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A multi-instrument view of tail reconnection at Saturn

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[1] Three instances of tail reconnection events at Saturn involving the ejection of plasmoids downtail have been reported by Jackman et al. (2007) using data from Cassini's magnetometer (MAG). Here we show two newly discovered events, as identified in the MAG data by northward/southward turnings and intensifications of the field. We discuss these events along with the original three, with the added benefit of plasma and energetic particle data. The northward/southward turnings of the field elucidate the position of the spacecraft relative to the reconnection point and passing plasmoids, while the variability of the azimuthal and radial field components during these events indicates corresponding changes in the angular momentum of the magnetotail plasma following reconnection. Other observable effects include a reversal in flow direction of energetic particles, and the apparent evacuation of the plasma sheet following the passage of plasmoids.

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1. Introduction

[2] Substorms have been widely studied at the Earth [e.g., *Akasofu*, 1964; *Russell and McPherron*, 1973] for many years, and more recently, Jovian and Kronian tail dynamics have become a subject of great interest [e.g., *Kronberg et al.*, 2005; *Jackman et al.*, 2007]. In the Earth's magnetotail, the key observable features of substorms are magnetic field reconfiguration (dipolarization), strong plasma flows, and plasma energization [e.g., *Nakamura et al.*, 2002]. The significance of field dipolarization is that it relaxes the stressed magnetic field, and thus releases magnetic energy that was accumulated beforehand. This energy may heat the plasma and in turn generate energetic particles.

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1.1. Jovian Tail Dynamics

[3] For Jupiter, Vasyliunas proposed a steady state magnetospheric model with reconnection on closed field lines that then sheds plasma islands down the tail and returns nearly empty flux tubes to the inner magnetosphere [*Vasyliunas*, 1983]. The Galileo observations at Jupiter indicate that beyond 40 R_J (one Jupiter radius, RJ, is taken throughout this paper to be 71373 km), the current sheet begins to tear, and beyond 50 R_J on the nightside explosive reconnection can occur as the tearing site reaches the low density lobe region above and below the current sheet [*Russell*, 2000]. Such tail reconnection events are evidenced by regions of strong northward and southward turnings in the magnetic field located in the postmidnight-predawn sector of the Jovian magnetosphere [*Russell et al.*, 1998].

[4] On the basis of Galileo magnetometer and energetic particle data, *Kronberg et al.* [2005] found two distinct states of the magnetotail. The first of these is the "quiet" state, which is dominated by plasma loading, characterized by plasma flow in the corotational direction, and associated with a thick and stable plasma sheet. The "disturbed" state, also known as the mass-release state, is associated with tailward/planetward plasma flow, a thin plasma sheet and magnetic reconnection. Overall, therefore, field and particle detectors on Galileo have shown energetic tail events to be associated with radial flows of energetic particles and magnetic perturbations in the current sheet.

1.2. Recent Saturn Observations

[5] By analogy with Earth and Jupiter, we may expect that at Saturn, at some distance down the Kronian magnetotail, oppositely directed field lines reconnect across the current sheet. This in turn may cause a plasmoid or

plasmoids to be released down the tail, and the newly shortened, dipolarized flux tubes to move rapidly planetward. Cassini's Saturn Orbit Insertion (SOI) maneuver was the first of many chances to glimpse the nightside magnetosphere and to attempt to decipher the dynamics and drivers of tail reconnection. On careful analysis of the structure of the interplanetary magnetic field (IMF) and comparison with Saturn Kilometric Radiation (SKR) emissions, *Jackman et al.* [2005] inferred that a solar wind compression region impacted the magnetosphere at some point during the outbound pass of SOI. *Bunce et al.* [2005] then studied this interval in detail, finding evidence for compression-induced tail collapse via magnetic reconnection and hot plasma acceleration. Since SOI, the most favorable period for looking for signatures of nightside reconnection was in 2006, when Cassini had several orbits deep in Saturn's magnetotail, albeit mostly south of the nominal current sheet location. Using data from the Cassini magnetometer (MAG), *Jackman et al.* [2007] found three examples of plasmoid passage down the tail, the features of which will be referred to in more detail in the discussion section.

[6] However, in order to obtain information on the location of the reconnection site itself, one either needs to be very lucky by having the spacecraft in the right place while reconnection is ongoing, or else have the benefit of reliable remote sensing techniques. *Mitchell et al.* [2005] used the Ion and Neutral Camera (INCA) on Cassini to image the magnetotail of Saturn, and detected bright emissions of energetic neutral atoms (ENA), which are well correlated with enhancements in SKR. Their results suggested that a process akin to terrestrial substorms plays a significant role in heating ions in Saturn's magnetotail, somewhere in the region between 20 and 30 R_S (one Saturn radius, R_S, is taken throughout this paper to be 60268 km). *Hill et al.* [2008] subsequently used INCA ENA emission data to infer the location of the reconnection site for a plasmoid event in 2006, and found it to be at $\sim$26.5 R_S.

