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Key Points:

- We investigate a double-arc dawn aurora at Jupiter and the associated reconnection signatures in magnetosphere for the poleward arc
- Poleward arc evolves rapidly and both arcs move equatorward, suggesting a combination of global reconfiguration and localized reconnection
- Multiple reconnection fronts observed by Juno are suggestive evidence of unsteady and/or drizzle-like reconnection processes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Jupiter's Double-Arc Aurora as a Signature of Magnetic Reconnection: Simultaneous Observations From HST and Juno

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Abstract Jupiter's powerful auroral emission is usually divided into the polar, main, and equatorward components. The driver of Jupiter's main aurora is a central question for the community. Previous investigations reveal many distinct substructures on the main auroral oval, which are indicators of fundamentally different magnetospheric processes. Understanding these substructures could provide key constraints for uncovering the driver of Jupiter's main aurora emission. In this study, we show the evolution of a double-auroral arc on the dawnside from observations by the Hubble Space Telescope (HST). Simultaneous in situ observations from the Juno spacecraft provide direct evidence of magnetic reconnection and magnetic dipolarization. By analyzing the datasets from Juno and HST, we suggest that the evolution of the double-arc structure is likely a consequence of the non-steady progress of magnetic reconnection.

Plain Language Summary Jupiter's most powerful aurora reflects the strong perturbations of energetic particles in the space environment. Besides the relatively steady main aurora, there are rapidly evolving structures that imply the transient plasma processes, for example, magnetic reconnection, wave-particle interaction, and so on. The relation between transient processes and auroral structures is poorly understood due to limited observations. Using the simultaneous measures from Juno and Hubble Space Telescope, we reveal the magnetospheric driver (i.e., magnetic reconnection) for an evolving double-arc auroral structure at the dawn sector. This study shows a good example of reconnection signature on the auroral image, which provides key implications to understand planetary space environment from dynamic auroral features.

1. Introduction

Jovian ultraviolet (UV) auroral emission shows distinct components. Some of these components are relatively steady while others are highly dynamic (Grodent, 2015). A relatively steady main auroral morphology is a key focus of the community (Ballester et al., 1996; Clarke et al., 1998; Gérard et al., 1994; Grodent et al., 2003). Corotation breakdown enforcement in the magnetosphere is a prevalent hypothesis for driving Jupiter's main emission (Cowley & Bunce, 2001; Hill, 1979, 2001; Southwood & Kivelson, 2001). Recently, it was realized that various observations cannot be exactly expected by the modeling frames based on the corotation breakdown enforcement mechanism (Bonfond et al., 2020). At lower latitudes than the main aurora, there are two major contributions: moon footprints and auroral signatures of injections. Wave-particle interactions are suggested to play a crucial role in these auroral emissions (Bonfond, 2010; Hess et al., 2010; Li et al., 2020; Radioti et al., 2009). The high latitude auroral emissions near the poles have remained a puzzling phenomenon, the source of which remains unknown. They distinguish Jupiter's magnetosphere from other planets in our solar system. A recent numerical simulation provides new insights into the near-pole auroral emissions at Jupiter (Zhang et al., 2021). These results suggest that the fast rotation effect dominates over the Dungey cycle even at the near pole region, resulting in the polar caps with closed field lines that are highly helical. The novel magnetic configuration could well explain the active auroral emissions in the polar region.

Jupiter's main auroral emission is an almost permanent feature of the planet's auroral displays. While the structure is observed in almost every observation, its brightness varies with time and magnetic local time (MLT) (Cowley et al., 2003; Grodent, 2015; Grodent et al., 2003; Hill, 2001). The discontinuity of the main emission near the subsolar point (Radioti, Gérard, et al., 2008), the dawn-dusk brightness asymmetry (Bonfond et al., 2015), and the global auroral brightening during solar wind compression of the magnetosphere (Nichols, Badman, et al., 2017; Nichols, Bunce, et al., 2007; Nichols, Clarke, et al., 2009; Yao, Bonfond, Grodent, et al., 2020), and so on, reveal that the main auroral emission is strongly modulated by the solar wind (Bonfond et al., 2020; Grodent et al., 2018). Additionally, transient brightening of the main auroral emission appears to recur on timescales of a few days (Kimura et al., 2015, 2018), which could be related to the 1.5–7 days variations of magnetic field and electron flux observed in the Jovian magnetosphere (Kronberg et al., 2009; Tao et al., 2021; Woch et al., 1998). Episodes of loading and unloading of Jovian magnetic flux and the enhancements of the main auroral emissions during the unloading interval are also shown to have a period of a few days (Yao et al., 2019).

