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Titan's influence on Saturnian substorm occurrence

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[1] Substorms play an important role in the energization and transport of plasmas in planetary magnetospheres, including the shedding of the mass added by moons in the case of Jupiter and Saturn. Mass shedding occurs through rapid reconnection in the near tail resulting in dipolarization on the magnetospheric side of the reconnection point and plasmoid formation down tail. Observations of these sudden reconnection events in Saturn's near-tail region provide additional insight into this process. Saturnian substorms, at least on occasion, have a plasmoid formation phase leading to a traveling compression region. Changes in the field strength across reconnection events suggest that open flux has been removed from the tail. The timing of tail reconnection events appears to be controlled by both the orbital phase of Titan, and the variable stretching of the near-tail field as Saturn rotates. **Citation:** Russell, C. T., C. M. Jackman, H. Y. Wei, C. Bertucci, and M. K. Dougherty (2008), Titan's influence on Saturnian substorm occurrence, *Geophys. Res. Lett.*, *35*, L12105, doi:10.1029/2008GL034080.

1. Introduction

[2] The terrestrial substorm is driven by dayside reconnection, magnetic flux transport and subsequent storage of that flux in the open field region of the tail lobes [*Dungey*, 1961]. The return of the flux to the closed magnetospheric field lines occurs via nightside reconnection, beginning on the closed magnetic field lines of the plasma sheet and producing a plasmoid [e.g., *Russell and McPherron*, 1973]. When reconnection reaches the open flux of the tail lobes, the lower density and higher field strength allows reconnection to proceed more rapidly, the expansion phase of the substorm begins, and the plasmoid is released down the tail. Circulation in the Jovian magnetosphere is driven by mass loading at Io, setting up a radial outflow of magnetized plasma [*Vasyliunas*, 1983]. In order to eject ions and retain magnetic flux, a neutral line forms on the nightside of the magnetosphere, ejecting ions in magnetic islands that transport no net magnetic flux. This process consists of a growth phase [*Ge et al.*, 2007] and an expansion phase [*Russell et al.*, 1998]. Circulation can be driven by dayside reconnection in outer planet magnetospheres [*Cowley et al.*, 2004], but mass loading transport is also significant. The latter may dominate due to the inefficiency of magnetic reconnection when the Mach number of the bow shock is high [*Scurry and Russell*, 1991]. Consistent with this picture, *Fukazawa et al.* [2007], using an MHD model of the solar wind interaction with the Saturnian magnetosphere, showed that dayside reconnection was inefficient under outer solar system conditions. At a minimum, the Jovian observations and Saturnian simulation show that plasmoid-forming substorms may not require dayside reconnection.

[3] Saturn has two moons that provide measurable mass loading that can drive plasma circulation. Enceladus, like Io at Jupiter, is deep within Saturn's magnetosphere where the magnetic field is strong and dominates plasma dynamics. The mass loading at Enceladus is weak, only about 2 kg/s [*Khurana et al.*, 2007], compared to the 1000 kg/s at Io [*Hill et al.*, 1983]. Estimates of the mass loading rate at Titan are less than this, ranging from 0.2 kg/s [*Nagy et al.*, 2001] to 1.0 kg/s [*Kabin et al.*, 1999], taking methane as the dominant mass-loading ion. The mass loading at Enceladus is sufficient to create a magnetodisk [*Arridge et al.*, 2007] when the mass is transported to greater distances. Furthermore, much like in the Jovian tail, reconnection in the Saturnian magnetotail is strong and rapid [*Jackman et al.*, 2007; A multi-instrument view of tail reconnection at Saturn, unpublished manuscript, 2008]. In this paper we note five phenomena occurring in the near-tail region of Saturn that give further evidence of the nature of the dynamics of the Saturnian tail: plasmoid formation, dipolarization of the field, removal of magnetic flux from the tail lobes, control of substorm occurrence by Titan's orbital position, and variable stretching of the magnetic field in Saturn's near-tail region as the planet rotates.

