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Recent advances in the magnetic reconnection, dipolarization, and auroral processes at giant planets from the perspective of comparative planetology

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Key Points:
- We briefly review the recent progress in magnetic reconnection and dipolarization at Saturn and Jupiter.
- Magnetic reconnection and dipolarization at these gas giants are found to be corotating.
- Magnetic reconnection is likely connected to the dawn storm region, while magnetic dipolarization can be related to auroral injections.

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Abstract: Magnetic reconnection and dipolarization are crucial processes driving magnetospheric dynamics, including particle energization, mass circulation, and auroral processes, among others. Recent studies have revealed that these processes at Saturn and Jupiter are fundamentally different from the ones at Earth. The reconnection and dipolarization processes are far more important than previously expected in the dayside magnetodisc of Saturn and potentially Jupiter. Dayside magnetodisc reconnection was directly identified by using Cassini measurements (Guo RL et al., 2018b) and was found to be drizzle-like and rotating in the magnetosphere of Saturn (Delamere et al., 2015b; Yao ZH et al., 2017a; Guo RL et al., 2019). Moreover, magnetic dipolarization could also exist at Saturn's dayside (Yao ZH et al., 2018), which is fundamentally different from the terrestrial situation. These new results significantly improve our understanding of giant planetary magnetospheric dynamics and provide key insights revealing the physics of planetary aurorae. Here, we briefly review these recent advances and their potential implications for future investigations.

Keywords: magnetosphere; magnetic reconnection; magnetic depolarization

1. A Brief History of Magnetic Reconnection and Dipolarization in Planetary Magnetospheres: From the Earth to Other Planets

Magnetic reconnection is a fundamental process in magnetized plasma environments, playing pivotal roles in particle energization –acceleration and mass circulation. The reconnection process is essential in a number of research communities, such as nuclear fusion laboratory physics, solar flares, and planetary magnetospheres (Zweibel and Yamada, 2009; Hesse and Cassak, 2020).

In planetary space sciences, magnetic reconnection is a key trigger for many fundamental phenomena. The magnetic field lines in the solar wind are connected with the field lines confined in a planet via magnetopause reconnection, and the particles and energy are thus transferred between the solar wind and the magnetosphere (Paschmann et al., 1979; Sato and Hayashi, 1979). The magnetopause reconnection is expected to exist on any planet with a global intrinsic magnetic field. At Earth, the dayside magnetopause reconnection transfers solar wind particles and energy into the magnetosphere, and the energy and mass are then gradually stored in the nightside magnetotail, forming a thin current sheet.

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The thin tail current sheet features antiparallel magnetic fields across the current sheet. As more and more energy and mass are stored in the nightside magnetotail, the thin tail current sheet becomes unstable and thus triggers magnetotail reconnection, which is the key energy conversion for powering explosive auroral emissions in polar atmospheres, known as auroral substorms (Akasofu, 1964; McPherron et al., 1973). If the magnetic flux transport by magnetopause reconnection is balanced by the nightside reconnection, then a steady circulation may form, which is known as the Dungey cycle (Dungey, 1961). The Dungey cycle is also expected to exist at Mercury, Saturn, and Jupiter besides the Earth. At the giant planets Saturn and Jupiter, however, it is believed that a Vasyliunas cycle, driven by planetary rotation, may play a more important role in mass and flux circulations (Vasyliunas, 1983). On Saturn and Jupiter, magnetic reconnection occurs at the magnetodisc, where a thin ring current forms through the outward transportation of heavy ions from the plasma tori in the inner magnetosphere. In the Vasyliunas cycle, the reconnection site is triggered in the pre-midnight sector, then rotates to the predawn sector while moving tailward.

The plasma sources in the giant planetary magnetosphere are mostly internally produced, from Jupiter's moon Io and Saturn's moon Enceladus (Mendillo et al., 1990; Schneider et al., 1991; Hansen et al., 2006; Waite et al., 2006). Both Jupiter and Saturn form giant planetary magnetospheres by interacting with the solar wind. Because of the large corotational electric field, the planetary rotation-driven space plasma corotation could dominate in the region up to the magnetopause (Delamere and Bagenal, 2010). The centrifugal force associated with planetary rotation thus radially transports the internal plasma source to the whole magnetodisc via interchange instability (Kull, 1991). The timescale of mass transport is usually tens of days (Delamere et al., 2015a), which is much longer than typical timescales for the magnetospheric dynamics.

Reconnection and dipolarization at Neptune and Uranus have been much less investigated compared with those at Earth, Saturn, and Jupiter. The major reason for the lack of observation is that they are difficult to reach. In 1986 and 1989, the Voyager 2 spacecraft made the first and only *in situ* observations of Uranus and Neptune. Because of the large angle between their spin axis and magnetic pole, the internal magnetic field configurations are extremely complex (Ness et al., 1986; Arridge, 2015). Magnetic reconnection is naturally expected by theory and has been confirmed by observational investigations at Uranus (Richardson et al., 1988; Masters, 2014; DiBraccio and Gershman, 2019) and Neptune (Masters, 2015). Venus and Mars are the only two planets in our solar system that do not have a global magnetic field, so they do not have a global magnetosphere similar to the other planets. Nevertheless, the interaction between the solar wind and Venus and Mars could form small magnetospheres, which also have elongated tails that allow reconnection to occur (Eastwood et al., 2008; Halekas et al., 2009; Zhang TL et al., 2012; Harada et al., 2015, 2017).

Reconnection in the magnetosphere can also generate fast plasma flows, which are pivotal to causing magnetospheric perturbations, such as a disturbed current system (Angelopoulos et al., 2008). Reconnection has also been thought to be responsible for accelerating auroral particles (Hoyle, 1949; Dungey, 1961). As more and more spaceborne and ground-based observations have become available, understanding of the connection between magnetic reconnection and auroral particles has significantly improved (Baker et al., 1996). The magnetotail has two key regions, namely, the midtail reconnection site at 20–30 Earth radii (R_E; Nagai and Machida, 1998) and the near-Earth dipolarization region at ~10 R_E (Shiokawa et al., 1997), which have a role in driving auroral breakup. High-speed plasma flows, known as bursty bulk flows, are thought to be the key media connecting the midtail reconnection site and the near-Earth dipolarization region. How terrestrial auroral substorms (or magnetic substorms) are initiated remains a long-standing question.

