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Northward field excursions in Saturn's magnetotail and their relationship to magnetospheric periodicities

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[1] We present results from an investigation of Cassini encounters with Saturn's magnetotail current sheet, using magnetic field and plasma data. In the first of two intervals shown, small periodic changes in the north-south component of the magnetic field are matched by periodic density enhancements associated with the plasma sheet center. In the second interval, a large plasmoid signature is observed set against a background of small-scale current sheet motions. We interpret the quasi-periodic small field deflections and density enhancements as large-scale wave-like motion of the current sheet. We stress that plasmoid signatures are of a clearly different character and occur much less frequently.
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1. Introduction

[2] The presence of a plasma sheet at Saturn was inferred from Voyager data [*Schardt et al.*, 1984] and has subsequently been studied by a number of authors [*Krupp et al.*, 2005; *Arridge et al.*, 2007, 2009; *McAndrews et al.*, 2009]. Pioneer 11 and Cassini magnetometer observations at Saturn have revealed a very dynamic current sheet within the plasma sheet which supports waves as evidenced by transient crossings lasting typically 10–20 minutes [*Arridge et al.*, 2007; *Smith et al.*, 1980]. Many recent modelling studies have addressed global periodic signatures, as seen in plasma, energetic particles, magnetic fields and radio emissions at Saturn [e.g., *Espinosa and Dougherty*, 2000; *Carbary et al.*, 2007; *Khurana et al.*, 2009]. Each model of the outer magnetospheric periodicities introduces some mechanism to produce periodic vertical motions of the tail current and plasma sheet, such that the sheet is periodically moved over the spacecraft. *Burch et al.* [2008] (hereinafter referred to as B08), studied periodic magnetic field and plasma signatures in the kronian magnetotail and interpreted them in terms of periodic reconnection driving plasmoids moving outward from 30–35 R_S along a spiral path. In their model a longitudinally localized outflow region produces an outflowing "plume" of plasma from ~15 R_S which follows a spiral trajectory. Once in the 30–35 R_S range reconnection on closed flux occurs and these plasmoids are lost down the magnetotail, or into the magnetosheath on the dayside.

[3] When magnetotail current sheets thin to the point where they undergo reconnection, plasmoids are released downtail and these can be detected directly by spacecraft near the plasma sheet, or indirectly through the observation of travelling compression regions (TCRs) which form as passing plasmoids compress the surrounding lobe magnetic field [*Slavin et al.*, 1984]. Both plasmoids and TCRs result in deflections in the north/south component of the magnetic field. However, care must be taken in the interpretation of such magnetic field deflections. *Nakagawa and Nishida* [1989] (hereinafter referred to as NN89), studied the motion of the terrestrial neutral sheet and noted regular deflections of the north/south component of the field. In some cases, they suggested that a southward magnetic field in the neutral sheet (opposite polarity to the normal local dipole field direction of Earth) could be interpreted as evidence for magnetotail reconnection, but only if accompanied by tailward streaming of plasma. *Hughes and Sibeck* [1987] had previously suggested that the southward field in the absence of tailward streaming could be part of the magnetic flux rope-like structure stretching across the tail. However, NN89 proposed an alternative explanation: that the magnetic field signatures could be interpreted in terms of wavy motion of the neutral sheet, possibly driven by the Kelvin-Helmholtz instability.

[4] At Saturn, just nine examples of plasmoids or TCRs have been documented to date [*Jackman et al.*, 2007, 2008, 2009]. These are identified primarily by strong north-south turnings of the magnetic field, with accompanying energization of electrons and rapid tailward flow of plasma [e.g., *Hill et al.*, 2008] (hereinafter referred to as H08). The correct interpretation of north/south magnetic field deflections is crucial for understanding the dynamics of the magnetotail. Thus, in this paper, we analyse two intervals of Cassini data to investigate the difference between small-scale current sheet motions and large scale plasmoid observations.

