



RESEARCH ARTICLE

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Recurrent Magnetic Dipolarization at Saturn: Revealed by Cassini

Key Points:

- We report a recurrent type of magnetic dipolarization at Saturn
- The associated processes could efficiently accelerate electrons and ions to tens to hundreds of kiloelectron volts
- Corotation of magnetosphere and planetary periodic oscillation are suggested as possible mechanisms

Supporting Information:

- Supporting Information S1

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Abstract Planetary magnetospheres receive plasma and energy from the Sun or moons of planets and consequently stretch magnetic field lines. The process may last for varied timescales at different planets. From time to time, energy is rapidly released in the magnetosphere and subsequently precipitated into the ionosphere and upper atmosphere. Usually, this energy dissipation is associated with magnetic dipolarization in the magnetosphere. This process is accompanied by plasma acceleration and field-aligned current formation, and subsequently auroral emissions are often significantly enhanced. Using measurements from multiple instruments on board the Cassini spacecraft, we reveal that magnetic dipolarization events at Saturn could reoccur after one planetary rotation and name them as recurrent dipolarizations. Three events are presented, including one from the dayside magnetosphere, which has no known precedent with terrestrial magnetospheric observations. During these events, recurrent energizations of plasma (electrons or ions) were also detected, which clearly demonstrate that these processes shall not be simply attributed to modulation of planetary periodic oscillation, although we do not exclude the possibility that the planetary periodic oscillation may modulate other processes (e.g., magnetic reconnection) which energizes particles. We discuss the potential physical mechanisms for generating the recurrent dipolarization process in a comprehensive view, including aurora and energetic neutral atom emissions.

Plain Language Summary Using measurements from the Cassini spacecraft, we reveal a new feature of magnetic dipolarization at Saturn, that is, the magnetic signature repeat after one planetary rotation, which is named recurrent dipolarization. Up to hundreds of kiloelectron volt electrons and ions are identified for the recurrent dipolarization events, suggesting that these particles have experienced efficient acceleration and cannot be purely due to planetary modulation. It remains a mystery why the magnetic dipolarization process associated with energetic ions and electrons could reoccur after one planetary rotation. Moreover, dipolarization process in Saturn's dayside magnetosphere is reported for the first time at Saturn, which has no known precedent with terrestrial or other planetary magnetospheric observations. The results demonstrate that magnetosphere-ionosphere coupling dynamics at Saturn and Earth have fundamental similarities and differences.

1. Introduction

In Saturn's magnetosphere, sources of energy and plasmas include the solar wind ejected from the Sun, moons and rings embedded within the system, and the planetary atmosphere (Blanc et al., 2015). Energy-loading processes occur when electrical currents driven by plasma dynamics reshape the magnetosphere from its steady state configuration. During the loading process, the planetary magnetic field becomes stretched, which

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corresponds to the formation of ring currents on the magnetodisc (Arridge et al., 2008). Both the solar wind and rapid planetary rotation can drive such energy-loading processes, with the rapid planetary rotation usually loading energy much faster than solar wind processes (Yao, 2017).

Magnetospheric dynamics often produce a rapid energy release from Saturn's magnetosphere, which subsequently drives particle precipitation into the ionosphere and upper atmosphere of Saturn (Kivelson, 2005). The rapid energy dissipation perturbs the current system in both the magnetosphere and ionosphere, reconfiguring the magnetospheric magnetic field and powering aurorae in the atmosphere. The magnetospheric and ionospheric phenomena are physically connected by field-aligned currents (Bunce et al., 2010; Schippers et al., 2012; Talboys et al., 2009) and field-aligned accelerated ions and electrons (Mitchell, Krimigis, et al., 2009; Mitchell, Kurth, et al., 2009; Saur et al., 2006; Yao, Coates, et al., 2017). The magnetic field reconfiguration in the magnetosphere is well known as magnetic dipolarization, that is, the magnetospheric currents divert into the ionosphere, and thus the dipole magnetic field from the planet dominates the near-planet space. The dipolarization process has been reported at Earth (Angelopoulos et al., 2008; Hesse & Birn, 1991; Lui, 1996), Mercury (Slavin et al., 2010), Saturn (Jackman et al., 2007), and Jupiter (Kronberg et al., 2005). However, it is not always easy to distinguish between a magnetic field change caused by the global current diversion from the magnetosphere to the ionosphere (McPherron et al., 1973) and the magnetic field modified by a local current system (Yao et al., 2013) from in situ data. Moreover, Yao, Grodent, et al., (2017) demonstrated that there are two fundamentally different processes that can produce the dipolarization-like magnetic signature at both the Earth and Saturn, while only the global current diversion is expected to produce a global-scale intensification of aurora.

Saturn's magnetosphere also rapidly rotates (Espinosa et al., 2003), which naturally imposes the spatial variations of magnetic field in azimuthal direction on the in situ measurements from spacecraft. Because Saturn's magnetosphere is rotating, a spacecraft would naturally measure longitudinal variation. The longitudinal variation could be any component of the magnetic field. Moreover, the measured magnetic field could also be modulated by planetary periodic oscillation (PPO; Cowley et al., 2006; Espinosa & Dougherty, 2000). The two systematic effects do not exist at terrestrial magnetotail, in which region the dynamics are usually compared with giant planets. Two PPO-related current systems (northern and southern hemispheres) combine together to modulate Saturn's magnetodisc (Andrews, 2011; Hunt et al., 2015; Provan et al., 2012) and thus produce sinusoidal variation of magnetic fields or periodic crossings of the magnetospheric current sheet (Arridge et al., 2011). In addition to the dual rotating current systems, Brandt et al. (2010) reveal that the electrical currents driven by the asymmetric pressure distribution composed of energetic particle distributions can also produce similar planetary periodic magnetic perturbations.

Regarding that many planetary modulations of magnetic fields are absent at Earth, analogy of magnetic signatures (e.g., magnetic dipolarization and magnetic islands) is not straightforward. Fundamentally different magnetospheric dynamics between Saturn and Earth are also reflected in their very different auroral dynamics. At Earth, auroral enhancements are usually very explosive (i.e., at a timescale of a few minutes; Lui et al., 2008; Henderson, 2009), while at Saturn the enhancements can last for a few hours (Nichols et al., 2014; Radioti et al., 2016). Besides the different timescales, previous studies also clearly demonstrate that Saturn auroral breakup region is rotating along Saturn's spin direction, which is fundamentally different from auroral breakup at Earth (Akasofu, 1964). Most likely the rotating of Saturn's auroral breakup region would require a rotating field-aligned current system and a rotating precipitating magnetospheric source.

The precise connection between auroral dynamics and magnetospheric dynamics at Saturn remains poorly understood. A major reason is the high variability of both auroral morphology and magnetospheric dynamics, particularly in the high-latitude polar region and their magnetospheric counterpart (Grodent et al., 2005; Mitchell, et al., 2016; Radioti et al., 2014, 2015; Stallard et al., 2008). The highly dynamical auroral emissions are associated with the formation of a field-aligned current system that couples the magnetosphere and the ionosphere (Bunce et al., 2008; Yao, Grodent, et al., 2017), as well as plasma waves in the magnetosphere (e.g., Yao, Radioti, et al., 2017). In addition to these high variabilities, Badman et al. (2006) present strong dawn-dusk asymmetry of auroral intensity, which strongly evidences the impact of solar wind.

