AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE
10.1002/2017JA024060

Special Section:
Observations, Simulations, and Theory of Electric Currents in the Solar System

Key Points:
- Two fundamentally different types of magnetic dipolarization are identified in Saturn
- The two types of dipolarization at Saturn share many similarities with Earth's dipolarization processes
- Internally driven process may produce both types of the magnetic dipolarization

Correspondence to:
Z. H. Yao,
zhonghua.yao@ulg.ac.be

Citation:
Yao, Z. H., et al. (2017), Two fundamentally different drivers of dipolarizations at Saturn, *J. Geophys. Res. Space Physics*, *122*, 4348–4356, doi:10.1002/2017JA024060.

Received 20 FEB 2017
Accepted 3 APR 2017
Accepted article online 7 APR 2017
Published online 25 APR 2017

Two fundamentally different drivers of dipolarizations at Saturn

Z. H. Yao[1,2], **D. Grodent**[2], **L. C. Ray**[3], **I. J. Rae**[1], **A. J. Coates**[1], **Z. Y. Pu**[4], **A. T. Lui**[5], **A. Radioti**[2], **J. H. Waite**[6], **G. H. Jones**[1], **R. L. Guo**[7], **and W. R. Dunn**[1]

[1]UCL Mullard Space Science Laboratory, Dorking, UK, [2]Laboratoire de Physique Atmosphérique et Planétaire, STAR Institute, Université de Liège, Liège, Belgium, [3]Department of Physics, Lancaster University, Bailrigg, UK, [4]School of Earth and Space Sciences, Peking University, Beijing, China, [5]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA, [6]Southwest Research Institute, San Antonio, Texas, United States, [7]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

Abstract Solar wind energy is transferred to planetary magnetospheres via magnetopause reconnection, driving magnetospheric dynamics. At giant planets like Saturn, rapid rotation and internal plasma sources from geologically active moons also drive magnetospheric dynamics. In both cases, magnetic energy is regularly released via magnetospheric current redistributions that usually result in a change of the global magnetic field topology (named substorm dipolarization at Earth). Besides this substorm dipolarization, the front boundary of the reconnection outflow can also lead to a strong but localized magnetic dipolarization, named a reconnection front. The enhancement of the north-south magnetic component is usually adopted as the indicator of magnetic dipolarization. However, this field increase alone cannot distinguish between the two fundamentally different mechanisms. Using measurements from Cassini, we present multiple cases whereby we identify the two distinct types of dipolarization at Saturn. A comparison between Earth and Saturn provides new insight to revealing the energy dissipation in planetary magnetospheres.

1. Introduction

For any planet with a magnetosphere in the solar system, energy from solar wind is transferred to the magnetosphere via magnetopause reconnection and then stored in the magnetotail [*Akasofu*, 1980]. In addition, reconnection in giant planetary magnetospheres could be a "drizzle-like" process, which forms a complex and patchy network of reconnection sites [*Delamere et al.*, 2015]. A magnetospheric substorm is a major space weather event that explosively releases the energy stored in the nightside terrestrial magnetosphere [*Akasofu*, 1964; *Hones*, 1979; *McPherron et al.*, 1973]. Studies indicate that this loading and unloading process also occurs at other planets, e.g., Mercury [*Slavin et al.*, 2010; *Sun et al.*, 2015], Saturn [*Jackman et al.*, 2013], and Jupiter [*Kronberg et al.*, 2005]. The most indicative feature of magnetospheric substorms is magnetic dipolarization in planetary magnetotails.

At Earth, magnetic dipolarization is usually considered a consequence of the reconfiguration of magnetotail current system, i.e., the cross-tail current disruption [*McPherron et al.*, 1973; *Kan*, 1991; *Pu et al.*, 2001]. A terrestrial substorm dipolarization process typically lasts for a few minutes to tens of minutes and is usually accompanied by strong magnetic perturbations [e.g., *Lui*, 1996; *Lui et al.*, 2008; *Yao et al.*, 2012]. The substorm dipolarization mechanism is under debate, in particular, its relation to near-Earth magnetotail reconnection [*Nakamura et al.*, 2009; *Birn and Hesse*, 2013]. Identification of substorm dipolarization from in situ magnetic field data alone is not straightforward as dipolarized magnetic fields also often exist in reconnection outflows. [*Sitnov et al.*, 2009; *Fu et al.*, 2013]. The substorm flux pileup model suggests that the stopping of reconnection outflows in the near-Earth magnetotail results in magnetic field dipolarization and eventually triggers the onset of the substorm expansion phase [*Baumjohann et al.*, 1999]. More recently, multiple studies have reported the Earthward propagation (from midtail to near Earth) of magnetic dipolarization signatures [*Angelopoulos et al.*, 2008; *Runov et al.*, 2011; *Sergeev et al.*, 2009; *Pu et al.*, 2010] using the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [*Angelopoulos*, 2009] that provides multiple spacecraft located at varied radial distances.

Nakamura et al. [2002] first used the term dipolarization front (DF) to describe the earthward propagating magnetic dipolarization signature. The structure is usually considered as the front boundary of earthward reconnection outflows [*Angelopoulos et al.*, 2013; *Yao et al.*, 2013, 2014], which is significantly different from substorm dipolarization, although they are often observed together. *Lui* [2014] recently demonstrated the differences in mechanisms and features between the two types of magnetic dipolarization. Each mechanism has a unique timescale, wave feature, and importance in substorm current formation. The significance of the two types of dipolarization in driving large-scale magnetospheric dynamics is very different [*Lui*, 2015].

Regarding the substantially different planetary environments at Earth and Saturn, we do not directly adopt the terminology “substorm” in Saturn, although we still use “substorm” in introducing previous literature for accurate interpretations. Moreover, we note here that the terrestrial substorm process is a loading-unloading process, but the corollary is not true; a loading-unloading process is not always a substorm process. Most dynamic processes in space plasmas can be considered as a loading-unloading process (e.g., magnetic reconnection and the development of plasma instability). Hence, and in keeping with the vast majority of planetary studies, we do not refer to the loading-unloading processes in planetary environments as a substorm before these processes are fully understood. In this study, we use current redistribution dipolarization (CRDD) to represent a magnetic topology change caused by large-scale magnetotail current redistribution and use transient dipolarizing flux bundle (TDFB) for reconnection outflow structures that contain strong magnetic field and are accompanied by depleted plasma [*Liu et al.*, 2013a, 2013b].