2. Growth Phase and Plasmoid Formation

[4] Figure 1 shows seven days of magnetic field data during a pass of Cassini through Saturn's tail inbound from 48 R_S in the midnight sector. The coordinate system is a spherical polar coordinate system referenced to Saturn's spin axis. The periodic reversal of the radial and phi components of the field is due to the flapping of the tail current sheet in synchronism with the planet's rotation. There are several northward turnings of the theta component (in the negative direction) indicating the spacecraft is on the plasmoid side of the reconnection point. These may all be associated with substorms. However, since they often occur at the time of current sheet crossings, it is difficult to determine the exact cause of the signature. One strong northward signature occurs on July 12, away from the current sheet. Interestingly, prior to this event indicated by the leftmost arrow in Figure 1, the magnetic field increased to values well above the pre-existing field strength and then dropped suddenly when the field turned northward. A second such event occurs on July 14 (at second arrow), but an unfortunate data gap occurs where the field drops and the direction might have changed. These two increases are likely due to the proximity of a forming plasmoid. Figure 2 shows enlargements of the event on July 12. The enhanced

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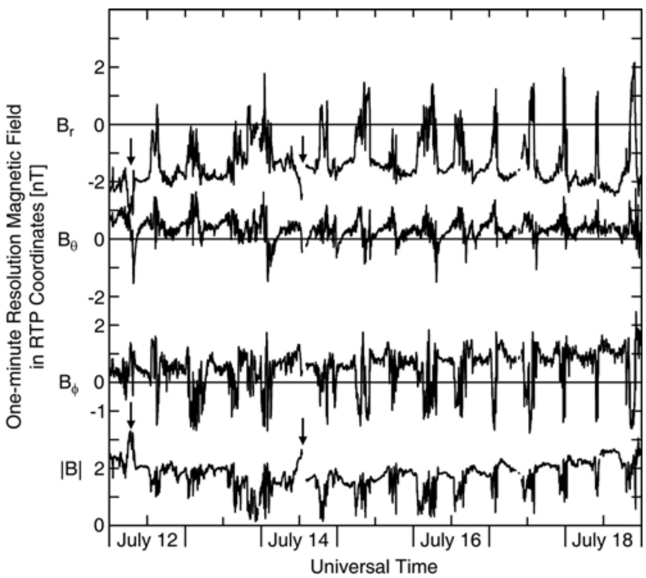

Figure 1. One-minute resolution magnetic field in a spherical polar coordinate aligned with Saturn's rotation axis. This seven-day interval shows periodic flapping of the tail current sheet in synchronism with Saturn's rotation as evidenced by the periodic reversals of the B_r component of the field. Arrows show two events with a significant increase in the field magnitude. The first one precedes a strong transient in B_θ. The second precedes a data gap. The spacecraft moves from 48.4 R_S at 2350 LT to 36.7 R_S at 1015 LT during the interval shown here.

southward field, followed by a strong northward field turning into a weak southward field, is consistent with the formation of a plasmoid near Cassini with the spacecraft initially in the tailward half of the plasmoid followed by its release and tailward motion. The dashed line shows the probable variation of the field strength just outside the plasmoid. This sequence of events has been termed a traveling compression region at Earth [*Slavin and Smith*, 1984]. We note also that there is a slight drop in the field strength across the full duration of the event, from above 2.4 nT to 2.1 nT. Similar small drops are present at other tail reconnection events, suggesting that the reconnection process that builds and releases the plasmoid also involves the reconnection of some tail lobe flux as well as stretched mass-loaded field lines. We draw this inference because this flux return reduces the flaring angle of the tail boundary and hence the angle of incidence of the solar wind on the tail. This reduces the pressure on the tail and the field strength [*Petrinec and Russell*, 1996, 1997].

3. Dipolarization

[5] The events identified as tail reconnection events by *Jackman et al.* [2007] were all at or beyond the X-point i.e. in or near the plasmoid. There are also events detected that are solely southward turning, signifying dipolarization inside the reconnection point. One such example is shown in Figure 3. The reduced phi component is consistent with inward motion and conservation of angular momentum. It is difficult to detect evidence of plasmoid formation here because the spacecraft entered the plasma sheet near the onset of the substorm but it is clear that the total magnetic field strength was lowered by about 0.5nT across the event.