Regarding the many differences in magnetospheric environments and auroral dynamics at Saturn and Earth, many similarities of fundamental plasma processes still exist at these planets, for example, magnetic reconnection and dipolarization. For example, similarities of magnetic dipolarization process have often been reported, including particle acceleration (Arridge et al., 2016; Smith et al., 2018; Yao, Grodent, et al., 2017),

field-aligned current formation (Jackman et al., 2013, 2015), planetward bursty flow (Thomsen et al., 2014), and tailward plasmoid phenomena (Jackman et al., 2011). It is intriguing to identify both the similarities and differences in the magnetosphere-ionosphere coupling processes between both planets. In this paper, we report recurrent magnetic dipolarization events at Saturn. The dipolarization process at Saturn is similar to the terrestrial dipolarization, while the recurrent feature is unknown at Earth. We also reveal the plasma features associated with these recurrent dipolarization events and discuss their potential mechanisms by taking into account results from multiple data sets (i.e., magnetic fields, ions and electrons at different energies, aurorae, and energetic neutral atom [ENA]). Their potential relations to ENA and auroral enhancements are also discussed in this study.

2. Observations

In this section, we detail three recurrent dipolarization events (note that each recurrent dipolarization includes two individual dipolarization events separately by about one planetary rotation period) at Saturn with observations made by multiple instruments on board the Cassini spacecraft. In the Cassini data set, we do not identify a dipolarization that appeared three times in succession, which could be due to two possible reasons: (1) the recurred dipolarization is a persisting structure that corotates with the planet and has a lifetime of less than two planetary rotations and (2) within two planetary rotations, Cassini would travel a relatively large distance and therefore would not be likely to measure a structure with limited spatial scale more than twice. From the periodic nature of ENA revealed in previous studies (Brandt et al., 2010; Mitchell, Krimigis, et al., 2009), we intend to suggest the second reason in this study, although we could not exclude the possibility of the first situation. Cassini-MAG (Dougherty et al., 2004) provides magnetic field. Cassini Plasma Spectrometer (CAPS) on board Cassini (Young et al., 2004) provides low-energy electron measurements with the Cassini electron spectrometer (CAPS-ELS) detector and ion measurements with the Ion Mass Spectrometer (IMS) detector. The energetic particle data used in this paper were collected by the Low Energy Magnetospheric Measurement System (LEMMS) of the Magnetosphere Imaging Instrument (MIMI; Krimigis et al., 2004). The auroral images of Saturn's polar region were obtained from the Cassini UltraViolet Imaging Spectrograph (UVIS) spectrograph (Esposito et al., 2004).

2.1. Recurrent Dipolarization Event 1: 7 August 2009

Figure 1 shows the overview of the magnetic fields and plasma data observed by the Cassini spacecraft on 7 August 2009. The 1-min resolution magnetic fields shown in Figures 1a–1c are provided in Kronographic Radial-Theta-Phi coordinate system. This is a Saturn-centered coordinate: radial vector r is directed from Saturn's center to the spacecraft, the azimuthal component ϕ is parallel to the direction of corotation, and the southward θ completes the right-hand set. Figures 1d and 1e show the differential electron energy flux measured by the CAPS-ELS detector and differential ion energy flux from the CAPS-IMS Singles (SNG) data product. Figures 1f and 1g show electron and ion counts fluxes at higher energies measured by MIMI instruments. During this period, Cassini was located premidnight between 20.6 and 20.9 Saturn local time (SLT), at latitudes from $\sim 9^\circ$ to 11° N of Saturn's equatorial plane and at radial distance from $R \sim 30$ to $32 R_S$ ($1 R_S = 60,268$ km). Magnetic fields show clear PPO (please see supporting information Figure S1 for a longer period of magnetic field, which has been discussed in previous literature; e.g., Andrews et al., 2012; Clarke et al., 2006; Cowley et al., 2006; Provan et al., 2018). On top of the regular magnetic PPO, we notice two distinctive B_r decreases from ~ 3 to ~ 2 nT (marked by the vertical dashed black lines). The separation between these two B_r decreases is 11 hr, almost exactly a planetary rotation period. We therefore call them recurrent dipolarization events, following similar descriptions (e.g., recurrent acceleration events) used in Mitchell, Krimigis, et al. (2009). The first B_r decrease was accompanied by B_θ increase from ~ 1 to ~ 2 nT. Meanwhile, enhancement of electron flux was also observed during the two B_r decrease periods. These are typical signatures of magnetospheric current redistribution dipolarization, as defined in Yao, Grodent, et al. (2017). More details on this event can be found in Yao, Grodent, et al. (2017). In the present study, our major focus is the long-term view of the dipolarization process and the associated energetic particles. It is important here to recall that the identification of dipolarization must rely on both the decrease of B_r and the increase of B_θ . B_r decrease is more indicative when a spacecraft is in the outer plasma sheet, while increase of B_θ usually serves as a good indicator when spacecraft is near the central current sheet. Plasma energization could serve as a good indicator to determine whether a process is a dipolarization or a pure current sheet flapping (Yao, Rae, Lui, et al., 2017). In our study, we clearly notice a large B_r during the whole period; therefore, we would need to treat B_r as the key indicator of a dipolarization process. To distinguish between the two dipolarization processes, we named the dipolar-

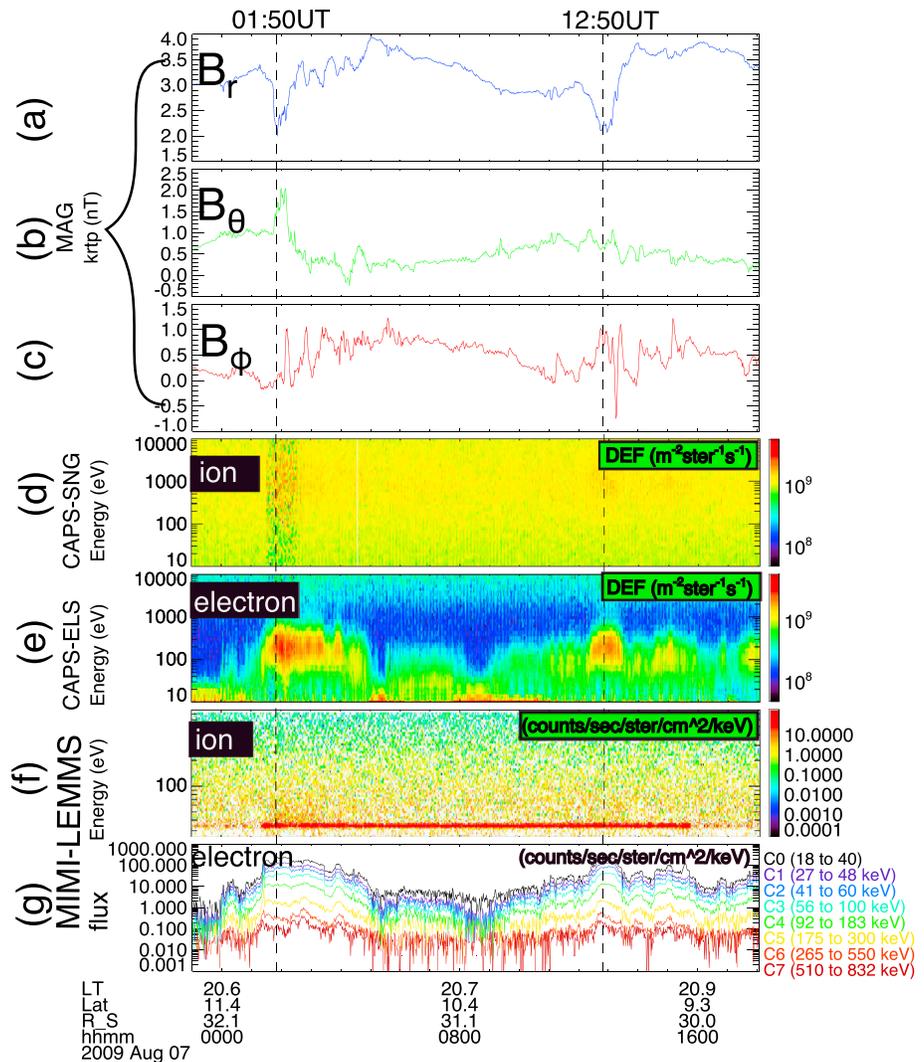


Figure 1. Overview of magnetic fields and plasma measurements on 7 August 2009. Two dipolarization processes are marked by the vertical dashed black lines. (a–c) the magnetic fields are in KRTP coordinates. (d) ion differential energy flux from CAPS-SNG. (e) electron differential energy flux from CAPS-ELS. (f) energetic ion counts from MIMI-LEMMS. (g) energetic electron counts from MIMI-LEMMS detector. KRTP = Kronographic Radial-Theta-Phi; CAPS-SNG = CAPS-IMS Singles; MIMI-LEMMS = Magnetosphere Imaging Instrument-Low Energy Magnetospheric Measurement System.

