Strong rapid dipolarizations in Saturn's magnetotail: In situ evidence of reconnection

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[1] The oppositely directed magnetic field in the kronian magnetic tail is expected eventually to reconnect across the current sheet, allowing plasma to escape in an anti-solar direction down the tail. This reconnection process accelerates ions and electrons both toward and away from the planet, allowing the magnetotail to relax to a more dipolar configuration. Previous missions to Saturn shed no light on the possible presence of this critical process in the kronian magnetosphere. Recent Cassini measurements of the magnetic field in the magnetotail, reported herein, reveal strong, rapid dipolarizations between 40 and 50 Saturn radii (R_S) downtail, signalling the episodic release of energy to the magnetosphere and ions to the solar wind. **Citation:** Jackman, C. M., C. T. Russell, D. J. Southwood, C. S. Arridge, N. Achilleos, and M. K. Dougherty (2007), Strong rapid dipolarizations in Saturn's magnetotail: In situ evidence of reconnection, *Geophys. Res. Lett.*, *34*, L11203, doi:10.1029/2007GL029764.

[2] The term "substorm" was first conceived of at the Earth, to describe a sequence of magnetospheric events, including auroral brightening, in which energy was deposited in the nightside ionosphere and upper atmosphere. Now it is understood in terms of a growth phase, where, through dayside merging and subsequent transport, the tail is loaded with magnetic flux and reconnection begins on closed magnetic field lines. This is followed by an expansion/onset during which a plasmoid is released down the tail and the magnetosphere dipolarizes, and a recovery phase, during which the plasma sheet recovers to its original state [*Russell and McPherron*, 1973]. The terrestrial substorm is best described in terms of *Dungey*'s [1961] model of reconnection of the interplanetary magnetic field with the dayside magnetosphere, in which magnetic flux is opened and carried to the tail where it is then closed by reconnection, thereby driving magnetospheric convection.

[3] At Jupiter, tail reconnection on stretched closed magnetic field lines also produces plasmoids, leading to the jettison of plasma originally added to the magnetosphere by Io and the return of (depleted) magnetic flux into the inner magnetosphere [*Vasyliunas*, 1983]. While *Vasyliunas*' [1983] model like *Dungey*'s [1961] was a steady state model, it too can work in a time-varying unsteady manner. Based on pre-Cassini observations (such as from the flyby missions Pioneer 11 and Voyager-1 and 2, e.g., *Bagenal* [1992]), it is often stated that Saturn's magnetosphere is intermediate between the case of the Earth, where the dominant processes are solar wind driven, and the case of Jupiter, where processes are driven by a large source of internal plasma, and rapid rotation.

[4] The observations presented here reveal some signatures similar to those seen at Jupiter [*Russell et al.*, 1998], with strong transient increases in the field strength and clear indications of field bending due to angular momentum conservation during radial transport. Such signatures were also observed by *Kronberg et al.* [2005], who studied the periodic release of mass from the jovian system. They concluded, on the basis of a statistical study, that at least some of the observed jovian reconfiguration events exhibit striking differences to terrestrial substorms in terms of driving mechanisms, and suggest that the role of the solar wind is minimal compared with that of internal plasma loading from Io. In the kronian system, it is now known that the icy moon Enceladus releases significant amounts of neutral water molecules, many of which become ionized and accelerated to Saturn's corotational velocity [e.g., *Dougherty et al.*, 2006, and references therein]. The ions that become trapped on the magnetic field lines produce ion cyclotron waves [*Leisner et al.*, 2006], while the field lines are stretched into a magnetodisk configuration [*Arridge et al.*, 2007]. The precise role of the solar wind versus internal control in the kronian system is a subject which has not yet been fully explored, however, the data display features that are consistent with different aspects of both driving mechanisms, and there is some cursory evidence for changes in the flux contained in the lobes of the magnetotail that are reminiscent of terrestrial flux closure.

[5] A major difference between the kronian and jovian magnetospheres is that there is a less than 1° tilt of the kronian magnetic dipole to its rotation axis, while the jovian dipole tilt is close to 10°, as is Earth's. Thus the tail is not expected to rock back and forth around the planet-sun line as the jovian and terrestrial magnetotails do. Saturn's rotation axis is strongly inclined to its orbit pole, and as such, the tail current sheet can be tilted away from Saturn's equator [*Arridge*, 2007]. Due to its orbital trajectory, Cassini has not had much prime observing time near the tail current sheet, and thus our search for tail reconnection events has been limited to relatively small tour segments thus far.