Two preferred theories for substorm mechanisms are the near-Earth current disruption (NECD) model and the near-Earth neutral line (NENL) model. In the NECD model, plasma instabilities in the near-Earth region initiate the disruption of cross-tail currents, forming a substorm current wedge and causing reconfiguration of the magnetic field (i.e., magnetic dipolarization). The region of current disruption then extends toward the tail, triggering reconnection in the midtail (Lui et al., 1992; Lui, 1996). The NENL model suggests that the midtail magnetic reconnection occurs at the beginning, which produces a tailward plasmoid and earthward bursty bulk flows that transport mass and energy to the near-Earth region. As more and more energy is accumulated in the near-Earth tail, flux pileup processes or plasma instabilities disrupt the cross-tail currents, leading to substorm expansion. A constellation of five satellites of THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission was planned to be distributed along the magnetotail at different distances to assess the two substorm models. The NENL model seems to be more consistent with observations (Angelopoulos et al., 2008), yet opinions on this differ (Lui, 2009). Other proposed models describe different relations between the near-Earth and midtail processes (Pu ZY et al., 2001; Murphy et al., 2014). Despite the debate, the two models reach consensus that magnetic reconnection and magnetic dipolarization are two fundamental processes located at different distances in the magnetotail.

Planetary magnetospheres are a fundamental consequence of the interaction between the solar wind and the intrinsic magnetic field of a planet. Because Mercury, the Earth, Saturn, and Jupiter are dominated by the dipole field in space, and with a relatively small angle between the magnetic pole and spin axis, their magnetospheres have many features in common. At Mercury, observations have confirmed the existence of dayside magnetopause reconnection (Slavin et al., 2009), nightside magnetotail reconnection (Slavin et al., 2012), and tail magnetic dipolarization (Sun WJ et al., 2015). The magnetosphere of Mercury is much smaller than the terrestrial magnetosphere; thus, in some extreme solar wind conditions, dayside magnetic reconnection can strip all closed magnetic field lines at the equator and form an equatorial cusp region (Slavin et al., 2010). Because of the lack of atmosphere and ionosphere, it is not expected to have auroral substorms and the associated magnetospheric processes, although similar energy deposits may be found (Aizawa et al., 2023).

The modulation of energetic particles is another important consequence of magnetic reconnection and dipolarization (Sergeev et al., 2009; Birn et al., 2015). Many distinctive acceleration features have been identified by spacecraft measurements (Zhou M et al., 2009; Ashour-Abdalla et al., 2011; Fu HS et al., 2012, 2013; Tang CL et al., 2013, 2016), indicating such features as potential mechanisms. Turbulent processes during reconnection have recently been reported as efficient contributors to electron acceleration (Upadhyay et al., 2023; Wang Z et al., 2023). The particle acceleration associated with reconnection and dipolarization is also a central focus in the community. Compared with the terrestrial process, reconnection at Saturn may last for a very long time (i.e., ~19 hours; Arridge et al., 2016). Particle acceleration signatures have been widely identified in magnetic dipolarization and reconnection processes at Saturn and Jupiter (Jackman et al., 2007, 2008, 2015; Radioti et al., 2011; Kronberg et al., 2012; Yao ZH et al., 2018).

Unlike the magnetospheres of the terrestrial planets, those of Jupiter and Saturn are giant, and the major plasma sources are from their volcanically active moons in addition to the solar wind. Similarly, dayside magnetopause reconnection and nightside reconnection have been identified at Saturn (Jackman et al., 2007; Hill et al., 2008; Masters et al., 2014; Arridge et al., 2016; Smith et al., 2018) and Jupiter (Russell et al., 1998; Vogt et al., 2010, 2020; Kronberg et al., 2012; Blöcker et al., 2023). It is noteworthy that many studies have often confused the concepts of magnetic dipolarization, the reconnection front (or dipolarization front), and magnetic reconnection in the giant planetary community. The occurrence of reconnection is mostly indicated by the appearance of a plasmoid and dipolarization which exhibit a negative and enhanced north–south magnetic component, respectively. In the diagram of the Vasyliunas cycle, the reconnection process is believed to be important for mass distribution in the nightside magnetosphere, with little contribution in the dayside magnetosphere.

Auroral breakup is a global consequence of magnetospheric energy dissipation, ionospheric electrical current flow, and atmospheric perturbation. Despite their varied temporal, spatial, and energetic scales, the auroral morphologies at the Earth, Saturn, and Jupiter are highly similar (Radioti et al., 2017, 2019; Yao ZH et al., 2020; Bonfond et al., 2021). These similarities likely imply commonalities in fundamental plasma processes in their magnetospheres and ionospheres; therefore, knowledge transfer between these planets is crucial for understanding their systems. Traditionally, the terrestrial magnetospheric mass circulation and energy circulation have been suggested as solar wind driven, and such processes at Jupiter have been suggested as internally driven. The mass circulation and energy circulation at Saturn are believed to be driven by both the solar wind and internal processes. Using Cassini measurements from Saturn's distant magnetotail, Yao ZH (2017) found that the magnetospheric loading–unloading circulation could be driven by the solar wind, internal processes, or both. Moreover, the different types of driving modes refer to only the loading process, meaning the energy accumulation could be driven by either internal processes or the solar wind as shown in Figures 1a and 1b, respectively. The unloading process, referring to the rapid energy dissipation from a planetary magnetosphere, is not treated as internal or external (shown by Figure 1c). Therefore, the energy and mass unloading processes at the Earth, Saturn, and Jupiter should be and can be directly compared, regardless of their varied energy accumulations.

Magnetic reconnection and dipolarization, two important mechanisms for unloading magnetospheric energy, are important processes in energizing charged particles. The field-aligned accel-