ization observed at ~ 01:50 UT as DP1 (the first vertical dashed black line), and the one observed at ~ 12:50 UT as DP2 (the second vertical dashed black line). For DP1 and DP2, Cassini ion instruments did not record any significant flux enhancements with energies from a few electron volts to hundreds of kiloelectron volts. However, electron fluxes were enhanced with energies from ~ 100 eV to ~ 500 keV.

In Figure 2, we compare the measured magnetic fields from DP1, DP2, and the measurements from one rotation prior to DP1 that could set as a baseline. The three 8-hr periods are marked by the blue (2009 August 06/13:00 UT to 21:00 UT), black (7 August 2009 at 00:00 UT to 08:00 UT) and red (7 August 2009 at 11:00 UT to 19:00 UT) patches at the top of Figure 2a. As shown in Figure 2b, a general consistent trend in the magnetic field's main component B_r is obvious for the three periods. During the baseline period (blue curve), B_r component changes smoothly, which includes effects from both the PPO's modulation and magnetosphere's rotation. Comparing to the baseline variation, the most significant differences of B_r during DP1 and DP2 periods exist between $T_0 + 1$ hr and $T_0 + 5$ hr. For the decrease of B_r , the magnitudes of decrease and the timescales were remarkably similar. The recurrent dipolarization event (DP1 and DP2) is significantly different from background variation (blue dashed curve in Figure 2b), and the two dipolarization events look like very localized structures since the variation returns to background profile rapidly. Therefore, the recurrent dipolar-

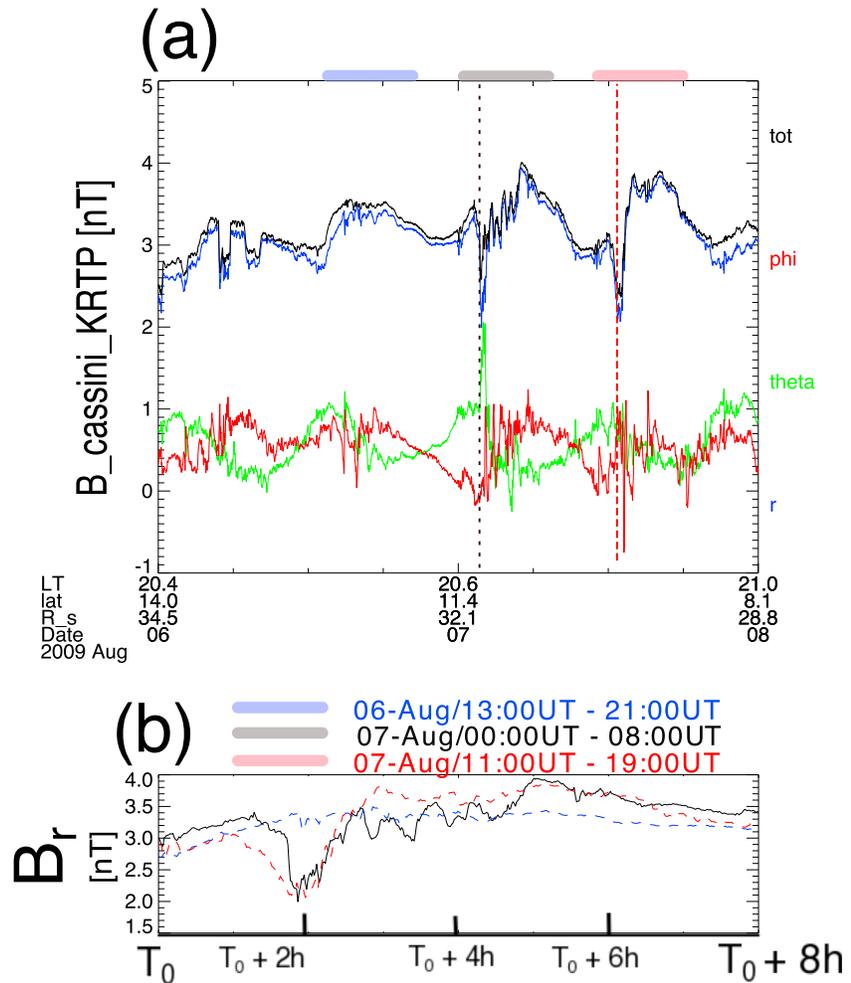


Figure 2. Comparison of the background (blue), DP1 (black), and DP2 (red) events. (a) Overview of the 1-min resolution magnetic field between 6 and 8 August and (b) superimposed plots of magnetic fields for the selected three periods. DP = dipolarization process; KRTP = Kronographic Radial-Theta-Phi.

ization event is clearly different from the PPO's modulation of long-term scale variation. Moreover, electrons shown in Figure 1g were accelerated up to ~ 500 keV, strong evidence that there was an efficient acceleration accompanying these structures, instead of a pure modulation process.

2.2. Recurrent Dipolarization Event 2: 6 February 2009

Figure 3 presents overview of another recurrent dipolarization event observed on 6 February 2009 with the same format as Figure 1. This event was detected 1 day prior to Cassini's Titan flyby (T-50), when Cassini was outbound traveling from $R \sim 18.7$ to $19.6 R_S$, at latitudes from $\sim -25^\circ$ to -7° south of Saturn's equatorial plane, and at prenoon from 9.5 to 10 SLT. Similar to event 1, a clear PPO modulation of magnetic fields is shown in Figures 3a–3c (please see the supporting information Figure S2 for a longer period of magnetic field. The two dashed vertical lines indicate two B_θ enhancements, accompanied by B_r decreases. As shown in Figures 3d and 3e, ~ 1 keV ions and few hundreds of electron volt electrons were observed prior to the two dipolarizations, indicating that the Cassini spacecraft was in the central plasma sheet but not at its outer boundary or in the lobe region (the case of Event 1).