Substorms (or CRDDs) at other planets are usually very different from terrestrial substorms, particularly in the temporal scale. The terrestrial substorm usually lasts tens of minutes, while at Mercury the energy loading and unloading process is usually completed within a few minutes [*Slavin et al.*, 2010]. At Jupiter and Saturn, the energy loading and unloading process can last for few hours to tens of hours [*Mitchell et al.*, 2005; *Kronberg et al.*, 2005]. The TDFB type dipolarization at giant planet is also reported in previous studies [e.g., *Kasahara et al.*, 2011]. It is poorly understood whether the loading-unloading processes in different planets are driven by solar wind or internal sources.

To identify the two types of dipolarization in Earth’s and Saturn’s magnetosphere, we consider the combined signature of B_θ and B_r. Figure 1 illustrates the expected magnetic components B_x and B_z for the two types of dipolarization at Earth. As shown in the schematic plot in Figure 1 (top), the magnetic field topology changed (from blue to red) due to the reduction of a current perpendicular to the plane. During this process, a spacecraft near the current sheet region should observe a CRDD feature, with an increase in B_z and decrease in B_x. Figure 1 (bottom) are adapted from a simulation paper [*Sitnov et al.*, 2009]. The bottom multiline plot shows a temporal evolution of the magnetic field B_z distribution on the central current sheet. It clearly demonstrates the growth of B_z magnitude in the reconnection outflow region. A spacecraft earthward of the reconnection site should observe a sudden enhancement of B_z, as illustrated by the schematic plot in the right bottom region of Figure 1. A spacecraft located away from the central plasma sheet should also observe an enhancement of B_x accompanying the B_z increase. Generally speaking, from a single spacecraft measurements (not exactly on the equatorial plane), a B_z enhancement is expected; however, the B_x variation shows opposite trends for each type of dipolarization. We would like to point out that at Earth, there are much more supporting information to identify two types of dipolarization, e.g., the ground-based magnetometers and auroral imagers; however, at other planets, the combination of all magnetic components and plasma measurements becomes almost the only method we could rely on.

In addition to the two types of dipolarization that we have introduced, “negative” dipolarizations are often reported at Saturn and Earth [*Jackman et al.*, 2007; *Li et al.*, 2014]. The negative dipolarization is suggested to form in the tailward reconnection site, showing opposite magnetic field direction to the dipolarization. At Earth, the negative dipolarization is called the antidipolarization front [*Li et al.*, 2014] and is suggested to be an early stage of the development of a plasmoid, which is also often observed at Saturn [*Hill et al.*, 2008; *Jackman et al.*, 2011], Jupiter [*Vogt et al.*, 2014], and Earth [*Ieda et al.*, 1998].

With in situ measurements from Cassini in Saturn’s magnetotail, we clearly distinguished, for the first time, CRDD and TDFB dipolarization events using both magnetic field and plasma measurements, and we present two events for each type of dipolarization in this paper. We also compare measurements from THEMIS in Earth’s magnetotail and Cassini in Saturn’s magnetosphere for each type of dipolarization. The magnetic

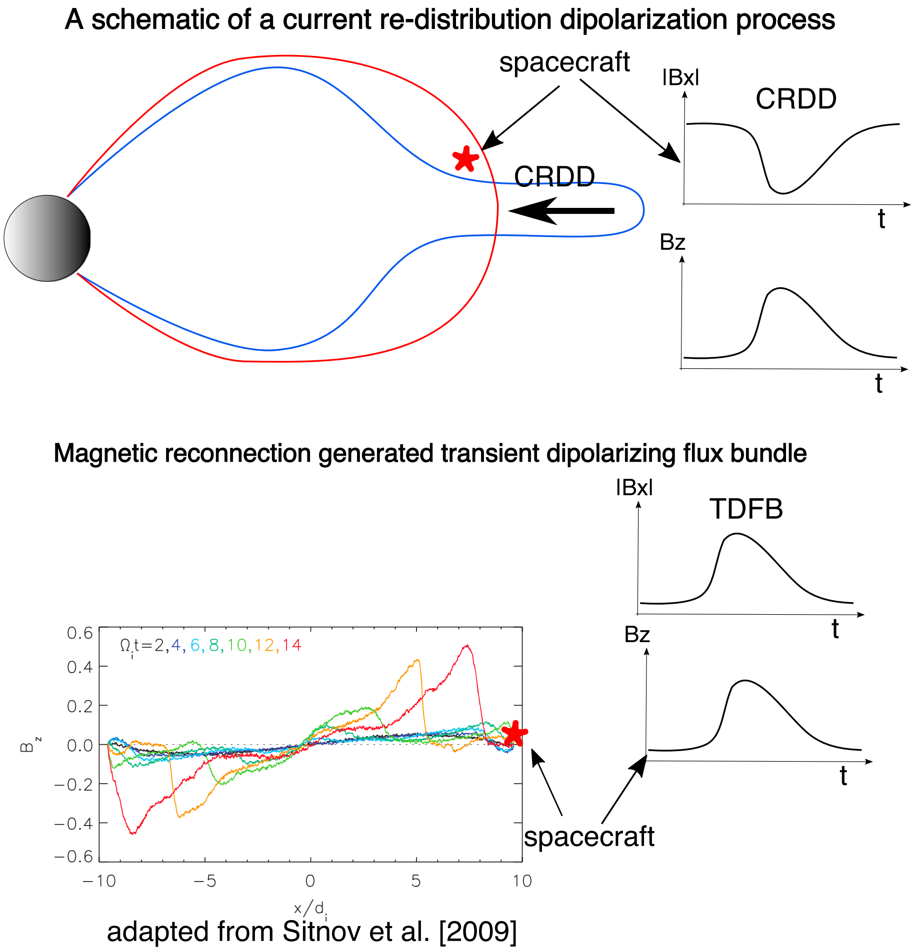

Figure 1. Illustration of the two types of dipolarization. The simulation result is adapted from *Sitnov et al.* [2009].

field measurements in this paper are from THEMIS/fluxgate magnetometer (FGM) [*Auster et al.*, 2009] and Cassini/FGM [*Dougherty et al.*, 2004]; electron measurements are from THEMIS/electrostatic analyzer (ESA) [*McFadden et al.*, 2008] and Cassini electron spectrometer [*Young et al.*, 2004].

