Reconnection and Dipolarization Driven Auroral Dawn Storms and Injections

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Abstract

Jupiter displays many distinct auroral structures, among which auroral dawn storms and auroral injections are often observed contemporaneously. However, it is unclear if the contemporaneous nature of the observations is a coincidence or part of an underlying physical connection. We show six clear examples from a recent Hubble Space Telescope campaign (GO-14634) that each display both auroral dawn storms and auroral injection signatures. We found that these conjugate phenomena could exist during intervals of either relatively low or high auroral activity, as evidenced by the varied levels of total auroral power. In-situ observations of the magnetosphere by Juno, show a strong magnetic reconnection event inside of 45 Jupiter Radii (RJ) on the predawn sector, followed by two dipolarization events within the following two hours, coincident with the auroral dawn storm and auroral injection event. We therefore suggest that the auroral dawn storm is the manifestation of magnetic reconnection in the dawnside magnetosphere. The dipolarization region mapped to the auroral injection, strongly suggesting that this was associated with the auroral injection. Since magnetic reconnection and dipolarization are physically connected, we therefore suggest that the often-conjugate auroral dawn storm and auroral injection events are also physically connected consequences.

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Abstract

Jupiter displays many distinct auroral structures, among which auroral dawn storms and auroral injections are often observed contemporaneously. However, it is unclear if the contemporaneous nature of the observations is a coincidence or part of an underlying physical connection. We show six clear examples from a recent Hubble Space Telescope campaign (GO-14634) that each display both auroral dawn storms and auroral injection signatures. We found that these conjugate phenomena could exist during intervals of either relatively low or high auroral activity, as evidenced by the varied levels of total auroral power. In-situ observations of the magnetosphere by Juno, show a strong magnetic reconnection event inside of 45 Jupiter Radii (R_J) on the predawn sector, followed by two dipolarization events within the following two hours, coincident with the auroral dawn storm and auroral injection event. We therefore

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Key points

1. Jupiter's auroral dawn storm and auroral injection events are conjugate and physically connected phenomena.
2. We report the recurrent nature of magnetic dipolarization at Jupiter.
3. These observations suggest that reconnection manifests auroral dawn storms and subsequent dipolarization produces auroral injection events

Introduction

Jupiter has the most powerful aurorae in the solar system. Through remote sensing of the aurorae in the past two decades, the morphologies and dynamics of the Jovian aurorae have been extensively investigated [*Clarke et al.*, 2005; *Clarke et al.*, 1998; *Grodent et al.*, 2018; *Grodent et al.*, 2003]. The major plasma source in the Jovian magnetosphere is the Io plasma torus, while the major driver for fundamental plasma processes is planetary rotation [*Clarke et al.*, 2004; *Delamere et al.*, 2015; *Khurana et al.*, 2004]. The mass and energy circulation in the Jovian magnetosphere are driven by both the Dungey cycle [*Dungey*, 1961] and the Vasyliunas cycle [*Vasyliunas*, 1983], although the later is often considered to dominate.

To fully understand the auroral drivers, it is critical to conduct auroral observations contemporaneous with in situ measurements of the magnetospheric dynamics[*Yao et al.*, 2019], however such opportunities remain rare. Physical interpretations of auroral dynamics based on only auroral images often require some essential assumptions, which can remain controversial. Breakdown of corotation is the predominant physical interpretation for the driver of Jupiter's main auroral emission [*Cowley and Bunce*, 2001; *Hill*, 1979; 2001; *Southwood and Kivelson*, 2001], which is generally believed to result in a reduction of the auroral main emission under enhanced solar wind dynamic ram pressure. However, studies have shown that instead the Jovian aurora appears to enhance during solar wind compressions [*Connerney and Satoh*, 2000; *Dunn et al.*, 2016; *Dunn et al.*, 2020; *Nichols et al.*, 2017; *Nichols et al.*, 2007]. This lead to the proposal of a time-varying model involving transient super-corotation of the plasma in the outer magnetosphere in order to mitigate the conflict between the classical model's prediction and the observations [*Cowley et al.*, 2007]. In addition, *Chané et al.* [2017] analysed results from a magnetohydrodynamic simulation to suggest that the buildup of the system's asymmetry (e.g., increase of spatial gradients (along local times) in magnetic field, electrical currents etc.) is crucial for auroral enhancement during solar wind compression. To date, however, the drivers of the main auroral emission still remain to be confirmed.

Amongst Jupiter's aurorae, a variety of transients and localized auroral structures (e.g., auroral dawn storms, injection events, multiple arcs etc.) are found to be common occurrences (e.g., *Grodent et al.* [2018]). The transient auroral structures are naturally expected to link to magnetospheric transient dynamics, e.g., magnetic reconnection, plasma interchange instabilities etc. Pertinent to this work, 'auroral injection' events are transient auroral structures occurring between the main auroral oval and the footprint of Io. These auroral structures are thought to be the consequence of energetic particles injected towards the planet in the middle magnetosphere [*Haggerty et al.*, 2019; *Mauk et al.*, 2002; *Mauk et al.*, 1997]. An understanding of auroral injections is crucial for understanding plasma transport in the magnetosphere and the ionosphere. Also key to this work, 'auroral dawn storm' events are major enhancements of the brightness of the dawn auroral arc with substantial broadening in latitude [*Gerard et al.*, 1994]. Previous work has suggested a connection between auroral injection events and dawn storms [*Kimura et al.*, 2017], and recent measurements from the Ultraviolet Spectrograph onboard Juno (Juno-UVS) [*Gladstone et al.*, 2017] show that an auroral dawn storm could eventually evolve into an injection event, providing direct evidence on their physical connection [*Bonfond et al.*, 2020]. Moreover, they present cases of 'non-isolated' dawn storms, in which multiple dawn storms can occur successively within a few hours.