Besides variations at a time scale of a few days, there are many more rapid variations in Jupiter's aurora. Adjacent to the main emission, dynamic auroral features have frequently been observed. A distinct pulsation at a timescale of 2–3 min has been identified in Jupiter's polar auroral region (Bonfond et al., 2011) and the intensity of the polar emission has been observed to increase by a factor of 30 within 70 s (Waite et al., 2001). Auroral spots with brightness oscillations at a period of ∼10 min were also observed within the main auroral emission, and are suggested to be driven by ultralow frequency waves (Nichols, Yeoman, et al., 2017). Along the dawn sector of the main emission, auroral dawn storms are often observed and sometimes evolve into injection events (Bonfond et al., 2021). Hot plasma injections together with wave-particle interactions are suggested to generate a secondary auroral oval (Gray et al., 2017). The hot plasma injections with energy-dispersed particle signatures are frequently observed within 30 R_J (Jupiter radius, 71,492 km) (Mauk et al., 1999), which represent a mature state of injection. Beyond 30 R_J, recent observational studies suggest that magnetic reconnection and dipolarization, which largely disturb magnetic field to form field-aligned current and locally accelerate particles, are responsible for the auroral dawn storms and fresh injections (i.e., dispersionless) (Yao, Bonfond, Clark, et al., 2020). Hot plasma injection and dipolarization are strongly coupled processes; in fact, they sometimes can be the same process and named as dipolarization injection in the terrestrial magnetosphere (e.g., Lui, 2004; Ohtani et al., 2007; Sergeev et al., 2009). Dipolarization is usually observed in "fresh" injection, meaning that dipolarization is highly relevant to the generation of plasma injection (Yao, Bonfond, Clark, et al., 2020). The two processes represent different perspectives, that is, from hot particles and magnetic configuration.

An outstanding feature appearing poleward of the main emission is the polar dawn spot (Gray et al., 2016; Grodent et al., 2004; Radioti, Grodent, et al., 2008), which are also found in auroral locations mapping to the Jupiter's nightside (Radioti, Grodent, Gérard, Vogt, et al., 2011) and at Saturn (Radioti, Grodent, Gérard, Milan, et al., 2011). These auroral spots generally corotate with the planets. Joint observations by the Galileo spacecraft and Hubble Space Telescope (HST) showed that inward moving plasma accelerated by magnetic reconnection on the nightside can generate nightside auroral spots (Radioti, Grodent, Gérard, Vogt, et al., 2011). Jovian tail reconnection and the related tail dipolarization events were also considered as a possible cause of the polar dawn spots (Grodent, 2015) since the footprints of the tail dipolarization in the ionosphere were close to the dawn auroral region (Ge et al., 2010). The recurrence of auroral spots may be associated with the recurrent nature of magnetic reconnection (Kronberg et al., 2007; Radioti, Grodent, et al., 2008; Yao et al., 2019).

At Jupiter, the corotating nature of the auroral spots suggests that if magnetic reconnection is the driver, then it is internally driven and likely occurs in the magnetodisc. A corotating reconnection event was reported at Saturn (Yao et al., 2017) and dayside magnetodisc reconnection was observed in the noon sector of Saturn's magnetosphere (Guo, Yao, Sergis, et al., 2018; Guo, Yao, Wei, et al., 2018). The reconnection sites in Saturn's magnetodisc are small-scale and can be observed at all local times, including the dawn sector (Guo et al., 2019). The Juno spacecraft also detected hundreds of magnetic reconnection events in the dawn sector of Jupiter's magnetosphere (Vogt et al., 2020). It remains unclear whether magnetic reconnection sites could corotate with Jupiter. Nevertheless, prominent reconnection jet fronts with energized particles have been observed by Galileo spacecraft and were found predominantly on the pre-dawn sector of Jovian magnetosphere, consisting with a rotation picture (Kasahara et al., 2011, 2013). Additionally, a magnetic dipolarization signature was observed to recur in Jupiter's magnetosphere after one planetary rotation (Yao, Bonfond, Clark, et al., 2020), which might suggest a recurrent feature for magnetic reconnection.