2. Results

2.1. Current Redistribution Dipolarization at Saturn and Earth

From top to bottom, Figures 2a–2d and 2e–2h present the three component magnetic fields in Kronographic Radial-Theta-Phi (KRTP) coordinates and electron differential energy flux for two substorm magnetic dipolarization events on 20 September 2006 (Figures 2a–2d) and 7 August 2009 (Figures 2e–2h), respectively. The enhancements of the north-south component of the magnetic field B_θ are indicated by purple arrows in Figures 2b and 2f, respectively, for both events. An enhancement in B_θ has previously been used as the most important criterion in determining a dipolarization event in Saturn's magnetotail [e.g., *Jackman et al.*, 2013].

As shown in Figures 2a and 2e, a clear decrease in B_r is accompanied with the B_θ increase for both events. Learning from the signature of two types of dipolarization that we have described in Figure 1 (top), we consider the decrease in B_r as a strong evidence of current sheet expansion. We also note that the magnetic field B_ϕ component also decreases simultaneously, which we suggest to be a consequence of global magnetic reconfiguration.

Figures 2d and 2h show the spectrum of electron differential energy flux for both dipolarization events. A significant flux enhancement was observed during the magnetic dipolarization for both events. The enhancement of electron flux is strong evidence of the current sheet expansion. Before dipolarization, Cassini was in

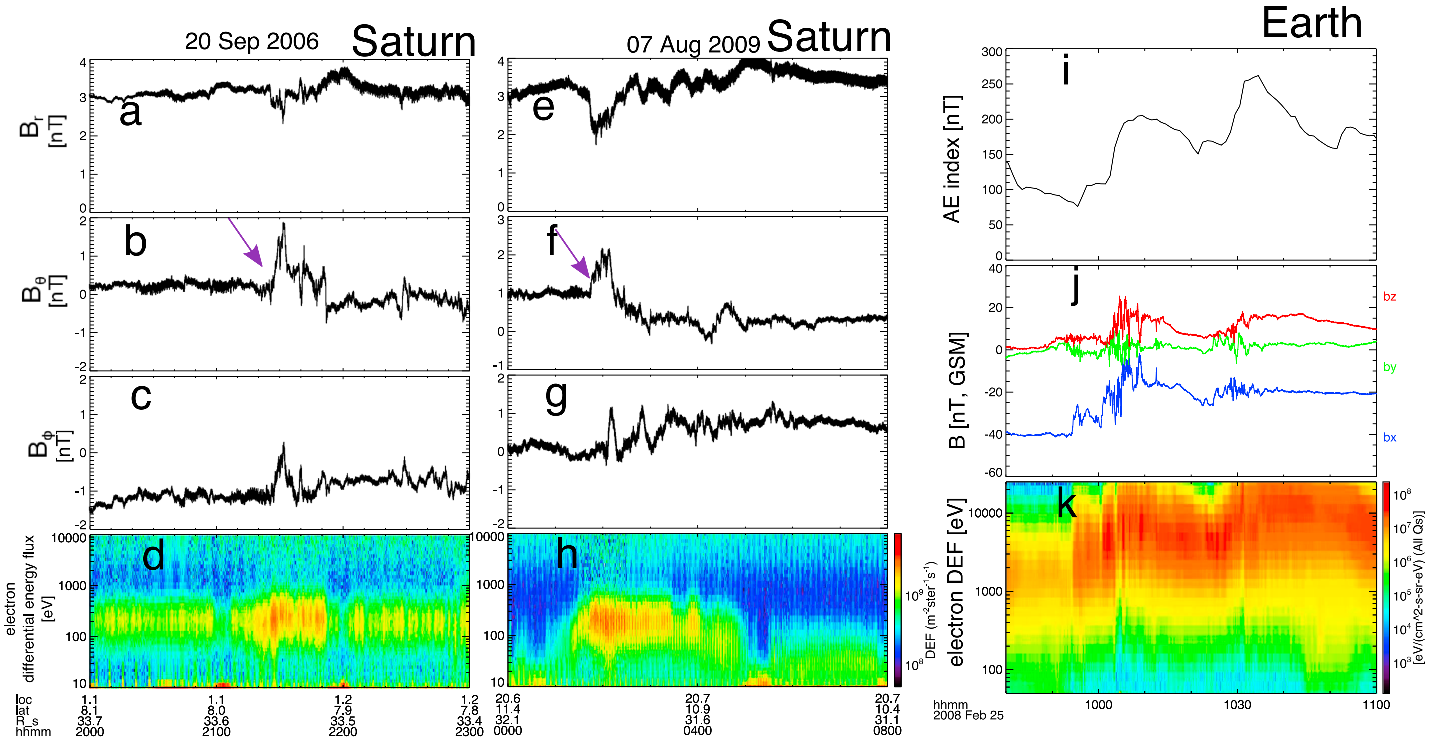

Figure 2. CRDD events at Saturn and Earth. (a–c) The three components of magnetic field in KRTP coordinates for the Saturn dipolarization event on 20 September 2006, (d) the electron differential energy flux spectrum on 20 September 2006, (e–h) the magnetic field and electron differential energy flux spectrum for the dipolarization event on 7 August 2009, with the same format as Figures 2a–2d. The measurements from THEMIS spacecraft for the Earth event on 25 Feb 2008. (i) The THEMIS pseudo *AE* index, (j) the vector magnetic components observed by THEMIS D, and (k) the electron differential energy flux observed by THEMIS D.

the outer plasma sheet or magnetotail lobe region, while after the expansion of the current sheet, Cassini detected enhanced electron flux, indicating that Cassini was in the inner plasma sheet. Here we would like to remind the reader that inner/outer plasma sheet refers to distances with respect to the central plasma which, while inner/outer magnetosphere refers to distances with respect to the planet.

In summary of the two CRDD dipolarization events at Saturn, we found that (1) B_θ increase was accompanied by B_r decrease and B_ϕ decrease. (2) Electron energy flux was enhanced in the dipolarized field region. (3) The dipolarization in the first event last for ∼1 h, while it lasts for 2–3 h in the second event.