Planetary magnetospheres are prone to perturbations caused by either the solar wind or internal sources. The subsequent energy accumulation and release are fundamental processes constantly at play in the magnetosphere. The energy release processes are often associated with a magnetospheric reconfiguration, when the magnetic field lines go from a stretched configuration to a dipole configuration. This change from stretched to dipole configuration is known as magnetic dipolarization [*Liou et al.*, 2002; *Lui et al.*, 1999] and it may have impacts to all local time sectors or only a limited set of local time sectors. For example, the magnetic dipolarization at Earth is confined to the nightside magnetotail [*Baumjohann et al.*, 1999], but at Saturn it can appear in the dayside sector as a consequence of the magnetosphere's rapid rotation [*Yao et al.*, 2018]. A dayside dipolarization process may therefore also be expected for Jupiter, where the rotationally driven processes are expected to be more pronounced. It is generally believed that magnetic dipolarization is a consequence of magnetic reconnection [*Angelopoulos et al.*, 2008; *Baker et al.*, 1996]. Reconnection outflows are pivotal in the reduction of cross-field currents and subsequent dipolarization [*Birn and Hesse*, 2013; *Shiokawa et al.*, 1997; *Yao et al.*, 2012]. In addition, plasma instabilities can also cause magnetic dipolarizations [*Henderson*, 2009; *Lui et al.*, 1992; *Lui*, 1996]. Magnetic reconnections and dipolarizations are fundamental space plasma processes widely existing in planetary magnetospheres, including the Earth [*Angelopoulos et al.*, 2008; *Baker et al.*, 1996; *Lui*, 1996; *McPherron et al.*, 1973], Saturn [*Badman et al.*, 2015; *Jackman et al.*, 2013; *Radioti et al.*, 2017; *Yao et al.*, 2017b; *Yao et al.*, 2018] and Jupiter [*Kronberg et al.*, 2005; *Vogt et al.*, 2020; *Yao et al.*, 2019]. For the terrestrial magnetosphere, it has been a long-lasting effort to build the connections between these magnetospheric dynamics and auroral emissions. For example, the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission uses five identical spacecraft to explore the terrestrial magnetosphere in coordination with ground auroral observatories, to uncover the mystery of substorm auroral mechanisms [*Angelopoulos*, 2008; *Angelopoulos et al.*, 2008]. The auroral consequences of these processes are crucial for understanding the magnetosphere-ionosphere coupling system. Moreover, a clear understanding of the aurora's magnetospheric driver would allow us to use auroral phenomena to diagnose planetary dynamics.

Using contemporaneous measurements from Juno and the Hubble Space Telescope (HST), *Yao et al.* [2019] showed a strong correlation between Jovian auroral emission and magnetic dipolarization. The magnetic dipolarization was found to be only partially dependent on the reconnection process (i.e., the occurrence rate of reconnection is observed to be slightly higher during dipolarization periods). Jovian polar dawn auroral enhancements are suggested to be a direct consequence of magnetic reconnection [*Louarn et al.*, 2015; *Radioti et al.*, 2008; *Radioti et al.*, 2011], although the detailed processes (e.g., particle acceleration, precipitation, field-aligned current formation, temporal and spatial scales) remain to be understood. To date, it is still poorly understood how magnetic dipolarization is involved in these connections at Jupiter. Plasma injections are a key consequence of magnetic dipolarizations at Earth [*Gabrielse et al.*, 2016; *Ohtani et al.*, 2007], but such a connection for Jupiter is not yet confirmed by observations. Auroral injection signatures are a counterpart of magnetospheric plasma injections at Jupiter [*Dumont et al.*, 2014; *Haggerty et al.*, 2019; *Mauk et al.*, 2002]. *Haggerty et al.* [2019] have also revealed that a plasma injection does not always produce an auroral injection signature. How a plasma injection is triggered in Jupiter's magnetosphere is yet to be confirmed by direct measurements. It is unknown which magnetospheric process could produce a plasma injection with an auroral counterpart.

In this paper, we show six examples of auroral injection signatures that occur with auroral dawn storms from the GO-14634 HST program during Juno's orbit 3 to 7 [*Grodent et al.*, 2018]. Furthermore, we leverage Juno's unique in-situ measurements to detail an example of an isolated magnetic perturbation event (i.e., the only distinct event of its kind over a period of several days). Using the coordinated ultraviolet (UV) aurora observations from HST, we find that this magnetic perturbation occurs simultaneously with an auroral injection signature and an auroral dawn storm. We find that the injection and dawn storm are also distinct events which, as with the magnetic perturbation, also do not appear during the days prior to and following this isolated magnetic perturbation. Instead, these auroral features only exist at the same time as the magnetic perturbation. Using the unprecedented simultaneous observations from Juno and HST, we demonstrate that the often-correlated auroral dawn storm and auroral injection events are driven by magnetic reconnection and dipolarization, respectively. It is noteworthy that the injection signatures can also appear independent of dawn storm events, as evidenced by UV auroral observations carried out during Juno's first perijove [*Bonfond et al.*, 2017].

Conjugate auroral phenomena: auroral dawn storms and auroral injection events

Figure 1 shows six auroral images from Jupiter's North pole. The observations are from the GO-14634 HST program during Juno orbits 3 to 7 [*Grodent et al.*, 2018]. The auroral images in Figure 1 are polar projections averaged over ~40 minutes. Each of the auroral images includes both distinct auroral dawn storms and auroral injection signatures. The total auroral power varies from ~1100 GW to 2100 GW, which are generally the powers of very quiet to rather active auroral events [*Grodent et al*., 2018]. The large variation of auroral power in these events suggests that the fundamental magnetospheric processes that drive the synchronized auroral dawn storm and auroral injection signatures can occur in rather quiet and active auroral periods.

Interestingly, as shown by the discrepancy between the main auroral oval and averaged location (particularly in the afternoon sector), the three relatively quiet events on December 14 2016, January 29 2017 and May 16 2017 show clear expansion to lower latitude of the main auroral oval, potentially suggesting a configuration of quite stretched magnetospheric field lines connecting to the main auroral oval. The events with relatively small auroral power may suggest that these events are driven by some localized processes but not involving global magnetospheric perturbations. Such events provide an ideal opportunity to investigate the fundamental processes driving the conjugate auroral dawn storms and auroral injection signatures, in isolation from other auroral enhancements and their respective causes.

