Long-standing Small-scale Reconnection Processes at Saturn Revealed by *Cassini*

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Abstract

The internal mass source from the icy moon Enceladus in Saturn's rapidly rotating magnetosphere drives electromagnetic dynamics in multiple spatial and temporal scales. The distribution and circulation of the internal plasma and associated energy are thus crucial in understanding Saturn's magnetospheric environment. Magnetic reconnection is one of the key processes in driving plasma and energy transport in the magnetosphere, and also a fundamental plasma process in energizing charged particles. Recent works suggested that reconnection driven by Saturn's rapid rotation might appear as a chain of microscale structures, named drizzle-like reconnection. The drizzle-like reconnection could exist not only in the nightside magnetodisk, but also in the dayside magnetodisk. Here, using in situ measurements from the *Cassini* spacecraft, we report multiple reconnection sites that were successively detected during a time interval longer than one rotation period. The time separation between two adjacently detected reconnection sites can be much less than one rotation period, implying that the reconnection processes are likely small-scale, or frequently repetitive. The spatial distribution of the identified long-standing multiple small reconnection site sequences shows no significant preference on local times. We propose that the small reconnection sites discussed in this Letter are rotationally driven and rotate with the magnetosphere. Since the reconnection process on Saturn can be long-durational, the rotational regime can cause these small-scale reconnection sites to spread to all local times, resulting in global release of energy and mass from the magnetosphere.

Unified Astronomy Thesaurus concepts: Solar magnetic reconnection (1504); Planetary magnetosphere (997); Interplanetary particle acceleration (826)

1. Introduction

Saturn's magnetosphere receives mass and energy from internal sources (e.g., moons, rings, and Saturn's atmosphere/ionosphere) and the solar wind. Magnetic reconnection, locally changing the magnetic topology, is a crucial process in energizing plasmas and circulating magnetic flux in the magnetosphere. Many relevant magnetospheric/ionospheric phenomena may follow magnetic reconnection processes (e.g., magnetic dipolarization, plasmoid release, field-aligned current formation, and auroral intensification). The solar wind–planetary magnetic field interaction leads to magnetic reconnection on the magnetopause, transferring energy and mass into the planetary magnetosphere. The mass and energy are accumulated in the nightside magnetotail, which eventually results in magnetotail reconnection to release mass back to the interplanetary space. This solar wind driven reconnection and plasma circulation are known as the Dungey cycle (Dungey 1961). At Saturn, heavy ions generated at the orbit of Enceladus are picked up by the induced electric field due to the rapid planetary rotation, and therefore impose a strong centrifugal force on magnetic flux tubes, leading to strong

stretch of the magnetic field near the magnetic equator to form a magnetodisk. Magnetic reconnection is expected to take place where the magnetic field is most stretched in the nightside, and is suggested to distribute further planetwards from dusk to dawn. This large-scale internally driven reconnection, also present at Jupiter, is known as the Vasyliunas cycle (Vasyliunas 1983; Kivelson & Southwood 2005). Plasmoids and dipolarizations triggered by reconnection processes during Dungey and Vasyliunas cycles are often associated with energetic particle injections which increase the intensity of energetic neutral atoms (ENA; Hill et al. 2008). The nightside quasi-steady large-scale Vasyliunas-type reconnection and the plasmoids are regarded as a mechanism for mass loss at Saturn and Jupiter, while not sufficient to account for the total plasma loss (Bagenal 2007; Thomsen 2013).

Recent studies using data from the *Cassini* spacecraft have substantially shifted the traditional understanding of magnetic reconnection in Saturn's magnetosphere. Delamere et al. (2015) proposed a drizzle-like reconnection process in circulating magnetic flux in the magnetosphere. Unlike the reconnection processes in the Dungey and Vasyliunas cycles, the drizzle-like reconnection could exist in the dayside well within the

magnetopause, and show a peak occurrence rate in the pre-noon local time sector. Guo et al. (2018a) provided direct evidence of a active magnetic reconnection diffusion region in pre-noon local times in the magnetodisk. Furthermore, Guo et al. (2018b) detailed the particle acceleration features of the dayside magnetodisk reconnection (DMR) with multiple events observed by *Cassini*. Although the DMR events in previous literature are believed to be driven by planetary rapid rotation and are thus suggested as "drizzle-like," there is still a lack of adequate observational evidence for the drizzle nature of those small-scale reconnection processes, i.e., multiple small reconnection sites coexisting in the magnetosphere. Since the drizzle process is important in driving the mass loss in Saturn's magnetosphere (Thomsen 2013; Delamere et al. 2015), the understanding of reconnection's drizzle nature and the direct evidence of drizzle process are crucial in Saturn's magnetospheric dynamics.

