008b) that the variability of the magnetic field translates in vertical motion of the magnetodisk past Titan's orbital plane. In such scenario, the expected anticorrelation between the stretch angle and the magnetic field strength is not so clear in the dataset corresponding to the spatial interval $0400<\mathrm{SLT}<0600$, $19<\rho<21\ R_S$ and $-0.5<Z<0.5\ R_S$. However, as shown in Arridge et al. (2008b), the anticorrelation is clear when orbits are examined individually.

The orientation of the background magnetic field dictates the geometry of Titan's induced magnetosphere and thereby the geometry of the access of low-energy magnetospheric particles (H^+, H_2^+) to Titan's upper atmosphere. The background magnetic field also determines the orientation of the convection electric field along which the local particles (CH_4^+, N_2^+) with finite gyroradii (comparable to the Titan radius) will tend to cluster. This aspect of particle kinetics alters the symmetry of the region where Titan's plasma escapes to Saturn's magnetosphere. Initially considered to be radially outward from Saturn, MAG measurements now confirm that the orientation of the convective electric field has an important southward component.

Apart from the effects on the collisionless regions of Titan's interaction, the present results are relevant to studies on ionospheric conductivities, which have been shown to be strongly dependent on the orientation and strength of the draped magnetic field (Rosenqvist et al., this issue).

In summary, the results described above represent the first attempt to characterize the variability of Saturn's magnetic field near Titan's orbit from a global perspective. Titan's plasma environment is influenced by solar wind pressure and SKR as these control the latitude of the central current sheet associated with Saturn magnetodisk. Titan's entry/exit to this current sheet results in different plasma regimes being coupled with different orientations of the ambient magnetic field. At the 'extremes' of the range of possible plasma regimes we find: (a) a lobe-type environment where Saturn's field is stretched (radial) and strong, with low plasma density (corresponding to SKR longitudes near 140°) and (b) a current sheet-type environment where the field is quasi-dipolar and the plasma is denser and hotter. Future work will be focused on characterizing the existing Cassini flybys as lobe or current sheet-type scenarios using both Cassini magnetic field and plasma observations to study the impact on the structure of Titan's induced magnetosphere and the atmospheric escape resulting from its interaction with Saturn.

Acknowledgments

CB was supported by a STFC Postdoctoral Fellowship at Imperial College London. CSA was funded by an STFC quota studentship at Imperial College London and by the STFC rolling grant to MSSL/UCL.

References

Achilleos, N., Arridge, C.S., Bertucci, C.L., Jackman, C.M., Dougherty, M.K., Khurana, K.K., Russell, C.T., 2008. Large-scale dynamics of Saturn's magnetopause: observations by Cassini. J. Geophys. Res. 113, A11209.

Arridge, C.S., Achilleos, N., Dougherty, M.K., Khurana, K.K., Russell, C.T., 2006. Modeling the size and shape of Saturn's magnetopause with variable dynamic pressure. J. Geophys. Res. 111 (A11), A11227.

Arridge, C.S., Russell, C.T., Khurana, K.K., Achilleos, N., André, N., Rymer, A.M., Dougherty, M.K., Coates, A.J., 2007. Mass of Saturn's magnetodisc: Cassini observations. Geophys. Res. Lett. 34 (9), L09108.

Arridge, C.S., Russell, C.T., Khurana, K.K., Achilleos, N., Cowley, S.W.H., Dougherty, M.K., Bunce, E.J., 2008a. Saturn's magnetodisc current sheet. J. Geophys. Res. 113, A04214.

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

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

Backes, H., Neubauer, F.M., Dougherty, M.K., Achilleos, N., André, N., Arridge, C.S., Bertucci, C., Jones, G.H., Khurana, K.K., Russell, C.T., Wennmacher, A., 2005. Titan's Magnetic Field Signature During the First Cassini Encounter. Science 308 (5724), 992–995.

Bertucci, C., et al., 2008. The magnetic memory of Titan's ionized atmosphere. Science 321, 1475.

Bertucci, C., 2009. Characteristics and variability of Titan's magnetic environment. Philos. Trans. R. Soc. A 367 (1889).

Bunce, E.J., Arridge, C.S., Cowley, S.W.H., Dougherty, M.K., 2008. Magnetic field structure of Saturn's dayside magnetosphere and its mapping to the ionosphere: results from ring current modeling. J. Geophys. Res. 113, A02207.

Carbary, J.F., Mitchell, D.G., Krimigis, S.M., Hamilton, D.C., Krupp, N., 2007. Charged particle periodicities in Saturn's outer magnetosphere. J. Geophys. Res. 112, A06246.

Cravens, T.E., Robertson, I.P., Ledvina, S.A., Mitchell, D., Krimigis, S.M., Waite, J.H., 2008. Energetic ion precipitation at Titan. Geophys. Res. Lett. 35 (3), L03103.