[6] We have, however, had a few brief glimpses of kronian tail dynamics since the arrival of Cassini at Saturn. *Bunce et al.* [2005] conducted a multi-instrument study on the spacecraft's outbound pass during the Saturn Orbit Insertion (SOI) interval. Ion and electron observations in

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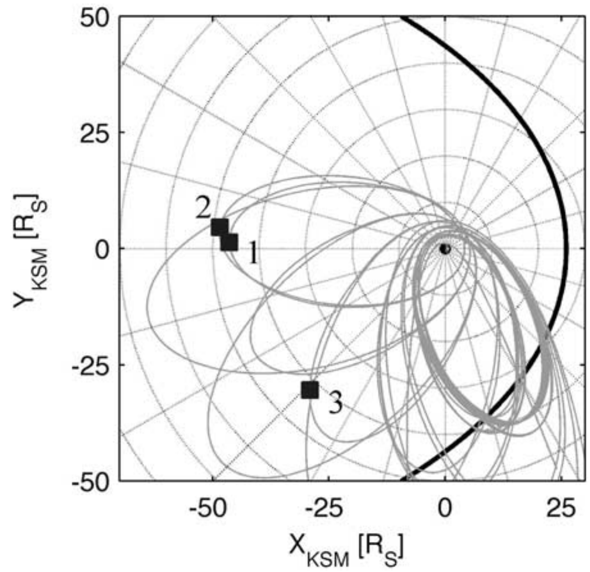

Figure 1. Orbit of the Cassini spacecraft around Saturn shown in an equatorial projection in KSM coordinates, where X points from Saturn to the Sun, and Z is north in the plane containing the X and Saturn axis. The Sun is to the right of the diagram, and the magnetopause with subsolar standoff distance of 26 R_S is shown in black [*Arridge et al.*, 2006]. The location of the spacecraft at the onset of each of the three events discussed is numbered and shown by the black squares.

the magnetotail show that the spacecraft was engulfed by a hot, tenuous plasma population and thus suggest that following the shock-compression that hit the planet during SOI, the magnetosphere underwent a significant reconfiguration, exemplified by a relaxation of the field and an injection of hot plasma. They interpreted the observation to be consistent with the model of *Cowley et al.* [2005], i.e. that this behaviour was caused by a major episode of tail reconnection, triggered by the impact of the compression region on Saturn's magnetosphere. Their model suggests that such magnetospheric compressions and tail collapses should be accompanied by hot plasma injection into the outer magnetosphere. During a separate period of the Cassini tour, *Mitchell et al.* [2005] used data from the Ion and Neutral Camera (INCA) on Cassini to probe the magnetotail, and found abrupt increases in the energetic neutral atom (ENA) flux coming from that general direction. These bursts of ion activity were well correlated with enhancements in the Saturn Kilometric Radiation (SKR). For one specific interval, the authors found evidence of ion acceleration/heating tailward of 20 R_S, close to the tail current sheet, and interpreted this as representing an Earth-like substorm. After two years of evolution of Cassini's orbit, data are now available from Saturn's tail to put the concept of tail reconnection and substorms at Saturn to a rigorous test. During some of the orbits in 2006 (in late July and early August in particular), Cassini was well positioned to examine the kronian magnetotail (Figure 1). The spacecraft was near midnight Saturn local time, and reached distances close to 50 R_S downtail, near to the distorted current sheet. The theta (north-south) component of the magnetic field is the one in which reconnection should be most apparent, as we look for signatures of the field lines moving from a tail-like to a more planetary-like (or plasmoid-like) configuration. Since Saturn's dipole moment is oriented northward of the ecliptic (similar to Jupiter's but opposite to Earth's) we expect to see northward turnings of the field (negative theta component) when the spacecraft is beyond the reconnection point, and southward when the spacecraft is closer to the planet than the reconnection point. However, we note that the reconnection events in question may result in a dramatic reconfiguration of the field, and we would also expect angular momentum conservation to play a role here, thus affecting the radial and azimuthal components. After surveying all of the Cassini data from the kronian magnetotail, we have selected three specific reconnection events for study (marked 1–3 on Figure 1).