[7] Pre-Cassini, Saturn's magnetosphere was commonly regarded as intermediate between the solar wind driven terrestrial magnetosphere, and Jupiter's rotationally driven system. Let us first consider the solar wind interaction at Saturn and its role in magnetospheric dynamics. *McAndrews et al.* [2008] have shown evidence for in situ dayside reconnection through heating of the electrons and acceleration of the ions at the dayside Kronian magnetopause. Estimates of the speed and direction of the observed accelerated flows agree with the predictions of the plasma behavior during reconnection at Earth, and the reconnection voltage is calculated from the examples to be 48 kV. *Jackman et al.* [2004] estimated the amount of open flux added to the Kronian system through dayside reconnection, based on an empirical formula adapted from Earth, and found an average value of $\sim$50 kV, in good agreement with the *McAndrews et al.* [2008] result. They consider the simple case where open flux is continually added to the system through dayside reconnection. When the open flux within the magnetosphere reaches above a certain threshold (taken to be 45 GWb [e.g., *Milan et al.*, 2005]) the magnetotail becomes unstable, reconnection occurs, and previously open flux is closed. These calculations led to an estimate (based purely on addition and removal of flux from the system) of $\sim$3–5 Kronian "substorms" per $\sim$25.5 day solar rotation, each closing 20 GWb of flux. *Badman et al.* [2005] estimated the amount of flux in the Kronian system from auroral images taken during the January 2004 Cassini-Hubble campaign. Using the poleward boundary of the auroral oval as a proxy for the open-closed field line boundary, they estimated the amount of open flux contained within the polar cap. By observing changes over the campaign, they inferred that intermittent intervals of tail reconnection occur at rates of $\sim$30–60 kV in rarefactions, compared with $\sim$100–200 kV during compressions. *Badman and Cowley* [2007] then went on to consider the contribution of the solar wind-driven Dungey cycle to flux transport in Saturn's magnetosphere. They concluded that in the middle and outer magnetosphere, the peak Dungey cycle voltages become comparable to the voltages associated with the flows driven by planetary rotation. As such, Dungey cycle "return" flow will make a significant contribution to the flux transport in the outer magnetospheric regions.

[8] We next consider the role of internal drivers. For the terrestrial case, there is no significant internal source of plasma. At Jupiter, however, the volcanic moon Io acts as a source of plasma, with a mass loading rate thought to be between $\sim$500–2500 kg/s [*Delamere and Bagenal*, 2003]. This plasma loading, combined with the fast rotation of the planet largely controls Jovian magnetospheric dynamics. At Saturn, the moon Titan has its own induced magnetosphere, and is suggested as the source of a large atomic nitrogen torus surrounding Saturn at L$\sim$20 [*Sittler et al.*, 2006]. Titan's flow wake is expected to be large in extent (>20 R_T - one Titan radius, R_T, is taken to be 2575 km) [*Ma et al.*, 2006], with a significant mass loading rate of up to $\sim 6 \times 10^{25}$ ions/s ($\sim$1.2 kg/s) [*Modolo et al.*, 2007; *Modolo and Chanteur*, 2008]. Various authors have also modeled the Cassini data from several flybys of the icy moon Enceladus, and estimates for the mass loading rate near the moon range from <3 kg/s to $\sim$100 kg/s [*Khurana et al.*, 2007; *Pontius and Hill*, 2006; *Burger et al.*, 2007]. Thus, the plasma source rates from Saturn's moons are an order of magnitude smaller than the rate for Io at Jupiter. However, that does not preclude them from playing a role in driving magnetospheric dynamics.

2. In Situ Observations

[9] In order to look for signatures of tail reconnection at Saturn, we surveyed all of the Cassini fluxgate magnetometer data [*Dougherty et al.*, 2004] from SOI through to the start of 2008. We searched over a wide local time range in the pre-midnight through to pre-dawn sectors of the magnetotail, and over radial ranges from $\sim$25 R_S out into the distant Kronian magnetotail beyond $\sim$70 R_S. We expected that, as at Jupiter, the signatures of reconnection would be prominent in the B_θ (north-south) component of the magnetic field in the first instance, but we would also expect to see the effects of angular momentum conservation in B_φ and B_r, the azimuthal and radial field components [e.g., *Hairston and Hill*, 1986]. Upon finding suitable magnetic field signatures, we were then able to compare with other data sets to see their corresponding features.

[10] *Jackman et al.* [2007] discussed three examples of plasmoid passage down the Kronian magnetotail, but our

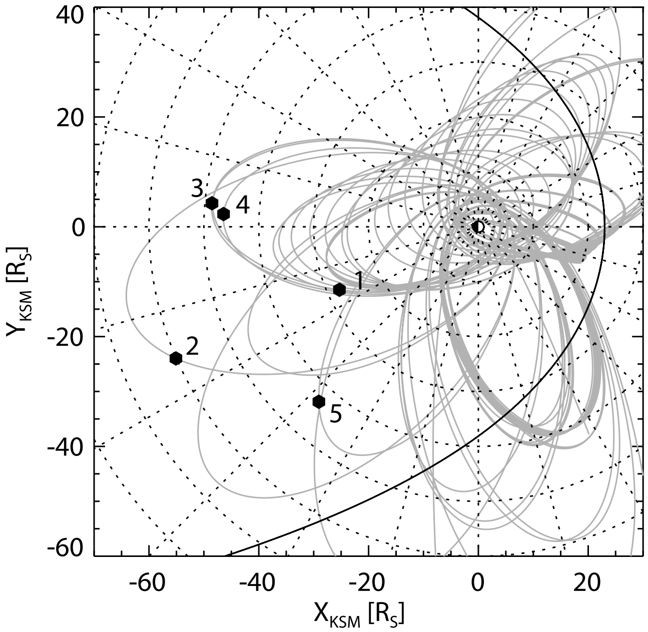

Figure 1. Orbit of the Cassini spacecraft around Saturn shown in an equatorial projection in Kronocentric Solar Magnetospheric (KSM) coordinates, where X points from Saturn to the Sun and Z is north in the plane containing X and the Saturn rotation axis. The Sun is to the right of the diagram, and the magnetopause with subsolar standoff distance of 26 R_S is shown in black [*Arridge et al.*, 2006]. The location of the spacecraft at the onset of each of the five events discussed in the paper is numbered and shown by the black hexagons. The dates of the events are (1) 6 September 2006, (2) 18 June 2006, (3) 4 August 2006, (4) 12 July 2006, and (5) 4 March 2006.