2. Observations

2.1. Example A: The 2006 Day 195–203

[5] In Figure 1 we show plasma and magnetic field data for the same interval discussed by B08, which extends from day 195 (14 July) to 203 (22 July) of 2006, while Cassini was in Saturn's magnetotail. The magnetic field data is shown in KRTP co-ordinates, where the radial component (B_r) is positive outward from Saturn, the theta component (B_θ) is positive southward, and the azimuthal component (B_φ) is

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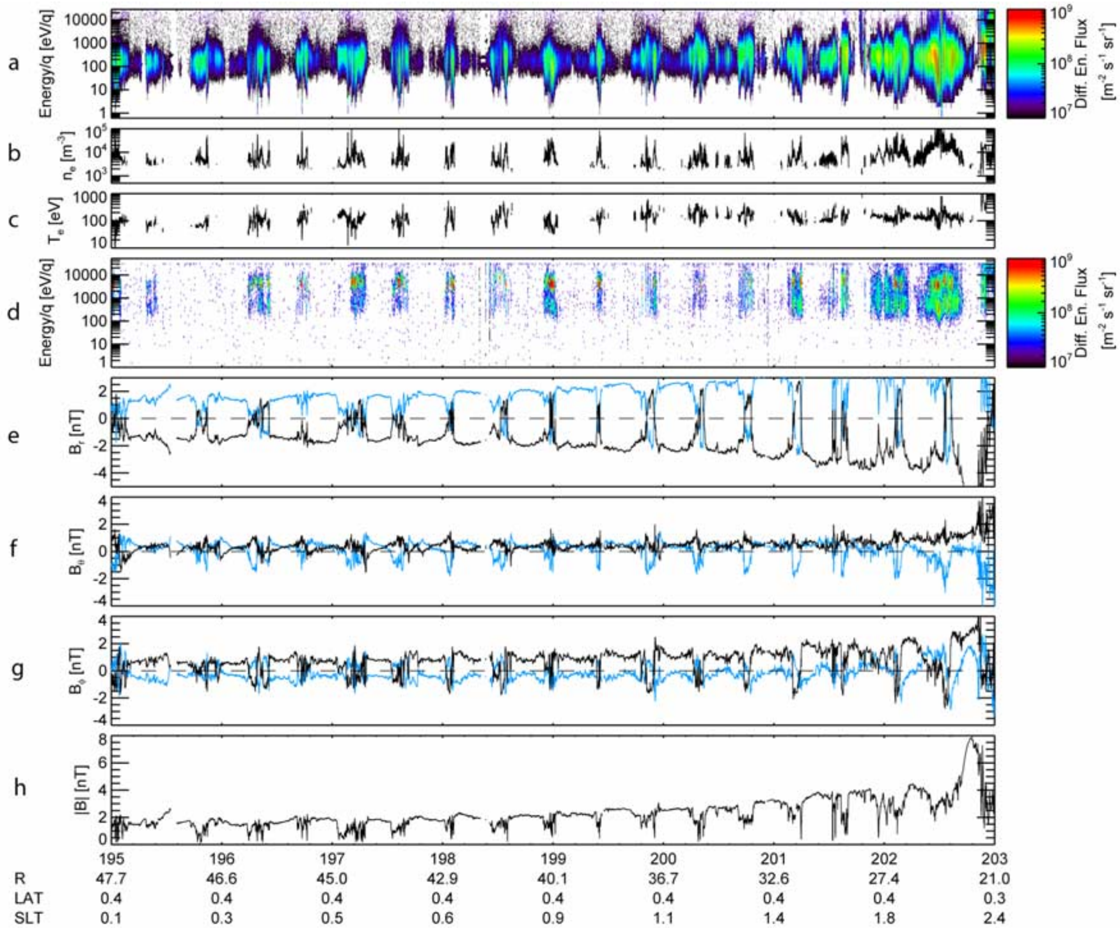

Figure 1. Plasma and magnetometer data from Saturn's magnetotail covering day 195 (14 July) to 203 (22 July) of 2006. (a) An energy-time electron spectrogram from CAPS/ELS (Cassini Plasma Science - Electron Spectrometer), (b) electron density and (c) temperature moments from CAPS-ELS, (d) an energy-time ion spectrogram from CAPS/IMS (Ion Mass Spectrometer), (e–g) the three components of the magnetic field in spherical polar KRTP coordinates (black) and KSO coordinates overplotted (blue) for ease of comparison, with B_{xKSO} in Figure 1e, B_{yKSO} in Figure 1g and B_{zKSO} in Figure 1f. (h) Total magnetic field strength. Day number, radial range, magnetic latitude and Saturn local time (SLT) are displayed at the bottom of the figure.

