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SPECIAL TOPICS

Magnetic reconnection in the magnetodisk of centrifugally dominated giant planets

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Abstract
Magnetic reconnection is crucial in understanding magnetospheric dynamics and aurorae processes at planets. In planetary magnetospheres, magnetic reconnection has often been identified on the dayside magnetopause and in the nightside magnetodisk, where thin-current-sheet conditions are conducive to reconnection. At the Earth, the magnetopause and magnetotail current sheets are primarily controlled by the upstream solar wind. At Jupiter and Saturn, their fast rotation and internal mass sources lead to an additional current sheet that encircles the planet, forming a magnetodisk inside the magnetosphere. The reconnection processes in the magnetodisk current sheet are associated with centrifugal force-driven dynamics. The magnetodisk reconnection is not limited to the nightside but is discretely distributed at all local times inside the magnetosphere. The reconnection sites also rotate with the magnetosphere. These widely distributed small-scale reconnection sites can result in the global release of energy and mass from the magnetosphere.

Keywords Magnetic reconnection · Giant planets · Magnetodisk · Magnetospheric dynamics

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1 Introduction to magnetic reconnection

In the universe, almost 99% of the mass is in the state of the plasma. The plasma consists of charged particles and is quasi-neutral in total. The plasma is coupled with magnetic fields, and they are frozen-in together on a macroscopic scale. When two plasma bundles from different sources are encountered, they are generally separated by the magnetic field lines and cannot mix directly. A current sheet can be formed at the intersection boundary of the two plasma bundles. The current density can represent the amount of the charge particles and the magnetic energy stored in the boundary. When a large amount of energy is assembled in the current sheet, magnetic reconnection occurs to change the magnetic topology and release the magnetic energy. Because of the reconnection process, the two plasma bundles are mixed due to the disconnection and reconnection of the magnetic field lines. The released magnetic energy energizes the electrons and ions to increase their temperatures and bulk velocities.

1.1 A brief history of magnetic reconnection

The discovery of magnetic reconnection process primarily explains the explosive phenomena of solar flares on the Sun. The magnetic annihilation process is too slow to support such outburst phenomena. Giovanelli (1946) first proposed the concept of re-connecting the magnetic field lines. Sweet and Parker provided the first reconnection model (Parker 1957, 1963; Sweet 1958). Their magnetohydrodynamic (MHD) model does not solve the reconnection diffusion region, where the field line is broken, and mainly deals with the flows and flux transportation outside the diffusion region. The electric field in the reconnection region is constant and transports the magnetic flux into the diffusion region and energizes the charged particles. The model is a quasi-2D model in which variation along the current flow direction (i.e., out-of-plane direction) is not considered. The background plasma flows into the diffusion region in the direction normal to the current sheet. The accelerated particles are expelled as the outflow in the current sheet along the direction nearly aligned with the magnetic field in the background.

The Sweet–Parker model indicates that the speed of the accelerated ions is approximately the Alfvenic speed and defines the reconnection rate. However, the Sweet–Parker model gives a very small reconnection rate, which cannot explain the solar flare exploration. Petschek (1964) reduced the length of the reconnection dissipation region in the outflow direction to increase the reconnection rate. To accelerate ions, slow-mode shocks are added at the separatrices. Petschek's model was found in some laboratory experiments and simulation results (e.g., (Baum and Bratenahl 1977; Ugai and Tsuda 1977; Pudovkin and Semenov 1985; Xu et al. 2022)), but was only found in a small number of observational results (Gosling et al. 2006a, b).

To tackle the challenge of the slow reconnection rate, it needs to go deep into the diffusion region. The ions and electrons are decoupled and unmagnetized inside the diffusion region, and two-fluid magnetohydrodynamic equations are used. The diffusion region is primarily divided into the ion diffusion region and the electron diffusion region. The ions are first unmagnetized when entering the diffusion region, while electrons are still ‘frozen-in’ with magnetic field lines. This region is the ion diffusion region. The electron diffusion region is around the reconnection X-line, the center of the magnetic reconnection, where the electrons are also unmagnetized. The ions behave differently from electrons, which form electric fields and currents at different regions of the diffusion region. In the ion diffusion region, the electrons are basically tied to the magnetic field lines and their velocities have significant parallel components. The inflow electrons (moving towards the electron diffusion region) and outflow electrons (moving out of the electron diffusion region) are separated by the separatrix, and their trajectories form a half loop. The ions cross the separatrix roughly perpendicularly. A current loop is formed in the direction opposite to the electron flow and generates magnetic fields in the orientation of the reconnection X-line. An electric field is created and points from the edges to the center of the current sheet to maintain pressure balance and overall charge neutrality (Pritchett 2001). The ions are accelerated by this electric field when crossing the separatrix. Because the picture described above is mainly from the Hall term of the generalized Ohm’s law (Birn et al. 2001), they are termed Hall current, Hall magnetic field, and Hall electric field. The Hall reconnection picture is illustrated in Fig. 1.

A comparison is conducted to compare the reconnection rates generated by different reconnection models (Birn et al. 2001). The simulation codes that include the Hall effect obtained a significantly high reconnection rate, and the reconnection rate

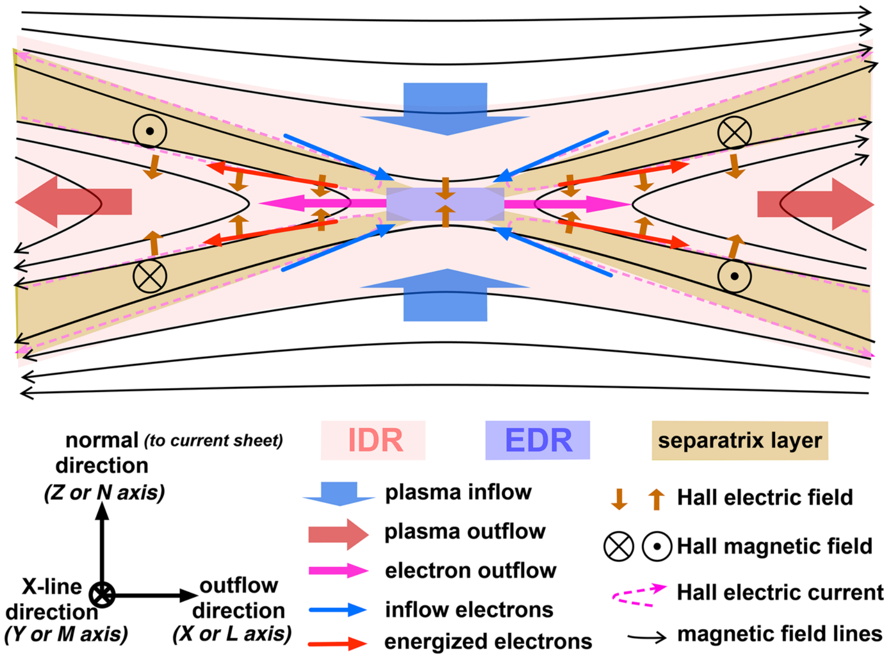

Fig. 1 Illustration of the diffusion region of magnetic reconnection process containing the Hall effect

in the MHD model with only resistive term is low. These simulation results also show that the Hall effect leads to whistler waves in the diffusion region. The dynamics of the whistler waves play a crucial role in the high reconnection rate.

1.2 Observation of magnetic reconnection

In the planetary magnetosphere and the interplanetary space, the plasma is collisionless and the resistive term in the generalized Ohm's law is negligible. The Hall term contributes primarily to the reconnection process. The signatures of the Hall effect for the collisionless reconnection are first observed in the terrestrial magnetotail by the WIND spacecraft (Øieroset et al. 2001). Afterward, spacecraft with high-resolution measurements offer a close look into the ion diffusion region and even the small electron diffusion region (e.g., He et al. 2008; Chen et al. 2009; Burch et al. 2016; Phan et al. 2018). The electrons are accelerated by the reconnection electric field along the X-line in the electron diffusion region to a velocity close to the electron Alfvenic velocity and turn direction to form the electron outflow outside the electron diffusion region. The ions are accelerated behind the electron outflow to reach a speed close to the ion Alfvenic speed. The magnetic field is compressed by the ion outflow and transported downstream, forming the dipolarization front with an enhanced magnetic component normal to the current sheet. The boundary of the inflow and outflow particles is the separatrix, which is a layer that contains different kinds of structures such as electron holes, double layers, and electron beams (e.g., (Nagai et al. 2001; Drake et al. 2003; Cattell 2005; Wang et al. 2014; Bai et al. 2019)). In the diffusion region and separatrix region, the whistler, kinetic Alfven wave, and lower-hybrid waves play a crucial role in particle energization (e.g., Wang et al. 2000; Rogers et al. 2001; Xiao et al. 2007; Deng et al. 2009; Fujimoto 2014). Turbulent features are also present in the outflow region (e.g., (Daughton et al. 2011; Guo et al. 2016)). The collisionless reconnection region is highly dynamic and the observed kinetic features are reviewed by Zhou et al. (2022).