subsequent search has uncovered two new events which we discuss in detail here. We support our analysis of these new events with a more general discussion of all five tail reconnection events uncovered thus far, and highlight their similarities and also some important differences when compared to substorm-like phenomena at Earth and Jupiter. These five events are the clearest examples from our exhaustive search of the Cassini magnetometer data. The most probable reason for lack of more in situ evidence of tail reconnection at Saturn is unfavorable viewing geometries. Unfortunately (for the purposes of studies such as this one), the nature of the Cassini trajectory over much of 2007–2008 was not favorable for searching for plasmoids in the Kronian tail, as the spacecraft moved into higher-latitude orbits and did not reach the downtail distances required to see such structures. Our search was also hampered by the fact that the Cassini tail passes were near the equatorial plane, which owing to current sheet hinging meant that the spacecraft was below the nominal current sheet location most of the time. However, further deep tail passes are planned for the Cassini extended mission phase, and so we are hopeful of expanding our database of these type of events. Figure 1 shows the location of the five events with 1 and 2 to be discussed in detail here, and 3, 4 and 5 having been discussed previously by *Jackman et al.* [2007].

2.1. Event 1 on 6 September 2006: Magnetic Field and Electron Observations

[11] The first event we are going to discuss occurred on 6 September (day 249) 2006 at ~1534 UT, when Cassini was at a radial distance of 28.21 R_S, a latitude of 3.1° and a local time of 1.6 h. Figure 2 shows MAG and CAPS-ELS data for the interval from 1200 to 1900 UT on 6 September. The top four panels show the three magnetic field components and field magnitude in KRTP coordinates, 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 positive in the direction of corotation. The fifth and sixth panels show the derived electron density and temperature values from the electron spectrometer (CAPS-ELS) instrument, while the bottom panel shows CAPS-ELS measurements of electrons in the energy range ~0.6–28 keV, in the form of an energy-time spectrogram from anode 5 of the ELS instrument [*Young et al.*, 2004]. The spectrogram distribution has been shifted to lower energies by subtracting the spacecraft potential from each energy bin. Thus we now only show particles with energies above this spacecraft potential, and avoid contamination by secondary electrons and photoelectrons.

[12] Throughout the interval shown there are several clear crossings of the current sheet (at the center of which the radial component of the field is zero). As expected, these crossings are coincident with local maxima in electron density. The presence of a current sheet at Saturn was inferred from Voyager data [*Behannon et al.*, 1981], and it is characterized by higher ion and electron intensities and radially stretched field lines, with the energetic particles concentrated in a disk-like layer around the equatorial plane of the planet [*Arridge et al.*, 2008; *Krupp et al.*, 2005]. In the second panel, the event of interest is a clear southward followed by northward turning of the field centered on ~1534 UT. Figure 3 shows an expanded plot of the field components and total field magnitude for a shorter interval surrounding this event, from 1520–1545 UT, and we refer the reader to this plot for closer examination of the behavior of the magnetic field over short time scales.

[13] The total field strength had been rising steadily prior to the event centered on 1534 UT, peaked (at >4 nT at ~1525 UT) and then began to fall. At ~1533 UT, the theta component then began to decrease and hovered ~0 nT while the total field strength was at a minimum of ~0.5 nT. Following this, the theta component then turned fully northward. During the southward-northward turning, the spacecraft had a brief (~1 min) encounter with the center of the current sheet. This is evidenced by a switch from negative to positive radial field, and indicates that the current sheet had moved down to meet Cassini which had previously been sitting below the current sheet's mid-plane. There is a clear localized density peak of ~4 × 10^4 electrons/m^3 coincident with the positive excursion of the radial component and the center of the current sheet. The temperature at this time shows a local minimum of ~100 eV. Statistical studies show that electron temperatures of 100–1000 eV, with a peak of ~300 eV, and electron densities between 5 × 10^4–5 × 10^5/m^3 are typical in the plasma sheet of Saturn [*Arridge et al.*, 2007]. From the spectrogram in the bottom panel, there is a clear cutoff in the higher-energy electron population after the event at 1534 UT.