4. Titan Control

[6] *Menietti et al.* [2007] have reported that Saturn kilometric radiation (SKR) is stronger when Titan is near midnight. In order to test if the SKR control extends to our events we have examined the location of Titan for the six substorms whose identities seem most certain, including the dipolarization event in Figure 3. The event in Figure 2

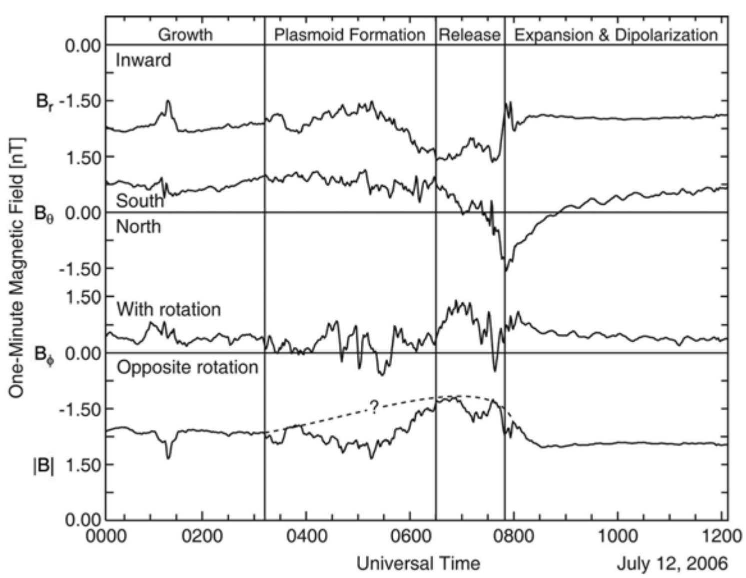

Figure 2. One-minute resolution data in r, θ, ϕ coordinates across the first substorm preceded by an increase in the magnetic field shown in Figure 1. When the magnetic field turns strongly northward, 0745 UT, the spacecraft is at 48.4 R_S and 2352 LT. The dashed line indicates the probable variation of the magnetic field in the lobe. It is obtained by drawing a smooth trace through the quiet portions of the magnetic field where plasma effects are minimal.

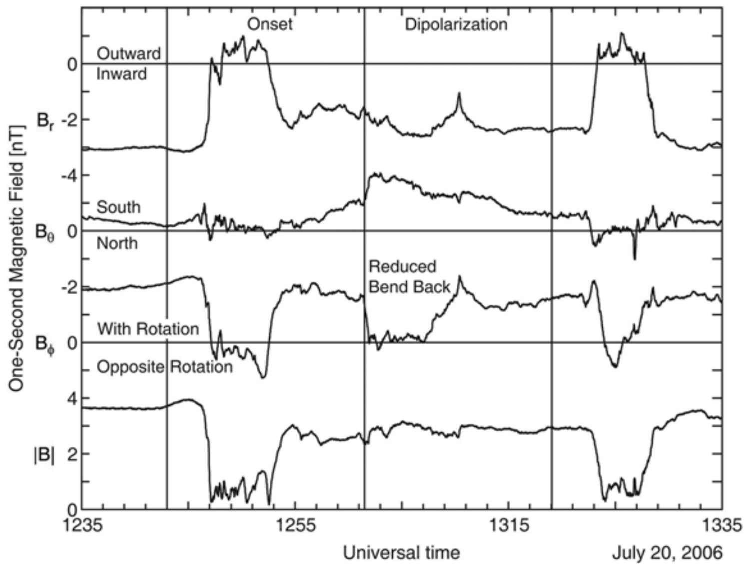

Figure 3. One-second resolution data in r, θ, ϕ coordinates during a substorm with a dipolarization of the magnetic field. The spacecraft enters the plasma sheet in the period that could be a brief growth phase. The spacecraft at 1300 UT is at 29.4 R_S and 0136 LT.