The reconnection diffusion region is generally much smaller compared to the magnetosphere. The satellites more frequently record the by-products of the magnetic reconnection than the diffusion itself. The by-products, i.e., the bursty bulk flow, flux rope, plasmoid, etc., impact the magnetosphere in a large area. Seeing from the plasma, the reconnection-generated phenomena contain the bursty bulk flow, which is the plasma outflow transferring downstream, and the plasmoid, which is a bundle of plasma enclosed by loop-shaped magnetic field lines (Zong et al. 2004). Meanwhile, energized electrons and ions can disperse to a broad area. Seeing from the magnetic signal, the large and rapid variations of the magnetic component that are normal to the current sheet are commonly treated as the representation of the magnetic reconnection. The dipolarization front, accompanied by the bursty bulk flow, displays a local enhancement in the magnetic component normal to the current sheet and a decrease in the magnetic component along the outflow direction (Angelopoulos et al. 2008; Yao et al. 2017c). A flux rope consists of helical magnetic field lines and is treated as a magnetic island when the strength of the magnetic component along its axis is negligible. A plasmoid refers to the plasma bundle restrained by the magnetic island. The flux rope, magnetic island, and plasmoid all show bipolar magnetic signatures in observation and compress magnetic field to form traveling compression regions outside the current sheet (Slavin et al. 2003a, b; Zong et al. 2004).

The magnetic reconnection process is the onset of most magnetospheric storm and substorm dynamics. It changes the magnetic topology to release the mass and energy stored in the current into the magnetosphere. The by-products of the magnetic reconnection transport most of the energy and mass freed by magnetic reconnection to the planet or to escape the magnetosphere. Meanwhile, particles with high energies (generally more than tens of keV in the magnetosphere) can move quickly along the magnetic field lines to enter the ionosphere.

1.3 Magnetic reconnection at earth

At Earth, the solar wind compresses the magnetosphere at the magnetopause. When the interplanetary magnetic field (IMF) mainly points to the south, magnetic reconnection occurs at the dayside magnetopause near the sub-solar point. Closed magnetospheric field lines are opened to the solar wind to transfer the mass and energy into the nightside magnetosphere to form a magnetotail current sheet. Accumulating to a critical level, the energy in the magnetotail current is released by the reconnection to expel particles to the inner magnetosphere and interplanetary space. This circulation of mass and energy is the 'Dungey Cycle' (Dungey 1961).

The magnetotail current sheet is thought to be formed beyond 10 R_E (Earth's radius). The magnetic reconnection sites are commonly detected at the middle magnetotail around 20–30 R_E. The accelerated particles march forward and are blocked at the near-Earth area (around 10 R_E). In the meantime, the stretched magnetic field evolves into a configuration close to a dipole field. This is a global dipolarization process, different from the dipolarization front formed by magnetic reconnection. A field-aligned current (FAC) is formed when the cross-tail current is disrupted at this region. The FACs connect to the ionosphere, illumine aurorae, and disturb the magnetic field at high latitudes. Energetic particles with energies higher than tens of keV can be injected into the inner magnetosphere inside the geosynchronous orbit. These particle injections provide seeds for the enhancement of the flux in the radiation belt and enhance the ring current, especially at the dusk side, to decrease the magnetic strength at the equator. The above processes are the major parts of the substorm and storm in the magnetosphere.

The main part of the terrestrial aurorae is generally not directly linked to a magnetic reconnection region. Most of the energy released by magnetic reconnection needs to move more than 10 R_E in the equatorial plane before it swerves to enter the ionosphere along the magnetic field lines. Nevertheless, the reconnection process within 10 R_E has been reported (Angelopoulos et al. 2020). Due to the strong magnetic field near Earth, the particles are accelerated to relativistic energies and directly injected into the inner magnetosphere (Runov et al. 2022). This near-Earth reconnection could also generate aurora near its footpoint in the ionosphere. At the cusp region, the high-latitude reconnection process can also directly generate aurora

(Phan et al. 2003). The time-series relationship between the aurora and the reconnection site is decided by the magnetic configuration, explicitly, the place where the majority of the released energy and particles can transmit along the magnetic field line.

2 Magnetic reconnection at Jupiter and Saturn

The solar wind impacts all the magnetospheres in the solar system. The solar wind-controlled Dungey cycle can also be found at Jupiter and Saturn. The solar wind has a Mach number of ~10 to 20 and a plasma beta of <1 at Jupiter and Saturn (e.g., Jackman and Arridge 2011; Ebert et al. 2014; Echer 2019), while the averaged Mach number is around 10 and the averaged plasma beta is larger than 1 at Earth (Hajra 2023). The interplanetary magnetic field is <1 nT for Jupiter and Saturn (Ebert et al. 2014; Echer 2019), much weaker than that at Earth (several to more than 10 nT). These parameters, combined with the characteristics in Jovian and Saturnian outer magnetospheres, are thought to suppress the dayside magnetopause reconnection (e.g., Huddleston et al. 1997; Swisdak et al. 2003; Desroche et al. 2012; Masters et al. 2012)). Nonetheless, evident signatures for magnetic reconnection at dawn magnetopause are observed by the Juno spacecraft at Jupiter (Ebert et al. 2017). At Saturn, the Cassini spacecraft recorded flux ropes generated by reconnection near the subsolar point of the magnetopause (Lai et al. 2012; Jasinski et al. 2016). These records of the magnetopause reconnection process support the picture that the Dungey cycle contributes to the mass and energy transportation in the giant planets.

The theoretical calculation and simulation results show that the energy from the solar wind that invades the magnetosphere of the two giant planets is small. At Jupiter, the ratio between the magnetic flux opened by the solar wind and the total dipole magnetic flux is no larger than 0.1 (Zhang et al. 2021). The small occurrence of the magnetopause reconnection and the fast rotation of the magnetospheres let the magnetic field lines linked to the polar regions be closed and helically threaded to the dawnside outer magnetosphere (Zhang et al. 2021). This configuration makes the magnetosphere different from the terrestrial magnetosphere. Another difference is that the Jovian and Saturnian magnetospheres are ‘inflated’, which means the size of the magnetosphere is much larger than that predicted by calculating the balance between the dynamic pressure of solar wind and the magnetic pressure of magnetosphere. This is due to the internal plasma sources, which primarily control the dynamics of the two giant planetary magnetospheres (Khurana et al. 2004).

2.1 Magnetodisk current sheet

Both Jupiter and Saturn systems consist of tens of natural satellites. The satellite near the planet, Io for Jupiter and Enceladus for Saturn, suffers a large tidal force that heats the satellite’s interior to form volcanos. Sulfur dioxide and water ice are spurted from Io and Enceladus, respectively. The molecules are broken down into atoms and then are ionized to form an ion torus in the magnetosphere. The ions are released into the magnetosphere at roughly ~1000 and ~100 kg/s for Jupiter and Saturn, respectively (Delamere and Bagenal 2013). The rotating magnetospheric field lines pick up these ions. Jupiter rotates at a period of ~9.9 h, which is ~10.5 h for Saturn (Kivelson 2015). The corotational electric field is significant due to the fast rotations of the two planets and surpasses the convectional electric field driven by the solar wind even at the outer magnetosphere (Mauk et al. 2009). Considering the large magnetosphere size (tens of planet radius, while Jupiter's radius (R_J) is 71,492 km and Saturn's radius (R_S) is 60,268 km), the ions can obtain a large rotation velocity (hundreds of km/s) and finally reach the Alfven speed (Woch et al. 2004; Thomsen et al. 2014). The sulfur and oxygen ions have a large mass number, are heavier than protons, and experience a strong centrifugal force during the rotation. Driven by the pressure gradient and the centrifugal force, the heavy ions are transported outward from the ion torus (at ~6 R_J for Jupiter and ~4 R_S for Saturn) inside the inner magnetosphere (Mauk et al. 1985; Arridge et al. 2007).

Additionally, the centrifugal force has a similar effect as the mirror force during the bounce motion of the heavy ions along the magnetic field lines. The heavy ions have a mirror point at a lower magnetic latitude than protons and are confined near the equatorial plane (Vogt et al. 2014b). The magnetic field lines near the equator are stretched radially by the outward-moving heavy ions. An electric current flowing in the azimuthal direction is formed (Cowley and Bunce 2001; Arridge et al. 2008). The stretched magnetic field lines and the current surrounding the planet form disc shapes, termed magnetodisk and ring current, respectively. A radial current carried by outward-moving heavy ions is closed by field-aligned currents, generating an azimuthal magnetic component (Cowley and Bunce 2001). As a result, the magnetic field lines in the magnetodisk show a spiral configuration.

In the inner magnetosphere, the plasma co-rotates with the planet. The corotation will break down at a distance to Jupiter of roughly 20–30 R_J (Hill 1979, 2001; Chané et al. 2013). The azimuthal velocity has a dawn-dusk asymmetry. The speed is more significant at the dawn sector to reach 800 km/s (Woch et al. 2004). The high-speed plasma could be accelerated and transported from the night side. The radial transportation is stopped before encountering the magnetopause. The magnetodisk can help the magnetosphere withstand the solar wind dynamic pressure to inflate the magnetosphere. In the dayside magnetosphere, the radial length and thickness of the magnetodisk current can be affected by solar wind compression (Kivelson and Southwood 2005). At nightside, the magnetodisk can evolve to a longer length and become thinner.