HST and Juno joint measurements of a short-lived magnetospheric and auroral event on May 16, 2017

In this section, we detail one HST auroral sequence with quasi-simultaneous measurements from Juno's magnetic field and particle instruments. A sequence of HST/STIS UV observations was conducted on May 13, 15, 16 and 17. The main auroral arc from dawn to noon sectors was extremely quiet on May 13, 15 and 17, while a small auroral dawn storm and afternoon auroral injection signature were both observed on May 16. Therefore, it is likely the May 16 auroral event is the only distinct event, i.e., an isolated auroral event lasting a period of a few Jupiter rotations or less. We call this type of auroral event a 'short-lived event' in the rest of this paper. Given the complexity of Jovian auroral dynamics, this isolated event provides an unprecedented opportunity to identify the auroral driving mechanism. Juno's MAG instrument provided simultaneous measurements of magnetic field in the dawnside magnetosphere [*Connerney et al.*, 2017]. Figure 2b shows the radial magnetic component B_r and the north-south magnetic component B_θ (System III coordinate system), the perturbations of which are usually key parameters for identifying fundamental magnetospheric processes, e.g., magnetic reconnections, dipolarizations and plasmoids. During the period between May 13 and 17, the variation of B_r and B_θ were mostly due to plasmadisc oscillations [*Khurana et al*., 2004; *Khurana and Schwarzl*, 2005], with the exception of a large B_θ bipolar signature on May 16, at ~02:00 UT. The B_θ bipolar signature is usually considered a signature of encountering a magnetic reconnection site or a plasmoid from a reconnection site [*Slavin et al*., 2003]. Contemporaneous particle energization (e.g., electrons, protons and heavy ions) was also observed around the B_θ bipolar signature as shown in Figure 3, further confirming that the B_θ bipolar signature is likely associated with a fresh magnetic reconnection.

Figure 3(a-c) shows the magnetic components in system III coordinates between 00 UT and 06 UT on May 16. Figure 3(d-f) show energy-time spectrograms for energetic electrons, proton and heavy ions (oxygen and sulphur ions) observed with Juno's Jupiter Energetic-particle Detector Instrument (JEDI) [*Mauk et al*., 2017], which measures electrons with energies ranging from ~25 to 1 MeV, protons from ~10 keV to 6 MeV and heavy ions from ~50 keV to 20 MeV.

We indicate four enhancements (pink shadows) of plasma fluxes in Figure 3. For the first flux enhancement, as indicated by the reversal of B_r, Juno traveled from the southern current sheet (negative B_r) to the northern current sheet (positive B_r), and the fluxes of all plasma species (i.e., protons, electrons and heavy ions) were enhanced during the plasma sheet crossing. Moreover, a distinct flux enhancement (the second enhancement) of electrons and protons was observed when the strong B_θ spike was detected (indicated by the black arrow in Figure 3b). The particle flux enhancements were not due to Juno approaching the central plasmadisc as indicated by the relatively large B_r (>8 nT) as opposed to the B_r reversal of its sign expected from the crossing of central current disk at about 02 UT. This B_θ spike should therefore be associated with a strong energization process. We suggest the B_θ spike to be a reconnection site or recently generated plasmoid from a reconnection site [*Kronberg et al.*, 2012]. The reconnection event is also identified in a recent statistical study using the Juno dataset [*Vogt et al.*, 2020]. The third flux enhancement shortly followed the reconnection signature, potentially suggesting that this enhancement is a subsequent consequence of magnetic reconnection. During this plasma flux enhancement, the magnetic field shows a strong B_r decrease and a slight B_θ increase. Such magnetic variation is a typical signature of magnetic dipolarization due to magnetospheric reconfiguration [*Yao et al.*, 2017b]. Moreover, the electrons are more energetic during this flux enhancement than the first enhancement due to a plasma sheet crossing, indicating that the third flux enhancement is indeed a dipolarization process that involves plasma energization, rather than a consequence of a pure plasma sheet flapping. After 02:40 UT, Juno entered the northern lobe magnetosphere, as evidenced by the large and flat B_r distribution, accompanied with a depletion of plasma content. The sharp enhancement of B_r and the simultaneous decrease of plasma flux also imply that they are spatial variations but not temporal variations. An unexpected enhancement (the fourth one) of all plasma species was observed between ~04:00 UT and ~04:30 UT (blue shadow).

We zoom into the interval of the unexpected plasma enhancement between ~04:00 UT and ~04:40 UT in Figure 4, showing magnetic components and electron spectrum. The two enhancements of electron flux were accompanied by a B_θ increase and a simultaneous B_r decrease, implying that these structures are due to magnetospheric current re-distribution according to the definition in *Yao et al.* [2017b]. *Yao et al.* [2017b] also demonstrated that the decrease of B_r is even more indicative of such re-configuration than the increase of B_θ when a spacecraft is relatively far from the central current disk.

Corotation of magnetic dipolarization

Recent studies using measurements from Cassini have revealed that a magnetic dipolarization region could corotate with Saturn - another giant planet with a rapidly rotating magnetosphere [*Yao et al.*, 2018]. Moreover, since we connect auroral injection signatures with magnetic dipolarization in this study, and it is known that auroral injection signatures often corotate with the planet [*Grodent*, 2015], it seems natural to expect that a magnetic dipolarization region shall corotate with Jupiter, similar to what has been discovered at Saturn. For a corotating magnetic dipolarization, the conventional electric field shall vanish in the corotating frame. The particle energization associated with a dipolarization could originate from either adiabatic or non-adiabatic acceleration. For adiabatic acceleration, Betatron and Fermi accelerations are the two best understood mechanisms [e.g., *Birn et al*., 2013; *Yao et al*., 2017c]. For non-adiabatic acceleration in a dipolarization, wave-particle interactions are the dominant process in energizing particles [*Zhang et al*., 2018].