[7] The largest of these tail reconnection events occurred on August 4 2006, and in Figure 2 we show data from the Cassini magnetometer in KRTP co-ordinates. The northward turning on this day is almost identical to a well-studied jovian tail reconnection event [*Russell et al.*, 1998]. In both events the spacecraft is situated close to the current sheet with a weak (outward) magnetic field, as evidenced from the radial component (top panel). The north-south field is weak and the azimuthal component is weaker than the radial. As can be seen from Figure 2, the sudden change in the north-south component more than doubles the field magnitude even when referenced to the strongest previous field strength. In the second panel, the total field strength (plus and minus) is plotted over the theta component. After the initial transient behaviour, we see the event onset clearly at ~1650 UT. The theta component becomes the primary one, being almost coincident with the total field trace, as the rapid and strong effects of tail-lobe reconnection reach the spacecraft. The field after the event is now mainly in the north-south direction, as opposed to the tail-like configuration prior to the onset. Cassini is beyond the reconnection point in this case, as illustrated in the schematic Figure 3a.

[8] A second example of a northward turning of the field is observed on July 12 2006 (Figure 4). This event occurs further from the current sheet as demonstrated by the larger, almost lobe-like field strengths prior to and after the event, and the unidirectional radial component throughout. Here we show a longer period of time to illustrate the full extent of the northward turning. This event has a clear onset at ~0700 UT, followed by a slow recovery beginning at ~0745 UT and lasting for several hours. The lower field strength at the end compared with the beginning of the interval shown in Figure 4 may indicate closure of a significant portion of accumulated flux, but this is difficult to quantify. Again, this northward turning indicates that Cassini was outside of the reconnection point, and its location further out from the current sheet is sketched in Figure 3a.

[9] A third example of a rapid dipolarization in the kronian magnetotail, is shown in Figure 5. During the interval shown here, from March 4 2006, we observe two northward turnings of the field. The first occurs at ~2200 UT for ~15 minutes, after which there are a number of current sheet crossings, as evidenced primarily by the fluctuating radial field component. However, the second turning of the field is much more dramatic. At ~2258 UT we see a very sharp southward

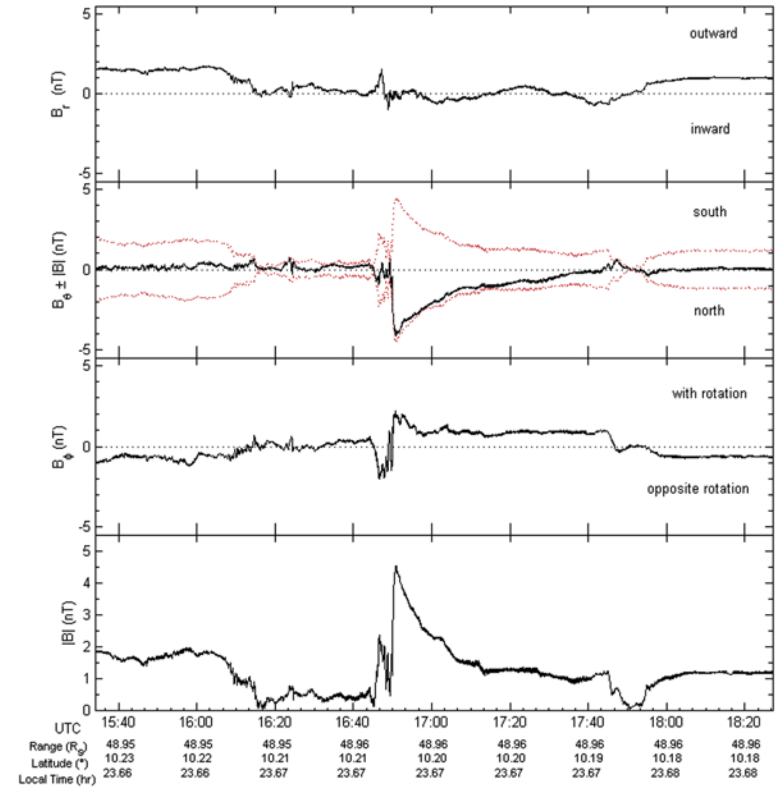

Figure 2. One second resolution magnetic field measurements from Cassini in Saturn's magnetotail for an interval from August 4, 2006. The panels show radial, theta, and azimuthal components in KRTP co-ordinates, and the total magnetic field strength. The radial component is positive outward from Saturn, the theta component is positive southward, and the azimuthal component ($B\varphi$) is positive in the direction of corotation. In the second panel, the magnitude of the field is superimposed in red (plus and minus) on the theta component, to illustrate when the values become comparable. Information detailing the radial distance, latitude, and local time of the spacecraft with respect to Saturn is given.

turning of the field followed by a rapid reversal to northward directed field ~2 minutes later. In the coordinates system used here, B_r and B_φ have opposite signs when they are bent back and the same sign when they are bent forward. After the second northward turning, the field becomes swept forward out of the meridian plane between ~2300 UT and ~2330 UT, indicating that plasma has been sped up from corotation. *Kronberg et al.* [2005] noted a similar swept-forward configuration during several tail reconnection events at Jupiter, and associated this with part of a mass-release process. After this second northward turning from Figure 5, the theta component slowly recovers. The fact that we have seen southward and northward turnings of the field in such rapid succession suggests that we may be encountering the passage of a plasmoid.