2.2 Vasyliunas cycle

The magnetodisk plasma could move more freely at nightside than dayside and then be detached from the inner magnetodisk by the magnetic reconnection process. Figure 2 illustrates the rotationally driven magnetic reconnection process in the giant magnetospheres. The magnetic field lines in the magnetodisk are all closed field lines linking to the northern and southern ionosphere. The reconnected field lines at the right side of the X-line in Fig. 2c are naturally closed and form a loop shape,

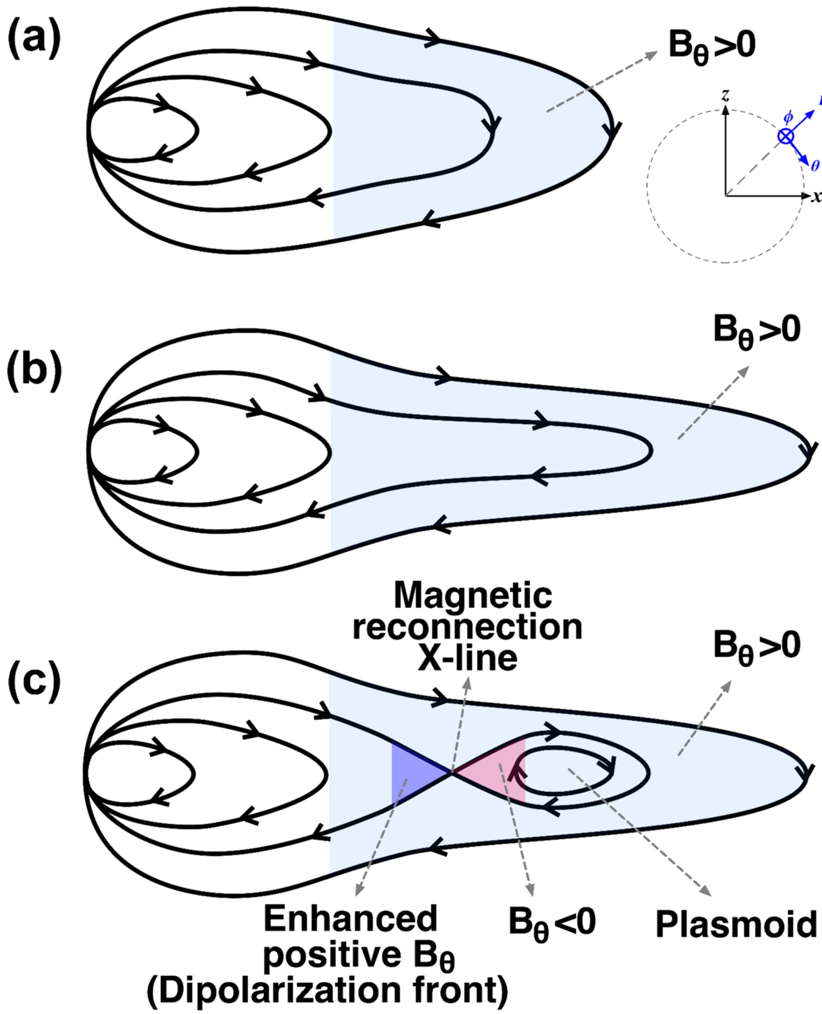

Fig. 2 The magnetic reconnection process in the magnetodisk of rapidly rotating magnetospheres. (Adapted from Vasyliunas (1983))

i.e., the 'O-line' or plasmoid, whose magnetic structure is generally a flux rope consisting of helical magnetic field lines in the three-dimensional space. Initially, the reconnection X-line and the plasmoid are wrapped by closed field lines. The plasmoid can only freely escape from the magnetotail when the last closed magnetic field line is reconnected, or it may encounter the magnetopause. This rotationally driven mass circulation is known as the 'Vasyliunas cycle' (Vasyliunas 1983). It is generally accepted that the magnetodisk reconnection site starts in the pre-evening sector and ends in the dawn sector before encountering magnetopause.

The observational data have confirmed this rotationally driven magnetic reconnection process. Because of the lack of plasma moments data with good time resolution, the way to identify a magnetic reconnection site is to find rapid change in the magnetic field. A spherical RTP (Radius-Theta-Phi) coordinates system is commonly utilized because the magnetic B_θ component is generally positive at the low latitude of the magnetosphere. A negative B_θ signature indicates a severe variation in the magnetodisk. Despite the waves can disturb the magnetic field and lead to limited negative B_θ in the current sheet, the magnetic reconnection process can change the magnetic topology and generate an area with distinct B_θ deviation from zero (Fig. 2c). Traversing a magnetic reconnection region with different trajectories, a spacecraft will record different signals: a significant negative B_θ, a rapidly enhanced positive B_θ, or a B_θ bipolar signature. After surveying Galileo spacecraft data in the Jovian magnetosphere, Vogt et al. (2010) found a potential X-line (Fig. 3b) that separates negative B_θ and positive B_θ events and has a location and orientation that accords with the X-line in the Vasyliunas cycle (Fig. 3a). Recently, the Juno measurement showed that the distribution of the reconnection sites at the dawn sector is not well-regulated (Fig. 3c) (Vogt et al. 2020). Plasma sheet boundary layers, which can be formed by spatially localized magnetic reconnection, are more pronounced in the dawn flank of the Jovian magnetodisk, indicating a dawn-dusk asymmetry in the distribution of the magnetodisk reconnection sites (Zhang et al. 2020). The X-line at Saturn's magnetotail surveyed by Smith et al. (2016) occurs at variable locations, and the average occurrence rate is ~5 events per day (i.e., 24 h). The reconnection events appear in clusters at both Jupiter and Saturn (Smith et al. 2016; Vogt et al. 2020). Field-aligned particles accelerated by magnetic reconnection can form localized field-aligned currents (Hunt et al. 2020, 2022) and increase electron thermal anisotropy in the magnetodisk current sheet (Artemyev et al. 2023).

Most of the investigated reconnection events are plasmoid events. When crossing a plasmoid, the spacecraft can record a significant B_θ bipolar signature. The plasmoid tends to move away from the planet, and the recorded B_θ turns from an enhanced positive value to a distinct negative value. The plasmoids are thought important for the ion loss process at Jupiter (e.g., Russell et al. 1998; Kronberg et al. 2005; Vogt et al. 2014a) and Saturn (e.g., Jackman et al. 2007; Hill et al. 2008). At Jupiter, the plasmoids are frequently observed inside 120 R_J and have a peak occurrence rate at ~100 R_J and post-midnight local time sector. The average duration to traverse a plasmoid by a spacecraft is ~7 min, and the plasmoid radial size is ~3 R_J (Vogt et al. 2014a). At Saturn, the average traversing duration of the plasmoids is ~18 min, and the average radial size is ~4 R_S (Jackman et al. 2014b). The plasmoids can lead to mass loss from the magnetosphere by encountering the magnetopause or escape along the magnetotail. The New Horizons spacecraft detected discrete plasma populations in the magnetotail at distances more than 2000 R_J, which is suggested to be the runway plasmoid generated by the Vasyliunas cycle (McComas et al. 2007). The rates of the mass loss by the plasmoids are up to more than 100 kg/s and several tens of kg/s for Jupiter and Saturn, respectively (e.g., Bagenal and Delamere 2011; Thomsen 2013; Jackman et al. 2014a; Vogt et al. 2014a).

In addition to the rotation-driven process, the solar wind-driven process has a significant role in Saturn's nightside magnetosphere (e.g., Badman and Cowley 2007; Jackman et al. 2011). Simulation results show that when the interplanetary magnetic field is northward, both the Vasyliunas and Dungey cycles take place, and the