Figure 5 shows B_r and the electron energy spectrum for two intervals: from 04:00 UT to 04:40 UT, and from 14:00 UT to 14:40 UT. As marked by the green shadows, there was a significant decrease of B_r during each interval, respectively at 04:10 UT and 14:25 UT. The B_r decreases were accompanied by a strong enhancement of electron flux with energies of 10s to 100s keV. Together, these evidence a magnetic dipolarization due to magnetospheric reconfiguration occurring within a limited longitude range. The footprint for the recurrent dipolarization observed at 14:25 UT is at a latitude of 54 degrees and longitude of 164 degrees, which is almost the same location as the auroral injection, further supporting that the corotating dipolarization process is the driver for the corotating auroral injection signatures. We note that the recurrent dipolarization may not be a perfect copy of the dipolarization in previous planetary rotation due to two important reasons. The first reason is that Juno moved 3 to 4 R_J between the two observations, so that the measurements were not exactly from the same location. This is also evidenced by the different background magnetic strengths for the two intervals in Figure 5. The second reason is that the dipolarization region itself may evolve during one planetary rotation, which might be related to the slow evolution of the auroral injection signature. The lifetime of the injection signatures is usually 5-10 hours, and sometimes can be longer [*Bonfond et al.*, 2012; *Dumont et al.*, 2018; *Haggerty et al.*, 2019]. The dipolarization associated with the auroral injection signature may exist for a longer period, as aurora is produced by the energized particles in the magnetic loss cone and the trapped energetic particles associated with dipolarization could remain for a longer time. Therefore, the recurrent dipolarization was observed up to one planetary rotation later, which is also a similar situation for Saturn's recurrent dipolarization [*Yao et al.*, 2017a; *Yao et al.*, 2018]. There are two dipolarization signatures between 04:00 to 04:40, but only one is detected a planetary rotation later. It is possible that the dipolarization at ~14:25 UT was relatively small. So that it could not be observed after one planetary rotation when the spacecraft was farther away from the plasma sheet as evidenced by a larger B_r. Alternatively, the dipolarization at ~14:25 UT may have evolved substantially so that it was not observed after one planetary rotation.

A physical connection between auroral dawn storms and multiple auroral injection signatures

As more and more Jovian auroral images have been collected by HST, we have found that auroral dawn storms and auroral injection signatures often co-exist in HST observations (e.g. Fig 1). In previous literature, auroral dawn storms are often suggested to be associated with magnetic reconnection [*Ge et al*., 2010; *Woch et al*., 2002]. Since the auroral injection signatures often appear together with auroral dawn storms, a natural question is thus raised: is there a physical connection between magnetic reconnection and auroral injection signatures? Simultaneous measurements of the magnetospheric processes and auroral dynamics on May 16 provide pivotal clues to uncover this physical connection.

The large magnetic bipolar signature on May 16 was observed at ~43 R_J, which is in a relatively inner region amongst previous reports of magnetic reconnection at Jupiter [*Vogt et al*., 2014; *Vogt et al*., 2010]. Following the reconnection process (i.e., the large magnetic bipolar signature), magnetic dipolarization was observed ~20 min (at ~02:30 UT), and ~2 hours later (at ~04:10 UT). We call the dipolarization observed at ~02:30 UT the 1st dipolarization, and the one observed at ~04:10 UT the 2nd dipolarization. When detecting the two dipolarizations, Juno was mapped to the longitude of ~150-170 degrees and latitude of ~56-60 degrees in System III coordinate, using a flux equivalence mapping model [*Vogt et al*., 2015; *Vogt et al*., 2011] with the JRM09 internal field model [*Connerney et al*., 2018]. The auroral image observed by HST between 07:11 UT to 07:52 UT, corresponded to a source emission at Jupiter between 06:32 UT and 07:13 by shifting for light traveling time of ~39 minutes. The auroral injection signature was observed at a longitude similar to the footprint of Juno when it detected the reconnection event and the latitude of the auroral injection signatures (~50-55 degrees) was slightly lower than the footprint of Juno's detection of dipolarization (~56 degree). Given that the dipolarization would act in a progressively inward direction through the magnetosphere, this minor latitudinal difference is physically consistent as the auroral image was taken at 2-4 hours later. As the dipolarization was magnetically connected to the location where the injection was initiated (i.e., the same longitude and very close latitudes), we thus suggest that the auroral injection signature was a natural consequence of the magnetic dipolarization during the 2-3 hours following the reconnection event. Multiple dipolarization events could originate from the reconnection event, producing multiple structures separated in longitude in the auroral injection region. In-situ spacecraft may not capture all dipolarizations if the spacecraft was not located at an ideal position (i.e., far away from the central plasmadisc), therefore it is possible that more magnetic dipolarizations may have occurred than those that were observed. Table 1 shows the timing sequence of the magnetic reconnection, dipolarization, auroral dawn storm and auroral injection signatures. Since the auroral dawn storm and injection are long-lasting signatures, the times when they were observed are not representative of the time when they were produced, so that we do not show the time relations to avoid potentially misleading information.

Table 1: timing results amongst the processes in the magnetosphere and aurora. The auroral timings have been shifted to account for the light travel time. Mapping was done with a flux equivalence model [*Vogt et al.*, 2015; *Vogt et al.*, 2011] and the JRM09 internal field [*Connerney et al.*, 2018].