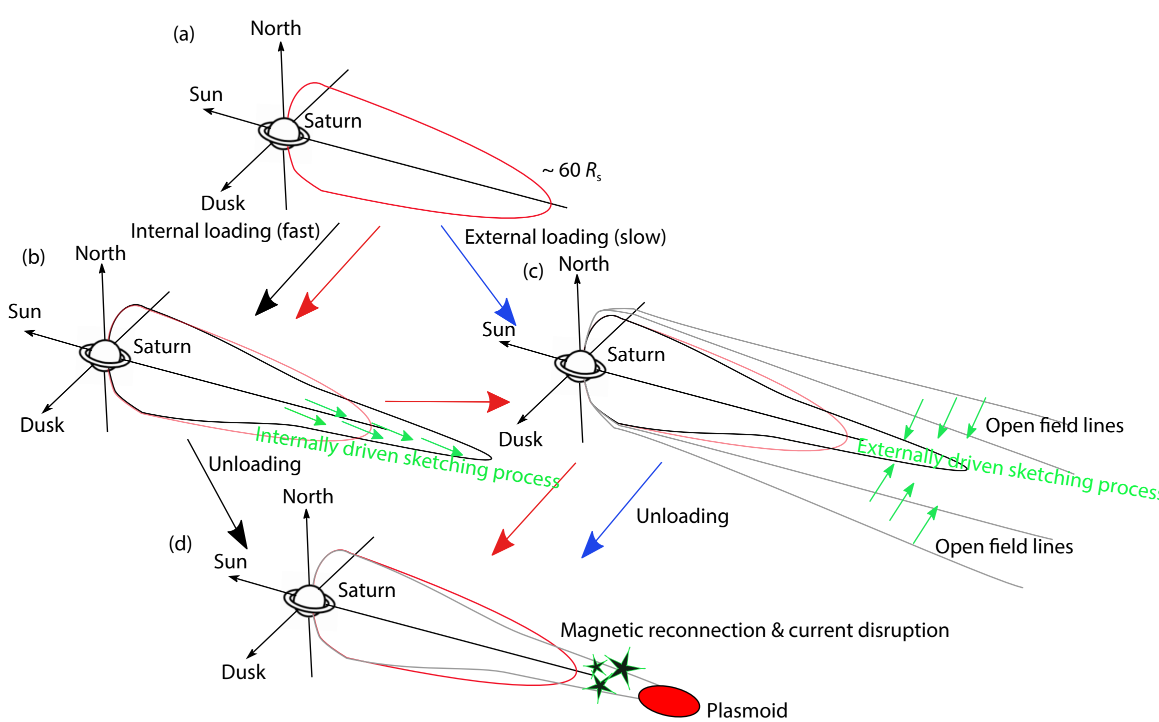

Figure 1. An illustration of three types of loading–unloading circulations in Saturn's distant magnetotail. Adapted from Yao ZH (2017).

eration of electrons and the tailward movement of flux ropes are common features of reconnection (Jackman et al., 2008; Kronberg et al., 2012), although reconnection may last for a much longer period at the giant planets (Arridge et al., 2016). The different energy sources (i.e., from the solar wind or internal processes) may affect the energization of certain particle species (Guo RL et al., 2018a, b), such as heavy ions, which are substantial components in giant planetary magnetospheres but are usually negligible in the terrestrial magnetosphere.

In this review article, we introduce recent progress in understanding magnetic reconnection and dipolarization at Saturn and Jupiter. These results are summarized in Sections 2 to 5, where we discuss two types of dipolarization at Saturn, the corotating nature of magnetic reconnection and dipolarization, the dayside dynamics in the magnetodisc, and the relation of these dynamics to aurorae. In Section 6, we present a summary and recent perspectives.

2. Cassini Observations Reveal Two Types of Magnetic Dipolarization at Saturn

Literally, magnetic dipolarization describes the process whereby a magnetic field line changes from a stretched configuration to a dipole shape. In the planetary magnetosphere, a stretched magnetic configuration is naturally formed in the nightside tail when the solar wind blows toward the Earth. The stretched magnetic fields are maintained by the electrical currents on the central plane, known as the neutral sheet (Pritchett et al., 1996), where the horizontal magnetic component vanishes. The electrical currents on the neutral sheet, also known as cross-tail currents, are unstable to solar wind perturbations. Magnetic dipolarization is expected as a consequence of substorm current wedge formation, during which the cross-tail currents are diverted into the ionosphere via field-aligned currents. Because the current disruption is initiated from ~10 R_E, propagating toward the tail, the associated magnetic dipolarization will also propagate toward the tail (Lui, 1991, 1996; Perraut et al., 2003; Tang CL et al., 2009). Using the observations from the Cluster multi-probe mission (Escoubet et al., 1997), Nakamura et al. (2002) identified an earthward-propagating dipolarization that is associated with high-speed plasma flow, which they named a "dipolarization front."

In later studies, the dipolarization front and the substorm magnetic dipolarization in Earth's magnetosphere were found to be two different processes (Lui, 2014). Unlike the substorm magnetic dipolarization that is associated with a global current redistribution, the dipolarization front is more like a magnetic discontinuity, which changes only the particle distribution (Sergeev et al., 2009; Fu HS et al., 2011, 2012; Zhou XZ et al., 2011, 2014) and current density (Liu J et al., 2013, 2018; Sun WJ et al., 2013; Yao ZH et al., 2013) in a localized region. The two types of magnetic dipolarization are often mistaken for each other because their typical signatures are both the enhancement of the north–south magnetic component (B_z). One of the obvious obser-

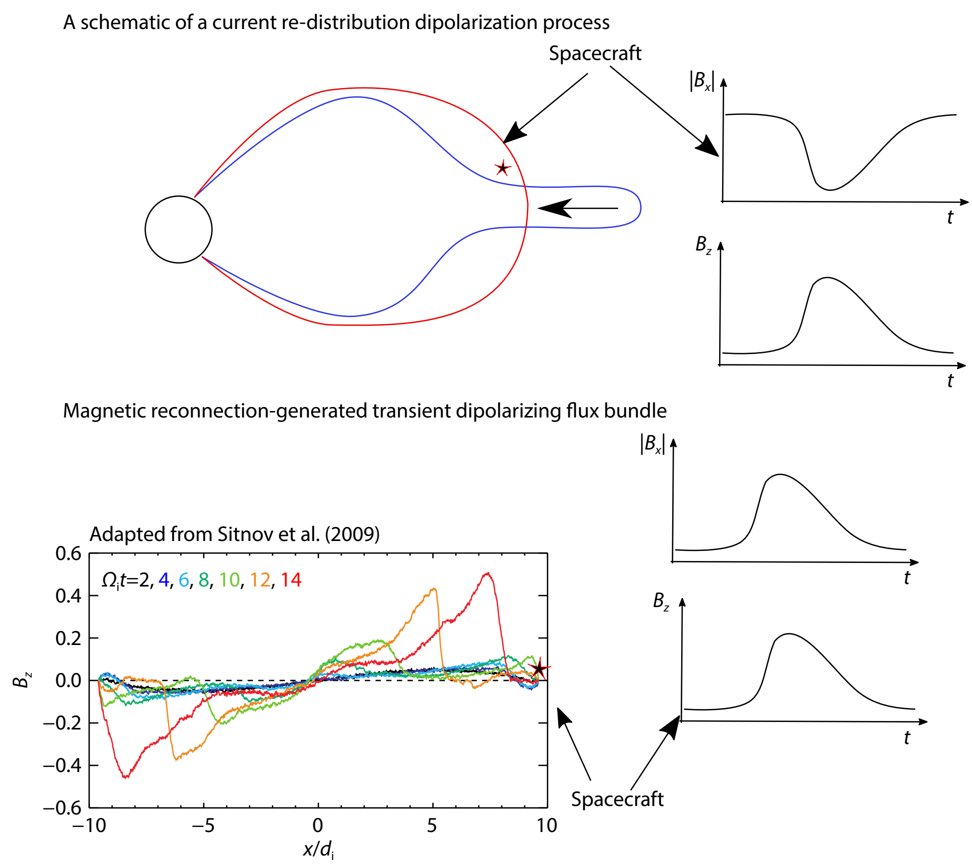

Figure 2. Illustration of the signatures ($|B_x|$ and B_z) for the two types of dipolarization. Adapted from Yao ZH et al. (2017b). The bottom left panel is the magnetic field B_z distribution and the evolution (in different colors) around the reconnection site. Adapted from Sitnov et al. (2009).

vational differences between them is that, as shown in Figure 2, the magnitude of the horizontal component (B_x) of the magnetic field is expected to decrease during a substorm dipolarization and to increase during a dipolarization front. We should point out that the substorm-like dipolarization is also known as current redistribution dipolarization, and the dipolarization front is known as a transient dipolarizing flux bundle.