was identified as a substorm by *Jackman et al.* [2007]. The result of this examination is surprising. Four of the substorms place Titan very close to midnight. This includes the dipolarization shown in Figure 3. The event shown in Figure 2 and one other event, place Titan on the dayside of the magnetosphere at substorm onset. The geometry of the six events is shown in Figure 4. Four events with Titan near midnight were triggered when Titan was within one Saturn rotation period of being exactly aligned with midnight. The other two events with Titan on the dayside, could be triggered, for example, by changes in the solar wind dynamic pressure, or they possibly could have happened

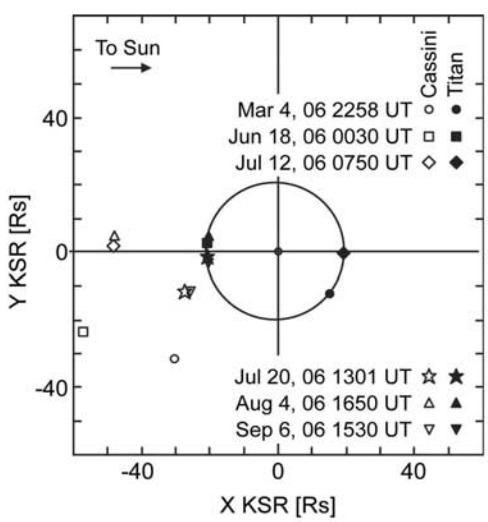

Figure 4. Location of Titan and Cassini during the six substorms identified herein and by *Jackman et al.* [2007]. KSR coordinates have their X axis in the rotational equator along the projection of the Saturn-Sun line. The Z axis is along the rotation axis (northward), and Y is along the cross product of Z and X.

without a trigger, as may occur in terrestrial substorms. The chance of four of six events occurring at random this close to Titan's crossing of midnight is less than 1×10^{-4}.

5. Field Line Stretching Near Midnight

[7] The magnetic field near Titan is dynamic, stretching and relaxing as Saturn rotates as measured by the field components in the "dipole" magnetic meridian. Figure 5 shows the inclination of the magnetic field, atan (B_r/B_θ) for two Saturn rotations on Cassini revolution 21 on February 27, 2006, near 0100 LT and at low inclinations. The magnetic field stretches and then dipolarizes over the course of Saturn's rotation, although the exact strength of this stretching exhibits some variability.

[8] This stretching helps explain the tight correlation of Titan's orbital phase and substorm occurrence. Not only does Titan have to be near midnight but perhaps also the

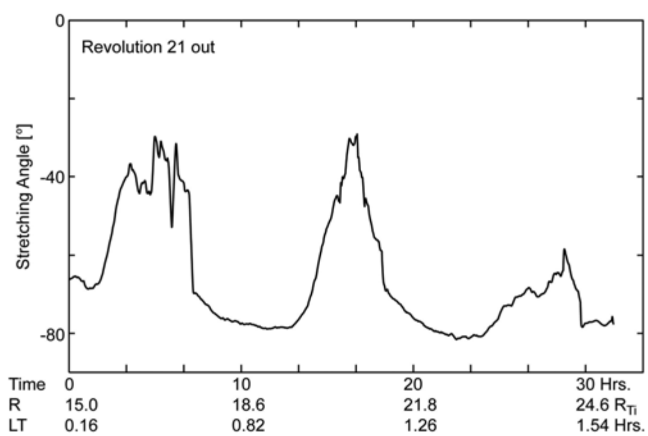

Figure 5. Inclination or stretching angle, atan (B_r/B_θ), in which ±90° is most stretched, for the near-Titan-orbit region of outbound Rev 21 near 0100 local time.