Figures 2i–2k show measurements of a typical CRDD event at Earth on 25 February 2008, with THEMIS pseudo auroral ejection (*AE*) index [*Mende et al.*, 2008; *Russell et al.*, 2009], magnetic components in geocentric solar magnetospheric (GSM) coordinate system, and electron differential energy flux. The *AE* index increases from ∼100 nT to ∼250 nT in ∼30 min, indicating that the measurements were made during a substorm period. The in situ magnetic field measurements from THEMIS D, located at [−10.7, 0, −2.4] R_E in GSM coordinates, show two distinct B_z increases, at ∼10:00 UT and ∼10:30 UT, respectively. Both B_z increases are accompanied by B_x decreases. The electron flux shown in Figure 2k was also clearly enhanced at both B_z enhancements. The energy for main population also increased from ∼1–2 keV to ∼5–10 keV. As shown by Figure 2k, the electron energy and differential energy flux simultaneously increase, which suggests that the spacecraft is now sampling the inner plasma sheet where the electrons are being accelerated. The measured electron number density typically increases during such an event, due to the expansion of the current sheet. In this case, the number density increased from ∼0.1 cm^{-3} to ∼0.3 cm^{-3}(not shown here). A significant increase in density is only observed when the spacecraft is initially sampling the outer plasma sheet (e.g., the events we present for Saturn and Earth in this paper), which has a very low density prior to dipolarization and current sheet expansion. The B_x decrease, B_z increase, and electron density enhancement are typical signatures expected in a CRDD event, the same as we have presented for the previous Saturn events.

We would like to point out two very interesting differences between Saturn's CRDD and Earth's CRDD from in situ measurements.

1. An Earth CRDD is followed by a long-term recovery phase and then the next growth phase, and magnetic field B_z and plasma characteristics slowly evolve to the preonset condition [*Pulkkinen et al.*, 1992, 1994; *Baumjohann et al.*, 1991]. However, as we see from the two CRDD events at Saturn, the magnetic field B_θ and electron flux suddenly drop (as quick as their enhancements) to background level. The suddenly change after dipolarization is explained as a consequence of Saturn's rotation [*Yao et al.*, 2017b].
2. A clear energization (from ∼1 keV to ∼4 keV) was accompanied with the CRDD process at Earth; however, the energization at Saturn was not obvious. We suggest that dipolarization at Saturn could certainly contribute to electron energization (at least adiabatic Fermi and Betatron acceleration), although the energization process may not be as efficient as during the Earth dipolarization due to their very different environments (e.g., magnetic topology, pressure gradient, and electrical current system). At Earth, the near-Earth dipolarization is usually accompanied by plasma waves, Joule heating, and adiabatic accelerations, it is still poorly understood whether these dynamics exist during Saturn's dipolarization process.

2.2. Transient Dipolarizing Flux Bundles at Saturn and Earth

Although TDFB and CRDD both have the common feature of a B_θ enhancement, they represent fundamentally different magnetotail dynamics. CRDD is a consequence of a global magnetic field reconfiguration, while TDFB is a localized magnetic structure usually generated by bursty magnetotail reconnection [*Fu et al.*, 2013]. Since reconnection usually generates fast speed, intense magnetic field, and low entropy plasma outflow [*Pontius and Wolf*, 1990; *Birn et al.*, 2011], the in situ measurements of a TDFB typically show depleted electron densities accompanied by an enhanced magnetic field. Note that the density depletion exists at low energies, while there is a density enhancement at high energies. *Birn et al.* [2014] used simulations to show that the increase/decrease boundary sits at energies ∼10 keV. However, this boundary in energy may vary with event and will also depend on the location of the observer.

We use the decrease/increase of electron flux as a cross validation to distinguish between TDFB and CRDD events for Saturn. The high-energy population density enhancement associated with TDFB has three potential sources: directly from magnetic reconnection site [*Huang et al.*, 2015], the adiabatic acceleration related to the magnetic reconfiguration when the flow moves toward the planet [*Ashour-Abdalla et al.*, 2011], and the accelerated population from the ambient plasma sheet [*Gabrielse et al.*, 2012; *Runov et al.*, 2015]. Moreover, *Runov et al.* [2015] statistically demonstrated that adiabatic heating of the ambient plasma in the increased magnetic field is the major factor in TDFB plasma heating. Considered a boundary between reconnection outflow and the ambient plasma, TDFB is typically accompanied by quick density drop and particle heating, while a CRDD does not correspond to a sharp boundary of plasma populations. The morphological difference is similar to the comparison of antidipolarization and plasmoids presented in *Li et al.* [2014].

Figure 3 presents the magnetic field and electron differential energy flux with the same format as in Figure 2 for two TDFB events on 7 September 2006 (a–d) and 25 August 2006 (e–h), respectively. The 7 September 2006 event was observed at ∼22 R_S, near the equator and at postmidnight (2.2 LT), and the 25 August 2006 event was observed at ∼45 R_S, near the equator and at premidnight (23 LT). The enhancements of the north-south magnetic field B_θ component (Figures 3b and 3f) are indicated by the red vertical lines in both figures. Unlike the CRDD events, no significant B_r decrease or B_ϕ decrease is expected to accompany the B_θ increase, as TDFB does not correspond to a global reconfiguration of magnetic field topology that we have demonstrated in section 1. In the 7 September 2006 event, two distinct dipolarizations were observed with a separation of approximately half an hour, and for the first dipolarization in this event, a B_r enhancement was detected with the B_θ increases. In the 25 August 2006 event, the B_θ ramp was accompanied by a B_ϕ increase. The simultaneous enhancements in multiple components is an important feature of TDFB [*Yao et al.*, 2015], which does not exist in CRDD.

Magnetic reconnection may be driven by both the solar wind source or internal sources [*Dungey*, 1961; *Vasyliunas*, 1983]. Since TDFB is a natural consequence of magnetic reconnection, we suggest that both internal and external drivers at Saturn may generate TDFB. From the locations of two events, we suggest that the 25 August 2006 event that was observed at ∼45 R_S and 2300 LT could be driven by the solar wind interaction [*Cowley et al.*, 2004; *Jia et al.*, 2012], while the 7 September 2006 event at ∼22 R_S may be driven by internal source.