At present, exploration of the Earth system is regularly carried out by using several simultaneous *in situ* spacecraft, as well as various types of ground stations (e.g., a ground auroral camera and ground magnetometer). Such concurrent observations are very rare for the exploration of Jupiter and Saturn. In particular, it is impossible to obtain ground observations, which are essential for determining whether a process is global or localized. Consequently, a comparison with what we have learned from the terrestrial magnetosphere is crucial to understanding the measurements made by a single probe in the magnetospheres of Saturn and Jupiter.

Figures 3 and 4 are reproduced from Yao ZH et al. (2017b). They provide a direct comparison of the two types of magnetic dipolarization for Earth and Saturn. Figures 3a to 3c show a typical substorm dipolarization event, with *in situ* measurements from one of the THEMIS spacecraft. As clearly shown by the auroral electrojet (*AE*) index, this is a moderate substorm event. Two steps of magnetic dipolarization occurred at ~10:00 universal time (UT) and ~10:30 UT, respectively. For each dipolarization, the north–south magnetic component (B_z) increased and was accompanied by a decrease in the magnitude of the horizontal component ($|B_x|$). Note that the minus sign of B_x indicates that the measurements were from the southern plasma sheet. The antiphase variations between B_z and B_x are typical features of substorm dipolarization. The event in Figures 3d to 3g and the event in Figures 3h to 3k show magnetic field and electron energy distribution measurements from Cassini at Saturn. In particular, we can see magnetic variations (i.e., the antiphase B_θ and B_r) and features of the electron energy spectrum similar to those in Figures 3a to 3c. Note that near the equatorial plane, B_θ in Kronographic Radial–Theta–Phi (KRTP) coordinates is equivalent to B_z in Geocentric Solar Magnetospheric (GSM) coordinates. And B_r in KRTP roughly corresponds to B_x in GSM in the night magnetotail. Although we could not directly examine whether the two events at Saturn triggered a global current redistribution, the magnetic variations and the particle features are reminiscent of the substorm current system at Earth.

Figures 4a to 4c show a typical dipolarization front event at Earth and at Saturn. As illustrated by the small *AE* index, this event did not cause a global geomagnetic perturbation. The rapid change in the magnetic field shows simultaneous enhancements in both the B_x and B_z components. The magnetic variation is like a discontinuity, separating two different plasma populations. The electron energy spectrum also confirms a rapid change in energy and flux. Similar to what was observed in the terrestrial magnetosphere, Cassini also detected such magnetic discontinuities, separating two plasma populations and showing in-phase variation in the two magnetic components (B_r and B_θ). The strikingly similar magnetic and particle features suggest that they are both dipolar-

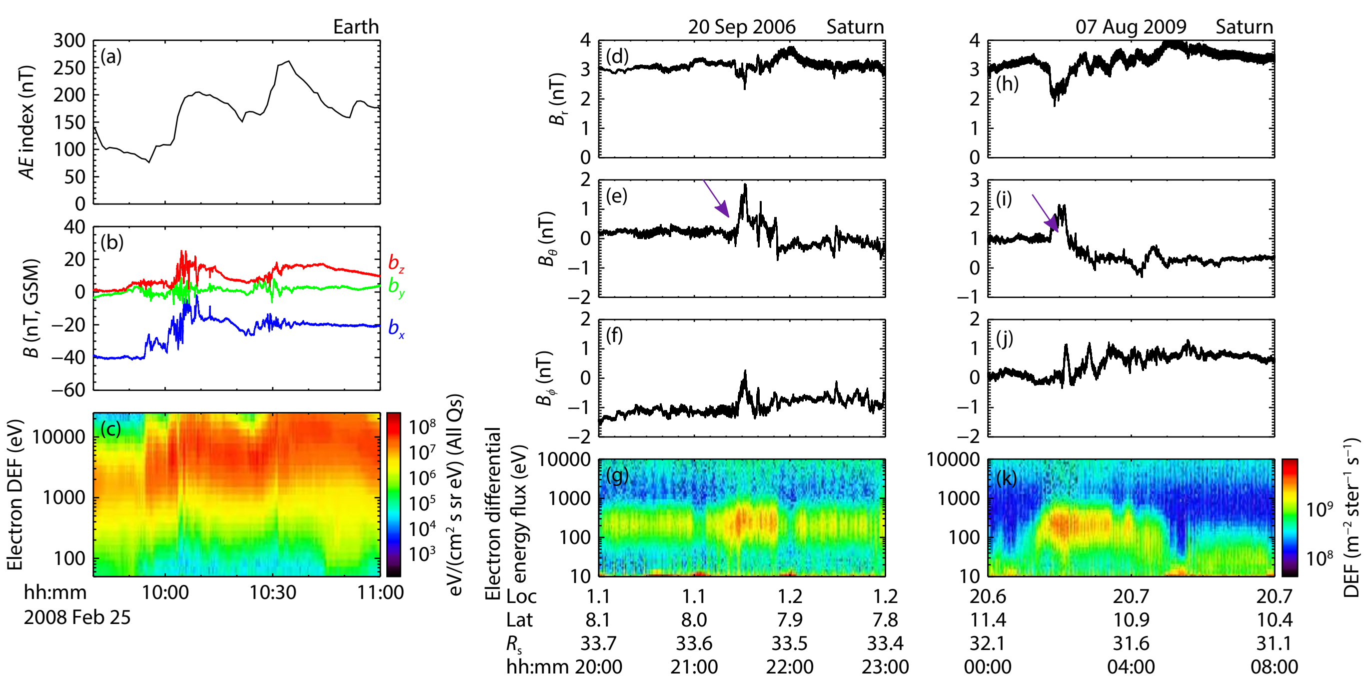

Figure 3. Reproduced from Yao ZH et al. (2017b). (a) The THEMIS pseudo-*AE* index. (b) The three components of the magnetic field in GSM coordinates for a dipolarization event at Earth on February 25, 2008. (c) The electron differential energy flux (DEF) observed by THEMIS-D. (d–f) The magnetic field components in KRTP coordinates and the differential energy flux spectrum on September 20, 2006. (h–k) The magnetic field and electron differential energy flux spectrum for the dipolarization event on August 7, 2009. Near the equatorial plane, the B_r and B_θ components in KRTP coordinates are in the horizontal and northern–southern directions, which roughly correspond to the THEMIS observations of B_x and B_z components in GSM coordinates.