[10] Figure 3b shows a schematic representation of the possible location of the spacecraft immediately before and after the field reversal at ~2258 UT. There is evidence suggesting that we are observing the plasmoid moving rapidly tailward across the spacecraft. Initially, at position 3a, at ~2258 UT, the spacecraft is likely to be located inside the plasmoid, experiencing strong southward-directed fields. If Cassini were to then travel directly through the centre of the plasmoid and out the other side, the field might be expected to turn weakly northward and then increase slowly in the northward sense. However, the data show a sharp northward turning accompanied by a total field

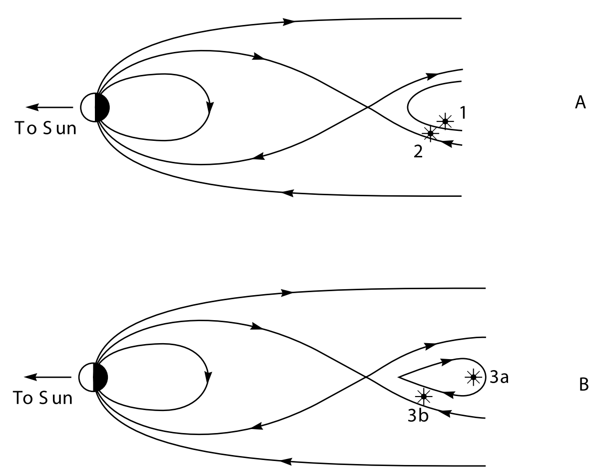

Figure 3. Schematics of slices through Saturn's magnetotail (not to scale). (a) A snapshot showing the approximate position of Cassini after the onset of events 1 and 2 on 4 August and 4 March respectively (marked with asterisks). The field has reconfigured from a tail-like configuration to this X-line geometry, with the spacecraft on the anti-planetward side of the reconnection point (northward turning of the field). (b) The approximate position of Cassini relative to a tailward-moving plasmoid during event 3 on July 12, 2006. Asterisk 3a shows the spacecraft before the southward turning at ~2258 UT, while asterisk 3b shows it after the subsequent northward turning.

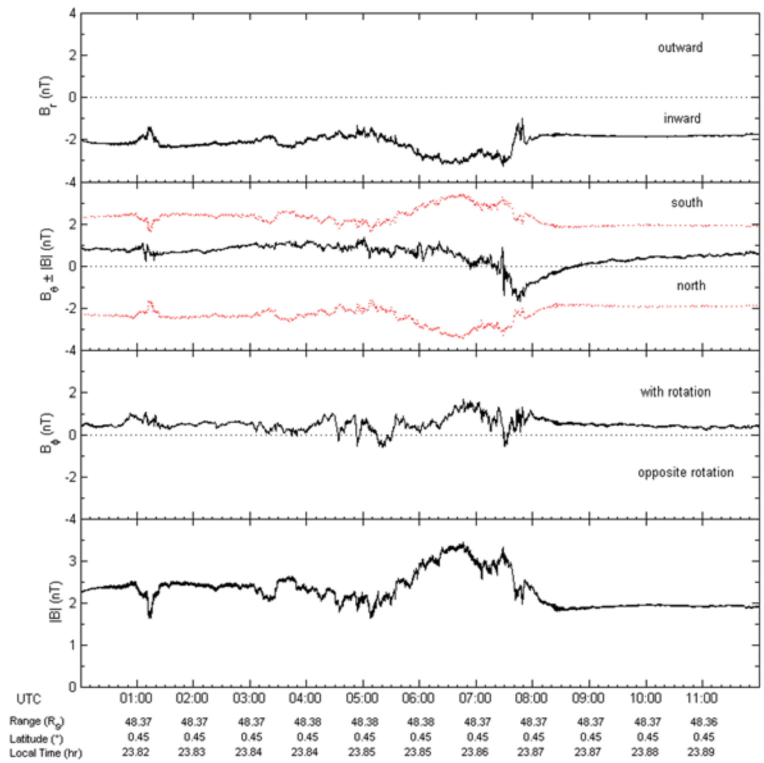

Figure 4. One second resolution magnetic field measurements from Cassini in Saturn's magnetotail for an interval from July 12, 2006, in the same format as Figure 2.