Event	**Time (UT)**	**Lon/Lat S3**	**Time since Reconnection (hours)**
Magnetic reconnection at 43 RJ	0210	144/65	0
Dipolarization #1 at 43 RJ	~0230	148/59	~0.3
Dipolarization #2 at 42 RJ	0410-0430	164-169/55	2
Auroral Dawn Storm	0632 - 0713	~200/60	N/A
Auroral Injection	0632 - 0713	~150-165/50-55	N/A

Among the six examples in Figure 1, three events (December 14 2016, January 29 2017 and May 16 2017) were observed during relatively quiet auroral conditions. The conjugate auroral dawn storm and auroral injection signature processes can therefore take place in relatively quiet auroral conditions, indicating that their magnetospheric driving processes could remain localized, without triggering a large global energy dissipation. The main auroral oval in the three events expanded to lower latitude, which suggests that the magnetosphere was undergoing heavy mass-loading and the magnetic field was more stretched [*Grodent et al.*, 2008]. Highly stretched magnetic fields are naturally favorable for reconnection to occur and therefore potentially cause or prime the magnetosphere for magnetic reconnection and auroral dawn storms.

Figure 6 shows a schematic to illustrate the connection between auroral dawn storms and auroral injection signatures. The yellow and green areas represent the main auroral oval and the polar region respectively. The main auroral oval corotates with the planet from the time at T1 to T2 and then to T3. A dawn storm occurs at T1, as marked by the red lightning symbol, which is likely a manifestation of reconnection processes on the dawn magnetosphere. The reconnection process produces dipolarization, which corotates with the planet and causes an auroral injection at T2 (the yellow finger-like structure). The reconnection-dipolarization-auroral injection connection could continue for a few hours and produce a massive auroral injection with multiple substructures, as illustrated by the auroral example from the very recent observations (March 19, 2019) in Figure 6. *Kimura et al.* [2015] also proposed that internally driven reconnection is responsible for the intense injection aurora in the postnoon sector, which is directly supported by the in situ measurements in this study. Interestingly, the reconnection-dipolarization combined driver is also known to produce double oval auroral intensifications (separated in latitude) [*Elphinstone et al.*, 1995] at Earth. Because the Earth's plasma sheet does not rapidly rotate, the double auroral intensifications are not significantly separated in longitude. While at Jupiter, dawn storms are roughly on the main auroral oval, while injections are often at latitudes below the main oval. Therefore, the dawn storm-injection connection may be analogous to the contemporaneous enhancements of terrestrial poleward and equatorial aurorae (i.e., the double oval).

Because auroral injection signatures are subsequent stages of dawn storms and because the injections corotate with the planet, the injection signatures would display over larger local times than auroral dawn storms, which are only observed on the dawn side. This series of connected events are all consistent with auroral observations. Further examinations will be needed to provide unambiguous support for the causal relationship that is hypothesized here.

Conclusion

In this study, we propose a physical connection between two Jovian auroral structures: the dawn storm and injection aurorae. Reconnection in the dawn magnetosphere produces dawn auroral storms. Following the reconnection process, magnetic dipolarization is initiated, which corotates with the planet and creates plasma injections into the inner region of the magnetosphere, leading to auroral injection signatures in a broad range of local time sectors. Reconnection may produce multiple dipolarization events within several hours, leading to multiple auroral injection signatures as is often observed by HST.

Following previous observations of corotating injections, we note that the dipolarizations that we observe at the footpoints of the injections must also corotate in the magnetosphere. By analysing the magnetic field and particle data, we reveal the recurrent nature of magnetic dipolarization at Jupiter, which is analogous to the recurrent dipolarizations recently revealed at Saturn.

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Figures and Captions

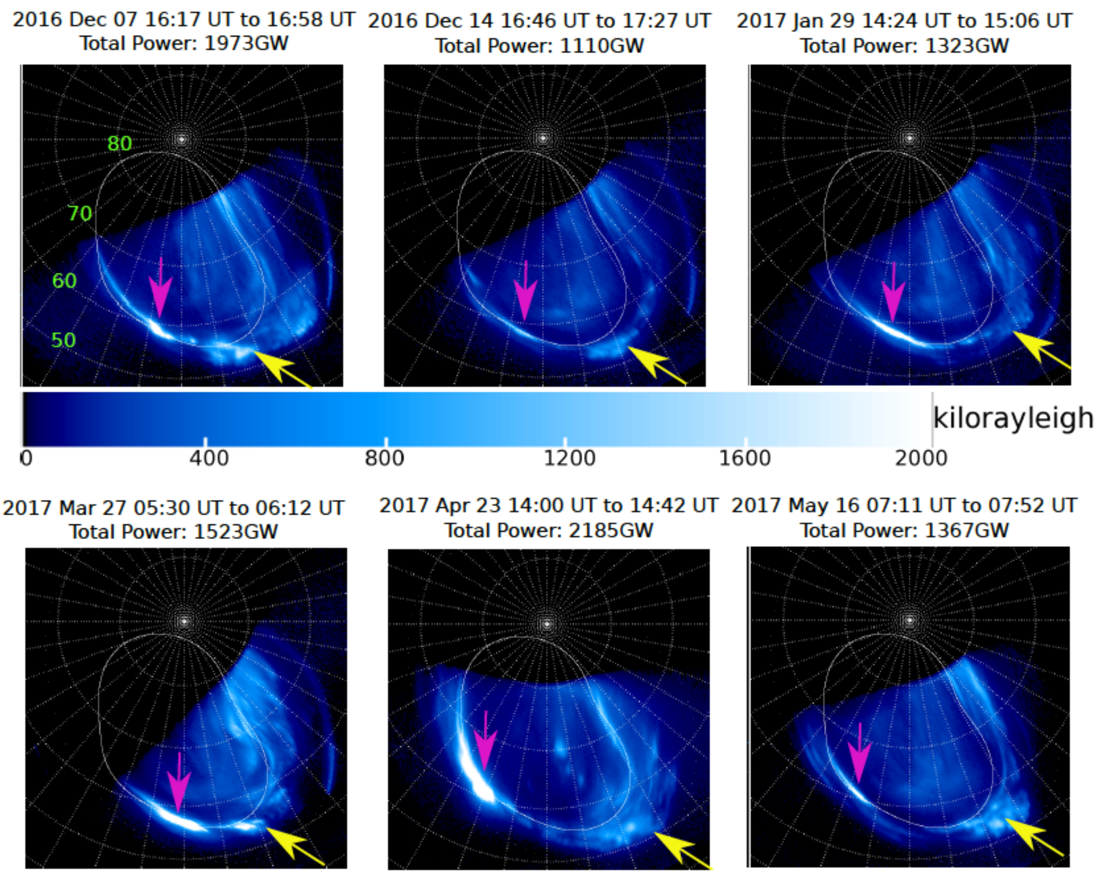

Figure 1. Auroral examples with synchronized auroral dawn storm (pink arrows) and auroral injection (yellow arrows).