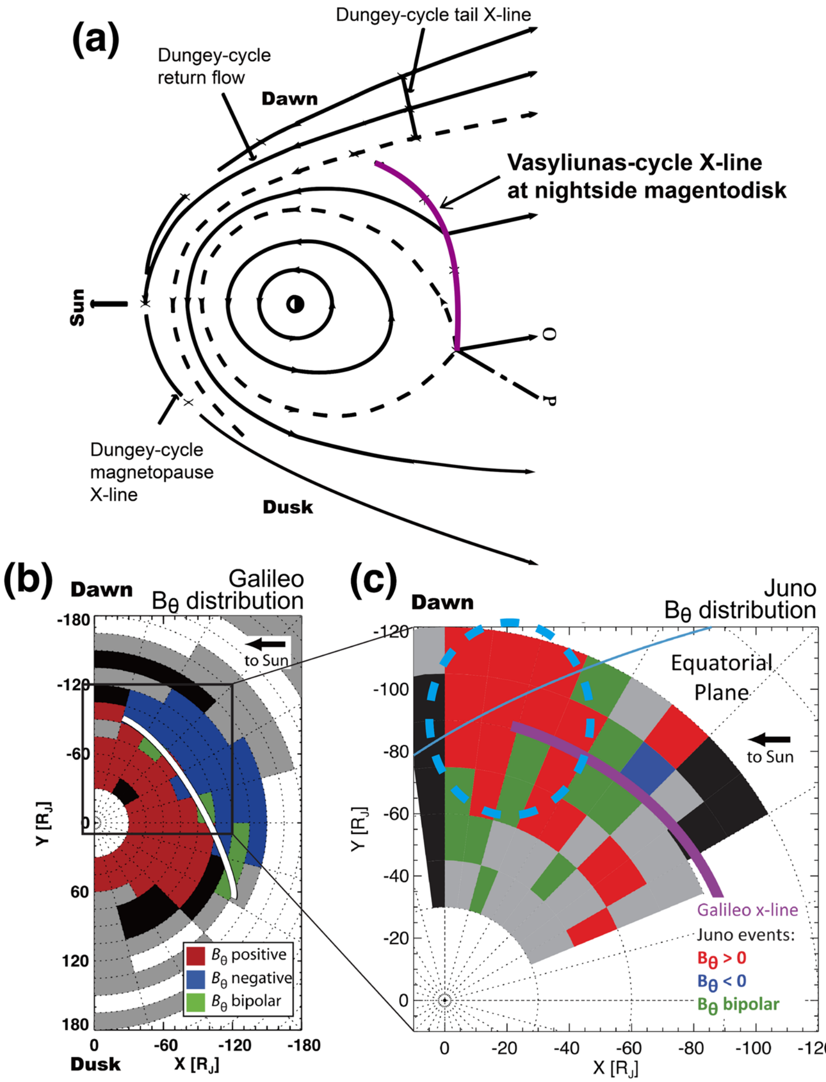

Fig. 3 The magnetic reconnection X-line in the Vasyliunas cycle. **a** Sketch of the reconnection X-line in the Jovian magnetosphere (adopted from Cowley et al. (2003)). **b**, **c** Statistical results of the Vasyliunas-cycle X-line (*thick white* and *purple lines*) using data from Galileo and Juno (Adapted from Vogt et al. (2020)) (colour figure online)

reconnection process involves open flux tubes in the lobe region, leading to a more substantial impact on the magnetospheric dynamics than when only the Vasyliunas cycle occurs (Jia et al. 2012). The open flux reconnection creates a post-plasmoid plasma sheet between the reconnection X-line and the plasmoid, resulting in an asymmetric bipolar signal in the observed B_θ component (Richardson et al. 1987; Jackman et al. 2011; Smith et al. 2016). The post-plasmoid plasma sheet exists at

Jupiter as well. It shows that the flux in the lobe closed by the open flux reconnection is only roughly 1% of the open flux in Jovian polar cap and tail lobes (Vogt et al. 2014a).

2.3 Unresolved problems

The plasma produced in the neutral tori radially moves outward under the centrifugal force with a relatively slow transport rate. The tailward plasmoid generated during the Vasyliunas cycle is treated as a potential way to eject plasma to escape quickly. However, the mass loss through ejecting the plasmoid is 6–150 kg/s at Jupiter (Bagenal 2007; Bagenal and Delamere 2011) and 0.8–22 kg/s at Saturn (Smith et al. 2016), which are far smaller than the average mass load rates of ~1000 and 100 kg/s for Jupiter and Saturn, respectively. A quasi-steady loss rate is suggested to be feasible if the plasma moves outward at a speed of 200 km/s through a region that roughly encircles Jupiter (Bagenal 2007). The mechanism for the quasi-steady loss rate has not been resolved. Small-scale plasmoid and drizzle-like loss progress are put forward for discussion (Kivelson and Southwood 2005; Bagenal 2007; Bagenal and Delamere 2011; Thomsen 2013). Meanwhile, there are some related unresolved questions like how the plasmoids evolve and where the plasmas go if the lobe reconnection is absent.

The reconnection X-line of the Vasyliunas cycle only evolves in the nightside of the magnetosphere. The reconnection process can be terminated when the reconnection site meets the dawn magnetopause. However, the events at around 40 R_J observed by Juno [e.g., (Vogt et al. 2020)] are far from the magnetopause and need to be ended by other mechanisms, otherwise, they could move into dayside areas.

In the dayside magnetosphere, energetic particle bursts are frequently observed. At Saturn, the energetic electrons with energies larger than 100 keV present a quasi-periodic 1-h pulsation feature at all the local time sectors (e.g., Mitchell et al. 2009b; Palmaerts et al. 2016b). Mechanisms such as the Kelvin–Helmholtz instabilities along the dawn flank of the magnetosphere (Masters et al. 2010), quasi-periodic electron injections (Roussos et al. 2016), and field line resonances (e.g., Cramm et al. 1998; Keiling 2009) are proposed to explain the quasi-periodic 1-h pulsation phenomena, but cannot be entirely consistent with the characteristics of the weak local time dependence and the nearly nondispersive feature. Palmaerts et al. (2016b) suggest that pulsations have a source at high latitudes because the radio bursts of the auroral hiss frequently coincide with the electron pulsations. There is still a debate about the generation mechanism.

3 A fresh picture for magnetodisk reconnection

The Vasyliunas cycle only focuses on the nightside magnetodisk, and its magnetic reconnection process has no impact on the phenomenon in the dayside magnetosphere. The dayside magnetodisk needs to be carefully investigated and surveyed to complete the global picture of the magnetospheric dynamics. The observation data is much limited in the Jovian dayside magnetosphere, but the Cassini spacecraft has passed most regions of the magnetodisk at Saturn. Unlike Jupiter's magnetodisk, Saturn's magnetodisk is highly sensitive to solar wind conditions and could be absent at dayside under strong solar wind compression (Arridge et al. 2008). When the solar wind dynamic pressure is low, the distance between Saturn and the subsolar point of the magnetopause can be large (>20 R_S), and the magnetodisk can be formed in the dayside magnetosphere (Arridge et al. 2008). The solar wind dynamic pressure has a significant occurrence rate (~57% of the data surveyed by Echer (2019) with values <0.03 nPa. Utilizing the magnetopause model of Arridge et al. (2006), the stand-off distance of the subsolar point of the magnetopause is ~22.5 R_S when the solar wind dynamic pressure is 0.03 nPa, implying the magnetodisk is essential in the dayside magnetosphere of Saturn. When the centrifugal force dominates the solar wind compression, dynamic processes such as magnetic reconnection should be developed at the magnetodisk current sheet.

3.1 Dayside magnetodisk reconnection

The magnetic field in the magnetodisk is bent back at most of the local time and bent forward at the dusk sector. When the magnetic reconnection takes place, the current sheet is thin, and the bend forward/back effect is enhanced and even reversed. Delamere et al. (2015b) use the conditions that the magnitude of the azimuth magnetic component B_φ is larger than half of the total magnetic strength and $B_\theta < 0$ to evaluate the likely reconnection sites. Their analysis shows that the potential reconnection sites have distinct occurrences in the noon and dusk sectors, larger than those in the midnight sector. They suggest the reconnection process does not take place at a global-scale (many R_S) X-line but is patchy and carried out on significant small-scales (<1 R_S), and termed them "reconnection drizzle". This statistical research implies that the reconnection model of the Vasyliunas cycle with a large-scale X-line on the night side is oversimplified. Delamere et al. (2015b) suggest that, even though large-scale plasmoids may be formed in the tail, the small-scale "reconnection drizzle" dominates the plasma loss process and leads plasma to exit on the dusk flank.

At Saturn's nightside magnetosphere, Yao et al. (2017b) report a corotating reconnection site that its B_θ bipolar signal repeats twice in a time separation of approximately one Saturn's rotation period (about 11 h). A magnetic reconnection with a period over 19 h has also been observed in Saturn's magnetotail (Arridge et al. 2016), suggesting that the reconnection process at Saturn can be sustained for a long duration. The corotating magnetic reconnection would naturally suggest the reconnection site occurs in the magnetodisk and passes the dayside magnetosphere at least once. These studies infer that magnetic reconnection can play a significant role in the dayside magnetosphere. It's desired to ascertain the existence of the reconnection sites in the noon and dusk sectors.

On September 30, 2008, Cassini encountered a significant negative B_θ (~−2 nT) at a local time (LT, the definition is similar to that at Earth, i.e., LT 0, LT 6, LT 12, and LT 18 represent midnight, dawn, noon, and dusk, respectively) of LT 11 and a distance to Saturn of ~17.5 R_S (Guo et al. 2018b). The spacecraft crossed the magnetopause 2 days ago and is inside the magnetodisk with a clear bend-back feature. After transferring to a local X-line coordinates system to remove the bend-back effect, the Hall effect of the ion diffusion region shows up in the *By* component of the magnetic field (Fig. 4b). The associated Hall current is presented by the electron behaviors around the separatrix layer (Figs. 4j–k): electrons with energies similar to the background electrons move towards the X-line, and the energized electrons run away from the X-line along the magnetic field lines. Despite the lack of plasma velocity data, the consistency in the signs of the Hall magnetic field, the north–south magnetic component, and the direction of the Hall electrons ensures that the spacecraft records a reconnection diffusion region in the dayside magnetodisk.