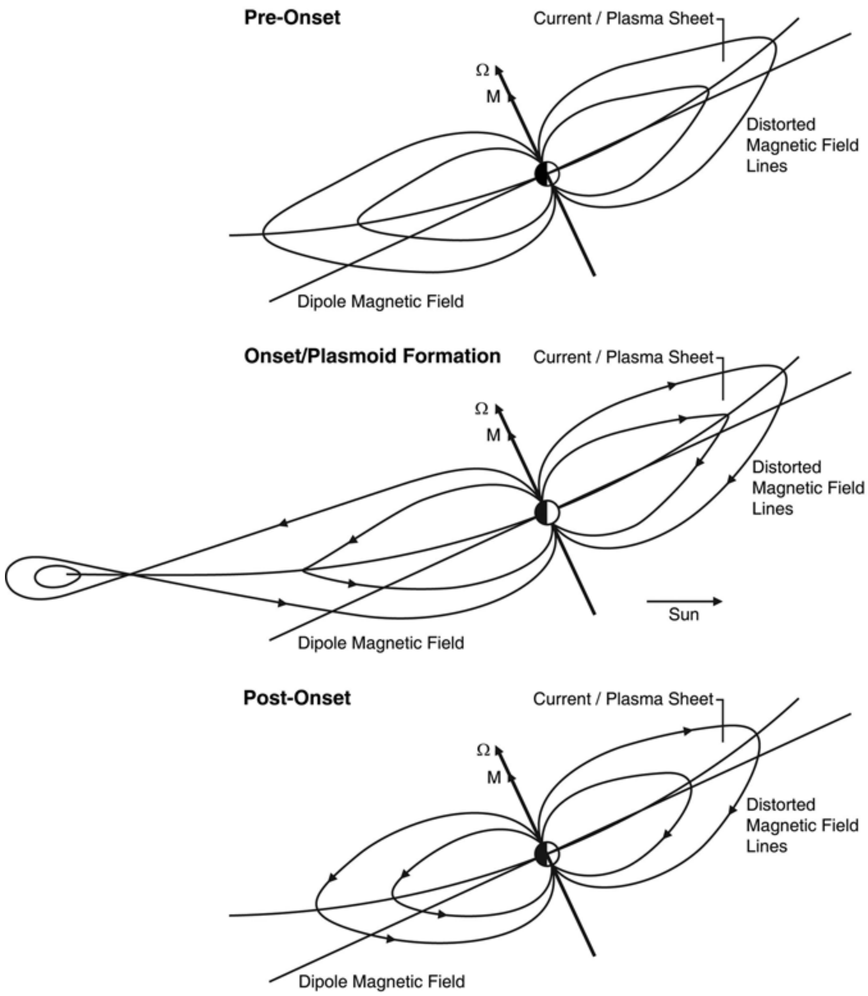

Figure 6. Sketches of magnetic field configuration in the noon-midnight meridian during three phases of a Saturnian substorm. In each panel the magnetodisk is bent upward with a bowl-shaped current sheet due to the solar wind forces on the magnetosphere when the rotation axis is tilted away from the Sun. The pre-onset state is drawn in the median configuration found by *Arridge et al.* [2007]. With time, mass addition from Enceladus and Titan stretch the magnetodisk at all local times but most effectively at midnight where reconnection begins on stretched field lines. Reconnection releases an ion-ladened plasmoid down the tail, and the magnetodisk shrinks at all local times.

magnetic field needs to be significantly stretched. As illustrated in Figure 5, tail field-line stretching occurs every rotation of Saturn, even though substorms do not occur that frequently. The additional mass loading of the magnetic field when Titan is near midnight and when the near-tail magnetic field is weak and stretched in the midnight sector, may provide enough centrifugal stress to overcome the force of the closed magnetic field lines and the field lines ‘‘snap’’ by reconnecting across the plasma sheet. As in the Earth’s tail we envision a neutral point forming first in the plasma sheet, reconnecting slowly at first, but ultimately reaching a low density plasma when reconnection reaches open flux tubes in the lobes. At this point the plasmoid can be released. It appears that the presence of Titan near midnight can act as a trigger for this process. Whether substorms occur at every passage of Titan through midnight cannot be answered in this study because the spacecraft is not always in position to detect substorms.

6. Summary and Conclusions

[9] The Saturnian system has some important differences from the Jovian and terrestrial magnetospheres. In particular, Titan appears to play a role in substorm timing in a way that Io does not. Nevertheless, all three magnetospheres appear to undergo a convection cycle that leads to tail dynamics. As illustrated in Figure 6, this dynamical sequence appears to have a growth phase, plasmoid formation with a consequent traveling compression region, expansion and recovery phases resulting in variations in the magnetodisk current sheet. Changes in the tail-lobe magnetic field across the substorms suggest that the magnetic flux content of Saturn’s tail does vary during the substorm process.

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