Desch, M.D., Kaiser, M.L., 1981. Voyager measurements of the rotation period of Saturn's magnetic field. Geophys. Res. Lett. 8 (3), 253–256.

Dougherty, M.K., et al., 2004. The Cassini magnetic field investigation. Space Sci. Rev. 114, 331–383.

Dougherty, M.K., et al., 2005. Cassini magnetometer observations during Saturn orbit insertion. Science 307 (5713), 1266–1270.

Espinosa, S.A., Southwood, D.J., Dougherty, M.K., 2003. Reanalysis of Saturn's magnetospheric field data view of spin-periodic perturbations. J. Geophys. Res. 108 (A2), 1085.

Garnier, P., Dandouras, I., Toublanc, D., Brandt, P.C., Roelof, E.C., Mitchell, D.G., Krimigis, S.M., Krupp, N., Hamilton, D.C., Waite, H., 2007. The exosphere of Titan and its interaction with the kronian, magnetosphere: MIMI observations and modeling. Planet. Space Sci. 55, 165–173.

Gurnett, D.A., Persoon, A.M., Kurth, W.S., Groene, J.B., Averkamp, T.F., Dougherty, M.K., Southwood, D.J., 2007. The variable rotation period of the inner region of Saturn's plasma disk. Science 316 (5823), 442.

Hartle, R.E., Sittler Jr., E.C., 2007. Pickup ion phase space distributions: effects of atmospheric spatial gradients. J. Geophys. Res. 112, A07104.

Kallio, E., Sillanpaä, I., Janhunen, P., 2004. Titan in subsonic and supersonic flow. Geophys. Res. Lett. 31, L15703.

Khurana, K.K., Kivelson, M.G., 1993. Inference of the angular velocity of plasma in the Jovian magnetosphere from the sweepback of magnetic field. J. Geophys. Res. 98 (A1), 67–79.

Kurth, W.S., et al., 2007. A Saturnian longitude system based on a variable kilometric radiation period. Geophys. Res. Lett. 34, L02201.

Kurth, W.S., et al., 2008. An update to a Saturnian longitude system based on kilometric radio emissions. J. Geophys. Res. 113, A05222.

McAndrews, H.J., Thomsen, M.F., Sittler, E.C., Jackman, C.M., Arridge, C.S., Coates, A.J., Dougherty, M.K., Henderson, M.G., Tokar, R.L., Wilson, R.J., 2008. Plasma in the Nightside Magnetosphere and the Implications for Global Circulation. American Geophysical Union, Fall Meeting 2007, abstract #SM43B-01.

McAndrews, H.J., Thomsen, M.F., Arridge, C.S., Jackman, C.M., Wilson, R.J., Henderson, M.G., Tokar, R.L., Khurana, K.K., Sittler, E.C., Coates, A.J., Dougherty M.K., 2009. Plasma in Saturn's nightside magnetosphere and the implications for global circulation. Plant. Space Sci., this issue, doi:10.1016/j.pss.2009.01.003.

Neubauer, F.M., et al., 2006. Titan's near magnetotail from magnetic field and electron plasma observations and modeling: Cassini flybys, TA, TB and T3. J. Geophys. Res. 111, A10220.

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

Ness, N.F., Acuña, M.H., Behannon, K.W., 1982. The induced magnetosphere of Titan. J. Geophys. Res. 87, 1369.

Rosenqvist, L., Wahlund, J.E., Ågren, K., Modolo, R., Opgenoorth, H.J., Mueller-Wodarg, I., Garnier, P., Bertucci, C., Strobel, D., Titan ionospheric conductivities, this issue.

Sergis, N., Krimigis, S.M., Mitchell, D.G., Hamilton, D.C., Krupp, N., Mauk, B.M., Roelof, E.C., Dougherty, M., 2007. Ring current at Saturn: energetic particle pressure in Saturn's equatorial magnetosphere measured with Cassini/MIMI. Geophys. Res. Lett. 34, L09102.

Smith, E.J., Davis, L., Jones, D.E., Coleman, P.J., Colburn, D.S., Dyal, P., Sonett, C.P., 1980. Saturn's magnetosphere and its interaction with the solar wind. J. Geophys. Res. 85 (A11), 5655–5674.

Southwood, D.J., Kivelson, M.G., 2007. Saturnian magnetospheric dynamics: elucidation of a camshaft model. J. Geophys. Res. 112, A12222.

Sittler, E.C., Hartle, R.E., Lipatov, A., Bertucci, C., Coates, A., Szego, K., Shappirio, M., Simpson, D.G., Composition of Upstream Flow for Titan's Interaction with Saturn's Magnetosphere during T9 Flyby, American Geophysical Union, Spring Meeting 2008, abstract #P31A-05.

Wolf, D., Neubauer, F.M., 1982. Titan's highly variable plasma environment. J. Geophys. Res. 87, 881–885.

Young, D.T., et al., 2004. Cassini plasma spectrometer investigation. Space Sci. Rev. 114, 1–112.