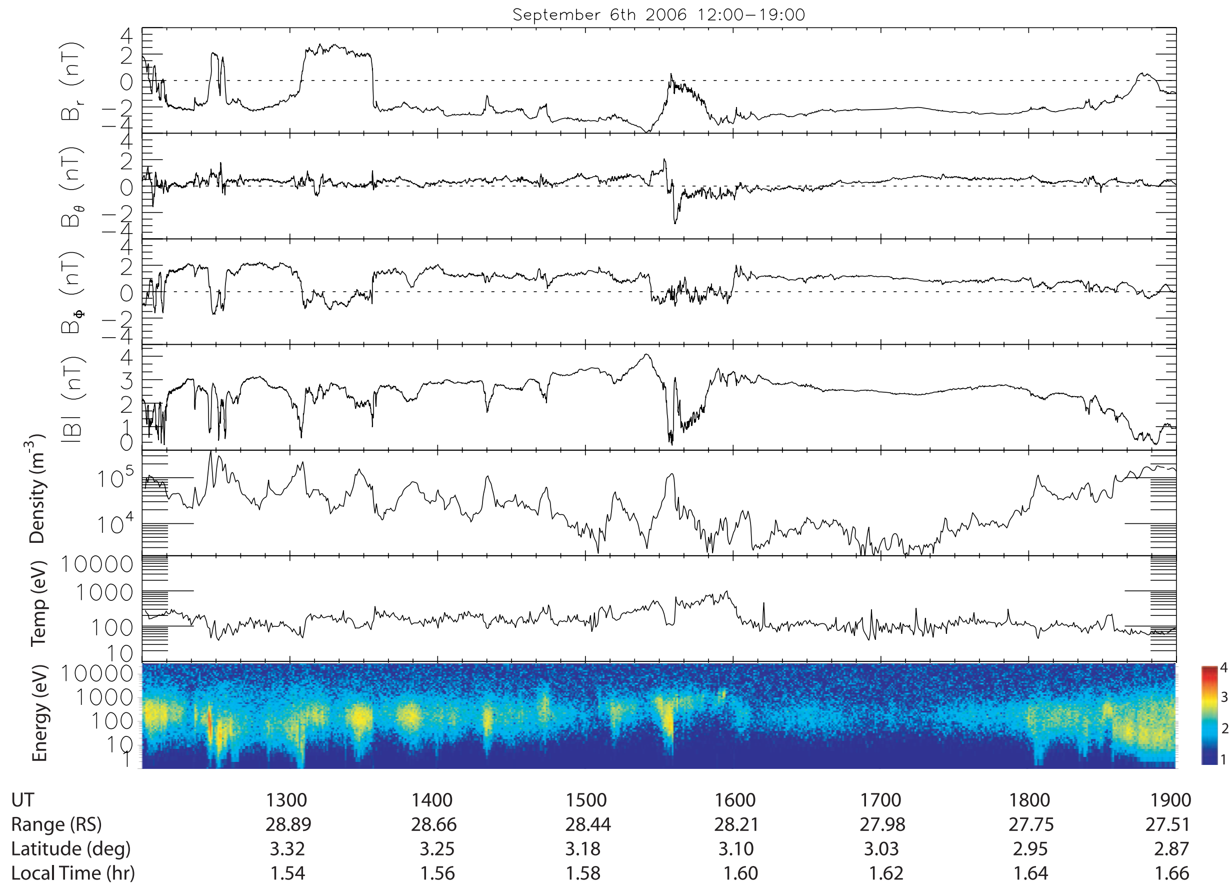

Figure 2. Magnetic field and CAPS-ELS measurements for an interval from 1200 to 1900 UT on 6 September 2006. The top four panels show the magnetic field components in KRTP coordinates and field magnitude, the next two panels show thermal electron density and temperature moments calculated from the CAPS-ELS instrument data, and the bottom panel shows an electron spectrogram. Information detailing the radial distance, latitude, and local time of Cassini with respect to Saturn is given at the bottom of the plot.

[14] Current estimates place the likely position of the reconnection site in the region of ~20–30 R_S [e.g., *Mitchell et al.*, 2005; *Hill et al.*, 2008]. The event shown in Figures 2 and 3 occurs with Cassini at ~28.21 R_S, and involves a very rapid south-north turning with a total maximum field deflection of ~4.8 nT, which is very significant relative to the surrounding field behavior. On close examination of the field components and electron signatures, we suggest that prior to ~1534 UT, Cassini was on the planetward side of a reconnecting field line, and that the south-north turning is indicative of a newly reconnected flux tube passing over the spacecraft. The timing of the minimum in total magnetic field strength, coincident with the point where the theta component goes through zero, acts to confirm this scenario. Last, the concurrent current sheet encounter could be the result of movement/deformation of the sheet in response to this dipolarization.

2.2. Event 2 on 18 June 2006: Magnetic Field and Electron Observations

[15] The next event we will discuss took place at ~0034 UT on 18 June (day 169) 2006, when Cassini was at a radial distance of ~62.15 R_S, a latitude of 0.3°, and a local time of 1.51 h. In Figure 4 we show MAG and CAPS-ELS data in a similar format to Figure 2 for the interval from 1800 UT on 17 June to 1800 UT on 18 June 2006. In the second panel, the magnitude of the field is superimposed (plus and minus) on the theta component, to illustrate when the theta component becomes the dominant one. We have omitted the density and temperature moments for this interval as the reliable values were somewhat sparse owing to poor signal-to-noise over much of the interval. This event is very different in character to that observed on 6 September for several reasons. First it was observed in the deep magnetotail of Saturn, far from the likely reconnection site, and second Cassini was south of the magnetic equator for the entire period shown in Figure 4 (as evidenced by the negative radial component), and thus did not encounter the center of the current sheet at any point. In the second panel, we observe the main event as a clear northward turning in the B_θ component at ~0034 UT on 18 June. This initial sharp turning was of magnitude ~1.8 nT followed by a slow recovery of the field over approximately 9 h. This northward turning is accompanied by a disturbance in the azimuthal component of the field (B_φ), indicative of the presence of hot plasma, and a peak in the total field magnitude. As evidenced from the spectrogram, there is a distinct disappearance of higher-energy electrons at