positive in the direction of corotation (in a prograde direction). This system is ideal for observing dynamics in the magnetotail, as strong changes in the north-south component can be indicative of magnetotail processes, as they directly give the field crossing the equatorial plane. Also the radial and azimuthal components provide information on the position of the spacecraft relative to the central current sheet, and elucidate the degree of corotation of the plasma (i.e. lagging or leading field lines). The Kronocentric Solar Orbital system (KSO, analogous to the GSE system) used by B08 has no plane close to Saturn's dipole magnetic equatorial plane and furthermore the system is rotated such that the B_z component contains information about both the sweep-back of the field and the location with respect to the center of the current sheet. Any dynamical features in the B_z component of KSO will naturally be contaminated with other features of the magnetotail; for example any periodic vertical motion of the current sheet will generate periodic features in the B_z component of KSO. KSO field components are overplotted on Figure 1 in blue for ease of comparison.

[6] The data in Figure 1 show encounters with the plasma and current sheet with a period of approximately 11 hours. Rapid changes of the B_r component from negative to small positive values and back again are indicative of transient crossings of the central current sheet, and are accompanied by depressions in the magnetic field. Due to the swept-back nature of the outer magnetospheric field lines the radial and azimuthal field components have an anti-phase relationship such that B_φ changes from positive to small negative values and back during current sheet encounters/crossings. Concurrent with these periodic current sheet crossings, the electron and ion signatures are characteristic of the central plasma sheet, where the electron density reaches a local maximum. The electron temperature typically varies by no more than a factor of two between the central plasma sheet and the lobes [*Arridge et al.*, 2009]. Throughout this period, the latitude of the spacecraft was relatively steady at ~0.4° indicating a constant angular distance from the equatorial plane. Thus the regular crossings of the current sheet imply a flapping motion. Where B_r is negative Cassini is south of the current sheet, and thus we can infer that the current sheet

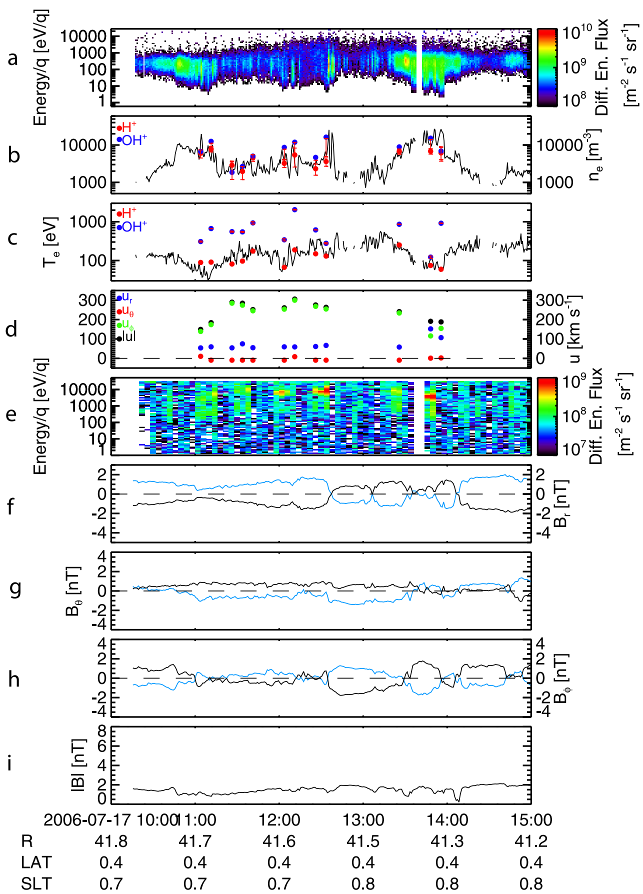

Figure 2. Plasma and magnetometer data from Saturn's magnetotail on 2006 day 198 from 10:00–15:00. (a) An energy-time electron spectrogram from CAPS/ELS, (b and c) electron and ion density and temperature moments from CAPS/ELS and CAPS/IMS, (d) ion velocity components and total ion velocity, (e) an ion spectrogram from anode 5 of CAPS/IMS, (f–h) components of the magnetic field in KRTP co-ordinates with KSO co-ordinates overplotted in blue, and (i) total magnetic field strength.