Using in situ measurements of magnetic fields and particles from the *Cassini* spacecraft, we present direct evidence of multiple reconnection sites. A series of reconnection sites are identified by *Cassini* during an interval spanning from several hours to several planetary rotation periods. The time separations between two adjacent reconnection sites are much shorter than one planetary rotation period. These long-standing small-scale reconnection sequences are observed with no obvious preference on local time. The existence of multiple reconnection sites in Saturn's magnetosphere would increase the corresponding mass-loss rate, manifesting the fundamentally different plasma processes in a rapid rotating magnetospheric environment compared to the Terrestrial magnetosphere.

2. *Cassini* Observations of Small-scale Magnetic Reconnection Events

The survey of the small-scale magnetic reconnection utilizes the measurements of magnetic field from the *Cassini*-MAG instrument (Dougherty et al. 2004), electrons with energy ranges up to 28 keV from *Cassini*-CAPS/IMS/ELS (Young et al. 2004), and energetic particles from the Low-Energy Magnetospheric Measurements System (LEMMS) and the Ion and Neutral Camera (INCA) on the Magnetosphere Imaging Instrument (MIMI) (Krimigis et al. 2004).

Figure 1 shows *Cassini*'s magnetic field and particle measurements from 2008 April 14/02:00 UT to 2008 April 16/00:00 UT. Figure 1(a) shows the B_θ component of the magnetic field in the Kronographic Radial-Theta-Phi coordinates (KRTP, a spherical polar coordinate system). The B_θ magnetic component displays a sequence of events with negative B_θ values (highlighted in yellow). The negative B_θ events at ~2008 April 15/00:00 (sequence 1 as numbered at the top of the figure) have been identified and studied as an example of the DMR event (Guo et al. 2018b). When *Cassini* encountered the reconnection site, the fluxes of the energetic electrons (Figures 1(b) and (c)), energetic ions (Figures 1(e)), and energetic oxygen ion (Figure 1(f)) were significantly enhanced, revealing that the particles were accelerated in the reconnection region. Since different particle species get accelerated at slightly different regions as a result of their different gyro-radii, the fluxes of electrons and ions could peak at different time intervals (Guo et al. 2018a). The time delays between electron flux, ion flux, and negative B_θ signatures are related to the trajectories of the spacecraft through the reconnection region. The information of Hall magnetic field

can be revealed from perturbations of the B_φ component (Figure 1(h)), which, however, is not always clear due to the disturbed current sheet (Guo et al. 2018b). The negative B_θ component is a common indicator for magnetic reconnection sites in Saturn's magnetosphere (Hill et al. 2008; Jackman et al. 2011; Smith et al. 2016), while the accompanied electron and/ or ion acceleration around the negative B_θ interval indicates active reconnection processes, as shown by the yellow highlighted intervals in Figure 1.

In addition to the negative B_θ interval, the reconnection outflow region can pile up the magnetic field fluxes to form a reconnection front, termed also as a dipolarization front (like sequence 5, as numbered at the top of the figure). The dipolarization front shows an abrupt increase of the B_θ component, accompanied by accelerated particles from the reconnection X-line (Arridge et al. 2016; Yao et al. 2018). Both the negative B_θ signature and dipolarization front could indicate that the spacecraft passed through or traveled close to a reconnection site. The time separations between two adjacent reconnection sites (considering both blue and yellow highlighted intervals together) are less than 5 hr, which is much shorter than the rigid rotation period. If the recurrences of reconnection sites were due to the vertical oscillations of the magnetodisk forcing the spacecraft to pass through the same reconnection sites several times, similar characteristics should be observed at each encounter of the reconnection site. However, the energetic electrons in Figures 1(b) and (c), and the hot (below several keV) and cold electrons in Figure 1(d) show very different characteristics in successive negative B_θ regions, implying that the successive events correspond to different reconnection regions (i.e., multiple individual reconnection sites).