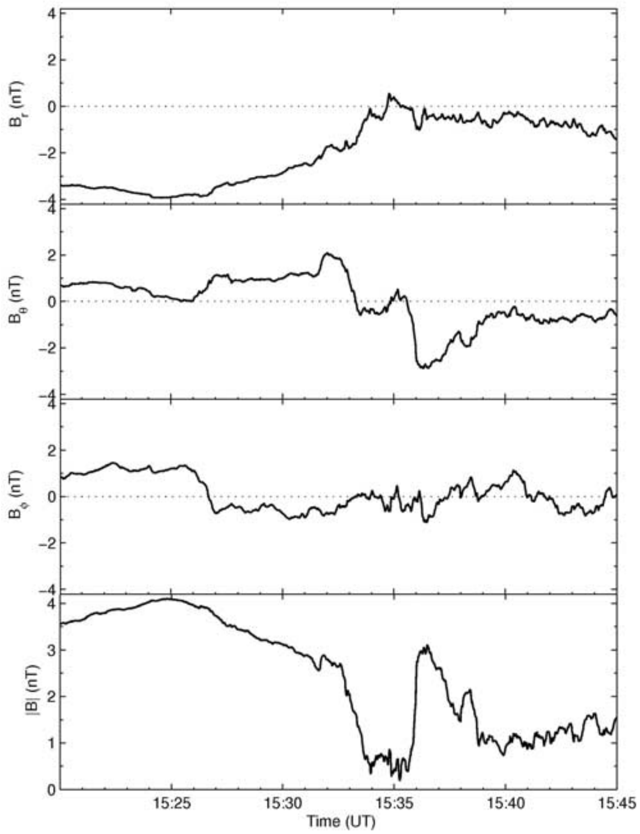

Figure 3. Expanded plot of magnetic field components and total magnetic field strength for the interval from 1520 to 1545 UT on 6 September 2006.

~0030 UT on 18 June, coincident with the northward turning of the field.

[16] At the beginning of the interval shown in Figure 4, Cassini was sampling tail-like fields with a small theta component. The northward turning of the field at ~0034 on 18 June then indicates that Cassini is tailward of the reconnection site. While the northward turning in this case was sharp, the magnitude of the field deflection (~1.8 nT) was a factor about two less than the average deflection for the other events discussed here. This decreased deflection magnitude is likely due to the spacecraft's location further downtail at ~62 R_S. At this distance, owing to hinging, Cassini was probably far from the nominal current sheet location, and we suggest that the spacecraft is observing a field deflection due to the Kronian equivalent of a Traveling Compression Region (TCR) [e.g., *Slavin et al.*, 1984]. TCRs are intensifications of the lobe magnetic field commonly observed in the terrestrial magnetosphere. They are thought to be caused by localized bulges in the plasma sheet due to the formation and rapid movement of plasmoid-type flux ropes moving down tail. We suggest that in the case we observe on 18 June 2006, a reconnection event has occurred closer to Saturn than the location of Cassini, a plasmoid or plasmoids have been released down the tail, and the signature observed by Cassini is consistent with magnetotail reconfiguration due to the plasmoid(s) squeezing past, disturbing the otherwise tail-like field lines. We expect that if the reconnection site is planetward of ~30 R_S, plasmoids would have evolved considerably by 62 R_S downtail, changing their shape and morphology as they proceed downtail, and expanding to achieve pressure balance.

3. Discussion

3.1. Magnetic Field

[17] In this paper we have shown two new observations at Saturn linked with tail reconnection, and these, together with the original three examples discussed first by *Jackman et al.* [2007] and subsequently by *Hill et al.* [2008] make up a data set of five examples from which to draw some general conclusions on the processes of reconnection in the Kronian magnetotail.

[18] In terms of the magnetic field data, tail reconnection events are characterized by north/south turnings of the magnetic field, suggesting reconfiguration of the field lines in the magnetotail, as has been observed for Jupiter by *Russell et al.* [1998]. Northward turnings of the field in the Kronian magnetotail can indicate that the spacecraft is tailward of the reconnection point, and can help to identify tailward movement of plasmoids and associated magnetic O-lines. Southward turnings can indicate a spacecraft location planetward of the reconnection point. These north/south turnings in several cases are accompanied by signatures of angular momentum conservation. As energetic reconnection events occur, the magnetized plasma is convected either toward or away from Saturn, and the azimuthal and radial field components may have the same sign, indicating that plasma has been sped up from corotation. The five examples occur at a range of downtail distances, from ~28 R_S to ~62 R_S, a reasonably narrow range of local times (23.67–3.08 h) in the midnight-dawn sector, and latitudes between 0.12–10.2°. Owing to the range of locations with respect to the equatorial plane, some intervals studied involve several current sheet crossings, while others never encounter the central part of this region. The magnitude of the field perturbations in the theta component varies considerably, from ±~1.5 nT to ±>4 nT, and this is in part due to varying viewing location, but also to varying plasmoid size or strength of the original reconnection event. As plasmoids travel rapidly down the magnetotail, we may expect that the field would be piled up against the plasma, a feature which is commonly seen at Earth associated with plasmoids and TCRs [e.g., *Taylor et al.*, 2006]. This manifests itself in enhancements in the total field strength, which are generally observed around the times of the events shown here. We also note that a growing plasmoid might change the tail flaring angle and the total field strength. The total field strength often displays an "overshoot" which can possibly be attributed to reconnection affecting the structure of the rarefied lobe region.