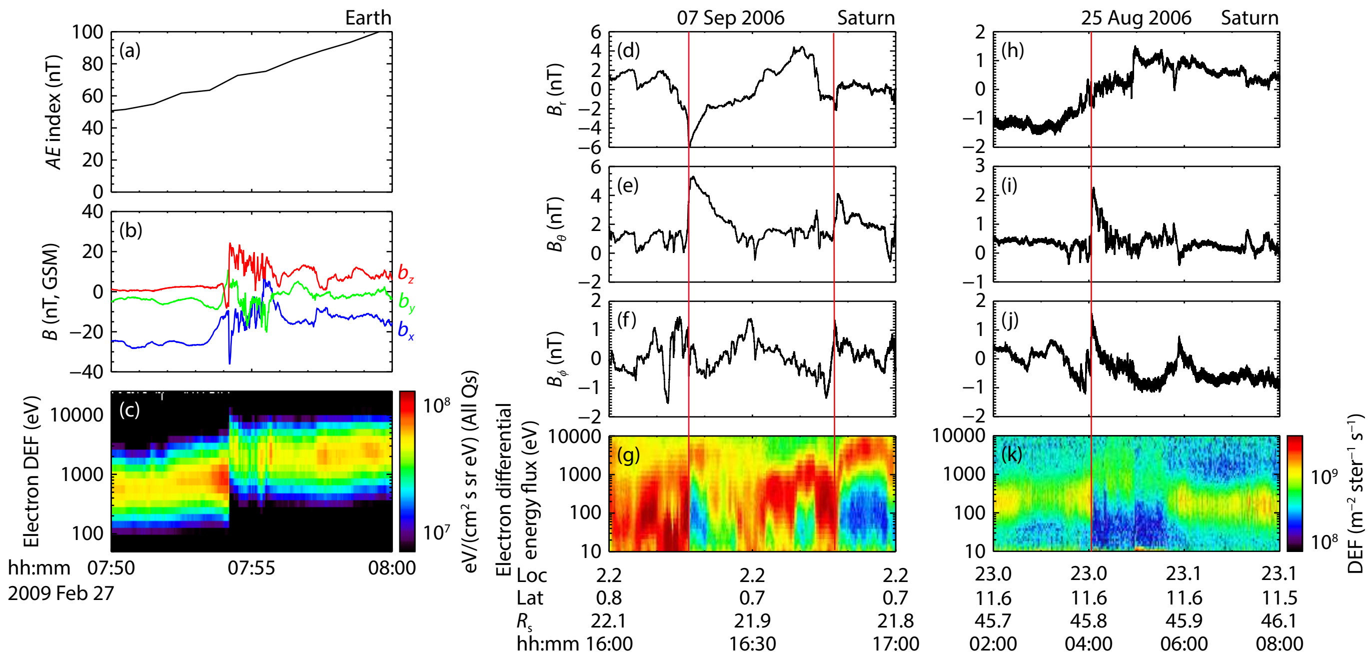

Figure 4. Reproduced from Yao ZH et al. (2017b). The format is the same as Figure 3.

ization front structures. Dipolarization fronts are also often observed at Jupiter (Vogt et al., 2010, 2020; Kasahara et al., 2013) and were found to be associated with particle energization (Artemyev et al., 2020). We should note that the substorm-like dipolarization has also been identified in Juno observations. In that case, the dipolarization was found to be associated with auroral injection, as recorded by simultaneous observations from the Hubble Space Telescope (HST; Yao ZH et al., 2020). Therefore, the two types of magnetic dipolarization are universal processes taking place in the magnetospheres of Earth, Saturn, and Jupiter.

Because the dipolarization front is formed by reconnection outflow, any planet with magnetotail reconnection is expected to produce dipolarization fronts. In contrast, the substorm-like magnetic dipolarization requires the formation of a current wedge system between the magnetosphere and the ionosphere. Therefore, it is likely that the Earth, Saturn, and Jupiter would have such processes. Note that in giant planetary magnetospheres, tidally induced geological activities from the moons supply a large portion of heavy ions (i.e., water based or sulfur dioxide based), such that the current carriers are different from those in the terrestrial magnetosphere, where the ions are mostly protons.

The existence of the two types of dipolarization at Saturn and Jupiter provides clear evidence that their magnetodiscs can allow magnetic reconnection and electrical current disruption individually. The causality between magnetic reconnection and current disruption is a long-standing controversial question in the Earth's magnetosphere community. It is challenging to confirm the chronological order of the two processes because they are expected to trigger one another within a few minutes, which is comparable to the timescale of the processes themselves (Angelopoulos et al., 2008; Lui, 2009). Unlike the Earth, Saturn and Jupiter have much larger magnetospheres. The reconnection site and the magnetospheric region leading to the main auroral emissions are separated by tens of planetary radii; therefore, the giant planetary magnetospheres provide ideal environments for investigating the fundamental question that has been puzzling the terrestrial community for decades. Nevertheless, the application of one planetary law to another would come with many caveats because their energy processes can be quite different. The energy processes for driving a terrestrial substorm are generally outside in, whereas the energy processes at giant planets are mostly inside out.

3. Corotating Nature of Magnetic Reconnection and Dipolarization

The giant planetary magnetospheres are different from the terrestrial magnetosphere in many respects. Because of the weaker influence of the solar wind and their strong internal constraints (e.g., stronger internal magnetic field and rapid rotation), the influence of planetary rotation extends to large distances in their magnetospheres (Delamere and Bagenal, 2010; Badman et al., 2015; Bader et al., 2019) and encompasses the source region of their aurorae. The investigations of magnetic reconnection in giant planetary magnetospheres are mostly considered in two-dimensional images, meaning the azimuthal variation is usually not taken into consideration (e.g., Jackman et al., 2011). The evolution of the two-dimensional reconnection image in the azimuthal direction has been a long-standing research topic that was originally proposed by Vasyliunas (1983). The later observational studies have not fully confirmed the proposed image that the reconnection *X*-line moves radially outward from dusk to the morningside via midnight (Vogt et al., 2010, 2020; Smith et al., 2016). The *X*-line distribution will require further investigation, either from larger datasets or numerical simulation. The reconstruction methods and multi-point spacecraft missions could lead to potential solutions to this long-standing research topic (Shi QQ et al., 2005, 2006; Sonnerup et al., 2006; Fu HS et al., 2015; Wang Z et al., 2020).

In Yao ZH et al. (2017a), the bipolar variation of the north–south magnetic component associated with magnetic reconnection at Saturn was, for the first time, explained in terms of azimuthal motion of the reconnection site, rather than by a radial retreat of the reconnection site, as claimed in previous studies. Their study compared the magnetic variation with the observations obtained after one planetary rotation. They found that the key features from the two successive sets of observations were very similar; thus, they suggested that the variations associated with magnetic reconnection can rotate with Saturn. In a later study, Guo RL et al. (2019) identified multiple reconnection sites that were successively detected during a time interval longer than one Saturnian rotation period. Each two successively detected reconnection sites were separated by approximately 1 hour, which could be a result of rotating small-scale spatial structures or frequently recurring processes. Their results also showed that the reconnection occurrence rate had no clear preference in a specific local time, suggesting that these drizzle-like reconnection sites were more likely corotating structures in the magnetosphere rather than repetitive structures in specific magnetic configurations (i.e., the nightside more stretched magnetic field). The corotating drizzle-like reconnection sites are illustrated in Figure 5. Note that the reconnection sites are distributed in more local times than previously expected; thus, they would lead to greater energization of particles, more auroral activities, and greater mass loss.