Figure 2 displays another two examples that *Cassini* crossed multiple reconnection sites repeatedly. Figures 2(a)–(c) show the observations of magnetic field and particle fluxes from 2005 February 19/00 UT to 2005 February 21/00 UT. *Cassini* was at the dawn side of Saturn's magnetosphere. The electron spectrum in Figure 2(c) also reveals that the spacecraft was inside the magnetosphere. The arrows in Figure 2(a) mark the magnetic structures with both negative B_θ and sharp B_θ bipolar signatures (quick increase/decrease followed by a quick decrease/increase). Each B_θ bipolar structure is accompanied by an enhancement of energetic electrons, which is a typical signature of a secondary island produced by magnetic reconnection (Chen et al. 2007). The time separations between these secondary islands can also be much shorter than one rigid rotation period. Figures 2(d)–(f) show the observations from 2008 September 29/5 UT to 2008 October 1/11 UT. The negative B_θ interval marked by the red arrow has been confirmed as an active ion diffusion region (Guo et al. 2018a). Before and after encountering this ion diffusion region, the black arrows mark the negative B_θ intervals accompanied by enhancements of energetic electrons. Their time separations are also only a few hours.

There are two major common characteristics in all three events. The first one is that magnetic reconnection signatures were recorded multiple times within one rotation period, during which the spacecraft was assumed to not move much. The second one is that the magnetic reconnection signatures can last sporadically for more than one rigid rotation period. A long-duration magnetic reconnection process has been reported in Saturn's magnetotail, revealing that reconnection can be
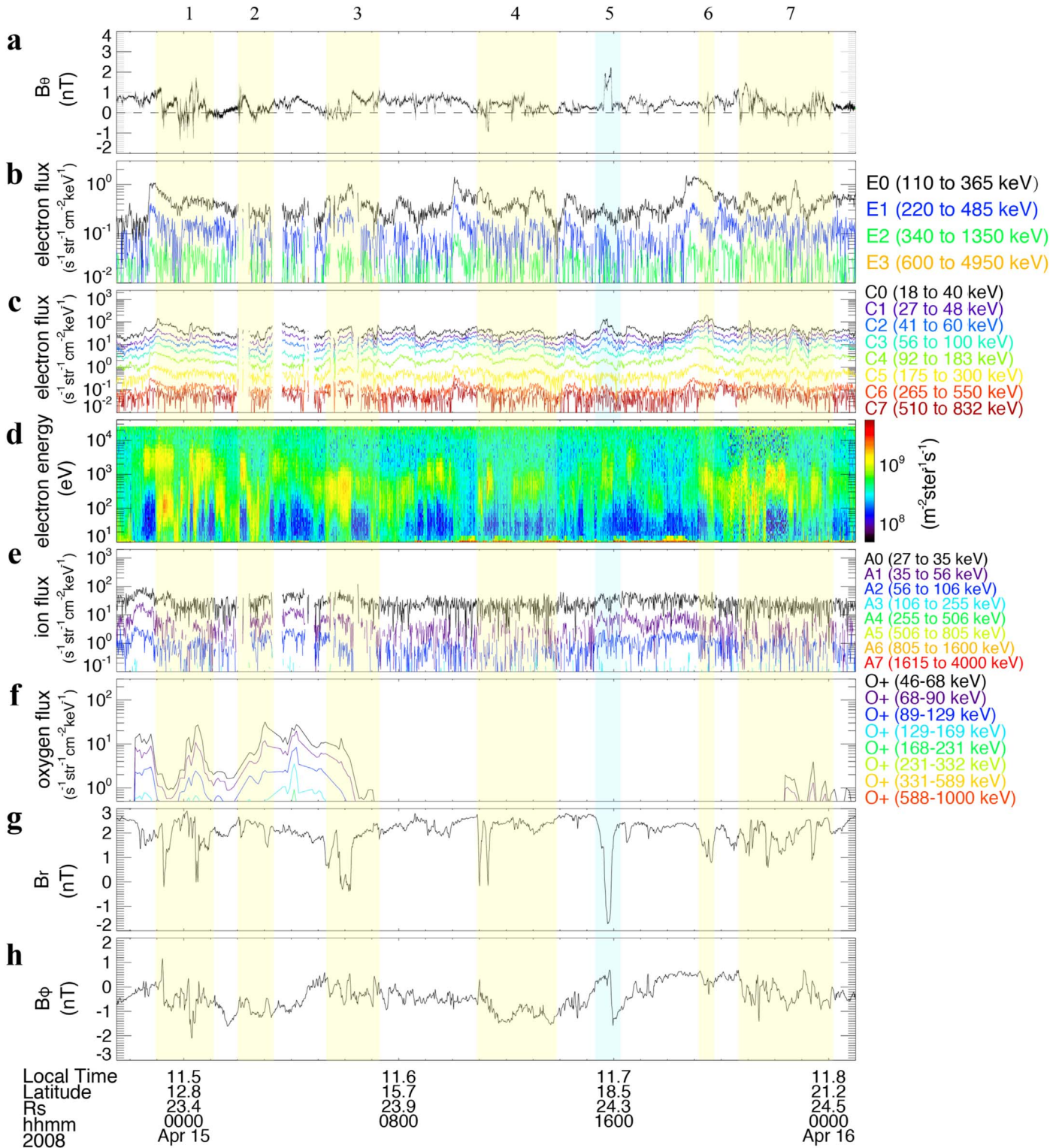
Figure 1. Recurrently observed reconnection signatures on Saturn. (a) B_θ magnetic component in the Kronographic Radial-Theta-Phi coordinates (KRTP, a spherical polar coordinate system), from the *Cassini*-MAG instrument (Dougherty et al. 2004). ((b) and (c)) Energetic electron differential flux from the Low-Energy Magnetospheric Measurements System (LEMMS) of the Magnetosphere Imaging Instrument (MIMI) (Krimigis et al. 2004). (d) Energy spectrogram of omnidirectional electron flux with energy range up to 28 keV from *Cassini*-CAPS/IMS/ELS (Young et al. 2004). (e) Energetic proton differential flux from MIMI-LEMMS. (f) Energetic oxygen ions differential flux from the Ion and Neutral Camera (INCA) of MIMI. (g) B_r and (h) B_φ components of magnetic field in KRTP coordinates. Yellow and blue highlighted intervals mark the reconnection signatures, i.e., negative B_θ or dipolarization front, accompanied by enhancement of high energy (>10 s of keV) electrons and/or ions.