3.2. Plasma Parameters

[19] While the magnetic field data alone gives us many clues as to the reconfiguration of the field lines in the tail, the addition of other data sets enables us to confirm some of these ideas, and gives us additional insight into the process of magnetotail reconnection at Saturn. In general, for the events studied here, plasmoid passage is associated with an initial enhancement in the electron fluxes seen in the CAPS-

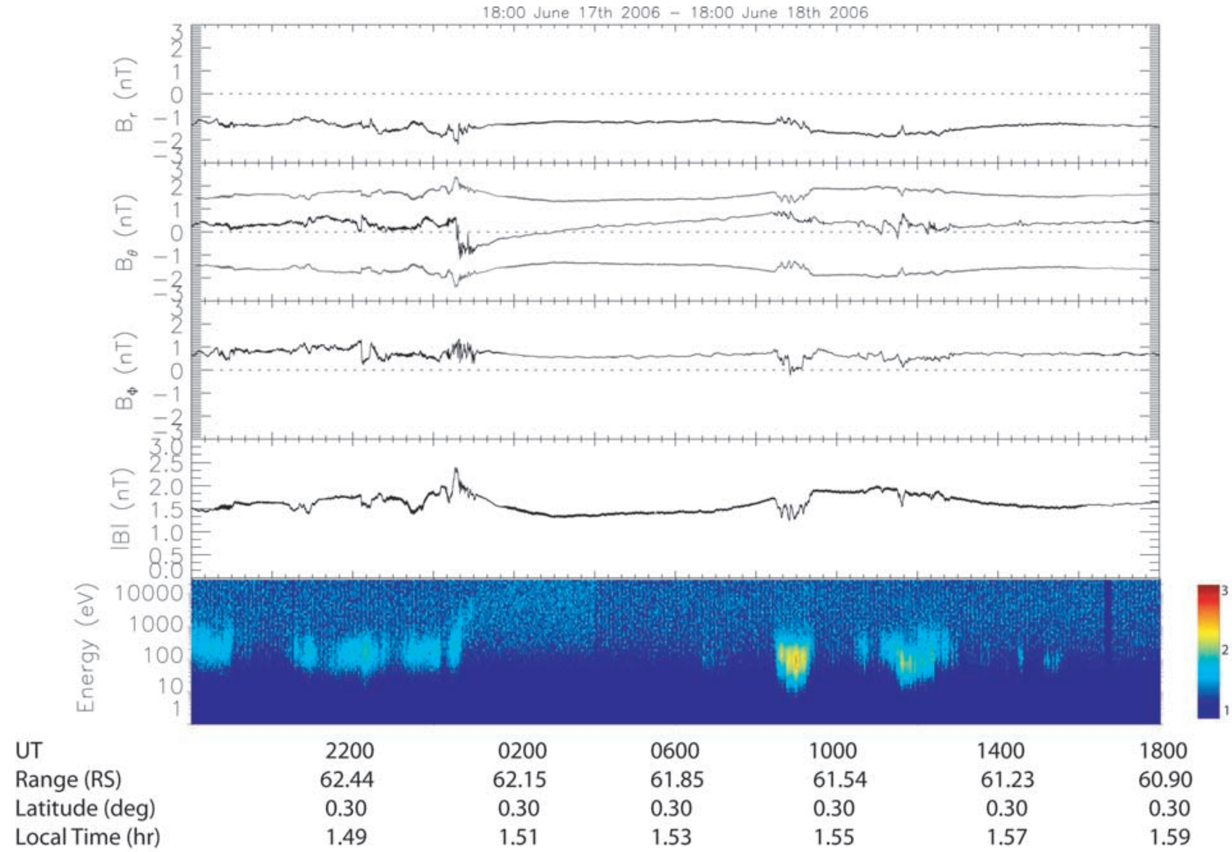

Figure 4. Plot of MAG and CAPS-ELS data in a similar format to Figure 2, with CAPS-ELS density and temperature moments omitted, for the interval from 1800 on 17 June to 1800 on 18 June 2006. In the second panel, plus and minus the total field magnitude is overplotted with thin solid lines.

ELS spectrograms, while after the main field signature the higher-energy population then abruptly cuts off. There are two possible explanations for this which are difficult to distinguish owing to measurement limitations; either Cassini has just moved out into a region with fewer ambient electrons, or Cassini has witnessed a sudden evacuation of plasma from the plasma sheet, consistent with the passage of a plasmoid. Following the abrupt cutoff in the electron population, Cassini is then in general immersed in a field and plasma configuration characteristic of the tail lobe. In general, the electron densities see a local peak prior to the magnetic field signatures, and then sharply decrease coincident with the passage of the plasmoids, in some cases by more than an order of magnitude. The density decreases could signify that Cassini is sampling a relatively empty magnetotail after plasmoid passage.

3.3. Energetic Particles

[20] The high-energy plasma data from MIMI yield clues as to the motion of the energetic particles before, during and after reconnection events. In Figure 5 we show an example of MIMI-INCA data from 4 August 2006 1220–2400 UT. The top panel shows high time resolution fluxes from INCA, where all ions are treated as if they were hydrogen, with the black line showing ions in the 50–80 keV range, and the orange line showing the 20–50 keV range. The second panel shows the magnetic field data in KRTP coordinates for reference, while the bottom panels show the spacecraft Quaternions and other spacecraft attitude information for the interval. Trajectory information is given at the bottom of the plot. Blue vertical lines are over-plotted to indicate times when INCA was pointed parallel to the corotation direction.