As numerous publications have indicated, magnetic reconnection and magnetic dipolarization are two closely connected processes. It is natural to expect corotating magnetic reconnection following the detection of corotating magnetic dipolarization. By re-examining the large dataset from Cassini, Yao ZH et al. (2018) showed that magnetic dipolarization events at Saturn could reoccur after one planetary rotation and could come with electron and ion energization. Moreover, the authors suggested that the recurrent magnetic dipolarization is a counterpart of the corotating energetic neutral atom enhancement (Krimigis et al., 2007) and the subcorotating auroral breakup at Saturn. The angular velocity

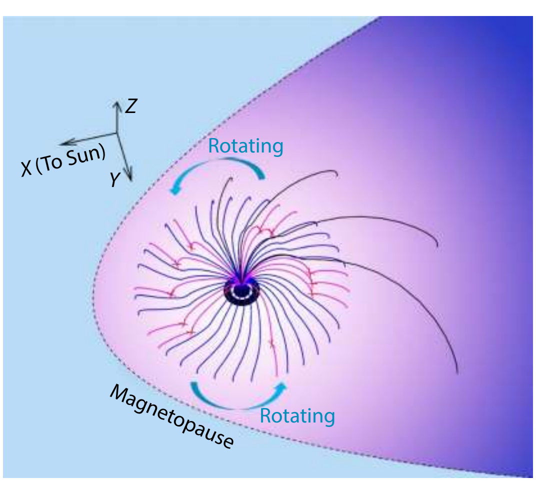

Figure 5. Reproduced from Guo RL et al. (2019). Schematic diagram showing Saturn's corotating magnetosphere with drizzle-like reconnections at all local times, as marked by the red crosses.

difference between the auroral breakup region and the magnetospheric process (e.g., energetic neutral atom enhancement or magnetic dipolarization) is explained as being a consequence of magnetic reconfiguration that changes the magnetic connection between the magnetosphere and the ionosphere. Figure 6 illustrates how a corotating magnetospheric source would lead to a subcorotating aurora during a magnetic reconfiguration, like the one associated with magnetic dipolarization. Additionally, Palmaerts et al. (2020) reported a nearly corotating auroral spiral structure at Saturn, which was related to synchronous dipolarization and enhanced corotating energetic neutral atom emission, directly supporting Figure 5.

Considering the large similarities between the magnetospheres of Jupiter and Saturn, these corotating processes may also exist at Jupiter. Using recent observations from the Juno spacecraft, Yao ZH et al. (2020) showed that the dipolarization signature measured by Juno reappeared after one planetary rotation, which suggests that the dipolarization site was corotating with Jupiter. Moreover, the dipolarization was found to be connected to the auroral injection region that often corotates with the planet (Dumont et al., 2018). These results are thus evidence of corotating magnetic dipolarization at Jupiter. Systematically examining the corotating nature of magnetic reconnection and dipolarization at Jupiter requires further investigation using the large datasets from the Galileo and Juno missions.

4. Unexpected Dayside Dynamics at Saturn

In the terrestrial magnetosphere, the dayside region is strongly compressed by dynamic pressure from the solar wind. In Earth's magnetosphere, internal reconnection is taking place only in the nightside stretched magnetotail, whereas for giant planets, centrifugal effects of the rotating plasma also stretch the dayside magnetosphere into a magnetodisc configuration that may be prone to reconnection. This is the standard image for a magnetosphere driven by a solar wind plasma source. The giant planetary

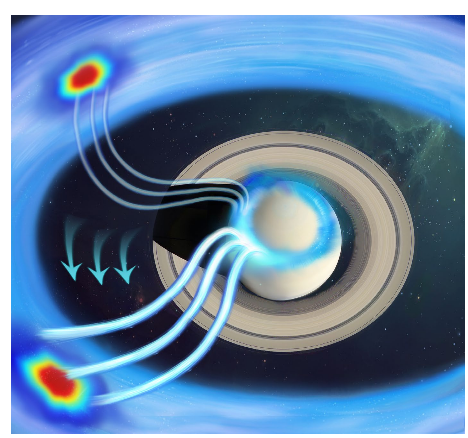

Figure 6. Reproduced from "Cassini Reveals a Missing Link on Saturn's Rotating Aurora" (https://eos.org/editor-highlights/cassini-reveals-a-missing-link-on-saturns-rotating-aurora). The energization site in the magnetosphere corotates with the planet, whereas the corresponding auroral signature may subcorotate because of the changing magnetic configuration. Credit: NASA/JPL/SSI for the visible image of Saturn captured by Cassini.

magnetospheres are believed to have a relatively stretched magnetic topology in the dayside compared with the terrestrial magnetosphere (Kivelson and Southwood, 2005). However, whether the magnetic field could be stretched enough for reconnection to occur is unclear.

Using the large dataset from the Cassini magnetometer (Dougherty et al., 2004), Delamere et al. (2015b) showed that negative B_θ magnetic components are widely distributed in Saturn's dayside magnetodisc, which may indicate magnetic reconnection. In a later study, Yao ZH et al. (2017a) identified some corotating magnetic reconnection sites in Saturn's magnetosphere, which imply that the reconnection may be detected in the dayside magnetodisc. Following these implications, Guo RL et al. (2018b) finally confirmed the existence of magnetic reconnection in Saturn's dayside magnetodisc by analyzing the magnetic field and particle data from Cassini. The observed Hall magnetic field and accelerated electrons indicated that the spacecraft measured the ion diffusion region, which is the core region of the reconnection. These results have updated our understanding of the rotationally driven reconnection in giant planetary magnetospheres, as illustrated in Figure 7. A multiple case study showed the basic features of heavy particle acceleration in the dayside magnetodisc reconnection sites and presented a secondary magnetic island formed by dayside reconnection (Guo RL et al., 2018a). A statistical investigation of magnetic reconnection at Saturn indicated that the reconnection occurrence rate in the dayside magnetosphere is comparable to that in the nightside, implying that the solar wind compression in the dayside magnetosphere cannot efficiently suppress reconnection processes.