is moving down to meet Cassini periodically [e.g., *Khurana et al.*, 2009].

[7] Generally the B_θ component of the field is small and positive indicating closed field lines directed southward across Saturn's equatorial plane. As clearly indicated by the radial and azimuthal components, the magnetotail is the location of substantial magnetospheric currents which produce an almost constant value of B_θ. As Cassini approaches Saturn this increases indicating that the observed field is being dominated by Saturn's internal field. About a thin current sheet the latitudinal variations in B_θ are directly related to the radial variations in B_r. From Figure 1 one can see that the radial gradient of B_r is fairly weak hence the latitudinal gradient in B_θ should be fairly weak, i.e., the value of B_θ should not strongly vary as the spacecraft moves in and out of the plasma sheet.

[8] However, we note that the B_θ (north-south) component of the magnetic field shows regular northward turnings of order 1 nT. Here we refer to the work of NN89 who observed positive B_θ on the trailing edge of current sheet crossings/encounters at Earth. They found that the magnetic field in the neutral sheet sometimes takes north and south polarities alternately at successive crossings. They interpreted this, not as B08 did for Saturn, in terms of rapidly recurring plasmoid observations, but rather as mere wavy motion of the neutral sheet that propagates in the dawn-dusk direction in the presence of the dawn-dusk components of the magnetic field. This effect is seen readily in Jovian current sheet crossings with a slight increase in B_θ before the current sheet crossing and a decrease on the trailing edge, sometimes becoming slightly negative [see *Khurana*, 1997, Figures 3 and 6]. We note from the work of *Jackman et al.* [2007, 2008] and H08 that strong northward turnings of the field observed in the tail accompanied by tailward streaming of plasma can be interpreted as evidence for reconnection and subsequent plasmoid release in Saturn's magnetotail. However, we suggest that the regular small fluctuations in the B_θ component seen in Figure 1 are merely those associated with wave-like motions of the current sheet, providing a challenge to the model of B08 who interpret such features in terms of plasmoids and spirals. We see no evidence for plasmoid passage during the interval shown in Figure 1, despite the fact that the spacecraft was in a suitable position to observe plasmoids had they passed.

[9] Figure 2 shows a zoom in of a section of the above interval from 2006 day 198 1000–1500 in a similar format to Figure 1 with the addition of ion data from the CAPS-IMS detector. The energy structure of the ions is due to the presence of two main ion populations, water-group and a light ion (primarily H+). The intermittent presence of the ions is due to the changing field of view of the instrument relative to the bulk flow direction. Moments are only calculated for times when the flow was well sampled by the instrument. The spectrograms for this interval do not show any significant energization of the ions. We compare this with the findings of H08 who noted that during a period which encompassed the passage of a plasmoid, the energy of the water-group ions within the plasmoid was increased such that it exceeded the IMS energy range (~50 keV). Furthermore the motion of the plasma is almost entirely in the corotation direction (see Figure 2d) and does not show evidence of significant deflection into a tailward flow as observed by H08 in two plasmoid observations. Finally we note that this period is similar to that shown by *McAndrews et al.* [2009] as an example of 'nominal', still-corotating plasma, further confirming our suggestion that the periodic field signatures in Figure 1 represent mere wave-like current sheet motions rather than regular plasmoids.