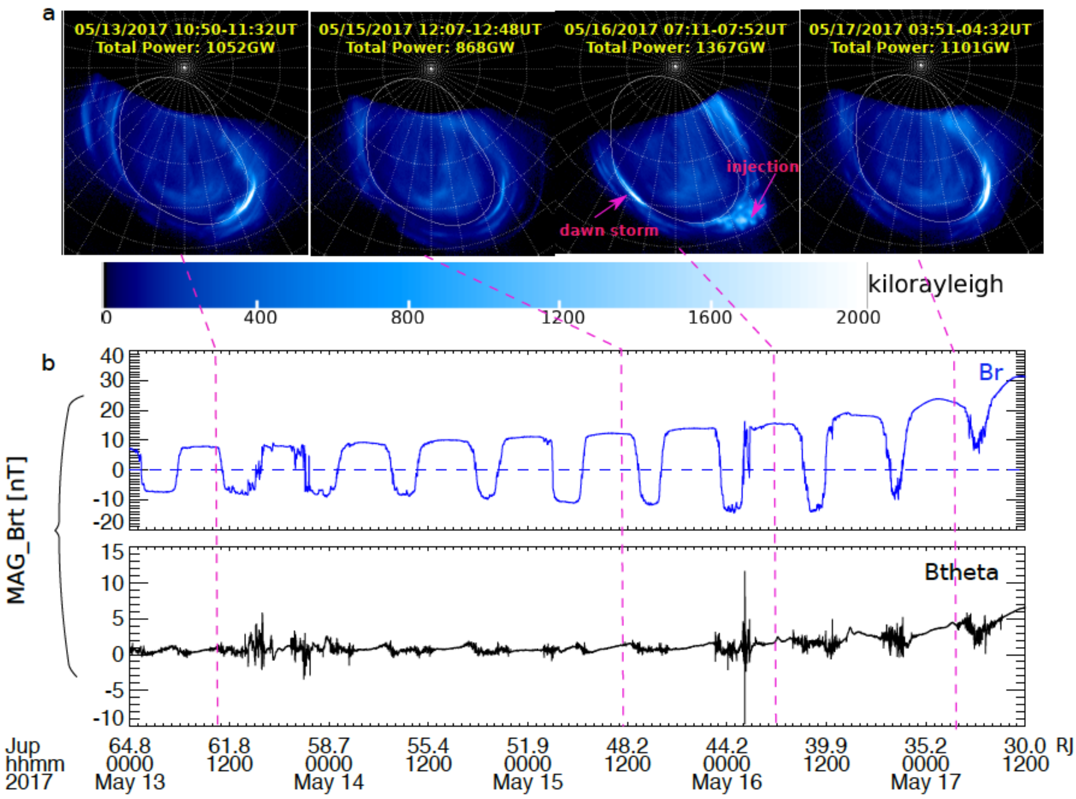

Figure 2. a. Auroral sequence obtained by HST from May 13 to May 17. Note that the times shown on each image are the time when HST took the measurements, which should be shifted to Jupiter by a light traveling time of ~39 minutes during this period. b. Magnetic B_r and B_θ components between 00 UT on May 13 and 12 UT on May 17.