The estimated dimensionless reconnection rate is roughly ~0.33 for this reconnection process (Guo et al. 2018b), suggesting a significant reconnection electric field that accelerates particles inside the diffusion region. The ions and electrons are accelerated to over 100 keV in the reconnection site. The oxygen ions reach an energy higher than 300 keV (Fig. 4f). Interestingly, the relativistic electrons with energies ranging from hundreds to thousands of keV display quasi-periodic 1-h pulsation signals (Fig. 4g). The pulsations show no energy dispersion feature, indicating that the electrons are not far from their acceleration region. The flux of these energetic electrons is enhanced before Cassini encounters the reconnection site and lasts for more than 14 h. Besides, Guo et al. (2018b) also estimate that the energy

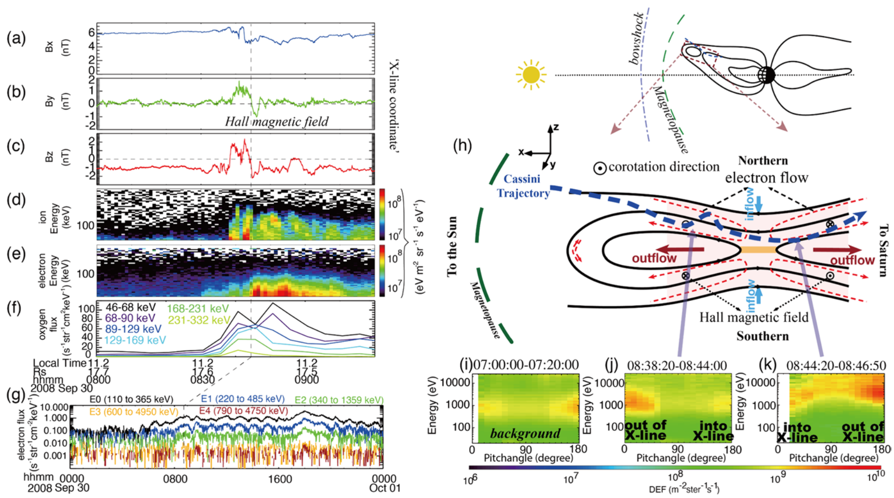

Fig. 4 Observational evidence of the dayside magnetodisk reconnection. **a**–**f** Magnetic fields, accelerated ions, electrons, and oxygen ions observed in the reconnection diffusion region. The X-line coordinate removed the bend-back effect. The X direction is along the background magnetic field, and the Y direction is perpendicular to the plane of the swept-back magnetic field (detailed in (Arridge et al. 2016)). **g** Energetic electrons with quasi-periodic 1–h Pulsation features. **h** Sketch of the relative trajectory of the spacecraft in the reconnection diffusion region. **i** Electron pitch-angle distribution in the non-reconnection region. **j**–**k** The electrons carrying the Hall current. At the separatrix layer, the background electrons move into the X-line, and the energized electrons move out of the X-line. (Adapted from Guo et al. (2018b))

released by the reconnection site can generate aurora with an intensity of up to 26 kR, which is an intermediate aurora emission at Saturn.

The observational evidence of the dayside magnetodisk reconnection and its impacts on the dayside magnetospheric dynamics require an update of the circulation model. Figure 5 illustrates that the rotationally driven dayside magnetodisk reconnection is as crucial as the nightside and magnetopause reconnection. Multiple reconnection sites can be recorded in succession during a short interval, and a secondary magnetic island is also found at the dayside magnetodisk, revealing that the reconnection process is not steady and is “drizzle-like” (Guo et al. 2018a). Furthermore, the by-products of the reconnection, i.e., the plasmoids and dipolarization fronts, are observed at the dayside magnetodisk (Xu et al. 2021a, b). The electron density inside the plasmoid peaks at LT ~ 11 at dayside and decreases from dusk-side to dawn-side in the nightside magnetosphere (Xu et al. 2021b). The dipolarization fronts are also widely distributed in Saturn’s magnetosphere and are more frequently detected in the dayside magnetosphere than the nightside (Xu et al. 2021a). These results expose that the dayside magnetodisk reconnection is a common phenomenon in Saturn’s magnetosphere.

3.2 Rotational and discrete reconnection sites

One of the most non-negligible characteristics of the giant planets is the fast rotation speed of the magnetosphere. The magnetic field lines in the magnetodisk are connected to the polar ionosphere. Moreover, as informed by the simulation results, most magnetic field lines outside the magnetodisk are close field lines at Jupiter (Zhang et al. 2021). It will naturally get the picture that the plasma and magnetic structures cannot easily escape the magnetosphere, and they need to rotate together. A relevant question is how far the reconnection sites and plasmoids can rotate in the magnetosphere.

Yao et al. (2017b) find that quasi-steady reconnection sites can corotate with the magnetosphere at least one turn. Unlike the usual radially retreat picture, the

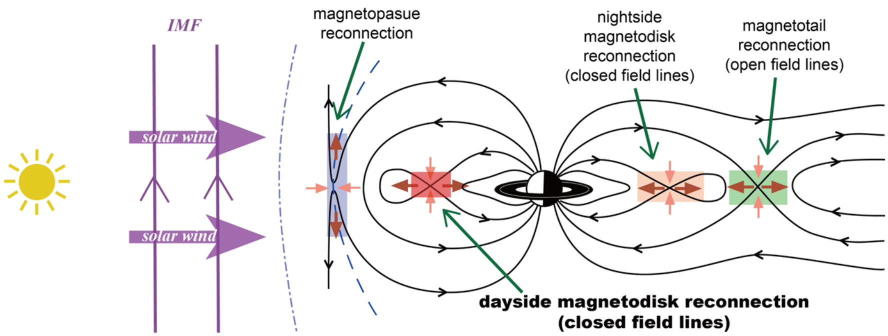

Fig. 5 Suitable places for magnetic reconnection sites in the magnetospheres of Saturn and Jupiter. At Saturn, the nightside magnetodisk reconnection and the magnetotail reconnection could occur at the same distance to the planets and generate a post-plasmoid plasma sheet. Unlike the Vasyliunas cycle, the magnetic reconnection can occur at the dayside magnetodisk

azimuthal motion of the reconnection X-line lets the spacecraft sweep it to record B_θ bipolar signal (Fig. 6). The corotating reconnection picture can only be driven by internal processes in magnetodisk since solar wind-driven reconnection disconnects Saturn's magnetosphere to remove flux from the magnetotail radially. After magnetodisk reconnection, the magnetic field line shrinks, which causes electrons to experience Fermi acceleration (Yao et al. 2017a, b). A current re-distribution dipolarization (a magnetic topology change caused by large-scale magnetotail current redistribution during the loading–unloading process) is displayed in the corotating picture. The current re-distribution dipolarization is not directly formed by magnetic reconnection. Still, they are strongly coupled in the loading–unloading process, during which the magnetic reconnection and the development of plasma instabilities release the magnetic energy. Both the current re-distribution dipolarization and the reconnection outflow generated dipolarization font show B_θ increase in the observation. However, different from the dipolarization front with enhanced strength of the magnetic component B_r (or B_x), the current re-distribution dipolarization shows a decrease in the B_r component (Yao et al. 2017c). Both the two dipolarizations recurring with a duration similar to the planetary rotation period have been reported in the evening and morning sectors of Saturn's magnetosphere (Yao et al. 2018; Xu et al. 2023) and at the dawn sector of Jupiter's magnetosphere (Yao et al. 2020).

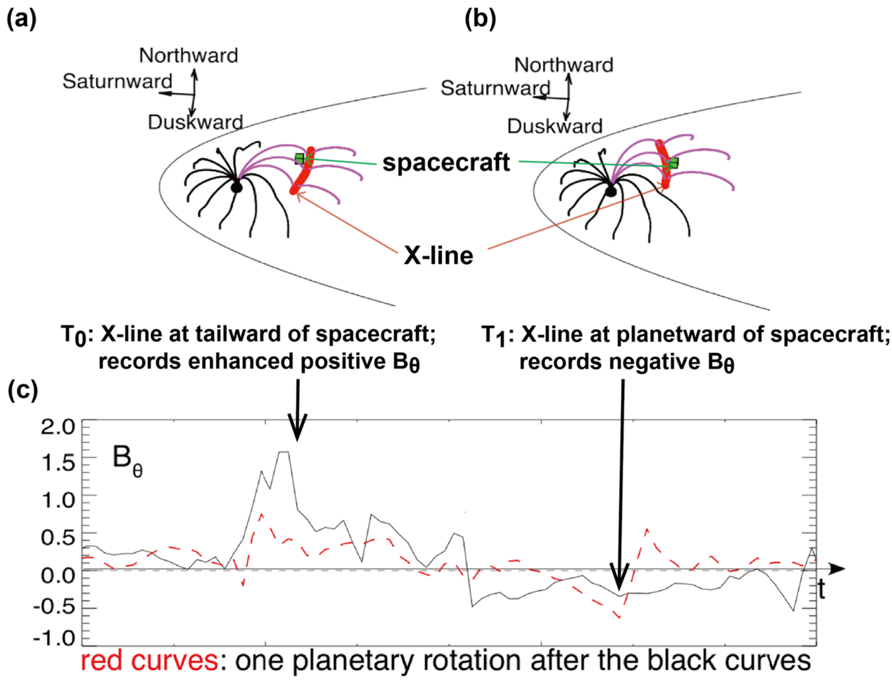

Fig. 6 Reconnection X-line rotates around the planet and sweeps the spacecraft. The X-line corotates with the planet, and the spacecraft records the B_θ bipolar signature twice. (Adapted from Yao et al. (2017b))