As shown in Figures 3d and 3f, ion fluxes are enhanced at energies from ~ 1 to ~ 200 keV, which is significantly different from Event 1. It is unclear whether this difference is caused by different locations (i.e., inner and outer current sheet) or due to different acceleration mechanisms. During the dipolarization processes, ambient electrons with energies at a few hundreds of electron volts were sufficiently accelerated to a few kiloelectron volts (Figure 3e). Moreover, energetic electrons with energy up to 500 keV were also significantly enhanced. For the energetic ions (Figure 3f, mostly protons) and electrons (Figure 3g), a pulsation (1–2 hr)

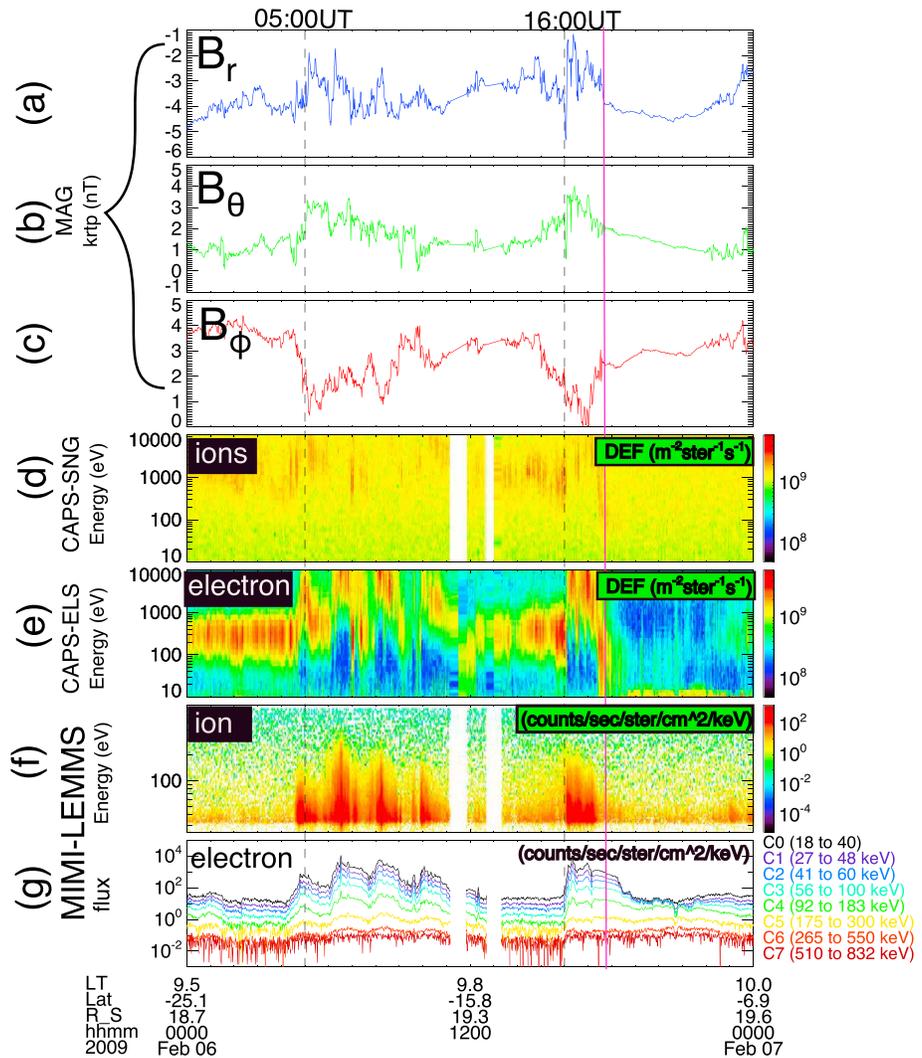


Figure 3. Overview of magnetic fields and plasma measurements on 6 February 2009. The format is the same as Figure 1.

that has been often identified in Saturn’s magnetosphere (e.g., Roussos et al., 2016 and Palmaerts et al., 2016) was clearly identified for the first dipolarization, while it was absent for the second one. The pulsations of electrons and ions were also detected at energies of a few kiloelectron volts by the CAPS instruments (Figures 3d and 3e). It is unclear whether the absence of pulsation in the second dipolarization is due to a different plasma process or not. There is a boundary likely associated with spatial variation as marked by the purple vertical line, which might be associated with the approach to Titan. This boundary can be seen clearly from all three field components, indicating that the field has a markedly different character. Although no literature that we are aware of has explained why the approach to Titan could produce a dropout of plasma fluxes, we have identified many similar features during Cassini’s other approaches to Titan. Since it is not within the scope of the present study, we do not go further into Titan’s interaction with Saturn’s magnetosphere in this research.

2.3. Recurrent Dipolarization Event 3: 19 September 2010

Event 3 was observed on 19 September 2010, when Cassini was located postevening at ~ 20 SLT, near equator with latitudes at $\sim -4^\circ$ south hemisphere and at radial distance from $R \sim 32$ to $29 R_S$. As demonstrated in Thomsen et al. (2017), PPO modulation of magnetic fields often shows asymmetries between northbound and southbound crossings in 2010. The asymmetric PPO modulation signature is clearly presented in Figures 4a–4c (please see the supporting information Figure S3 for a longer period of magnetic field); that is, the north to south crossings were much more rapid than south to north crossings (or B_r positive to negative changing was quicker than negative to north changing). Within the large-scale modulation, rapid

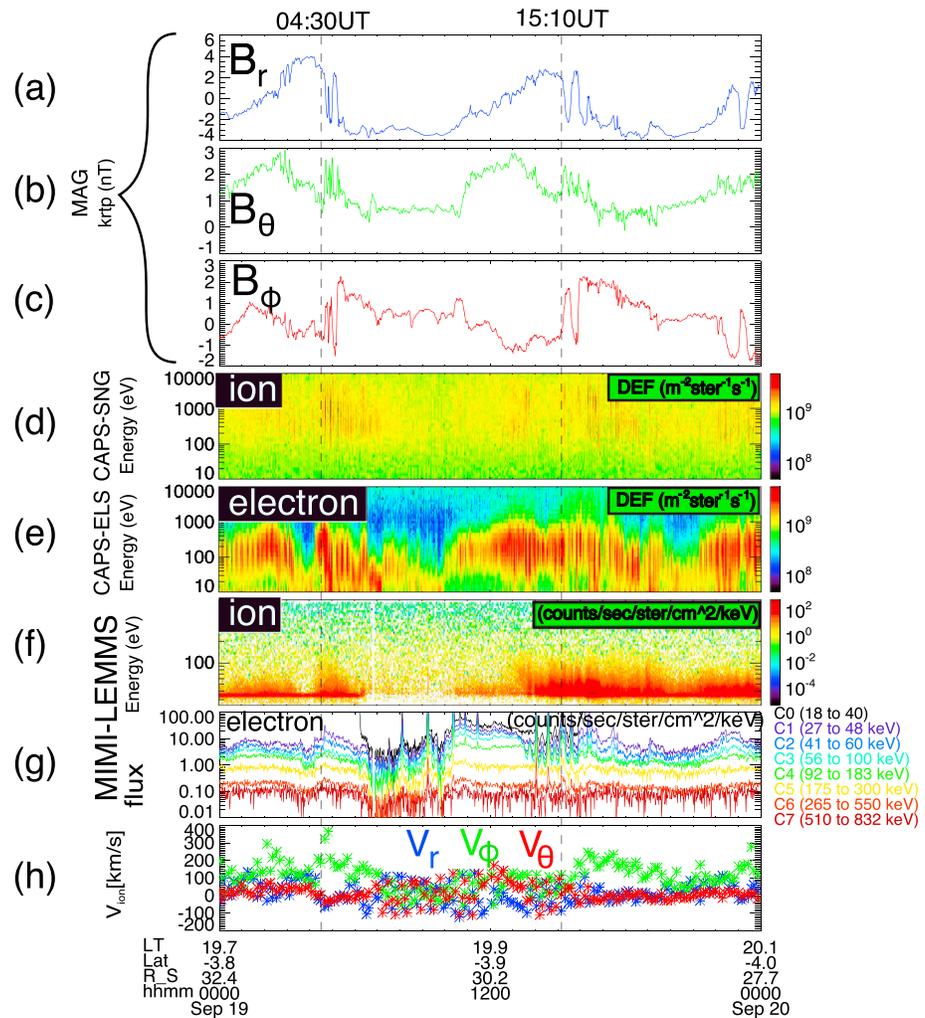


Figure 4. Overview of magnetic fields and plasma measurements on 19 September 2010. The format of Figures 4a–4g is the same as in Figure 1. Figure 4h shows the derived ion velocity by numerical integration of CAPS Ion Mass Spectrometer measurements.

enhancements of B_θ were observed at the trailing phase of each period, which was also accompanied by short-duration wiggle structures in B_r and B_ϕ components. The two distinctive B_θ enhancements are separated by about 10.7 hour, almost a planetary rotation. Since the spacecraft was very close to the equator (indicated by the small latitude and small B_r), the variation of B_θ shall be considered as the most important indicator, which is very different from the situation when a spacecraft was in the outer current sheet, for example, in event 1.