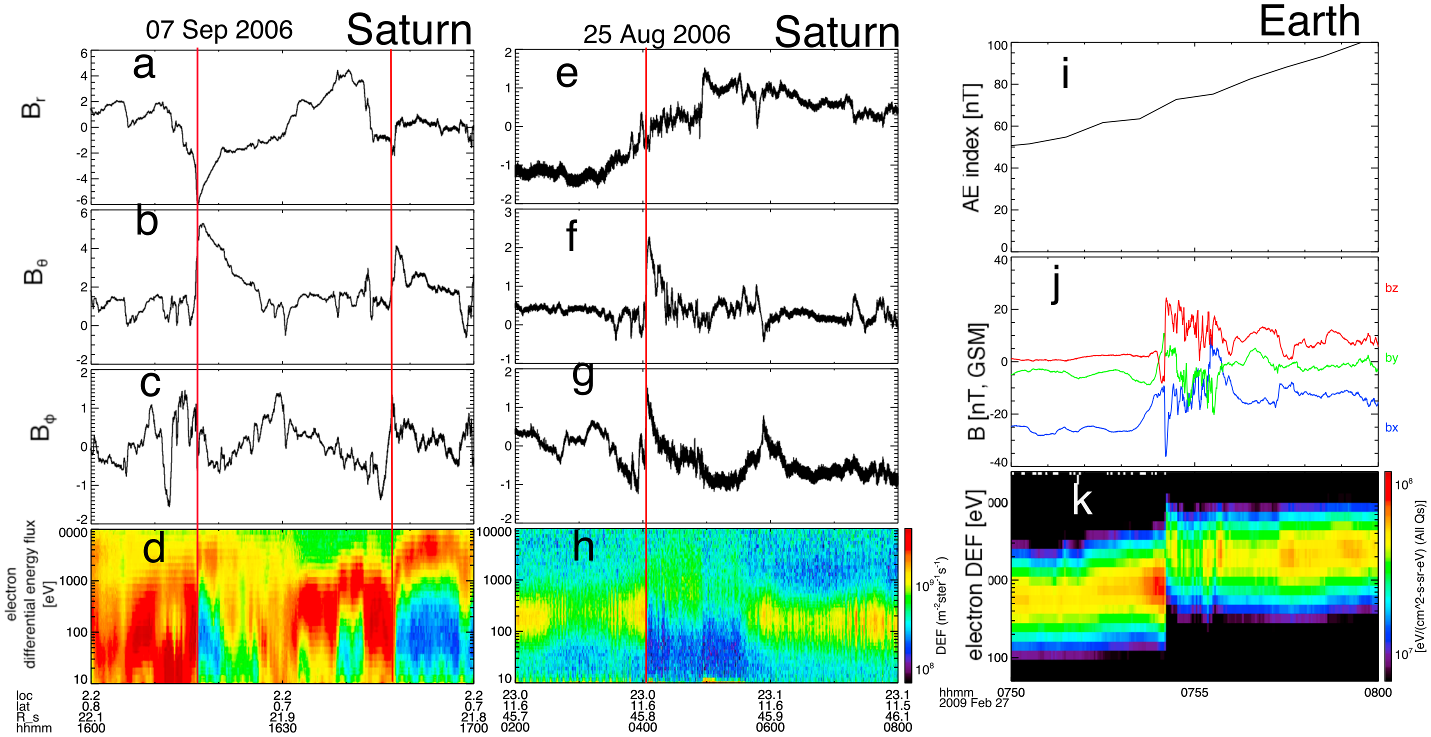

Figure 3. TDFB events at Saturn and Earth. (a–h) The observations of magnetic field and electron differential energy flux for two Saturn dipolarization events on 7 September 2006 and 25 August 2006, respectively. (i–k) The measurements of the Earth event on 27 February 2009 observed by THEMIS E. The format is the same as Figure 2.

To summarize (1) two TDFB events were detected by Cassini at ~22 R_S and ~45 R_S, respectively, (2) the enhancements of B_θ were accompanied by enhancements in other components; electron fluxes at main population energies dramatically decreased, while increasing at higher energies, which is likely caused by reconnection acceleration or accelerated ambient plasmas. The two events may correspond to internal and external drivers, respectively.

Figures 3i–3k show measurements of a typical TDFB event on 27 February 2009, in the same format as Figures 2i–2k. During this event, the *AE* index (Figure 3i) was small (,100 nT), suggesting a geomagnetic quiet time period. The magnetic field (Figure 3j) observed by THEMIS E, located at [−11.1, −1.7, −2.4] R_E in GSM coordinates, shows a sharp ramp at 07:54 UT. Meanwhile, an increase in B_x accompanies the B_z enhancement. The electron flux in Figure 3k shows a significant decrease at the main population (~400– 800 eV), with an increase at higher energies (2–10 keV). The B_z increase, B_x decrease, and the decrease of electron flux in the main population are typical features as we have shown for Saturn's TDFB events in the previous section. Multiple fronts are presented in TDFB events at both the Earth and Saturn, which may imply a pulsating behaviour in magnetotail reconnection. The TDFB at Earth are usually associated with significant field-aligned currents on a scale of ion gyroradius [*Hwang et al.*, 2011; *Fu et al.*, 2013; *Yao et al.*, 2016, 2017a]. The high temporal resolution of particle measurement from recently launched NASA/*Juno* mission [*Bolton*, 2010] may provide a good opportunity to examine small-scale current systems at a giant planet system like Jupiter.

2.3. Summary

CRDD and TDFB dipolarizations have recently became well understood using measurements from multiprobe missions (i.e., Cluster [*Escoubet et al.*, 2001] and THEMIS) in Earth's magnetosphere. It is very instructive and useful for us to reexamine Cassini measurements at Saturn to discover if the fundamentally different dipolarization mechanisms also occur in Saturn's magnetosphere. At Earth, the two types of dipolarization play very different roles in driving magnetosphere-ionosphere coupling dynamics, which we believe could be similar at Saturn. By analyzing Cassini measurements of Saturn's magnetosphere, we have identified CRDD and TDFB dipolarizations at Saturn, using the similar criteria adopted at Earth. Understanding CRDD and TDFB dipolarizations in giant planetary magnetospheres is essential for revealing the auroral dynamics at Saturn and Jupiter. Although the major dipolarization signatures (i.e., magnetic variation and electron enhancement) are similar at both Saturn and Earth, it is prudent to point out that there are several important differences between the two magnetospheres. The energy and plasma source in Saturn's magnetosphere does not only come from solar wind, moon-induced plasma and centrifugal forces caused by Saturn's fast rotation drive the major magnetospheric dynamics [*Kivelson and Southwood*, 2005]. Solar wind-driven reconnection (like the Earth) at Saturn may continue for a much longer period. For example, *Arridge et al.* [2016] reported a reconnection event that lasted for up to ~6 h. In this study, the CRDD event on 7 August 2009 and the TDFB event on 7 September 2006 are observed within 22 R_S, a region dominated by centrifugal force [*Arridge et al.*, 2007]. Hence, we suggest that the internally driven process alone can drive the two types of magnetic dipolarization. Whether or not the solar wind can drive CRDD in Saturn's magnetosphere is still unknown. The two types of dipolarization at Earth are usually considered to be related, although the connection between the two is still poorly understood. *Liu et al.* [2015] suggest that multiple TDFB contribute to a CRDD, while the calculation in *Lui* [2015] implies that 50–1000 TDFBs are required to form a CRDD. The relation between TDFB and CRDD at other planets might be different from at Earth, which deserves further investigation. However, we can conclude that at Saturn the TDFB represents a localized process that is generated by magnetic reconnection, and the CRDD represents a global process that is due to current redistribution.