Rather than just one magnetic reconnection site being detected during a rotation period, magnetic reconnection sites are often shown in groups in Saturn's magnetosphere (Guo et al. 2018a, 2019). Figure 7 shows a Cassini observation within a duration of ~5 Saturn rotation periods (from 2008 September 29 to October 1). The red arrow in Fig. 7a marks the confirmed active ion diffusion region (Guo et al. 2018a) featured by the significant negative B_θ. The black arrows mark the negative B_θ intervals before and after the ion diffusion region event. These negative B_θ intervals

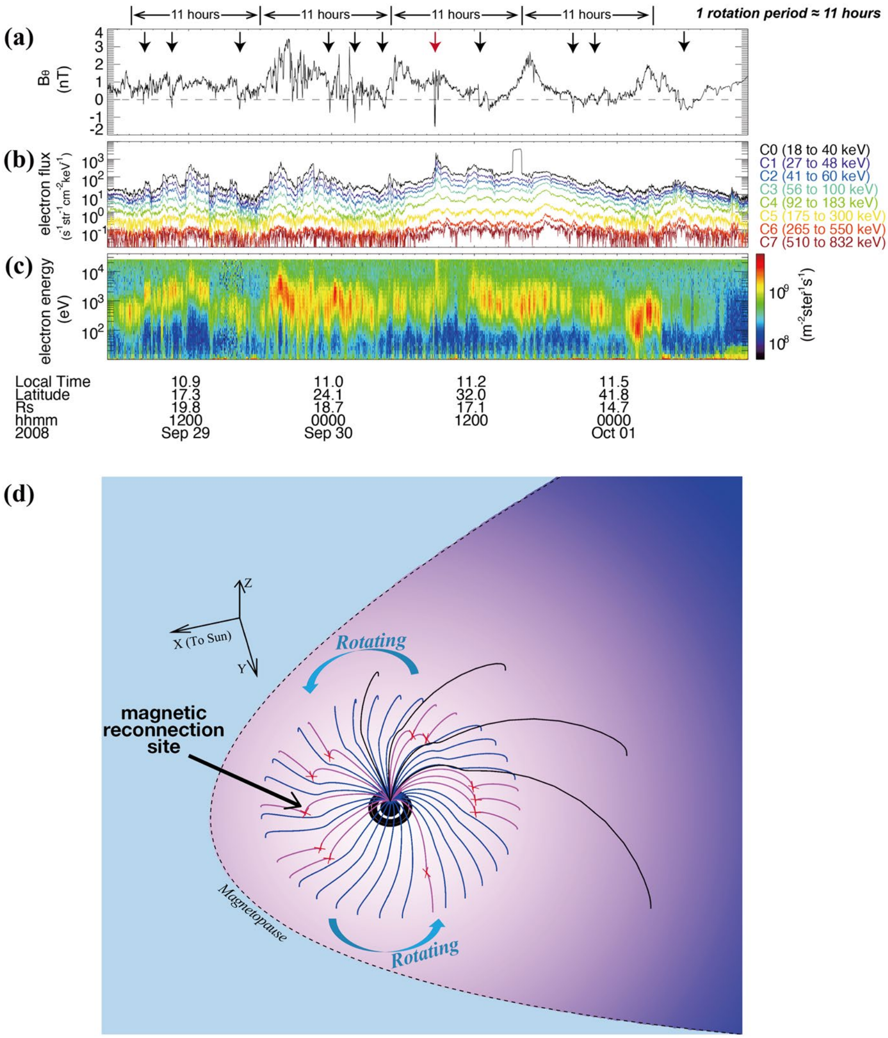

Fig. 7 The long-standing small-scale magnetodisk reconnection process. **a**–**c** B_θ magnetic component, energetic electron differential flux, and energy spectrogram of hot electron for the long-standing small-scale magnetodisk reconnection event observed by Cassini. **d** Sketch of long-standing small-scale magnetodisk reconnection model. Red curves present reconnected magnetic field lines, while the cross signs (×) indicate the reconnection site. (Adapted from Guo et al. (2019))

are accompanied by enhanced energetic electrons, suggesting that the spacecraft encountered a series of reconnection sites. The spacecraft moves with a speed much smaller than the planet's rotation speed and can be treated as roughly staying in one place in a rotation period. The energetic electrons (Fig. 7b) and thermal electrons (Fig. 7c) show different characteristics in different negative B_θ intervals, implying that the recurrence of reconnection sites is not due to the vertical oscillation of the magnetodisk to let the spacecraft cross a reconnection site several times (Guo et al. 2019). The observed reconnection sites are different sites.

The event displays two significant characteristics: (1) multiple magnetic reconnection sites exist within one rotation period; (2) the phenomenon of the sporadically distributed magnetic reconnection sites can last for more than one rotation period. Many similar events have been observed at most local times [see Table 1 in (Guo et al. 2019)]. The time separation between two reconnection sites can range from nearly 1 h to longer than one rotating period. While the magnetosphere is rapidly rotating, the reconnection site should also rotate at a considerable speed (even if it might move slower than the magnetosphere) and not stay at a fixed local time sector. The global picture should be illustrated by Fig. 7d: small-scale reconnection sites (as demonstrated by the red magnetic field lines, which are different from a single X-line extending several local times as shown in Fig. 3a) are azimuthally and discretely distributed at all local times (and at different distances to the planet), and lots of them can last for several tens of hours; these small-scale reconnection sites are rotating with the magnetosphere; observing at any position for a long duration, a spacecraft will record each reconnection sites in sequence. During rotation, the reconnection sites and their by-products evolve (reconnection can be unsteady; plasmoid can be expanded or contracted) or cease, and new reconnection sites can be triggered in the magnetodisk, leading to a complex configuration of the magnetosphere.

Previous studies have suggested that the "drizzle" processes could dominate the plasma loss. The model of the long-standing small-scale magnetodisk reconnection makes the process much more explicit: the magnetic and particle fluxes can be separated from the inner magnetosphere at all local times incessantly during the rotation. The detached plasma would first accumulate in closed field lines, rotate with the planet, and finally escape at some disturbed regions. The long-term rotating reconnection sites can strongly impact magnetospheric dynamics and even aurora emissions.

3.3 Relation to the magnetosphere-ionosphere coupling

In addition to removing mass from the magnetosphere, the reconnection process can trigger aurorae at the ionosphere by energizing particles and generating FACs. The Cassini spacecraft has observed high-energy protons in the dawn FACs, which are likely injected from tail reconnection (Hunt et al. 2020, 2022). The energetic ions can collide with the background cold atoms, producing energetic neutral atoms (ENA) in the magnetosphere. The electron beams in FACs with energies of hundreds of eV to several keV can produce a broadband whistler-mode wave, i.e., the auroral hiss (Gurnett 1966). The aurora hiss has a close relation with quasi-periodic pulsations (Mitchell et al. 2009b; Palmaerts et al. 2016b) of energetic electrons and the rotating ENA (Mitchell et al. 2016; Palmaerts et al. 2016a) at Saturn. The rotating ENA is also collocated in local time with the aurora brighten region (Mitchell et al. 2009a). The magnetopause/magnetotail reconnection and Kelvin–Helmholtz instabilities are frequently mentioned as the possible driving mechanisms (e.g., Mitchell et al. 2009a, 2016; Masters et al. 2010; Radioti et al. 2013; Palmaerts et al. 2016a).

The auroral and the ENA images often show discrete features. Radioti et al. (2015) reported a sub-corotating auroral event that consists of detached features and auroral spirals at Saturn. One of the auroral patches evolves into a spiral feature during the rotation. The auroral emissions show different rotational velocities at different latitudes, from 85% of the rigid corotation speed at 70° and only 68% at 74° (Radioti et al. 2015). This suggests an azimuthal velocity gradient in the equator plane, and the auroral spirals could be related to it. Another candidate mechanism discussed by Radioti et al. (2015) is the field line deformation from the magnetosphere to the ionosphere.

The auroral in Radioti's sub-corotating event covers at least half of the local times (from the pre-dawn sector to the dusk sector), as shown in Figs. 8a–c. The ENA also covers over half of the local times (see Figure B2 in (Guo et al. 2021a)). However, at the time when the aurora is recorded, only part of the ENA is recorded due to the limited field of view of the Cassini-MIMI instrument (Fig. 8d). The projection in Fig. 8e shows that the local times of the observed ENA blocks are consistent with the aurorae. Though the spatial resolution is low, it is still able to recognize substructures in the ENA image that correspond to different auroral patches. When crossing the magnetic field lines connecting the auroral patches, the spacecraft records several pairs of downward and upward FACs (Guo et al. 2021a). The aurorae brighten at the downward FACs carried by electrons going into the ionosphere, while the upward FACs contain low-energy electrons (around 100 eV, as highlighted by the red dashed rectangle in Fig. 8j, and their pitch-angle can be found in Figure B3 in Guo et al. (2021a)) coming from the ionosphere. Energetic electrons are enhanced in the FACs, agreeing with the ENAs in the magnetodisk.

Both the ENAs and aurorae could exist and rotate for a time duration longer than the rotation period of Saturn. The FACs, auroral intensity, and energetic electron fluxes are co-enhanced and present separated features (Figs. 8g–i), implying that the magnetosphere contains different and separated acceleration regions and current systems. A comprehensive picture is illustrated in Fig. 9. Multiple isolated active regions in the equatorial plane accelerate ions and electrons, form multiple FAC pairs, and generate multiple auroral patches in the ionosphere. Meanwhile, all these structures rotate around the planet.