[21] At the beginning of the interval shown, the spacecraft was rotating about the z axis (as shown by the pink lines in the bottom panel), and this spin axis was pointed toward Earth. The INCA ion intensities were smoothly modulated by this spacecraft roll, with flux maxima occurring when the INCA field of view faces into the convective (corotation direction) flow and the minima occurring when INCA faces away from the flow. Corotation flow is perpendicular to the z axis (spin axis), and in the dusk-to-dawn direction. Cassini stopped rolling at ~1630 UT, and resumed rolling again at ~1700 UT. This roll stoppage encompassed the key feature in the magnetic field data; the sharp northward turning at 1650 UT, which indicated the passage of the plasmoid. This northward turning was preceded by a region of depressed magnetic field, and a sharp enhancement in the intensity of the fluxes observed by INCA. Reconnection would be expected to heat the plasma sheet locally, thus leading to increased plasma pressure, and decreasing field magnitude, so these signatures seem consistent with the plasmoid picture. During the plasmoid passage however, the INCA measurements show that the

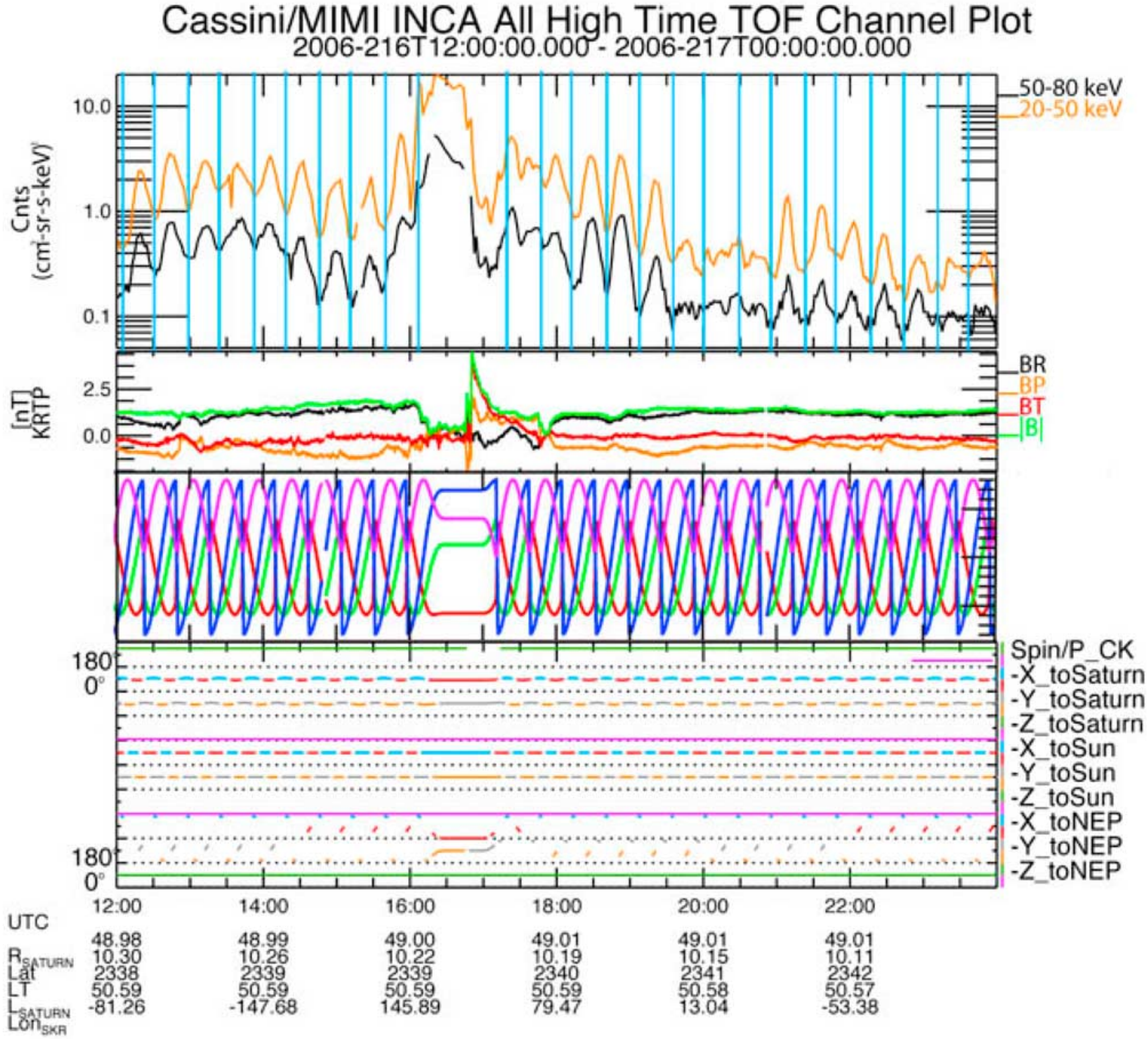

Figure 5. Plot of MIMI-INCA and MAG data for the interval from 1200 to 0000 UT on 4 August 2006. The top panel shows INCA ion intensities in two energy ranges, the second panel shows the magnetic field data, color-coded according to the legend on the right, and the bottom panels show the spacecraft Quaternions and further spacecraft attitude information. Blue vertical lines are drawn at times when INCA is pointed parallel to the corotation direction. Trajectory information is shown at the bottom of the plot.

flow direction was nearly reversed away from the nominal corotation direction. Once the plasmoid had gone by, and for the rest of the day while Cassini is rolling, the previous pattern of INCA observations resumes, whereby flux maxima are observed when INCA looks into the corotation direction.