prolonged at Saturn (Arridge et al. 2016). In this study, the magnetic reconnection in the regions of the three reported events may not be lasting as long as reported by Arridge et al. (2016); nevertheless, we could still propose that the small-scale reconnection process is a common and long-standing phenomenon in Saturn's magnetosphere.
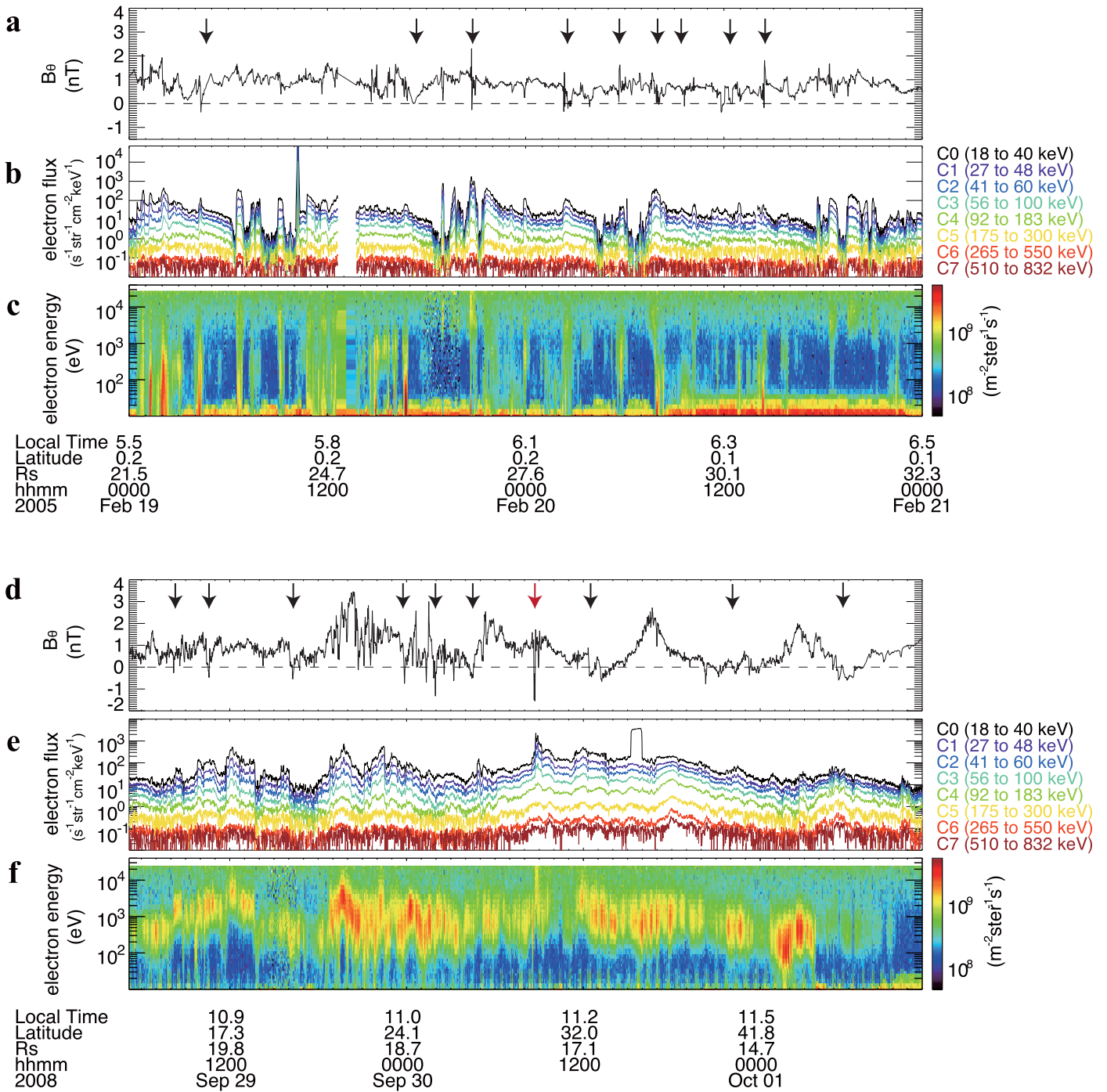
Figure 2. Two additional events that display multiple small-scale reconnection sites. ((a) and (d)) B_θ magnetic field component. ((b) and (e)) Energetic electron differential flux from MIMI-LEMMS. ((c) and (f)) Energy spectrogram of omnidirectional electron flux from CAPS-ELS. The arrows mark the reconnection signatures.