In this paper, we reveal two types of dipolarization at Saturn, which correspond to fundamentally different processes. We have also compared magnetic dipolarization features between Earth and Saturn. The main results are summarized below.

1. Both the reconnection generated TDFB and current sheet expansion generated CRDD exist in Saturn's magnetotail.
2. We have demonstrated clear criteria to identify the two types of dipolarization based on the measurements of magnetic field and electron flux.
3. Internally driven processes could generate two types of dipolarization at Saturn.
4. The multiple fronts feature of TDFBs implies a pulsating nature of magnetotail reconnection.

Acknowledgments
Z.Y. is a Marie-Curie COFUND postdoctoral fellow at the University of Liege. Cofunded by the European Union. A.J.C., G.H.J., I.J.R., W.R.D., and Z.Y. are supported by a UK Science and Technology Facilities Council (STFC) grant (ST/L005638/1) at UCL/MSSL. A.R. is funded by the Belgian Fund for Scientific Research (FNRS). We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS mission. Specifically, We thank J.W. Bonnell and F.S. Mozer for the use of EFI data; K.H. Glassmeier, U. Auster, C.W. Carlson, and J.P. McFadden for the use of ESA data; D. Larson and R. P. Lin for use of SST data; and W. Baumjohann for the use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302. We also thank S. Mende and E. Donovan for use of the ASI data, the CSA for logistical support in fielding and data retrieval from the GBO stations, and NSF for support of GIMNAST through grant AGS-1004736. Cassini operations are supported by NASA (managed by the Jet Propulsion Laboratory) and ESA. The THEMIS data are available from http://themis.ssl.berkeley.edu/data/themis/, and the Cassini data presented in this paper are available from the NASA Planetary Data System http://pds.jpl.nasa.gov.

References

Akasofu, S.-I. (1964), The development of the auroral substorm, *Planet. Space Sci.*, *12*(4), 273–282.

Akasofu, S.-I. (1980), Magnetic energy conversion, magnetospheric substorms and solar flares, *Nature*, *284*, 248–249.

Angelopoulos, V. (2009), *The THEMIS Mission*, pp. 5–34, Springer, New York.

Angelopoulos, V., et al. (2008), Tail reconnection triggering substorm onset, *Science*, *321*(5891), 931–935.

Angelopoulos, V., A. Runov, X.-Z. Zhou, D. Turner, S. Kiehas, S.-S. Li, and I. Shinohara (2013), Electromagnetic energy conversion at reconnection fronts, *Science*, *341*(6153), 1478–1482.

Arridge, C., C. Russell, K. Khurana, N. Achilleos, N. André, A. Rymer, M. Dougherty, and A. Coates (2007), Mass of Saturn's magnetodisc: Cassini observations, *Geophys. Res. Lett.*, *34*, L09108, doi:10.1029/2006GL028921.

Arridge, C. S., et al. (2016), Cassini in situ observations of long-duration magnetic reconnection in Saturn's magnetotail, *Nat. Phys.*, *12*(3), 268–271.

Ashour-Abdalla, M., M. El-Alaoui, M. L. Goldstein, M. Zhou, D. Schriver, R. Richard, R. Walker, M. G. Kivelson, and K.-J. Hwang (2011), Observations and simulations of non-local acceleration of electrons in magnetotail magnetic reconnection events, *Nat. Phys.*, *7*(4), 360–365.

Auster, H., et al. (2009), The THEMIS fluxgate magnetometer, in *The THEMIS Mission*, edited by J. L. Burch and V. Angelopoulos, pp. 235–264, Springer, New York.

Baumjohann, W., G. Paschmann, T. Nagai, and H. Lühr (1991), Superposed epoch analysis of the substorm plasma sheet, *J. Geophys. Res.*, *96*(A7), 11,605–11,608.

Baumjohann, W., M. Hesse, S. Kokubun, T. Mukai, T. Nagai, and A. Petrukovich (1999), Substorm dipolarization and recovery, *J. Geophys. Res.*, *104*(A11), 24,995–25,000.

Birn, J., and M. Hesse (2013), The substorm current wedge in MHD simulations, *J. Geophys. Res. Space Physics*, *118*, 3364–3376, doi:10.1002/jgra.50187.

Birn, J., R. Nakamura, E. Panov, and M. Hesse (2011), Bursty bulk flows and dipolarization in MHD simulations of magnetotail reconnection, *J. Geophys. Res.*, *116*, A01210, doi:10.1029/2010JA016083.

Birn, J., A. Runov, and M. Hesse (2014), Energetic electrons in dipolarization events: Spatial properties and anisotropy, *J. Geophys. Res. Space Physics*, *119*, 3604–3616, doi:10.1002/2013JA019738.

Bolton, S. (2010), The Juno mission, *Proc. Int. Astron. Union*, *6*(S269), 92–100.

Cowley, S., E. Bunce, and R. Prangé (2004), Saturn's polar ionospheric flows and their relation to the main auroral oval, *Ann. Geophys.*, *22*, 1379–1394.

Delamere, P., A. Otto, X. Ma, F. Bagenal, and R. Wilson (2015), Magnetic flux circulation in the rotationally driven giant magnetospheres, *J. Geophys. Res. Space Physics*, *120*, 4229–4245, doi:10.1002/2015JA021036.

Dougherty, M., et al. (2004), The Cassini magnetic field investigation, in *The Cassini-Huygens Mission*, edited by C. T. Russell, pp. 331–383, Springer, Netherlands.

Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*(2), 47–48.

Escoubet, C., M. Fehringer, and M. Goldstein (2001), Introduction the Cluster mission, *Ann. Geophys.*, *19*, 1197–1200.

Fu, H., et al. (2013), Dipolarization fronts as a consequence of transient reconnection: In situ evidence, *Geophys. Res. Lett.*, *40*, 6023–6027, doi:10.1002/2013GL058620.

Gabrielse, C., V. Angelopoulos, A. Runov, and D. Turner (2012), The effects of transient, localized electric fields on equatorial electron acceleration and transport toward the inner magnetosphere, *J. Geophys. Res.*, *117*, A10213, doi:10.1029/2012JA017873.

Hill, T., et al. (2008), Plasmoids in Saturn's magnetotail, *J. Geophys. Res.*, *113*, A01214, doi:10.1029/2007JA012626.

Hones, E. W. (1979), Transient phenomena in the magnetotail and their relation to substorms, *Space Sci. Rev.*, *23*(3), 393–410.

Huang, C., M. Wu, Q. Lu, R. Wang, and S. Wang (2015), Electron acceleration in the dipolarization front driven by magnetic reconnection, *J. Geophys. Res. Space Physics*, *120*, 1759–1765, doi:10.1002/2014JA020918.

Hwang, K.-J., M. L. Goldstein, E. Lee, and J. S. Pickett (2011), Cluster observations of multiple dipolarization fronts, *J. Geophys. Res.*, *116*, A00I32, doi:10.1029/2010JA015742.

Ieda, A., S. Machida, T. Mukai, Y. Saito, T. Yamamoto, A. Nishida, T. Terasawa, and S. Kokubun (1998), Statistical analysis of the plasmoid evolution with geotail observations, *J. Geophys. Res.*, *103*(A3), 4453–4465.

Jackman, C., C. Russell, D. Southwood, C. Arridge, N. Achilleos, and M. Dougherty (2007), Strong rapid dipolarizations in Saturn's magnetotail: In situ evidence of reconnection, *Geophys. Res. Lett.*, *34*, L11203, doi:10.1029/2007GL029764.

Jackman, C., J. Slavin, and S. Cowley (2011), Cassini observations of plasmoid structure and dynamics: Implications for the role of magnetic reconnection in magnetospheric circulation at Saturn, *J. Geophys. Res.*, *116*, A10212, doi:10.1029/2011JA016682.

Jackman, C. M., N. Achilleos, S. W. Cowley, E. J. Bunce, A. Radioti, D. Grodent, S. V. Badman, M. K. Dougherty, and W. Pryor (2013), Auroral counterpart of magnetic field dipolarizations in Saturn's tail, *Planet. Space Sci.*, *82*, 34–42.

Jia, X., K. C. Hansen, T. I. Gombosi, M. G. Kivelson, G. Tóth, D. L. DeZeeuw, and A. J. Ridley (2012), Magnetospheric configuration and dynamics of Saturn's magnetosphere: A global MHD simulation, *J. Geophys. Res.*, *117*, A05225, doi:10.1029/2012JA017575.

Kan, J. (1991), Dipolarization: A consequence of substorm expansion onset, *Geophys. Res. Lett.*, *18*(1), 57–60.

Kasahara, S., E. Kronberg, N. Krupp, T. Kimura, C. Tao, S. Badman, A. Retinò, and M. Fujimoto (2011), Magnetic reconnection in the Jovian tail: X-line evolution and consequent plasma sheet structures, *J. Geophys. Res.*, *116*, A11219, doi:10.1029/2011JA016892.

Kivelson, M., and D. Southwood (2005), Dynamical consequences of two modes of centrifugal instability in Jupiter's outer magnetosphere, *J. Geophys. Res.*, *110*, A12209, doi:10.1029/2005JA011176.

Kronberg, E., J. Woch, N. Krupp, A. Lagg, K. Khurana, and K.-H. Glassmeier (2005), Mass release at Jupiter: Substorm-like processes in the Jovian magnetotail, *J. Geophys. Res.*, *110*, A03211, doi:10.1029/2004JA010777.

Li, S.-S., J. Liu, V. Angelopoulos, A. Runov, X.-Z. Zhou, and S. Kiehas (2014), Antidipolarization fronts observed by ARTEMIS, *J. Geophys. Res. Space Physics*, *119*, 7181–7198, doi:10.1002/2014JA020062.

Liu, J., V. Angelopoulos, A. Runov, and X.-Z. Zhou (2013a), On the current sheets surrounding dipolarizing flux bundles in the magnetotail: The case for wedgelets, *J. Geophys. Res. Space Physics*, *118*, 2000–2020, doi:10.1002/jgra.50092.

Liu, J., V. Angelopoulos, X.-Z. Zhou, A. Runov, and Z. Yao (2013b), On the role of pressure and flow perturbations around dipolarizing flux bundles, *J. Geophys. Res. Space Physics*, *118*, 7104–7118, doi:10.1002/2013JA019256.

Liu, J., V. Angelopoulos, X. Chu, X.-Z. Zhou, and C. Yue (2015), Substorm current wedge composition by wedgelets, *Geophys. Res. Lett.*, *42*, 1669–1676, doi:10.1002/2015GL063289.

Lui, A. (1996), Current disruption in the Earth's magnetosphere: Observations and models, *J. Geophys. Res.*, *101*(A6), 13,067–13,088.

Lui, A. (2014), Evidence for two types of dipolarization in the Earth's magnetotail, *J. Atmos. Sol. Terr. Phys.*, *115*, 17–24.

Lui, A. (2015), Dipolarization fronts and magnetic flux transport, *Geosci. Lett.*, *2*(1), 1–8.

Lui, A., P. Yoon, C. Mok, and C.-M. Ryu (2008), Inverse cascade feature in current disruption, *J. Geophys. Res.*, *113*, A00C06, doi:10.1029/2008JA013521.

McFadden, J., C. Carlson, D. Larson, M. Ludlam, R. Abiad, B. Elliott, P. Turin, M. Marckwordt, and V. Angelopoulos (2008), The THEMIS ESA plasma instrument and in-flight calibration, *Space Sci. Rev.*, *141*(1–4), 277–302.

McPherron, R., C. Russell, M. Kivelson, and P. Coleman (1973), Substorms in space: The correlation between ground and satellite observations of the magnetic field, *Radio Sci.*, *8*(11), 1059–1076.