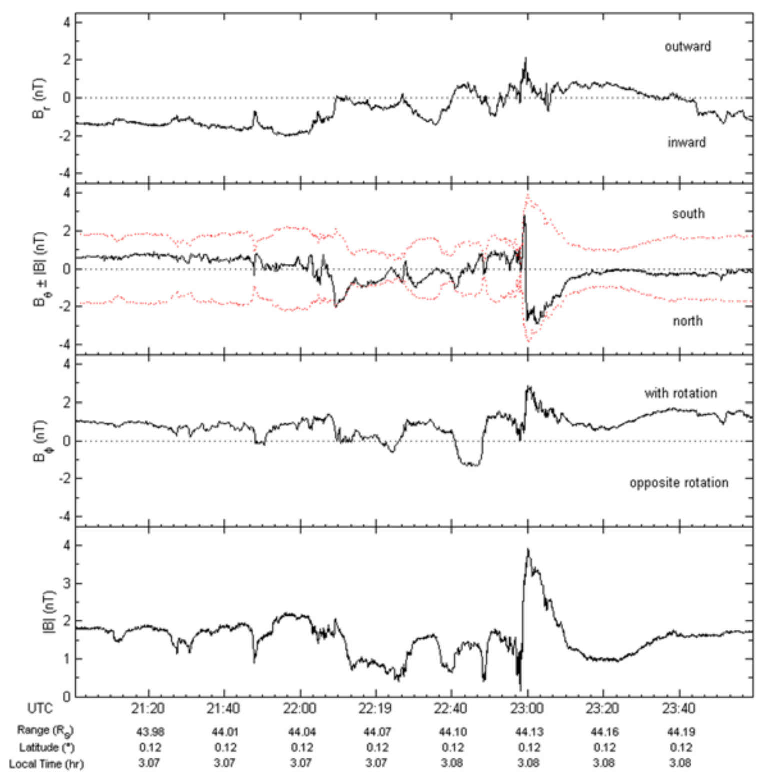

Figure 5. One second resolution magnetic field measurements from Cassini in Saturn's magnetotail for an interval from March 4, 2006, in the same format as Figure 2.

strength that reaches more than double the previous value, followed by a slow recovery. This could be attributed to a build-up of magnetic pressure that is necessary to accelerate the plasma tailward. We also note that the plasmoid shape may be distorted, and that the location of 44 RS downtail and 3 LT may be slightly offset from the direct line of motion of the plasmoids. As such, Cassini may just be encountering a section of the structures. The shape, velocity, and approximate size of plasmoids may be more accurately determined with the use of multiple data sets from Cassini. The fluctuations in the magnetic field in the hour preceding the plasmoid may be attributed to plasma sheet motions.

[11] Using the Cassini magnetometer, we have observed strong rapid dipolarizations in the kronian tail with northward and southward turnings helping to identify the approximate location of reconnection sites and the passage of plasmoids. Saturn, like Jupiter, is a very fast rotator, and both magnetospheres have internal sources of plasma, though the output rate from Enceladus is likely an order of magnitude smaller than that from Io. As such, angular momentum conservation plays an important role in the magnetic field structure. However, there are similarities to the terrestrial system too, and these tail reconnection events may result in significant changes in the open flux in the tail lobe. It is an important aim to quantify the relative importance of solar wind driving versus internal control at Saturn. We expect that the timescales for flux accumulation at Saturn are likely to be much longer than at the Earth. On the basis of the work by *Jackman et al.* [2004], dayside reconnection results in the intermittent addition of magnetic flux to the kronian system, and simple calculations based on six months of upstream data yield an average time of $\sim$5–7 days between tail reconnection events. This timescale is found to be reasonable by the model of *Milan et al.* [2005], which assumes that above a 45 GWb threshold, the tail lobes become unstable and flux is closed by tail reconnection. However, the role of internal mass loading should not be dismissed when considering the triggering and frequency of reconnection events. Thus, we can draw parallels and contrasts with the behaviour at other planets, but in essence, the kronian system can be thought of as unique.

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