As shown in Figures 4d and 4e, ions and electrons remained at roughly ambient energies. The fluxes of electrons and ions were enhanced for the first dipolarization, with no significant enhancement during the second dipolarization for this recurrent event. The ion counts shown in Figure 4f show slight enhancements associated with the two dipolarization periods at relatively low-energy channels (< 100 keV). From Figure 4g, we also see that there was a very slight enhancement in energetic electrons with energies below 100 keV. The pulsating enhancements of energetic electrons between 14 UT and 16 UT are likely associated with the rotation of spacecraft during this period. From the electron flux shown in Figure 4e, we do not clearly see energization of electrons and sharp boundary to distinguish between the predipolarization and after dipolarization populations; therefore, we could conclude that the pair of dipolarization events are current redistribution dipolarizations rather than dipolarization fronts as defined in Yao, Grodent, et al., (2017).

In this event, Cassini was relatively close to the central plasmadisc and was able to provide ion velocity components, as shown in Figure 4h. The pair of dipolarization events were accompanied with significant bulk flow in the planetary corotating direction. The peak flow velocity for the first dipolarization was about 360 km/s, and for the second was about 250 km/s. Both velocities are very close to the rigid corotating velocity (~ 300 km/s), and the azimuthal flow velocity was higher than planetary rotation during the first dipolarization. The faster than planetary rotation plasma flow is explained as supercorotating return flow from reconnection in Saturn's magnetotail (Masters et al., 2011). The relation between fast plasma flow and magnetic dipolarization is very complicated and remains controversial even by combining multiple data sets from multiprobe missions and ground stations in terrestrial research (Keiling et al., 2009; Yao et al., 2012). Since their relation is not a major focus of this paper, we therefore do not go further on this point.

3. Discussion

Magnetic reconnection, substorm dipolarization, current disruption, and field-aligned current formation are strongly coupled processes. At Earth these processes usually take place in the nightside magnetotail, with a preference at premidnight local time (Runov et al., 2017). In giant planetary magnetospheres, internal drivers usually dominate magnetospheric dynamics and would lead to a preference during postmidnight local times (Vasyliunas, 1983). The survey of dipolarization events in the nightside magnetosphere also revealed higher occurrences during postmidnight (Smith et al., 2018). Although previous investigations on magnetic dipolarization are restricted to the nightside magnetosphere, it may need to be updated, since the magnetic reconnection process that is strongly coupled to dipolarization has been recently proposed by Delamere et al. (2015) and observed by Guo et al. (2018) to take place in Saturn's dayside magnetodisc.

Bend back configuration of magnetic field is an expected feature produced by net mass outflow, and bend forward configuration is expected to follow magnetic reconnection. By surveying bend forward magnetic configuration from 2004 to 2012 with Cassini-MAG instrument, Delamere et al. (2015) revealed that reconnection could take place in all local times. Furthermore, they show high probabilities of reconnection at prenoon and afternoon sectors and proposed a *drizzle-like* process to explain their observations. Furthermore, Guo et al. (2018), using Cassini in situ measurements, identified the reconnection-associated Hall current system and reconnection-accelerated plasma (including electrons and ions) in near-noon magnetodisc for the first time. Guo et al. (2018) also detailed that the reconnection produced acceleration of heavy ions and pulsating energetic electrons. Following these studies, we would naturally expect magnetic dipolarization processes to exist in Saturn's dayside magnetosphere. In this study, event 2 was observed at about 10 SLT, which further evidences that the internal processes are important in driving dayside magnetospheric dynamics and demonstrates that magnetic dipolarization processes exist in Saturn's dayside.

The recurrent nature of dipolarization is very intriguing, leading to many open questions. One of the major difficulties is to distinguish between spatial variation and temporal variation from a single spacecraft's in situ measurements. The recurrent magnetic dipolarization events could be detected if a dipolarized region corotates with Saturn or explained as a not yet known PPO-modulated phenomenon. Each of them also has fundamental difficulties to be compatible with some previous observations.

3.1. Implications From the Rotation of Auroral Breakup Sites and ENA Emissions at Saturn

A natural explanation for recurrent phenomena would be corotation of magnetospheric sources. If a dipolarized region could corotate with the planet, we could then expect to measure the same structure after one planetary rotation. This would also perfectly explain why DF1 and DF2 in event 1 are so consistent, as shown in Figure 2b. Moreover, rotation of magnetospheric sources (e.g., ENA enhancements) and their consequent aurorae has been extensively studied. The rotation of magnetospheric source at up to $30 R_S$ in the night would cause a mystery: What would happen when the source experiences the dayside interaction? Besides the current system in the magnetodisc, the Chapman-Ferraro current system on magnetopause induced by solar wind can also make the magnetosphere asymmetric. The magnetopause current leads to a day-night asymmetry in the magnetosphere, indicating that the magnetic field lines extend farther from the planet at the nightside than the dayside (similar to the Earth; see Figure 1 in Hones, 1963). Therefore, due to the aforementioned asymmetry and the asymmetric flow patterns inside the magnetosphere (e.g., Allen et al., 2018 and Dialynas, 2018), the events that are discussed in the present study could naturally remain inside the magnetopause at a closer distance when they reach the dayside. The first event (on 7 August 2009) was observed at about $30 R_S$ in the postdusk sector; we could also expect the site to remain in the magnetosphere following

the dawn-dusk asymmetry revealed by Pilkington et al. (2015), who showed from Cassini's large data set that the magnetosphere extends farther from the planet on the dawnside of the planet by 6% to 8%. Since there is no similar modeling study that we are aware of at Saturn as Hones (1963) performed for the Earth, we could not quantify the dayside location that corresponds to the nightside at $30 R_S$.

Subcorotation of aurora at Saturn has been reported in previous research. Using measurements from Hubble Space Telescope, Grodent et al. (2005) showed that the bulk auroral emission region is rotating at $65 \pm 10\%$ of the angular velocity of rigid planetary rotating velocity. Angular velocity for some extreme isolated auroral structures constantly decreases with time, down to 20° per hour. Similar evidence that aurora subcorotates with the planet has also been provided by measurements from Cassini-UVIS instrument (e.g., Mitchell et al., 2016; Radioti et al., 2014).