Similar phenomena exist in Earth's magnetosphere, known as the wedgelet current system, which only occurs at nightside and has a lifetime on the order of several minutes (e.g., Liang et al. 2008; Rae et al. 2009; Liu et al. 2015). The large spatial scale and long duration of the rotating multiple FACs on Saturn suggest that the mechanism differs from that at Earth. The rotating multiple FAC system can result from the rotating long-standing small-scale magnetodisk reconnection (Guo

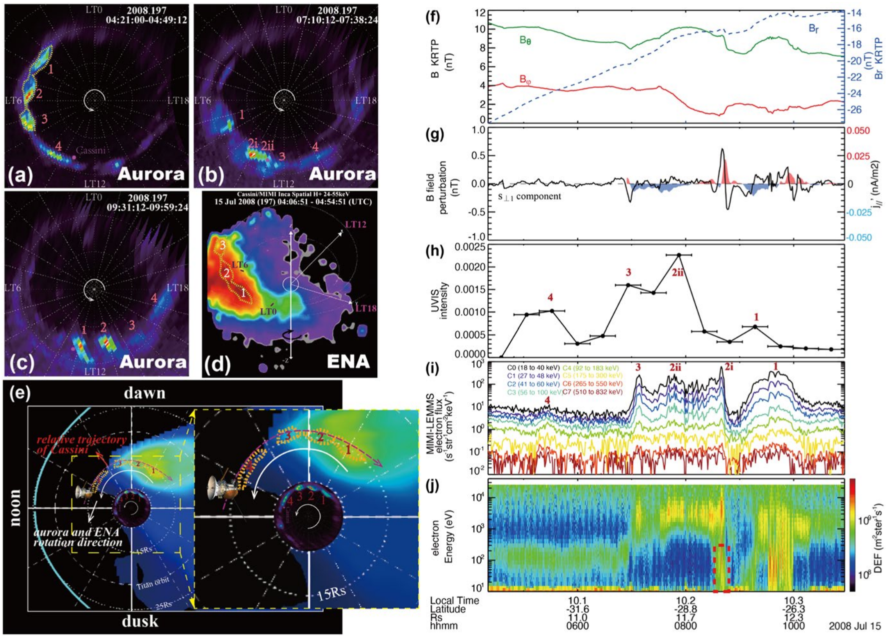

Fig. 8 Simultaneously observed rotating auroral patches, ENAs, FACs, and accelerated electrons. **a**–**c** Patchy aurorae observed by Cassini-UVIS instrument. **d** 24–55 keV hydrogen ENA image. **e** Mapping of the ENA image and auroral on the equatorial plane. The region corresponding to the auroral patch 4 is out of the view of the instrument, and the missing data of ENA is filled by *black*. **f** Magnetic field components. **g** The perpendicular perturbation of the magnetic field (*black curve*) and the field-aligned current density (area highlighted in *blue*/*red*). *Blue* indicates negative values (out of the ionosphere), and red indicates positive values (going into the ionosphere). **h** Variation of the auroral intensity at the magnetic footpoint of Cassini. **i** Energetic electron flux. **j** Electron energy spectrum. (Adapted from Guo et al. (2021a)) (colour figure online)

et al. 2019). These observations reveal that the dynamic processes and active regions are discretely distributed in the magnetodisk. The rotation of these isolated active regions could produce quasi-periodical phenomena in the magnetosphere.

3.4 Relation between the reconnection sites and aurorae

The magnetic reconnection process is closely related to the reconfiguration of the magnetosphere and the development of substorm/storm at Earth, resulting in auroral emissions in the ionosphere. The aurorae experience a more complex process at Jupiter and Saturn than Earth. Grodent (2015) summarized the morphology of the aurorae at two giant planets and divided the aurorae into several distinct features relating to different mechanisms. The dawn arcs and spots at Jupiter are proposed to be produced by the magnetotail reconnection (Grodent et al. 2003; Radioti et al. 2008, 2010; Ge et al. 2010). The auroral spot at Jupiter's dusk side is also reported to be triggered by the nightside reconnection (Radioti et al. 2011b). The tail reconnection and related plasma flows and dipolarization fronts at Saturn are

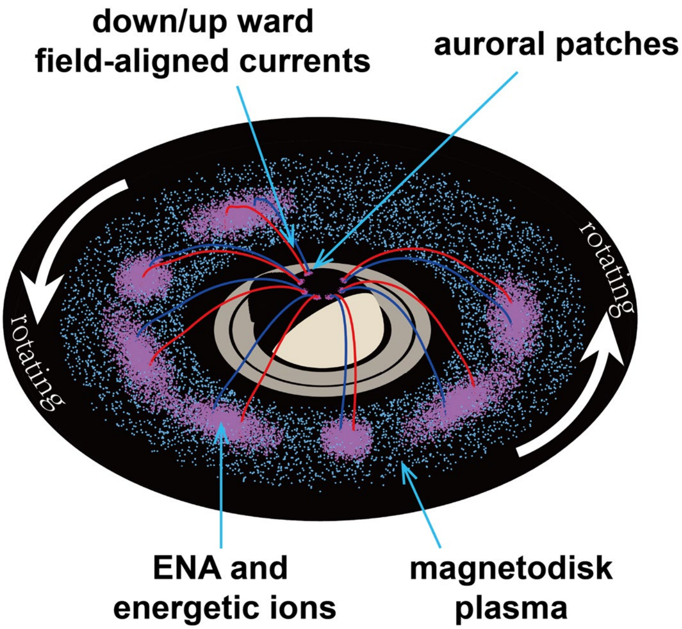

Fig. 9 A rotating multiple field-aligned current system in the magnetosphere of giant planets. ENA and energetic ions accelerated by multiple isolated active regions are represented by magenta areas in the equatorial plane. The magenta spots on the north polar region represent auroral patches in the ionosphere. The *blue* and *red* curves represent the FAC pairs. (Adapted from Guo et al. (2021a)) (colour figure online)

also responsible for auroral signatures, like auroral arcs, spots, and midnight to dawn auroral activities (e.g., Mitchell et al. 2009a; Jackman et al. 2013; Nichols et al. 2014; Radioti et al. 2014). The auroral spots often recur several times, which may be associated with the recurrent nature of magnetic reconnection (Kronberg et al. 2007; Radioti et al. 2008; Yao et al. 2019). Furthermore, the dayside magnetopause reconnection can place signatures in the auroral emission at Jupiter and Saturn as well, such as bifurcations and arcs in the dayside auroral emission at Saturn (Radioti et al. 2011a; Badman et al. 2012) and flares recurring at a period of 2–3 min at local times between LT 10 and LT 18 at Jupiter (Bonfond et al. 2011).

Most of the auroral signatures rotate (even corotate) with the planets. This is inconsistent with the picture that the reconnection regions move radially but could accord with the rotating small-scale reconnection sites. Guo et al. (2021b) provide direct evidence that a series of reconnection sites observed by the Juno spacecraft corresponds to the main auroral emission and can cause a double-arc auroral feature at the dawn sector of Jupiter's ionosphere. Several reconnection fronts are identified by enhanced B_θ, Hall magnetic field, and energized electrons (Figs. 10a–c). The respective perturbations of the B_θ component and multiple enhancements of electron energy fluxes indicate that the rotating small-scale reconnection process takes place (Guo et al. 2019). When recording the multiple reconnection signatures, the spacecraft's position, ~57 R_J to the Jupiter center, is mapped to the main auroral