To obtain a systematic understanding of the small-scale reconnection sites, we surveyed *Cassini* data from 2005 to 2010. The targeting event is long-standing small-scale reconnection sites. First, the intervals that B_θ are negative are obtained. The intervals that are affected by a Titan pass-by are excluded, as the moon can perturb the magnetosphere locally. If two adjacent intervals are separated by more than one hour, then the two intervals are treated as two events, otherwise we list them as one event. In each event, the minimum value of B_θ needs to be less than -0.1 nT, or the event is discarded. The intervals that are accompanied by enhanced fluxes of

accelerated electrons with energies of 10 s of keV are marked as active reconnection events. From all the active reconnection events, the long-standing small-scale reconnection events satisfy the following criteria: (1) the average of time separations between adjacent reconnection regions is shorter than one rotation period of Saturn; (2) the duration of the intervals containing the reconnection signatures are longer than one (rigid) rotation period. The statistical results analyzed by Smith et al. (2016) showed that the minimum of the averaged negative B_θ is ~ 0.1 nT. We set the minimum value of B_θ to be less than -0.1 nT to exclude ambiguous events. The

Table 1
List of Long-standing Multiple Small-scale Reconnection Regions (MRs) Encountered by *Cassini*

Start Time (UT)	Duration (hr)	Number of MRs (counts)	Separations (min/max) (hr)	Local Time (hr)	Distance to Saturn (R_s)	Accelerated Particles	Catalog
2005 Nov 25/4	~13	3	~5.9 (3.5/8.3)	8.8–9.2	23.8–20.2	yes	Noon
2008 Sep 29/7	~45	10	~5.1 (2.3/9.1)	10.8–11.7	20.0–13.5	yes	
2008 Apr 14/21	~28	7	~3.5 (2.6/4.9)	11.3–11.8	22.3–24.5	yes	
2008 May 14/7	~28	4	~8.5 (2.4/13.1)	11.5–11.8	22.2–20.6	yes	
2007 Mar 27/6	~39	5	~9.2 (4.8/12.8)	14.5–15.2	25.3–29.8	yes	Dusk
2010 May 14/19	~27	5	~5.9 (4.0/6.7)	20.1–20.6	30.4–25.1	yes	
2010 Apr 24/7	~26	5	~5.8 (3.0/9.5)	20.2–20.5	30.4–25.8	yes	
2006 Sep 15/8	~26	7	~4.1 (1.5/6.7)	23.8–24.0	35.5–36.8	yes	Night
2006 Sep 17/14	~31	5	~6.4 (3.9/8.1)	0.4–0.6	37.6–37.2	yes	
2006 Sep 21/1	~35	6	~6.5 (4.9/8.2)	1.2–1.6	33.0–28.8	yes	
2006 Oct 7/19	~19	5	~4.5 (2.3/6.0)	1.3–1.6	30.0–27.6	yes	
2005 Nov 1/12	~29	5	~6.7 (3.2/11.5)	3.6–4.2	25.4–32.1	yes	Dawn
2005 Mar 11/5	~27	6	~5.2 (1.8/9.3)	5.3–6.0	19.8–26.7	yes	
2005 Feb 19/4	~35	9	~4.3 (1.3/11.6)	5.6–6.3	22.6–30.5	yes	
2006 Mar 2/7	~125	19	~6.6 (2.0/12.5)	2.5–3.4	35.9–47.0	yes	Periodical
2006 Jul 17/2	~46	7	~7.0 (2.9/10.0)	0.7–1.1	42.6–37.0	yes	
2009 Oct 27/5	~90	13	~7.2 (1.5/12.0)	20.1–21.2	38.2–23.4	yes	

dipolarization fronts were not included in the survey, because one reconnection site may continuously produce multiple dipolarization fronts and they can travel rather far from a given reconnection site. Table 1 lists all events that satisfy the above two criteria. The events expand to most of the local times, i.e., seem dispersedly distributed at noon, dusk, night, and dawn. The ranges (distances to the center of Saturn) of the events in the list appear as asymmetric characteristics. The radial distances (normalized by Saturn's Radius, 1 R_S = 60,268 km) from Saturn's center at the noon sector (~20 R_S) are smaller than that at the night sector (~30 R_S). This local time asymmetric feature might be a result of the trajectory bias of *Cassini* or the limited data set. Nonetheless, the Saturnian ring current itself is characterized by a significant local time asymmetry, being stronger and more extended in the nightside (Sergis et al. 2017). The shortest averaged time separation in the event list is only ~3.5 hr, while the time separations in the list vary from nearly 1 hr to longer than one rigid rotating period. The large range of the time separations implies that the occurrence of the small-scale reconnection is rather random.

3. Discussion and Conclusion

It has been reported that magnetodisk reconnection sites are not only triggered at nightside of Saturn's magnetosphere, but also exist in dayside sectors (Delamere et al. 2015; Guo et al. 2018a). The reconnection processes are suggested to be small-scale and "drizzle-like" (Delamere et al. 2015; Guo et al. 2018b). In this study, we reveal that the small-scale reconnection processes are long-standing and could exist at all local times in Saturn's magnetosphere. An alternative interpretation of the repetitive reconnection sites could be switching on/off of unsteady reconnection processes near the spacecraft, or multiple crossings of the reconnection region due to rapid vertical motion of the current sheet relative to the spacecraft. These mechanisms would manifest the repetitive reconnection signatures as temporal effects. However, the hypothesis of multiple reconnection region crossings due to current sheet

motion is refuted by the diverse plasma features, which imply that the reconnection sites were not the same one. The local time of the spacecraft does not change by much during a long-standing event, while the magnetosphere is rotating with a considerable speed. A reconnection site should not stay within a fixed local time sector while the host magnetosphere is rotating to cause the phenomena we report in this study. We propose that there are multiple (steady, unsteady, or transient) reconnection sites rotating with Saturn, as also supported by the observed rotating ENA blobs, produced by the colocated energized oxygen ions.