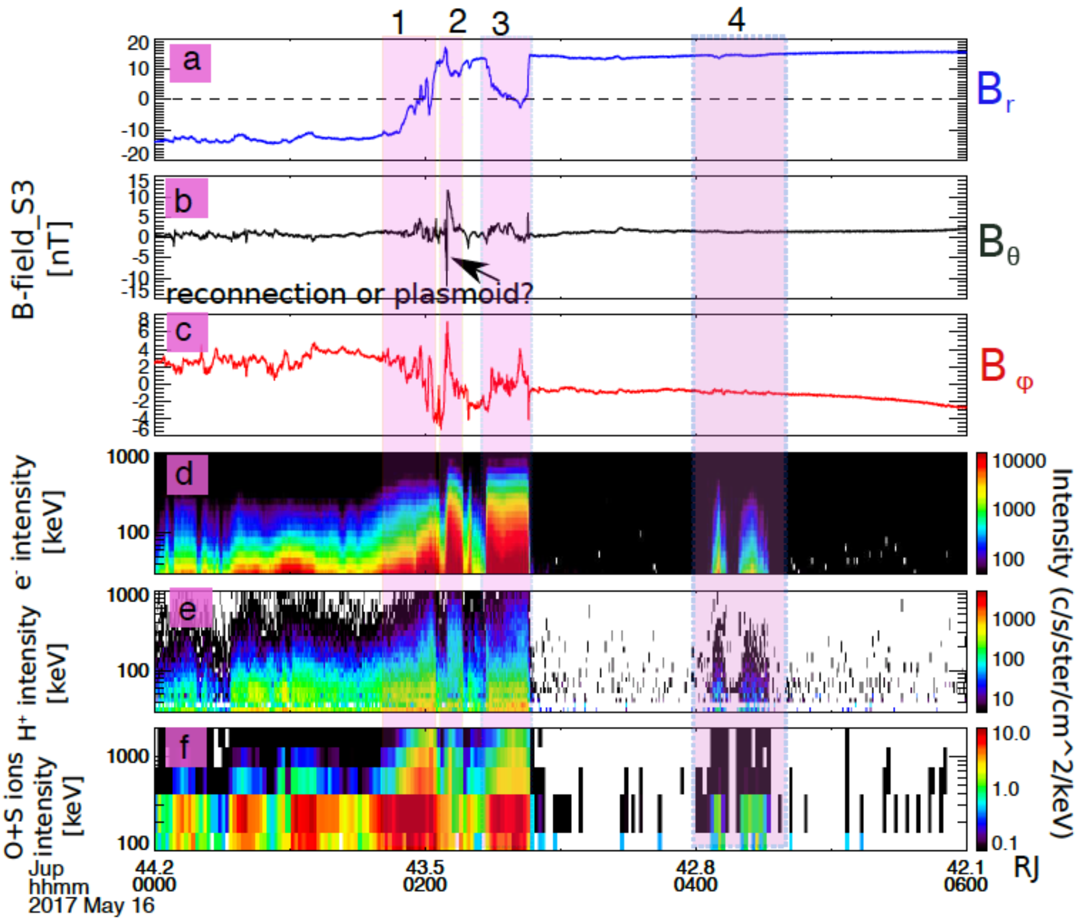

Figure 3. (a-c) Measurements of magnetic field and (d-f) energy spectrums of electrons, protons and heavy ions (oxygen and sulphur) between 00 UT and 06 UT on May 16, 2017. Pink shaded regions 1, 2, 3 and 4 are discussed in the main text.

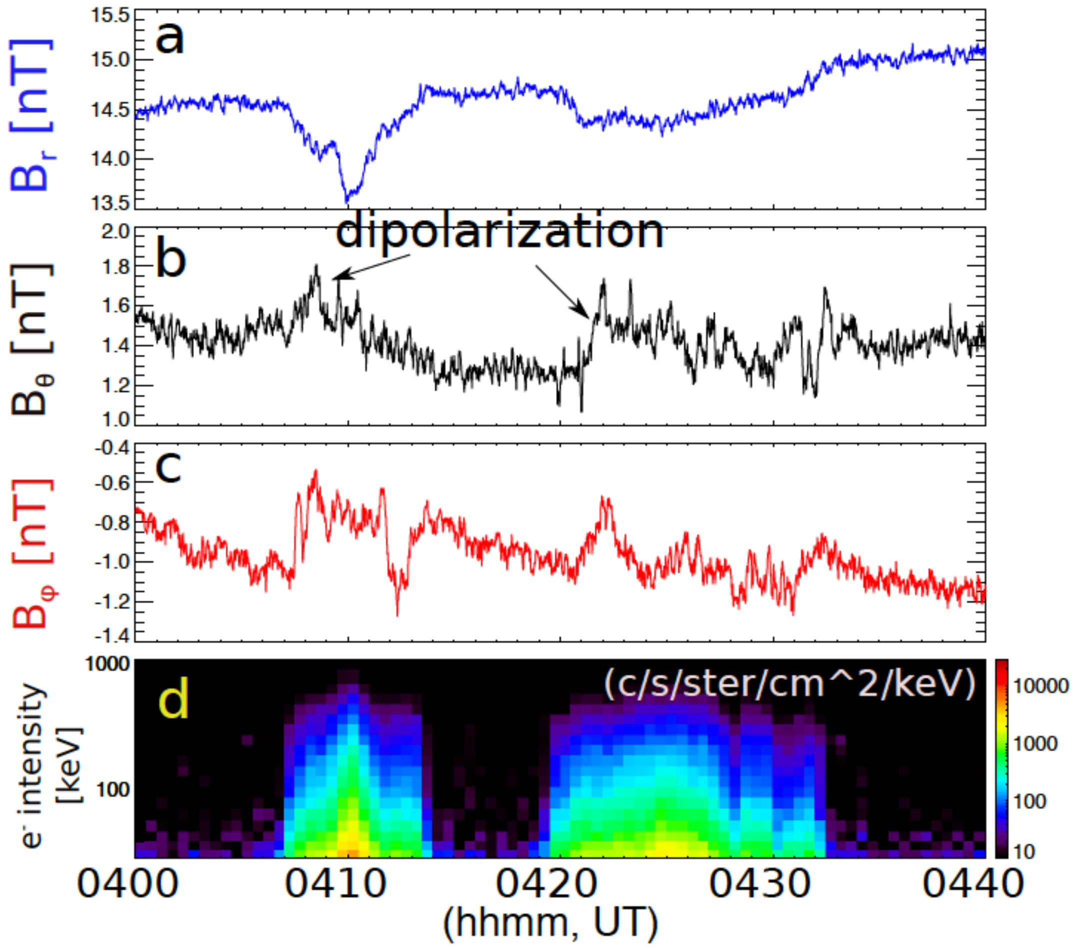

Figure 4. (a-d) Magnetic components and electron energy spectrum between 04:00 UT and 04:40 UT.