The discovery of magnetic reconnection at Saturn's dayside magnetodisc provides evidence that the dayside magnetospheric processes at giant planets are fundamentally different from what we have learned from the Earth. This new finding also suggests that centrifugal force in the rapidly rotating giant magnetospheres could sufficiently stretch the magnetic field in the dayside to allow magnetic reconnection. The stretched magnetic field configuration indicates strong cross-field electrical currents, which may form the current wedge when connecting with the ionosphere during a magnetospheric perturbation. Moreover, the auroral breakup at Saturn could extend from nightside to dayside (Radioti et al., 2014), implying the formation of a current wedge in the dayside. Therefore, it is natural to expect magnetic dipolarization, a consequence of current wedge formation, to be observed in Saturn's dayside. Yao ZH et al. (2018) showed direct observations of magnetic dipolarization in Saturn's dayside magnetosphere, which eventually connected the dayside auroral breakup and the expected current wedge system. These results collectively indicated that plasma processes in Saturn's dayside magnetodisc are analogous in many ways to the conditions in the terrestrial magnetotail. In the dawnside magnetodisc, the magnetic field could also show the dipolarization feature, which could potentially extend to the morning-side disc (Gershman et al., 2018; Yao ZH et al., 2019). Although not yet reported in any literature that we are aware of, we would expect magnetic reconnection and dipolarization to exist in Jupiter's dayside magnetodisc. An examination of the Galileo dataset would help resolve this issue. A high-resolution numerical simulation would be another potential tool to understand the dayside magnetodisc reconnection.

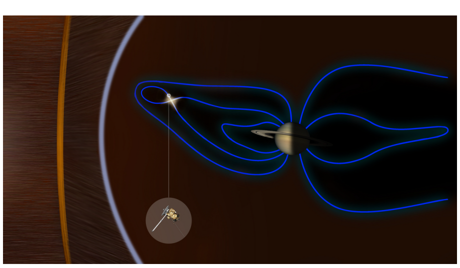

Figure 7. The updated reconnection image for Saturn, reprinted from "Magnetic Reconnection within Saturn's Magnetosphere" (June 5, 2018; https://sci.esa.int/web/cassini-huygens/-/60384-magnetic-reconnection-within-saturn-s-magnetosphere). Traditionally, reconnection was believed to take place on the dayside magnetopause or nightside magnetotail of a planet. Observations from Cassini confirmed that reconnection could also take place in the dayside magnetodisc.

5. Improved Understandings of Auroral Processes from New Observations

In the past 4 years, the Cassini proximal orbits and the HST campaign during the Juno mission have massively extended the observations of aurorae at Jupiter and Saturn (Connerney et al., 2017; Radioti et al., 2017, 2019; Grodent et al., 2018; Palmaerts et al., 2018). The Cassini proximal orbits have provided us with unprecedentedly high-resolution auroral images, revealing the auroral beads, which are likely driven by plasma instabilities (Radioti et al., 2019). The discovery of auroral beads implies a similar magnetic configuration between Saturn's magnetodisc and the terrestrial magnetotail; however, such a configuration at Saturn exists in a large local time range from pre-midnight to the morning sectors. The auroral beads rotate with the planets and are connected to energetic neutral atom blocks in the equator by multiple field-aligned current pairs (Guo RL et al., 2021a). Auroral streamers, which are associated with the planetward reconnection outflow in the terrestrial magnetosphere, have also been identified by the high-resolution observations from the Cassini-ultraviolet imaging spectrograph (UVIS) instrument (Radioti et al., 2017). The auroral streamer extends from the most poleward auroral arc to the equatorial arc and leads to an auroral enhancement on the equatorial arc, which is strikingly similar to the terrestrial auroral streamer processes (Nishimura et al., 2010; Yao ZH et al., 2017c). Bader et al. (2019) showed that the auroral intensity is modulated by the planetary rotation, and the intense aurora on the dawnside is mostly caused by transient processes (e.g., magnetic reconnection or plasma injection). The large dataset from the HST allows us to summarize auroral morphologies. We may also potentially infer the evolution of the auroral morphology by using the quasi-continuous observations (Grodent et al., 2018).

The large HST dataset and the unprecedented view from proximal orbits provide us with an opportunity to understand small-scale details and systematic patterns of auroral processes for Jupiter. Moreover, we can more often have auroral observations with simultaneous *in situ* measurements, which are crucial for understanding auroral drivers. Yao ZH et al. (2019) analyzed contemporaneous measurements from the HST and Juno, which revealed that the auroral intensification is modulated by the accumulation and release of magnetic energy in the magnetosphere. In other cases, Nichols et al. (2020) found that auroral brightening is associated with the corotation enforcement theory. The two studies showed somewhat contradictory conclusions regarding the connection between the magnetic field configuration and auroral intensification, partially because of the differently focused mechanisms in each study. In Yao ZH et al. (2019), the process focused on the magnetic changes rather than the magnetic configuration itself, the latter of which was the focus in Nichols et al. (2020). Both the magnetic configuration and the changes are important in determining the auroral emission. The configuration determines the main auroral morphologies, such as the six auroral families proposed in Grodent et al. (2018), whereas the changes in magnetic configuration would provide significant modulation of the same auroral family. It is noteworthy that a recent commentary article provided six pieces of evidence against the corotation enforcement theory, which is heavily based on simultaneous observations from the HST and Juno (Bonfond et al., 2020).

The role of magnetic reconnection and dipolarization in driving the Jovian aurora is still poorly understood. Radioti et al. (2008) and Grodent et al. (2004) suggested that polar dawn spots are a direct consequence of magnetic reconnection based on the auroral morphologies, but simultaneous observations of reconnection and dawn spots do not yet exist. Using coordinated observations from Juno and the HST, Yao ZH et al. (2020) found that the auroral injection is associated with the dipolarization injection, which is known to cause hot plasma injection in the magnetosphere (Gabrielse et al., 2012, 2016). Moreover, their results showed that the auroral dawn storm is likely associated with magnetic reconnection, which continually produces plasma injections in the dawnside magnetosphere, leading to multiple auroral injection structures when rotating to larger local times. For the first time, the Juno-ultraviolet spectrograph (UVS) instrument obtained a high-resolution auroral image from Jupiter's nightside (Bonfond et al., 2017; Connerney et al., 2017; Gladstone et al., 2017), which revealed that the auroral dawn storm is initiated in the nightside poleward of the main aurora (Bonfond et al., 2021) as illustrated by the time sequence images in Figure 8. The poleward-initiating auroral signature is likely a signature of magnetic reconnection, which is consistent with the proposed images in Yao ZH et al. (2020).

Although the close connection between the Jovian aurora and magnetic reconnection is widely accepted, simultaneous observations of reconnection and the connected auroral emission are rare. The HST campaigns during the Juno mission provided an unprecedented opportunity to examine the connection between magnetospheric processes and auroral emissions (Grodent et al., 2018). Yao ZH et al. (2020) reported the direct connection between magnetic reconnection and an auroral dawn storm by using the coordinated HST and Juno observations. Other magnetospheric observations during a dawn storm also supported the connection (Swithenbank-Harris et al., 2021). Besides the connection with dawn storms, magnetic reconnection was found to be associated with a thin auroral arc above the main oval, forming a double-arc structure (Guo RL et al., 2021b). The double-arc structure-related reconnection is likely a localized process, whereas the dawn storm-related reconnection can cause a global reconfiguration. The exact relation will require further investigation, from either more observations or a numerical simulation.