At dayside, the reconnection sites should occur in the current sheet of the magnetodisk, as indicated by the elongated magnetic field lines. The azimuthal flow speed of the plasma has been found to vary from ~50% to 70% of rigid corotation (Thomsen et al. 2010). The magnetic structure can also rotate with the magnetosphere (Vasyliunas 1983), or at least with a fractional corotating speed. At nightside, beyond ~25 R_S, the plasma flow has a large rotating component and an outflow component, while sometimes plasma flows in the azimuthal direction and reaches the corotation speed (Thomsen et al. 2014). Given the rotation effect of the magnetosphere, the time separation recorded by the spacecraft reflects a spatial separation in the azimuthal direction, not only the temporal variation (e.g., Yao et al. 2017, 2018). The reconnection sites studied in this Letter would azimuthally distribute around Saturn and rotate with the magnetosphere, as illustrated in Figure 3, which is consistent with the fact in Table 1 that the long-standing small-scale reconnection events have no evident preference on local time.

Besides the small-scale feature, the last three events in Table 1 display an occurrence rate near the rigid corotation period. In previous studies, the near rigid rotation periodical phenomena are suggested to have resulted from PPO (Planetary Period Oscillations; Cowley & Provan 2016). Recently, such a periodical occurrence of both magnetic reconnection X-line and dipolarization front have been reported (Yao et al. 2017, 2018), and the nearly corotating magnetosphere was proposed to explain their presence (Yao et al. 2017). Under
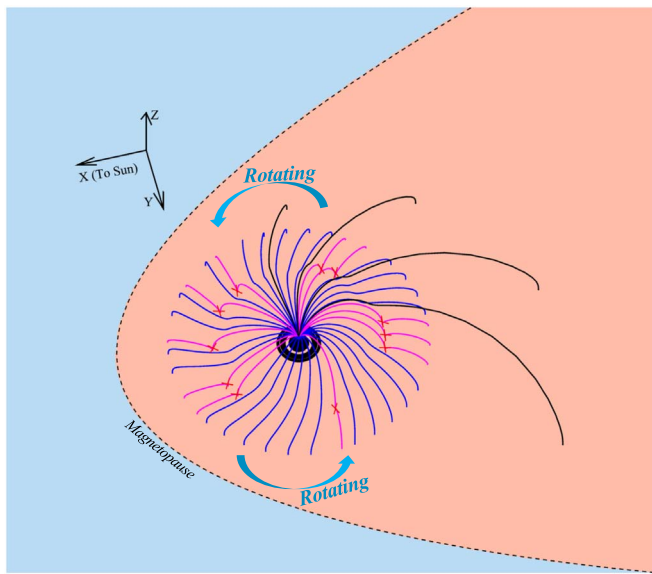
Figure 3. Illustration of the rotating multiple small-scale reconnection regions. Red curves present reconnected magnetic field lines while the cross signs (×) indicate the reconnection site. Blue and black curves show the magnetic field lines in the magnetodisk and the magnetotail.

certain conditions, the rigid corotation can occur and last, as raveled by the statistical analysis of the plasma flow in Thomsen et al. (2014) when protons dominate the number density of the thermal plasma. As a result, the reconnection site could corotate with Saturn and recur several times when the reconnection process can last a sufficiently long duration (i.e., well over a rotation period; Arridge et al. 2016). The azimuthal velocity could vary, and the reconfiguration of the current system could also change the rotating rate of the magnetic structure. Meanwhile, as the reconnection process is unsteady, the periodical features of the reconnection process may not be visible in most events.

Previous statistical approaches have suggested that the "drizzle" processes might dominate the plasma loss over the large-scale nightside reconnection events. In this research, we show that multiple small-scale magnetic reconnection sites are nearly uniformly distributed at all local times and are long-standing for tens of hours, which would transport magnetic and particle fluxes from all local times incessantly. The long-termed and omnidirectional energy release and particle acceleration by small-scale reconnections can be an important mechanism of plasma transport with a strong impact on magnetospheric dynamics and even aurora emissions on rotation-dominated magnetospheric regimes, such as those of Saturn and Jupiter.

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