To demonstrate how auroral breakup region rotates, we here quantify the angular rotating velocity of a typical auroral intensification event on day of year 129, 2008, which has also been discussed in detail by Mitchell et al. (2016). The aurora sequence consists of 24 images, from 08:08 UT to 13:39 UT. We specifically focus on a distinctive dawnside auroral intensification from 08:53 UT to 11:53 UT. A sequence of auroral images is shown in Figure 5a, with 1-hr separation between them. It is clear that the auroral patch was rotating and enhanced (also expanded) during this sequence. We need to point out that there is no perfect method to quantify the rotating angular velocity for such a dynamic structure. In this study, we provide an empirical method to quantify potential lower and upper limits of the rotating angular velocity. We integrate aurora intensity over latitude between 68° and 76° (indicated by the two other circles) and obtained an intensity distribution along local time for each image, as shown in Figure 5b. From 08:53 UT to 11:53 UT, the intensity has been clearly enhanced and distributed in a wider local time range, with an obvious bulk shift in local time. In Figure 5c, we add an angular velocity of 1.2 SLT per hour (SLT/hr) for the profiles of 08:53 UT, 09:53 UT, and 10:53 UT and obtain a consistency in the trailing edge (i.e., low local time) of these profiles of enhanced aurora intensity for the four given times, to be compared with the profile at 11:53 UT. Similarly, if we add a rotating angular velocity of 1.5 SLT/hr for these profiles, we can find a good consistency on their leading edges (i.e., high local time) in Figure 5d, with the exception for the 08:53 UT profile. The 08:53 UT profile shows a similar center to other profiles in Figure 5d. The 08:53 auroral intensification was limited in a much narrower region than the other three, and therefore we shall not aim to match the boundary of the 08:53 UT profile to determine a rotating velocity. From Figures 5c and 5d, we suggest that the rotating angular velocity of this auroral intensification region was from 1.2 to 1.5 SLT/hr, that is, 53% to 66% of the rigid planetary rotating angular velocity. This result is consistent with the multicase statistical results in Grodent et al. (2005).

Auroral intensification has also been found to coexist with enhancement in ENA emission at the same local time (Mitchell, Krimigis, et al., 2009), which provides a strong evidence that the ENA emission is likely associated with the magnetospheric source of aurorae. Their results may suggest either that the ENA region is the source for aurora or that the ENA enhancement and aurora are two individual consequences of the same magnetospheric dynamics. Therefore, dipolarization, enhancement of the ENA emission, is strongly connected with auroral enhancements, which is believed to be associated with magnetic dipolarization, and they likely represent three different views of the same magnetosphere-ionosphere coupling dynamics. ENAs are charge exchange products between fast ions and background neutral gas populations, resident in Saturn's magnetosphere (mainly sourced from Enceladus water vapor plumes; Waite et al., 2006). It is important to have in mind that ENAs carry not only spectral information but also compositional information of the source plasma, that is, are always of the same species as their parent ion population, independently of the target neutral gas distribution, and therefore, they can be considered as long distance communicators of the processes that their parent ion distributions undergo (e.g., Dialynas et al., 2013, for details).

Auroral intensification region for the event presented in this study rotates with 53% to 66% of planetary rotating velocity, which is also consistent with previous studies. The enhanced ENA emission on average rotates at angular velocity ranging from $\sim 28^\circ/\text{hr}$ at $5 R_S$ to $\sim 21^\circ/\text{hr}$ between 10 and $20 R_S$, corresponding to 85% and 64% of rigid corotation (Carbary & Mitchell, 2014). We also notice that it is difficult to determine rotating velocity of enhancement of ENA emission for individual events, as the shape of ENA emission is usually very dynamic. However, the angular velocity for long-duration ENA potentially can be accurately determined. For example, if an ENA event lasts for one planetary rotation, then a shape change of 1–2 hr in local time would only involve an uncertainty of less than 10%. On average, ENA emissions are found to subcorotate with planet without distinguishing the different mechanisms generating these ENA emissions. However, rigidly corotating

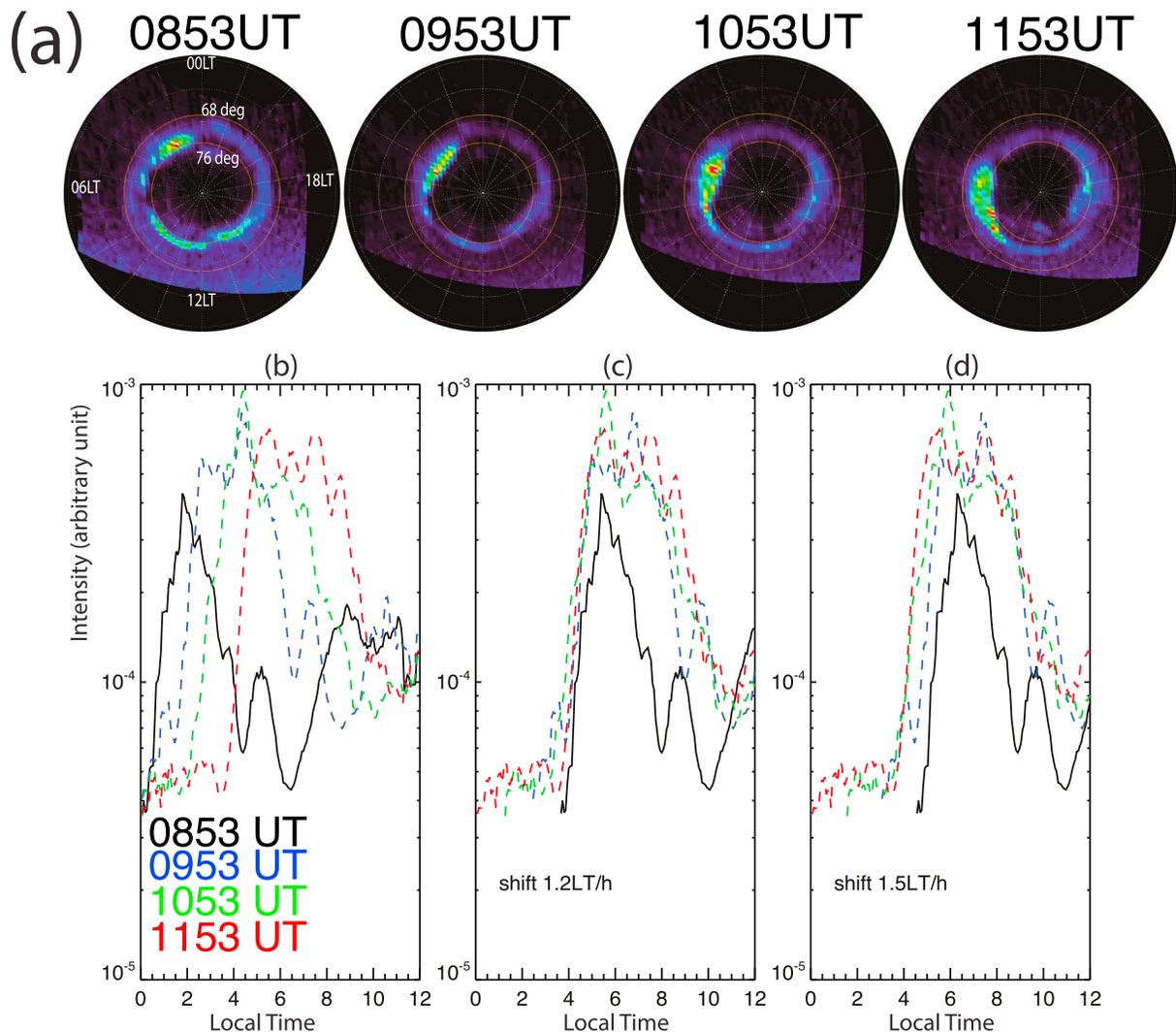


Figure 5. (a) A sequence of aurora images from 08:53 UT to 11:53 UT (separated by 1 hr between each two) on day of year 129, 2008. (b) Local time distribution of integrated auroral intensity between 68° and 76° latitudes for the four images in Figure 5a. (c, d) The profiles of 08:53 UT, 09:53 UT, and 10:53 UT are shifted to 11:53 UT by adding a local time rate of 1.2 LT/hr and 1.5 LT/hr.