[10] Figure 3 shows a schematic (after NN89, Figure 2) of the magnetic and plasma signatures that result from such wave propagation. As the orientation of the current sheet changes with respect to the background (spherical polar) coordinate system the orientation of the field in and around the current sheet will change. Large amplitude oscillations and thick current sheets will produce changes in sign of B_θ. Encounters with the centre of the current sheet will produce enhancements in the electron density (see Figure 2). Thinner current sheets with small oscillation amplitudes will only produce increases and decreases in the magnitude of B_θ. Changes in the wavelength of the wave modifies the amplitude of the B_θ deflections. The qualitative time series

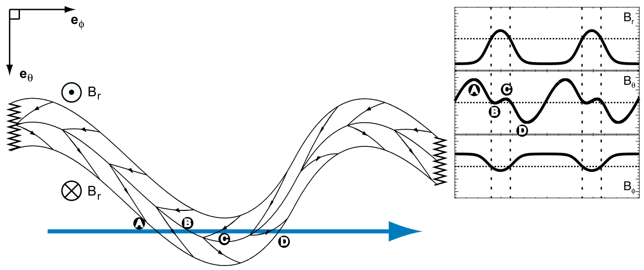

Figure 3. Illustration of Cassini's path taken through an oscillating current sheet where both radial and azimuthal currents are present, leading to both the azimuthal and radial components of the magnetic field reversing across the center of the sheet (adapted from *Arridge* [2007]). The orientation of the current sheet with respect to the background coordinate system changes with the phase of the wave. The thickness of the sheet and the amplitude of the oscillation control the distortions in the B_θ component of the field and control whether that component will change sign during a current sheet encounter/crossing.

in Figure 3 was obtained by using a travelling wave to deform [*Tsyganenko*, 1998] a planar current sheet with a finite normal component.

2.2. Example B: The 2006 Day 212–220

[11] In Figure 4 we show an interval from day 212 (31 July) to 220 (08 August) 2006 in the same format as Figure 1. In this example, multiple current sheet encounters and small deflections of the B_θ component are observed, much like in Figure 1, although in this case Cassini was at a higher magnetic latitude. However, at ~1650 UT on day 216 we observe a very strong rapid northward turning of the field, representing a 4 nT deflection. The increase in field magnitude in this case was to almost twice the value of the typical lobe field strength at that radial distance, and this observation was interpreted by *Jackman et al.* [2007] as the passage of a plasmoid. It is clear that the plasmoid signature is strongly significant relative to the quasi-periodic small northward turnings of the field which we attribute to current sheet flapping motions. H08 analysed the plasma data surrounding the event on day 216 and found that ion fluxes became too small for moment extraction close to the time of the northward turning of the field. The electron density then dropped by a factor of ~4. Crucially, before the loss of the ion signal, a decrease in v_φ and an increase in v_r was observed. This