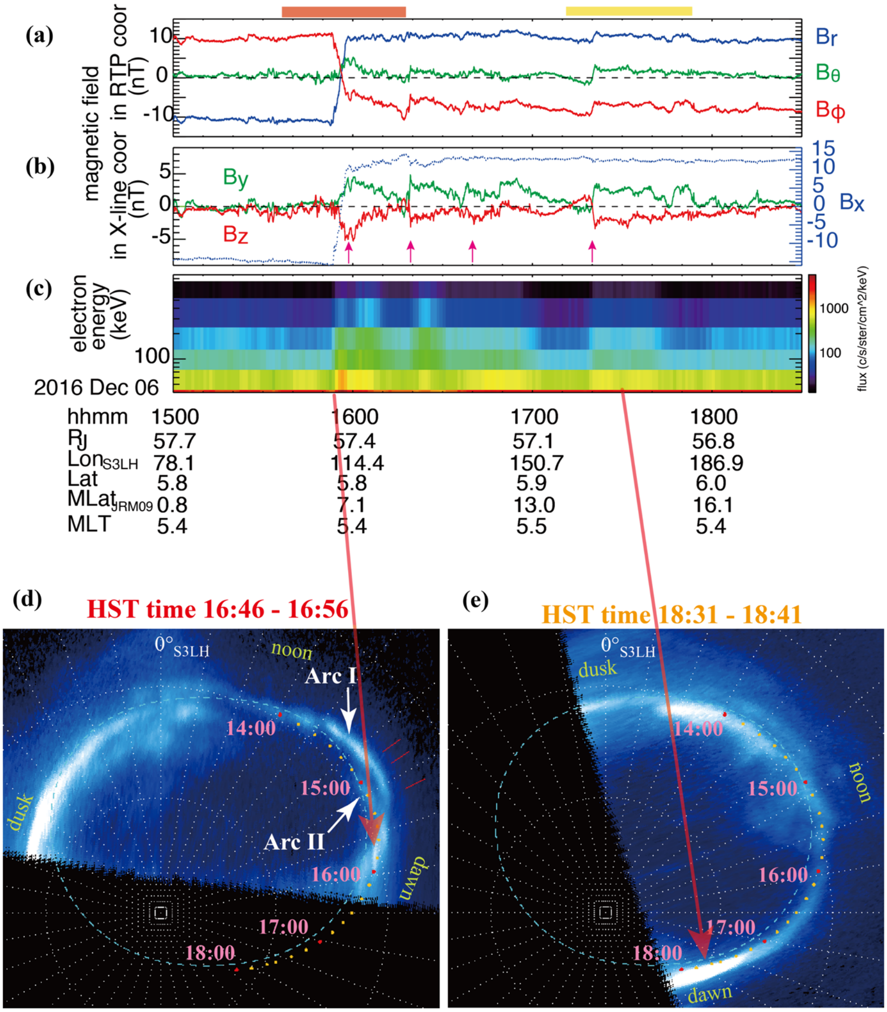

Fig. 10 Observational evidence that reconnection sites observed by the Juno spacecraft correspond to the main auroral emission at the dawn sector of Jupiter's ionosphere. **a** and **b** Magnetic components in spherical coordinates and local X-line coordinates. **c** Spectrum of energized electrons. **d** and **e** Aurorae at Jovian southern ionosphere observed by Hubble Space Telescope. The *yellow* and *red dots* mark the magnetically mapped trajectory of the Juno spacecraft, and the labeled times for the *red footpoints* are the Universal Time at Jupiter. The *red arrows* highlight the times that the brightening of aurorae corresponds to the observed reconnection sites. (Adapted from Guo et al. (2021b)) (colour figure online)

emission region, and the spacecraft's footpoint sweeps an extensive longitude range (Figs. 10d–e). After considering the light travel time from Jupiter to the Hubble space telescope, the aurorae enhanced when the reconnection emerged. Meanwhile, the aurora is moving equatorward, which could be caused by the reshaping of the magnetosphere (e.g., Liu et al. 2007; Radioti et al. 2017). The observed double-arc feature might be generated by two reconnection processes at similar longitudes. A reconnection site was indeed recorded by Juno at a similar location about 10 h ago (see Figure S1 in (Guo et al. 2021b)). The rapidly evolving auroral arcs indicate the reconnection could be unsteady.

The auroral structures and reconnection sites are magnetically connected, either direct or indirect. Combined observations have shown that auroral intensification and magnetic reconnection are directly connected in several regions of the terrestrial magnetosphere, such as at the high-latitude magnetopause (Øieroset et al. 1997; Phan et al. 2003), low-latitude magnetopause (Fuselier et al. 2007), near-Earth magnetotail (<20 R_E) (Borg et al. 2007; Varsani et al. 2017; Matar et al. 2020). In Earth's magnetotail, the two most discussed substorm models, i.e., the near-Earth current disruption model (e.g., McPherron 1979; Cao et al. 2008; Pu et al. 2010) and the near-Earth neutral line model (Lui 1991), both suggest that the FAC is formed at the near-Earth region and the bursty bulk flows transfer energy released by magnetic reconnection from the mid-tail region to the near-Earth region. Nevertheless, the energized particles accelerated by the near-Earth magnetotail reconnection site within 10 R_E (Angelopoulos et al. 2020) could precipitate into the auroral region along the magnetic field lines before moving a long distance in the equator plane. On Jupiter and Saturn, it is worth studying whether auroras are directly produced by magnetic reconnection or if the energized particles accelerated by reconnection are transported inward to the near-dipole region to form auroral FACs. Moreover, it is still unclear why the auroral arc moves in latitude.

4 Concluding remarks

At Jupiter and Saturn, both the Dungey and Vasyliunas cycles involve magnetic reconnection. Since the solar wind parameters and IMF orientation differ from that at 1AU, the magnetopause current sheets of Jupiter and Saturn are less likely to trigger magnetic reconnection compared to Earth. The internally driven magnetic reconnection process dominates over that driven by solar wind. In-situ measurements have identified the nightside reconnection X-line predicted in the Vasyliunas cycle. Recently, dayside magnetodisk reconnection sites have been observed. A fresh picture of the internally driven process is that small-scale magnetic reconnection sites can occur at any local time in the magnetodisk and rotate with the planet. The reconnection process at giant planets can last for a long duration and allow it to orbit the planet at least once. The energetic particles, FACs, and aurorae show discrete characteristics corresponding to the rotating discretely distributed reconnection sites.

The magnetic reconnection process is far from being solved in plasma physics. Its evolution in different plasma environments provides clues about the nature of the reconnection process. The magnetodisk reconnection at Jupiter and Saturn is triggered essentially by the centrifugal force and involves multiple ion species with different masses. The centrifugal force makes the magnetodisk currents evolve to extend in the radial direction. It's different from the solar wind, which compresses the current sheet to become thin.

The magnetodisk reconnection is more likely to occur spontaneously. As a mass source, the volcano activities of the natural satellites should affect the reconnection process. However, the evolution from volcanic eruption to magnetodisk reconnection is mainly controlled by the centrifugal force caused by the rapid rotation, and how long the evolution takes is still being determined. The magnetic loading–unloading process, a counterpart of the mass loading–unloading process (Bagenal and Delamere 2011; Delamere et al. 2015a), has a period of several days at Jupiter. This period varies from 1 to 7 days (Kronberg et al. 2009) and shows no clear systemical pattern. Magnetic reconnection has been found to exist during both loading and unloading processes (Yao et al. 2019). Therefore, determining how and when the magnetic reconnection can be triggered after the eruption of the natural satellites remains challenging. In addition, the magnetodisk can show a force-free current sheet configuration supported by electron field-aligned anisotropy (Artemyev et al. 2023). How the force-free magnetodisk current sheet contributes to the magnetic reconnection process is unclear.

The participation of heavy ions is another critical topic. At Earth, when the oxygen ion flux reaches the same level as the proton flux during magnetic storms, the signs of multi-layer ion diffusion zones can be seen in observations. The influence of multi-layer ion diffusion regions on magnetic reconnection is still unclear. On Jupiter and Saturn, protons and heavy ions also work together. The impact of this multi-fluid reconnection process on particle acceleration and ion escape plays a vital role in the magnetospheric dynamics of giant planets. However, the resolution of the spacecraft data is low, which is not conducive to revealing such micro-scale physical processes.

In the radial direction, the motion of magnetic reconnection could be different from that in the Earth's magnetotail. It is suggested that the movement of the reconnection line, or the X-line retreat in the terrestrial magnetotail, is due to the magnetic dipolarization on the earthward side and/or by external effect from the interplanetary magnetic field (Russell and McPherron 1973; Oka et al. 2008, 2011). The earthward outflow is blocked while the tailward outflow leaves sufficiently, leading to a motion of the diffusion region away from Earth. At Jupiter and Saturn, the magnetodisk reconnection occurs in closed filed lines, and the outflows at both sides, especially for the dayside magnetodisk reconnection, are blocked. Besides, the solar wind and the interplanetary magnetic field have minimal effects on the magnetodisk. It is hard to tell how the magnetodisk reconnection X-line moves in the radial direction.

Along the azimuthal direction, the extension of the reconnection X-line is also a fundamental question in the magnetodisk. The rotating small-scale magnetic reconnection picture (Guo et al. 2019) reveals that the magnetic reconnection X-line has a restricted length. The length of the X-line is still a mystery in magnetic reconnection research, and we know nothing about the endpoints of the X-line. In addition, the X-line is not entirely along the azimuthal direction, which leads to observing the B_θ bipolar signal for a corotation reconnection (Yao et al. 2017b). The magnetodisk is a ring current sheet. Any change in the current system may impact the entire ring current system, which could be related to the rotating multiple FACs system (Guo et al. 2021a). When the solar wind is extremely weak, and the disk is closer to axial symmetry, how is magnetic reconnection formed and distributed in the azimuthal direction? Is there an azimuthal wave mode that limits the extension of magnetic reconnection, thus leading to multiple small-scale reconnection sites? Is interchange instability related or coupled to the multiple reconnection systems?

The model that magnetic reconnection can occur throughout the magnetodisk is important for explaining many phenomena. For example, at Jupiter, the energetic ions and electrons with energies of tens to hundreds of keV can be injected into the inner magnetosphere to ~9 R_J and have no apparent local time dependence (e.g., Mauk et al. 1997, 2005); a large amount of X-ray emissions occurs in the dayside ionosphere (e.g., Gladstone et al. 2002; Dunn et al. 2020, 2022)). The dayside magnetodisk reconnection can be the energy source for these energetic events. Besides, the Vasyliunas X-line cannot fully provide the loss process in the mass circulation. Considering the magnetodisk can be reconnected at all local times, can it offer a sufficient loss rate? Where does the dayside plasmoid go? How does the plasmoid interact with the magnetopause? There are still many mysteries waiting to be solved.

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Data availability All the planetary data can be found on the Planetary Data System at https://pdsppi.igpp.ucla.edu/.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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