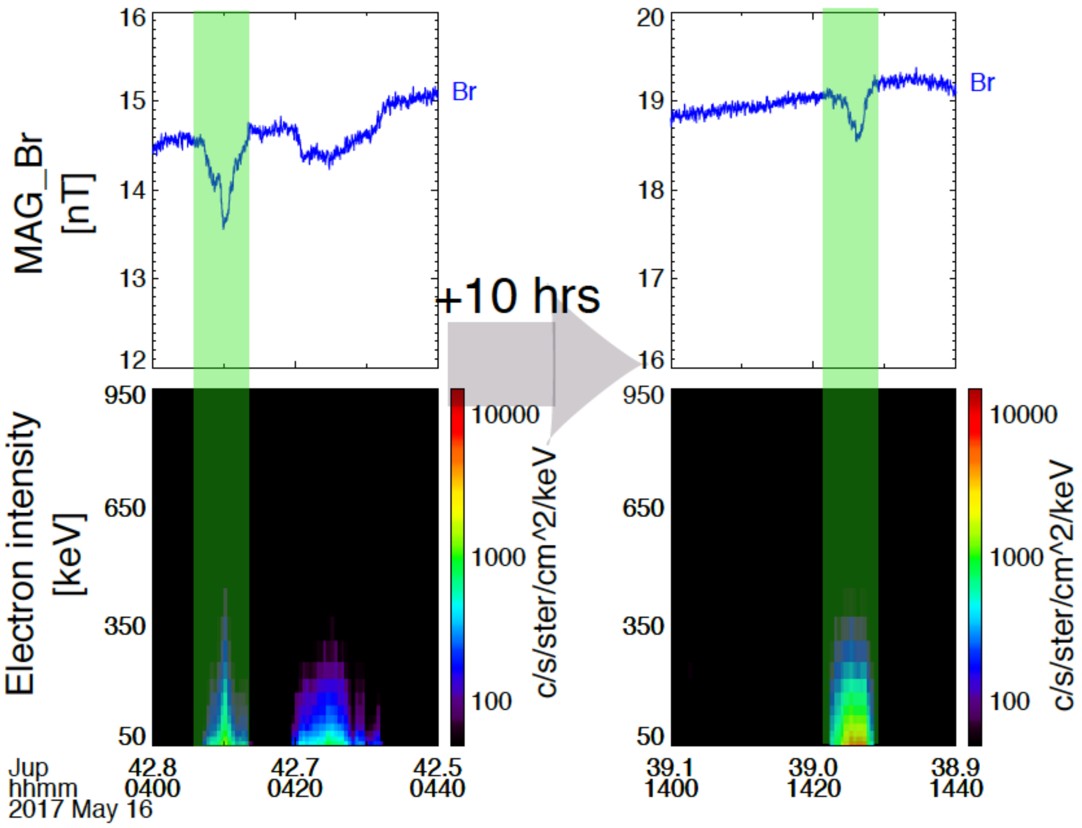

Figure 5. B_r and electron energy spectrum for two intervals separated by 10 hours, from 04:00 UT to 04:40 UT, and from 14:00 UT to 14:40 UT. The two green shadows highlight two distinct dipolarizations.

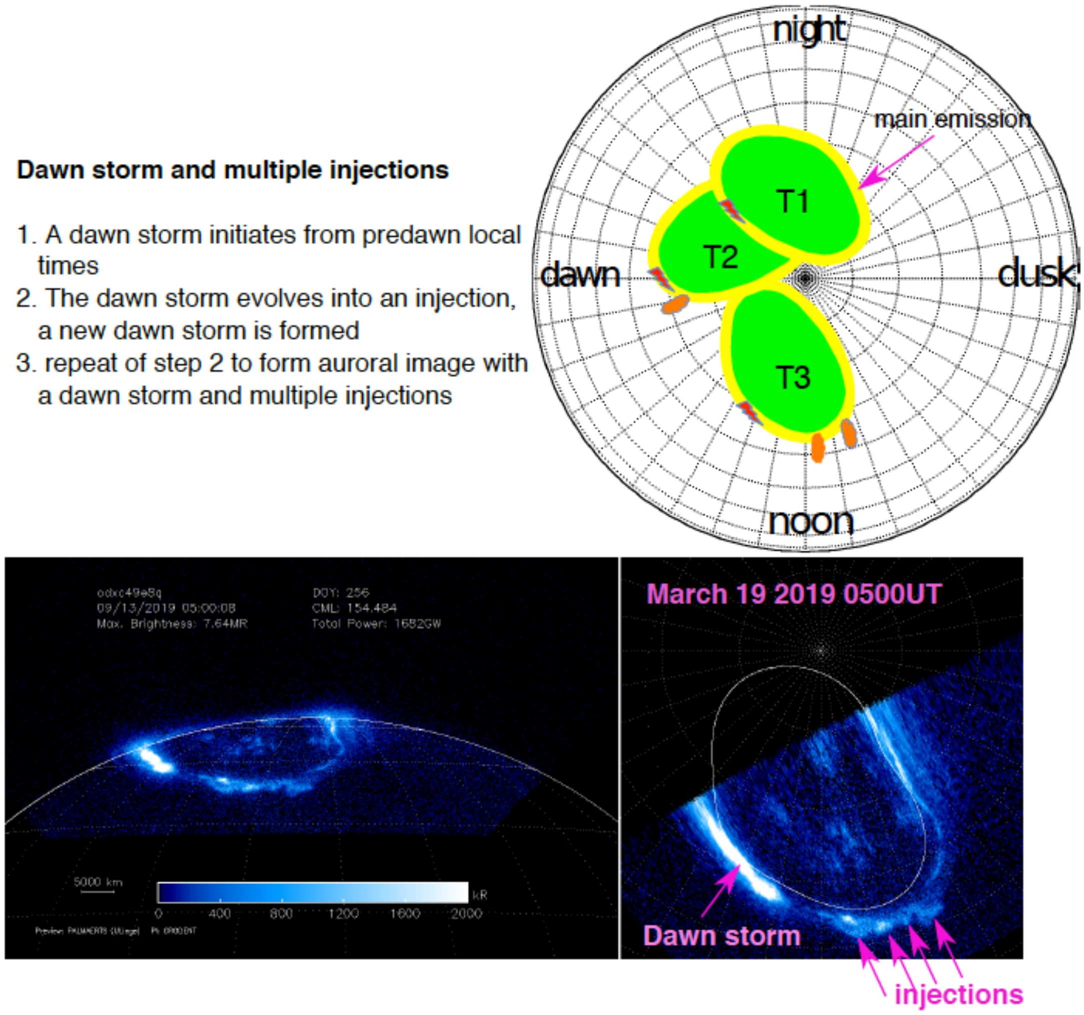

Figure 6. A schematic to illustrate the physical connection between dawn auroral storm and auroral injection, and the associated magnetospheric processes. The yellow and green areas represent main auroral oval and polar region. On the top sketch, the red lightning symbol marks the dawn storm, and the yellow finger-like structures denote auroral injection signatures. The bottom auroral figure is Jupiter's northern aurora taken by HST on September 13, 2019. The left panel is the view from Earth orbit, and the right panel is a projection to the northern polar region.