[22] Thus, the data for this example clearly show how the pattern of flow maxima with the corotation direction can be dramatically disturbed by the passage of a plasmoid. This is similar to observations by *Kronberg et al.* [2005] for Jupiter where they found a "disturbed" state of the magnetotail following reconnection, where tailward/planetward flow of energetic particles was observed as opposed to the typical flow in the corotational direction during "quiet" phases. Another example of flow disturbance at Saturn was reported by *Hill et al.* [2008] for the event on 4 March 2006. They noted that during the approach of the plasmoid, the flow vector rotated away from the azimuthal direction and toward the radial direction, while toward the end of the plasmoid encounter the flow became generally tailward.

3.4. Plasmoid Properties

[23] *Kronberg et al.* [2008] studied such properties as speed, length and associated convection electric field for Jovian plasmoids, based on a larger selection of observations from the magnetometer and energetic particles detec-

tor on Galileo. They found the average speed of plasmoids in the plasma sheet to be between 350 and 500 km s^{-1} (approximately Alfvenic speed), and the duration of the events to be between 10 and 20 min. The associated plasmoid length is typically ~9 R_J, and the convection electric field is ~1–2 mV m^{-1}.

[24] Thus far at Saturn, in situ velocity data has been limited, but *Hill et al.* [2008] presented estimates for the velocity of a plasmoid observed on 4 March 2006 at ~44 R_S downtail from the planet. On the basis of data from the ion mass spectrometer (IMS) on Cassini, they estimated that the plasmoid approached the spacecraft at speeds of the order of ~1.1–1.4 R_S/min (1106–1407 km/s) [*Hill et al.*, 2008]. They placed an upper limit of 1000 km/s on the magnetic O-line speed tailward, with a suggested average x-line speed of 500 km/s. If we assume an average ion bulk velocity of 500 km/s, and a average deflection in the theta component of the field of 3.2 nT, we find an average convection electric field of ~1.6 mV/m, based on four events. We note that we exclude the event of 6 September 2006 as this was not a direct observation of a plasmoid. This value of convection electric field is about an order of magnitude higher than the typical ambient Kronian value, similar to the condition found by *Kronberg et al.* [2008] for Jupiter.

4. Conclusions and Future Directions

[25] As mentioned in the introduction, the search for tail reconnection events at Saturn has been limited by viewing geometries, apart from the period in 2006 where Cassini was exploring the deep Kronian magnetotail. However, some of the planned orbits for the Cassini extended mission may afford us the opportunity to search for plasmoids. In the intervening period, the discovery of these five events opens up several possibilities for further analysis. Current work is focusing on the role of the SKR emissions in these events (C. M. Jackman et al., The relationship between SKR and substorms, manuscript in preparation, 2008). SKR is an excellent monitor of global magnetospheric dynamics, and it may ultimately help to separate out the relative importance of solar wind versus internal control in the Kronian system. Previous work has shown evidence for solar wind compression-induced tail reconnection at Saturn linked with a large burst of SKR [*Bunce et al.*, 2005]. However, a link between the position of Titan and the occurrence probability of SKR has also been reported [*Menietti et al.*, 2007], and the role of Titan as an internal driver of dynamics explored [*Russell et al.*, 2008].

[26] Various approaches have been developed for Earth and Jupiter to model the processes which drive tail reconnection in their respective magnetospheres. *Freeman and Morley* [2004] developed a minimal substorm model (hereafter, MSM) for Earth, driven with a power input derived from solar wind observations, which then outputted a sequence of simulated substorm onsets. The distribution of waiting times between substorms was reasonably similar to that found by *Borovsky et al.* [1993] from 1 year of energetic particle observations at geostationary orbit. Cassini's magnetometer took continuous data upstream of Saturn for many months prior to SOI, and the structure of the IMF at ~9AU has been well characterized [e.g., *Jackman et al.*, 2004, 2008]. As such, there is scope to develop models with a number of simple rules similar to the MSM, based on solar wind input to Saturn's magnetosphere, to try to predict the frequency and duration of tail reconnection events at Saturn. For the case of Jupiter, *Kronberg et al.* [2007] observed the periodic signatures of tail reconnection events, and presented a simple conceptual model assuming internal mass loading and fast planetary rotation with field line stretching. Their model found that the intrinsic time constant of the Jovian reconfiguration process depends primarily on internal parameters such as the mass-loading rate, but is effected by the external solar wind conditions. They took into account tearing instability thresholds required for reconnection to occur in the Jovian magnetotail, and a similar paradigm may be applied to Saturn.

[27] The events shown here are the five clearest examples we have seen to date as evidence of magnetic reconnection in Saturn's magnetotail. Future orbits of Cassini will hopefully lead to further in situ observations, and enable us to better constrain the typical properties of Kronian substorms. The studies presented here enforce the fact that Saturn's magnetosphere is neither Earth-like nor is it Jupiter-like, but that the magnetospheric dynamics at Saturn are entirely unique.

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