6. Summary and Perspectives

In the past few years, the increasing amount of data from Cassini, Galileo, Juno, and the HST have provided an unprecedented opportunity for understanding the global system of Jupiter and Saturn. Simultaneous observations from *in situ* spacecraft in their magnetospheres and remote sensing instruments are becoming available, which has allowed us to obtain a global image and localized parameters at the same time.

In this article, we have briefly reviewed the recent progress in magnetic reconnection and magnetic dipolarization at Saturn and Jupiter. A key characteristic of recent research is that these studies have focused more on differences in the terrestrial processes rather than their similarities, which were the main focus in many earlier studies. Moreover, new observations from the Juno-UVS instrument revealed that Jupiter's nightside auroral evolution has fundamental similarities to the Earth's auroral substorm, which may provide crucial clues to understanding the origin of Jovian aurorae. The major recent advances are summarized below:

(1) Two types of magnetic dipolarization signatures are revealed at Saturn, one of which is related to electrical current redistribution and the other to magnetic reconnection outflow (Yao ZH et al., 2017b).

(2) Magnetic reconnection regions are drizzle-like, as suggested by Delamere et al. (2015b), and recent investigations show that

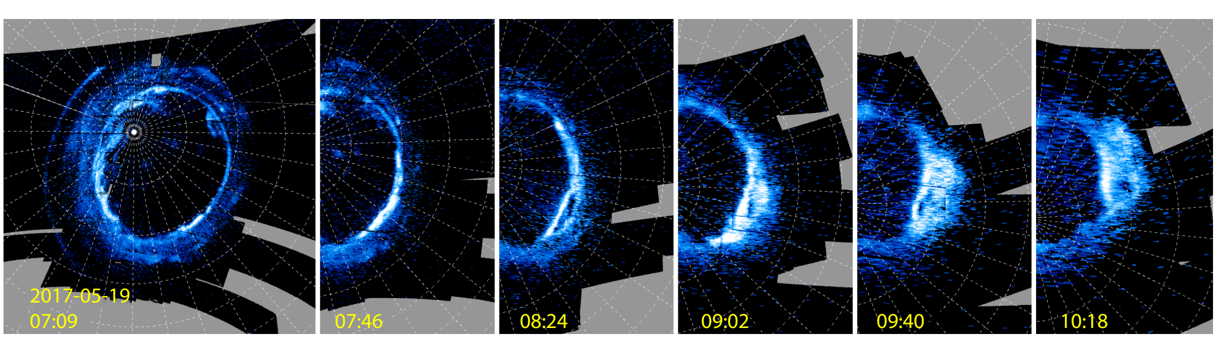

Figure 8. Evolution of an auroral dawn storm during Juno's Perijove 6 orbit, observed on May 19, 2017. Reproduced from Bonfond et al. (2021).

these drizzle-like reconnection sites corotate with the planet. Similarly, magnetic dipolarizations are found to corotate with Saturn (Yao ZH et al., 2018) and Jupiter (Yao ZH et al., 2020). The corotating magnetic dipolarization at Jupiter is associated with the well-known corotating auroral injection (Yao ZH et al., 2020).

(3) Magnetic reconnection, magnetic dipolarization, and their associated particle energization are also identified in the dayside magnetodisc at Saturn and Jupiter, which clearly demonstrates that the dayside magnetospheric dynamics are far more important than we ever expected.

(4) Magnetic reconnection, dipolarization, and auroral emissions are highly connected. It is likely that the reconnection often corresponds to the dawn storm region, whereas dipolarization is related to auroral injections.

These recent findings clearly demonstrate that the corotating electric field may be more important than previously considered, which would potentially influence our previous understanding of the dayside dynamics in giant planets (e.g., energetic particles and auroral brightening). The updates in dayside magnetospheric dynamics are also crucial to planetary mass circulation; therefore, some important questions may potentially be answered by using this recent progress, such as the overall mass balance problem at Saturn (Thomsen, 2013). The rotating auroral spots (Radioti et al., 2015) may also be associated with plasma instabilities in a rotating magnetosphere.

Compared with the understanding of the terrestrial magnetosphere, we are still in a relatively early stage of exploring the magnetospheres of Jupiter and Saturn. The giant magnetospheres are far more complicated in the view of energy sources, particle species, planet–moon interactions, the solar wind–internal force balance, and the multiple spatial–temporal scales. However, only three space missions (i.e., Cassini, Galileo, and Juno) have been dedicated to these systems. Many important questions are yet to be solved. As a review of recent progress, we would also like to provide some perspectives on key questions for future investigations:

(1) In Earth's magnetosphere, magnetic dipolarization and plasma injection are often coupled (Moore et al., 1981; Mauk and Meng, 1987; Liou et al., 2001; Zhang JC et al., 2008). Similar connections are naturally expected to exist on other planets, such as Jupiter and Saturn. However, because of the limited number of spacecraft observations, the investigations at Jupiter are rather limited. In contrast, the injection features on auroral images are very significant and have been extensively investigated. The connections among magnetic dipolarization, plasma injection, and auroral injection are far from well understood. The campaigned observations between Juno and the HST provided an unprecedented opportunity to further the understandings on this topic (Yao ZH et al., 2021, 2022).

(2) Magnetic reconnection is a fundamental process in energy conversion in the planetary magnetospheres. The terrestrial magnetosphere has been investigated by tens of space missions for decades, and we have obtained a relatively comprehensive picture of reconnection at the magnetopause and magnetotail. Unlike the Earth, Jupiter has a highly complex magnetodisc. Although the reconnection in the nightside magnetosphere is usually believed to exist widely beyond 50 R_J, the global distribution of reconnection sites is not clear. Moreover, because of the discovery of Saturn's dayside magnetodisc reconnection, it is a natural question whether such reconnection sites also exist at Jupiter. Regarding the magnetic reconnection at Jupiter, many important questions are unsolved, such as how planetary rotation modulates the reconnection site in the disc, and what processes determine whether a reconnection causes a localized perturbation or a global disruption.

(3) The terrestrial and Jovian magnetospheres are different in many aspects, and the difference in their ion species is one of the most distinctive differences. Unlike the terrestrial magnetosphere, which is mainly sourced by protons, Jupiter's magnetosphere has several major species, including heavy ions (e.g., sulfur and oxygen). The heavy ions would have a larger gyro-radius and perhaps a longer gyro-period, which could potentially cause important influences on the magnetospheric dynamics, such as how heavy ions influence the reconnection processes and the associated particle acceleration. In the terrestrial magnetosphere, the dipolarization front has been found to have a spatial scale of proton gyro-radius. The question is how the multiple species of ions would modify the spatial scale of the dipolarization front in Jupiter's magnetosphere.

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