ENA emission enhancement can also often be identified; for example, Krimigis et al. (2007) present a rigidly corotating ENA emission event that lasted for longer than one planetary rotation, which is associated with enhanced partial ring currents. Other near corotating ENA emission enhancement events can also be found from the online data set (http://cassini-mimi.jhuapl.edu/PDS_Volumes/COMIMI_I001/BROWSE/)

Many potential mechanisms may lead to enhancements of ENA emissions in Saturn's magnetosphere (e.g., enhancement of partial ring currents, Krimigis et al., 2007; plasma injection, Mauk et al., 2005; and Titan's interaction with Saturn's magnetosphere, Mitchell et al., 2005), and probably different mechanisms would produce different angular velocities. Moreover, the ENA angular velocity may evolve during the rotation, since it would constantly interact with the electromagnetic environment. Here we speculate that the ENA emission enhancements associated with dipolarization process would have high rotating velocity and may even rigidly corotate with the planet. Besides ENA emission, we also propose a physical picture to connect the corotating dipolarized region and subcorotating auroral intensification, which is illustrated in Figure 6. A corotating dipolarized site, as indicated by the blue lines in Figure 6a, rotates from 0 hr LT to 24 hr LT every planetary rotation period, and can be observed by an observer (the green arrow on the left) only once during each rotation. Note that here we assume that the observer's position does not significantly change in latitude and local time in the timescale of planetary rotation period, which is the case for Cassini spacecraft in the magnetosphere at the

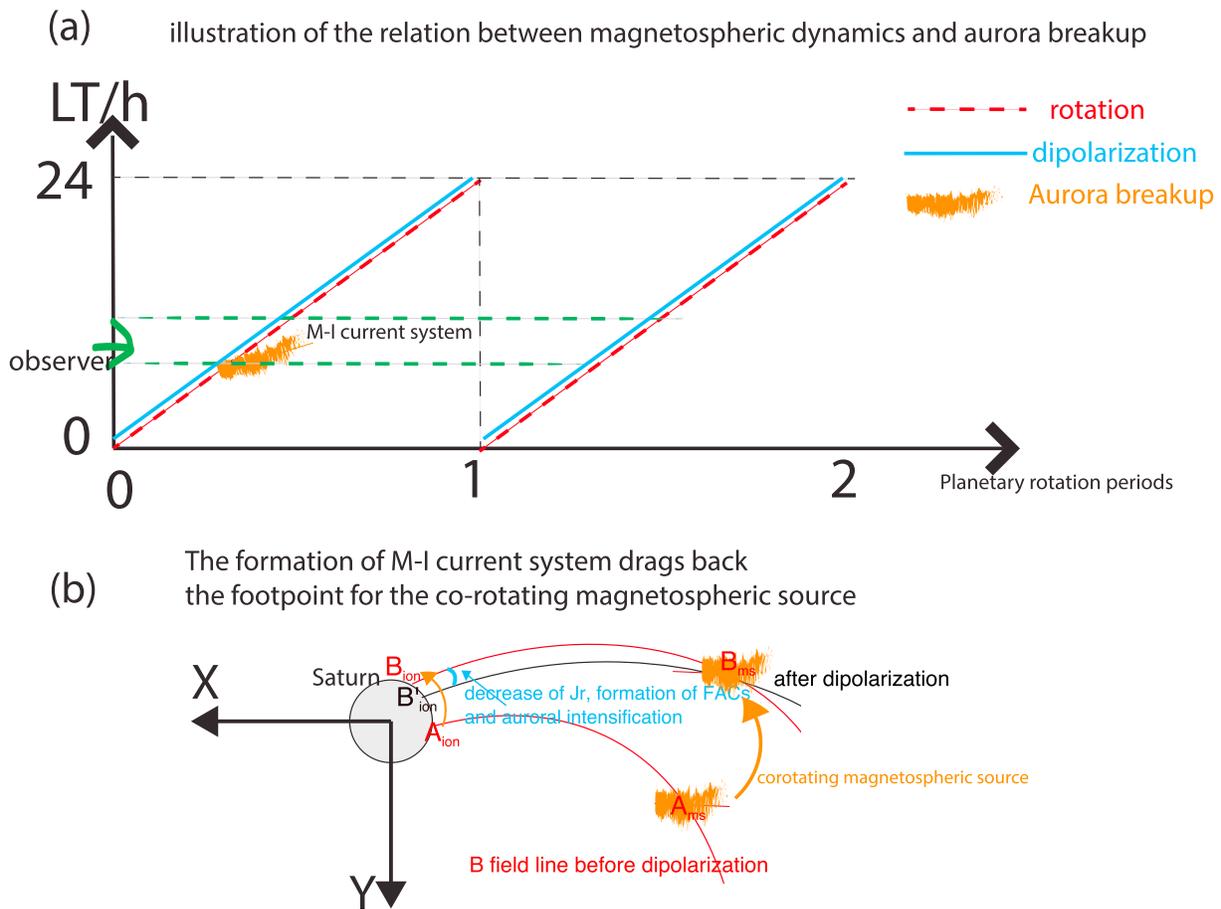


Figure 6. Illustration of relations between aurora breakup and magnetospheric sources. (a) How local time of dipolarization and aurora change with time. The red dashed line indicates rigid planetary rotation, the solid blue line shows local time of dipolarization site changes with time, and the orange cloud indicates the local time of enhanced aurora site changing with time. (b) How the footprint of magnetospheric source changes during the development of auroral current system, in the view from the north pole of Saturn. The two red curves ($A_{ms}-A_{ion}$ and $B_{ms}-B_{ion}$) represent two field lines in a steady state magnetospheric configuration; the $A_{ms}-A_{ion}$ field line would naturally rotate to $B_{ms}-B_{ion}$ if there is no reconfiguration of magnetic field. During auroral intensification period, the magnetic field $B_{ms}-B_{ion}$ would evolve into the black curve ($B_{ms}-B'_{ion}$) during and after dipolarization due to the formation of the magnetosphere-ionosphere current system. During this process, the footprint of a corotating magnetospheric source would subcorotate with the planet, due to the changing geometry of magnetic field lines that connect the magnetosphere and ionosphere. Therefore, the footprint would have a lower angular velocity than the magnetospheric counterpart.

time to make observations that we used in this study. The orange cloud in Figure 6a illustrates how the local time position of the aurora intensification site changes with time.

Unlike the enhanced ENA emissions or dipolarization process that could last for longer than one planetary rotation period, auroral intensification structure usually decays in a few hours. This is understandable, as auroral intensifications are generally caused by enhanced electron precipitations, which would disappear after a few electron bouncing periods if no new source fills in the loss cone of the particle distributions when the energy source of aurora is exhausted. ENA emission suggests trapped energetic particles in the magnetosphere, and dipolarization suggests a relaxed state of the magnetosphere. The trapped energetic population could exist for much longer time than the transient auroral emissions. The transient auroral intensification usually suggests an enhancement of electron precipitation and formation of field-aligned currents, which is a consequence of magnetospheric currents diversion into the ionosphere. During this process, azimuthal magnetic field component is expected to decrease and to form a sharp spatial gradient that corresponds to formation of field-aligned currents (Balogh et al., 1992; Cowley et al., 2008). The rapid decrease in azimuthal component B_{ϕ} would produce a change of magnetic geometry and hence would change the footprint of magnetospheric source in the ionosphere. Therefore, during a transient process like magnetic dipolarization that involves field-aligned current formation, the footprint of magnetospheric site would move in azimuthal

direction, meaning that conjugated sites in the magnetosphere and ionosphere could rotate at different angular velocity.