Mende, S., S. Harris, H. Frey, V. Angelopoulos, C. Russell, E. Donovan, B. Jackel, M. Greffen, and L. Peticolas (2008), The THEMIS array of ground-based observatories for the study of auroral substorms, *Space Sci. Rev.*, *141*, 357–387.

Mitchell, D., et al. (2005), Energetic ion acceleration in Saturn's magnetotail: Substorms at Saturn?, *Geophys. Res. Lett.*, *32*, L20S01, doi:10.1029/2005GL022647.

Nakamura, R., et al. (2002), Motion of the dipolarization front during a flow burst event observed by Cluster, *Geophys. Res. Lett.*, *29*(20), 1942, doi:10.1029/2002GL015763.

Nakamura, R., A. Retinò, W. Baumjohann, M. Volwerk, N. Erkaev, B. Klecker, E. Lucek, I. Dandouras, M. André, and Y. Khotyaintsev (2009), Evolution of dipolarization in the near-Earth current sheet induced by earthward rapid flux transport, *Ann. Geophys.*, *27*, 1743–1754.

Pontius, D., and R. Wolf (1990), Transient flux tubes in the terrestrial magnetosphere, *Geophys. Res. Lett.*, *17*(1), 49–52.

Pu, Z., A. Korth, Z. Chen, Z. Liu, S. Fu, G. Zong, M. Hong, and X. Wang (2001), A global synthesis model of dipolarization at substorm expansion onset, *J. Atmos. Sol. Terr. Phys.*, *63*(7), 671–681.

Pu, Z., et al. (2010), THEMIS observations of substorms on 26 February 2008 initiated by magnetotail reconnection, *J. Geophys. Res.*, *115*, A02212, doi:10.1029/2009JA014217.

Pulkkinen, T., D. Baker, R. Pellinen, J. Büchner, H. Koskinen, R. Lopez, R. Dyson, and L. Frank (1992), Particle scattering and current sheet stability in the geomagnetic tail during the substorm growth phase, *J. Geophys. Res.*, *97*(A12), 19,283–19,297.

Pulkkinen, T., D. Baker, P. Toivanen, R. Pellinen, R. Friedel, and A. Korth (1994), Magnetospheric field and current distributions during the substorm recovery phase, *J. Geophys. Res.*, *99*(A6), 10,955–10,966.

Runov, A., V. Angelopoulos, X.-Z. Zhou, X.-J. Zhang, S. Li, F. Plaschke, and J. Bonnell (2011), A themis multicase study of dipolarization fronts in the magnetotail plasma sheet, *J. Geophys. Res.*, *116*, A05216, doi:10.1029/2010JA016316.

Runov, A., V. Angelopoulos, C. Gabrielse, J. Liu, D. Turner, and X.-Z. Zhou (2015), Average thermodynamic and spectral properties of plasma in and around dipolarizing flux bundles, *J. Geophys. Res. Space Physics*, *120*, 4369–4383, doi:10.1002/2015JA021166.

Russell, C., P. Chi, D. Dearborn, Y. Ge, B. Kuo-Tiong, J. Means, D. Pierce, K. Rowe, and R. Snare (2009), THEMIS ground-based magnetometers, in *The THEMIS Mission*, edited by J. L. Burch and V. Angelopoulos, pp. 389–412, Springer, New York.

Sergeev, V., V. Angelopoulos, S. Apatenkov, J. Bonnell, R. Ergun, R. Nakamura, J. McFadden, D. Larson, and A. Runov (2009), Kinetic structure of the sharp injection/dipolarization front in the flow-braking region, *Geophys. Res. Lett.*, *36*, L21105, doi:10.1029/2009GL040658.

Sitnov, M. I., M. Swisdak, and A. V. Divin (2009), Dipolarization fronts as a signature of transient reconnection in the magnetotail, *J. Geophys. Res.*, *114*, A04202, doi:10.1029/2008JA013980.

Slavin, J. A., et al. (2010), Messenger observations of extreme loading and unloading of Mercury's magnetic tail, *Science*, *329*(5992), 665–668.

Sun, W.-J., et al. (2015), Messenger observations of magnetospheric substorm activity in Mercury's near magnetotail, *Geophys. Res. Lett.*, *42*, 3692–3699, doi:10.1002/2015GL064052.

Vasyliunas, V. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, vol. 1, edited by A. J. Dessler, pp. 395–453, Cambridge Univ. Press, Cambridge and New York.

Vogt, M. F., C. M. Jackman, J. A. Slavin, E. J. Bunce, S. W. Cowley, M. G. Kivelson, and K. K. Khurana (2014), Structure and statistical properties of plasmoids in Jupiter's magnetotail, *J. Geophys. Res. Space Physics*, *119*, 821–843, doi:10.1002/2013JA019393.

Yao, Z., et al. (2012), Mechanism of substorm current wedge formation: THEMIS observations, *Geophys. Res. Lett.*, *39*, L13102, doi:10.1029/2012GL052055.

Yao, Z., et al. (2013), Current structures associated with dipolarization fronts, *J. Geophys. Res. Space Physics*, *118*, 6980–6985, doi:10.1002/2013JA019290.

Yao, Z., et al. (2014), Current reduction in a pseudo-breakup event: THEMIS observations, *J. Geophys. Res. Space Physics*, *119*, 8178–8187, doi:10.1002/2014JA020186.

Yao, Z., et al. (2016), Substructures within a dipolarization front revealed by high-temporal resolution Cluster observations, *J. Geophys. Res. Space Physics*, *121*, 5185–5202, doi:10.1002/2015JA022238.

Yao, Z., et al. (2017a), A direct examination of the dynamics of dipolarization fronts using MMS, *J. Geophys. Res. Space Physics*, *122*, doi:10.1002/2016JA023401.

Yao, Z., et al. (2017b), Discovery of co-rotating magnetic reconnection in Saturn's magnetosphere, doi:arXiv:1701.04559, arXiv preprint.

Yao, Z. H., et al. (2015), A physical explanation for the magnetic decrease ahead of dipolarization fronts, *Ann. Geophys.*, *33*(10), 1301–1309, doi:10.5194/angeo-33-1301-2015.

Young, D., et al. (2004), Cassini plasma spectrometer investigation, in *The Cassini-Huygens Mission*, edited by C. T. Russell, pp. 1–112, Springer, Netherlands.