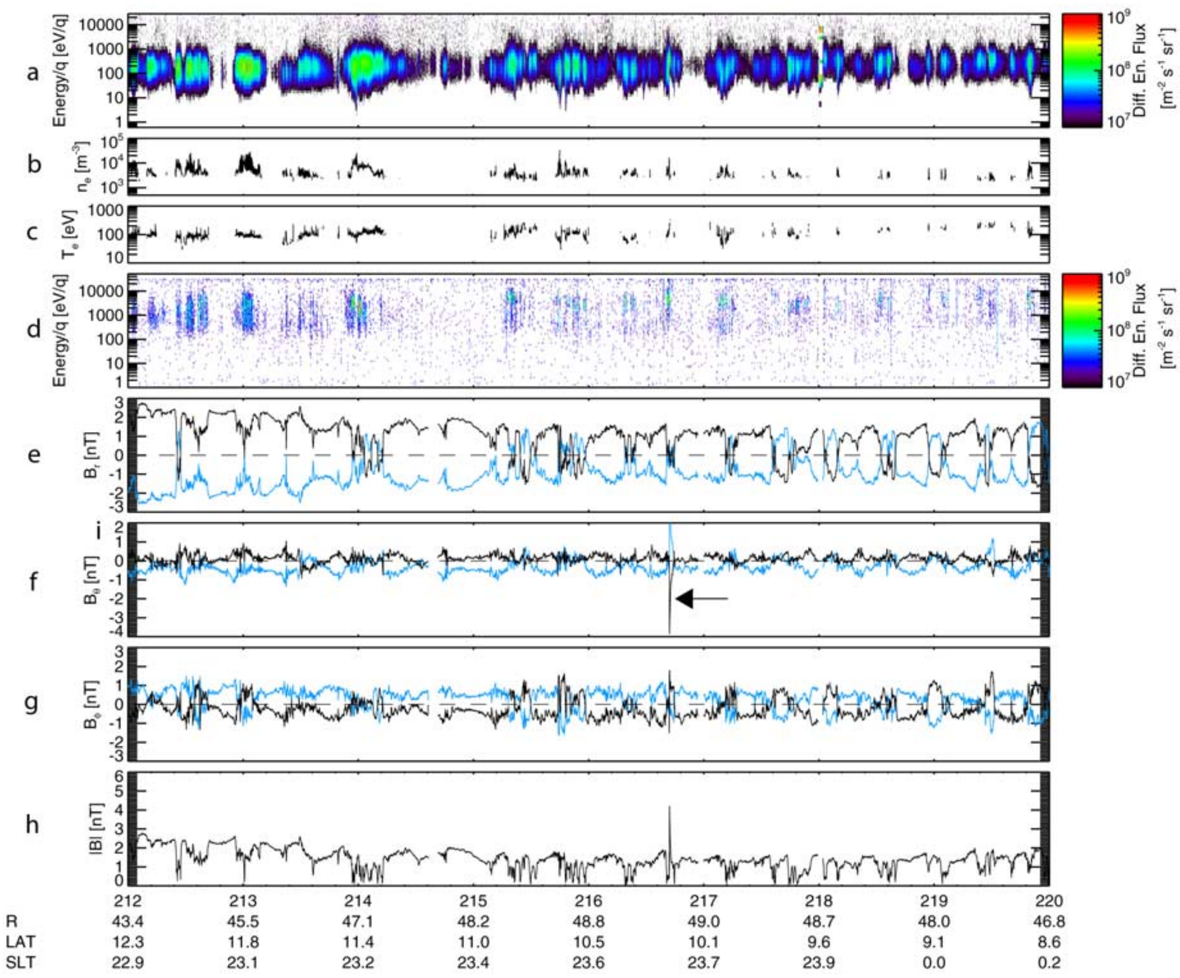

Figure 4. Plasma and magnetometer data from Saturn's magnetotail covering day 212 (31 July) to 220 (08 August) 2006 in the same format as Figure 1, with a black arrow marking the plasmoid observation.

corresponds to a deflection of the flow away from the corotation direction and toward the tailward direction.

3. Discussion

[12] In this paper we have examined plasma and magnetic field data in Saturn's magnetotail. We have paid particular attention to the origin of small-scale deflections in the north-south component of the magnetic field, previously attributed to the periodic release of plasmoids (B08). We have shown that expressing the magnetic field data in spherical polar coordinates reduces the magnitude of these deflections in the north-south field component. Finally we have shown that these residual deflections are entirely consistent with changes in orientation of the current sheet brought about by a global large-scale flapping of the current and plasma sheet.

[13] There is scant evidence for large-scale energization of the ions in either of the intervals shown in Figures 1 and 4 but as noted above, any energization induced, e.g., by the passage of a plasmoid may well have exceeded the energy range of the CAPS-IMS instrument. We note also that H08 found the composition of the ions in a tailward-moving plasmoid was unchanged from nominal plasma sheet composition. It is expected that planetward of any internally-triggered reconnection site there would be a preferential depletion of the heavy ions which are more equatorially confined. However, no such returning flux tubes have as yet, been knowingly sampled.

[14] Regarding the frequency of plasmoid release at Saturn, *Jackman et al.* [2009] found that for eight of nine examples studied, magnetotail reconnection occurs at a preferential phase of the planetary rotation. However, as illustrated by the data in Figure 1, even when Cassini is in a position to sample plasmoids on many consecutive days, they are not observed. Thus we conclude that the recurrence rate for magnetotail reconnection events are Saturn is likely much longer than the timescale for planetary rotation, and the repeating field signatures seen on timescales of $\sim$10–11 hours are mere wave-like motions of the current sheet.

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