As illustrated in Figure 6b, the magnetic field line in equatorial plane would change from the black curve to the red curve, and therefore the footpoint of the magnetospheric source would drift opposite to planetary rotation. In the description below, the subscript *ms* refers to the magnetosphere, and *ion* refers to the ionosphere. A_{ms} - A_{ion} and B_{ms} - B_{ion} represent the two red field lines in a steady state magnetospheric configuration; the A_{ms} - A_{ion} line would move to B_{ms} - B_{ion} if the two lines rigidly rotate. However, when dipolarization is involved when magnetospheric population rotates from A_{ms} to B_{ms} , the reconfigured magnetic field line (black) would connect the magnetospheric B_{ms} to B'_{ion} in the ionosphere instead of the original B_{ion} . Since the footpoint changes from A_{ion} to B'_{ion} when A_{ms} rotates to B_{ms} , the ionospheric counterpart therefore has a lower angular velocity than the magnetospheric counterpart. As a consequence, we would expect the auroral intensification region to rotate at a lower angular velocity than its magnetospheric source, that is, dipolarization. The divergence of footpoints (B_{ion} and B'_{ion}) in the ionosphere is illustrated by the blue curve, which is produced by the formation of field-aligned currents and decrease of radial currents in the magnetosphere. We stress the importance of carefully comparing phenomena with different temporal scales. The transient phenomena often involve ongoing dynamics that change the connecting relations between the magnetosphere and ionosphere. By understanding the different angular velocities between these signatures, we could also potentially improve Saturn's magnetic model.

Although corotation of the dipolarized site could potentially well explain the recurrent nature of dipolarization and the associated subcorotating auroral region, corotation of the dipolarization might be in conflict with ion flows derived from Cassini's particle instruments that are well below rigid corotating velocity (McAndrews et al., 2009; Thomsen et al., 2010, 2014). We would like to point out that the subcorotations of magnetospheric sources (i.e., ENA emission and ion flow) are only average descriptions, while it remains mysterious why individual cases significantly vary. Thomsen et al. (2010) also show that different ion species (i.e., proton and water group) rotates at different angular velocities, which also vary with distance. It is then reasonable to assume a different angular velocity for electrons. In plasma environments, electrons are usually the most important current carriers and are also most likely frozen onto magnetic fields. Analysis of generalized Ohm's law with comprehensive measurements from magnetic field, plasma momentum, and electric field is crucial to understand how ions and electrons are frozen onto magnetic fields (Yao, Rae, Guo, et al., 2017).

3.2. PPO Modulation on Magnetospheric Dynamics

Modulation from PPO was clearly identified at all three events presented in this study. Since the recurrent dipolarization event reappeared after about one planetary rotation, each dipolarization shall be observed at a similar phase of PPO. It is unclear whether the dipolarization signature is caused by PPO's modulation.

PPO can not only produce periodic motion of Saturn's plasma sheet at nightside (Arridge et al., 2011) but also cause periodic variations in the thickness of Saturn's nightside plasma sheet. However, there is no evidence that the modulation of plasma sheet motion or thickness can produce efficient particle acceleration, particularly for the hundreds of kiloelectron volt population. Even if we assume that PPO could trigger reconnection and current disruption, this cannot explain why one planetary rotation later, the preconditions are the same (Figure 2b for event 1). If PPO triggered a reconnection and current disruption at a certain modulation phase (e.g., Jackman et al., 2016b), after one planetary rotation period, there is no reason to assume the same thin current sheet condition for current disruption and reconnection again. The blue curve in Figure 2b was unperturbed at the same phase of PPO, which also suggests that the later recurrent dipolarization is not purely a PPO modulation; otherwise there should be a similar decrease of B_r on the blue curve at the same phase of PPO. Internal processes (e.g., plasma instabilities) or external effects (e.g., the solar wind) may have influence in causing the observed recurrent B_r decrease.

If PPO produces dipolarization and the consequent aurora, then aurora should rotate with the same angular velocity as PPO (i.e., rigid rotation) and not only about 50% to 60% percent. If a source in the subcorotating magnetosphere causes the auroral intensification, then the auroral breakup region shall not rotate faster than the magnetosphere when considering the reconfiguration of magnetic field during auroral precipitation, which however is not supported by previous observations of ions and ENA. Thomsen et al. (2014) presented a statistical distribution of azimuthal ion velocity at different distance and found that ion velocity remains roughly 100 km/s above $20 R_S$, which corresponds to $\sim 30\%$ to 50% of planetary rigid corotation at 20 to $30 R_S$. Either way, there exists fundamental conflict.

By checking the relative phases of the PPO for each event, we were surprised to find that all the events were observed with north phases at around 90° and south phases at around 300° , in which plasma and field lines are displaced inward and the current sheet is thick. Both effects are not favorable for reconnection, plasmoid, or dipolarization to occur, which is opposite to the findings in Jackman et al. (2016a). Clearly the events presented in this paper are not supported by PPO modulation on reconnection (or dipolarization), while it remains unclear what controlled these processes. We would like to recall that we do not consider the inconsistency with PPO phase in strong conflict with the discovery in Jackman et al. (2016a), as we here report on dipolarization events while their research was about plasmoid. As we mentioned, the relations among dipolarization, reconnection, and plasmoid could be extremely complicated.

Neither corotation of dipolarized region nor PPO triggering dipolarization could fully explain the recurrent dipolarization phenomena reported in this paper. The two processes shall together be involved, while it is unclear whether the two mechanisms could cooperate to produce such process. It requires further investigations on the two potential mechanisms, particularly with a combined view from other data sets, for example, ENA and auroral emissions.

4. Summary

Magnetic dipolarization describes a reconfiguration of magnetic geometry from stretched magnetic field lines to more dipolar field lines. The change of magnetic field suggests a current system evolution, that is, magnetospheric currents divert into the ionosphere and is usually accompanied by precipitation of energetic electrons into the ionosphere and atmosphere. Therefore, magnetospheric dipolarization process is usually considered as an indicator of the magnetospheric dynamics for generating auroral intensifications in planetary polar regions. Although many pieces of evidence demonstrate the connections among these transient phenomena, we shall notice that details on their relations are far from understood.

Using measurements from multiple instruments on board the Cassini spacecraft, we report recurrent type of dipolarization with three events. Our main results are summarized below.

1. We reported three pairs of dipolarization events which reappeared by one planetary rotation period.
2. We report dipolarization events (i.e., event 2) that exist at the dayside magnetosphere.
3. Energetic electrons or ions are observed in all the three recurrent dipolarization events. In events 1 and 3, electrons were accelerated to hundreds of kiloelectron volts. In events 2 and 3, energetic ions were detected mostly at tens of kiloelectron volts, although 100–300 keV ions were also detected in event 2.

In our discussion, we compared two potential mechanisms (i.e., corotation and PPO modulation) in generating the recurrent dipolarization events, however each of them remains inconsistent with some previous measurements. What produced the recurrent dipolarization remains mysterious. Corotation of dipolarization site could well explain the reappearance of energetic particles, while it is unclear why or how the site remains structured after one planetary rotation. The hypothesis of corotating dipolarization site also leads to a crisis in understanding the well-known subcorotating plasma flows revealed by a previous plasma data set. This crisis does not exist in the other mechanism, that is, the PPO modulation. However, the PPO picture only provides a modulation of the magnetic field outside of $10 R_S$, while it does not directly involve particle acceleration up to $30 R_S$. Moreover, the relative phases of the PPO in all the three events correspond to thick and displaced inward plasma, which are not favorable for magnetic reconnection, plasmoid, and dipolarization to occur.

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