Although the dawn reconnection and rotating reconnection processes are expected to cause transient auroral emission, the physical connection between these features is far from being fully understood. An important reason comes from the lack of simultaneous measurements of the aurora and the magnetospheric processes. The HST campaigns supporting the Juno mission provide an unprecedented opportunity to examine how the reconnection in the dawn sector triggers the auroral substructures on Jupiter. Here, we present a dynamically evolving double-arc auroral structure and show the corresponding reconnection signature in the magnetosphere.

2. Observations

2.1. Data and Instruments

The auroral observations used in this study were taken by the ultraviolet Space Telescope Imaging Spectrograph (STIS) onboard HST in the frame of HST program GO-14634 (Grodent et al., 2018). Each HST visit of Jupiter was constrained by an orbital visibility period of ∼41 min. This HST program was dedicated to joint observation with the Juno mission (Bolton et al., 2017). The magnetic field in the Jovian magnetosphere is obtained from Juno's Magnetic Field investigation (MAG) (Connerney et al., 2017). Distributions of ions and electrons with energy >30 keV are observed with Juno's Jupiter Energetic-Particle Detector Instrument (JEDI) (Mauk et al., 2017). Vogt's magnetosphere-ionosphere mapping method (Vogt et al., 2011, 2015), using the JRM09 internal magnetic field model (Connerney et al., 2018), is applied to project the spatial coordinates of Juno in Jupiter's ionosphere and to map the auroral emission in the magnetosphere. Different from methods tracing magnetic field lines, Vogt's method considers that the magnetic fluxes of a specified region in the equator and its mapped area in the ionosphere should be equal. During the magnetic flux calculation, the bend-back effect is taken into account. The mapping error of the flux equivalence approach is estimated to be ∼10 R_J in the radial distance and ∼1 h in local time and up to a few degrees in the ionosphere, and the precise results of the flux mapping approach depend on the choice of internal field model (Vogt et al., 2015). As analyzed below, the mapping result is used as a reference to help qualitatively understand the relation between the dynamics in magnetosphere and ionosphere, not used for quantitative calculations. Therefore, the main conclusions in this study are not seriously affected by the uncertainties of the mapping method or by the choice of internal field model (in this case, JRM09).

2.2. Dawn Auroral Substructures

Figure 1 shows auroral images taken by HST-STIS on December 6, 2016 of Jupiter's south pole. There are three HST visits on this day. Figures 1a–1d are 10-min images extracted from the second 41-min visit, and Figures 1e and 1f are 10-min images extracted from the first and third visits, respectively. On the dawn side, a double-arc feature (highlighted by white arrows in Figure 1a) is observed at longitude around ∼ 60° in the left-hand Jupiter System III (S3LH) coordinates and extends over ∼10° in longitude. The equatorward arc (marked as Arc I) is located at ∼2° equatorward of the mean reference oval (cyan dashed curve) obtained by Bonfond et al. (2012). The poleward arc (Arc II) was dynamically evolving and faded at the end of HST visit 2 (Figure 1d).

The three keograms in Figure 2 show the time evolutions of auroral brightness of the two arcs along latitudes at three longitudes (54°, 57°, and 63°, highlighted by three short red lines in Figures 1a–1d). Arc II lasted for a shorter duration at lower longitudes, revealing that the noon-side edge of Arc II was moving dawn-ward. Figure 2c shows that the two arcs moved equatorward by ∼1° at the longitude of 63° during this HST visit. The equatorward motion is clearly displayed in the line cuts through the keogram. Figure 2d shows two brightness profiles versus latitude at a longitude of 57° (near the center of the double-arc structure), that is, vertical cuts at two time moments in Figure 2b. The red and blue curves are the profiles

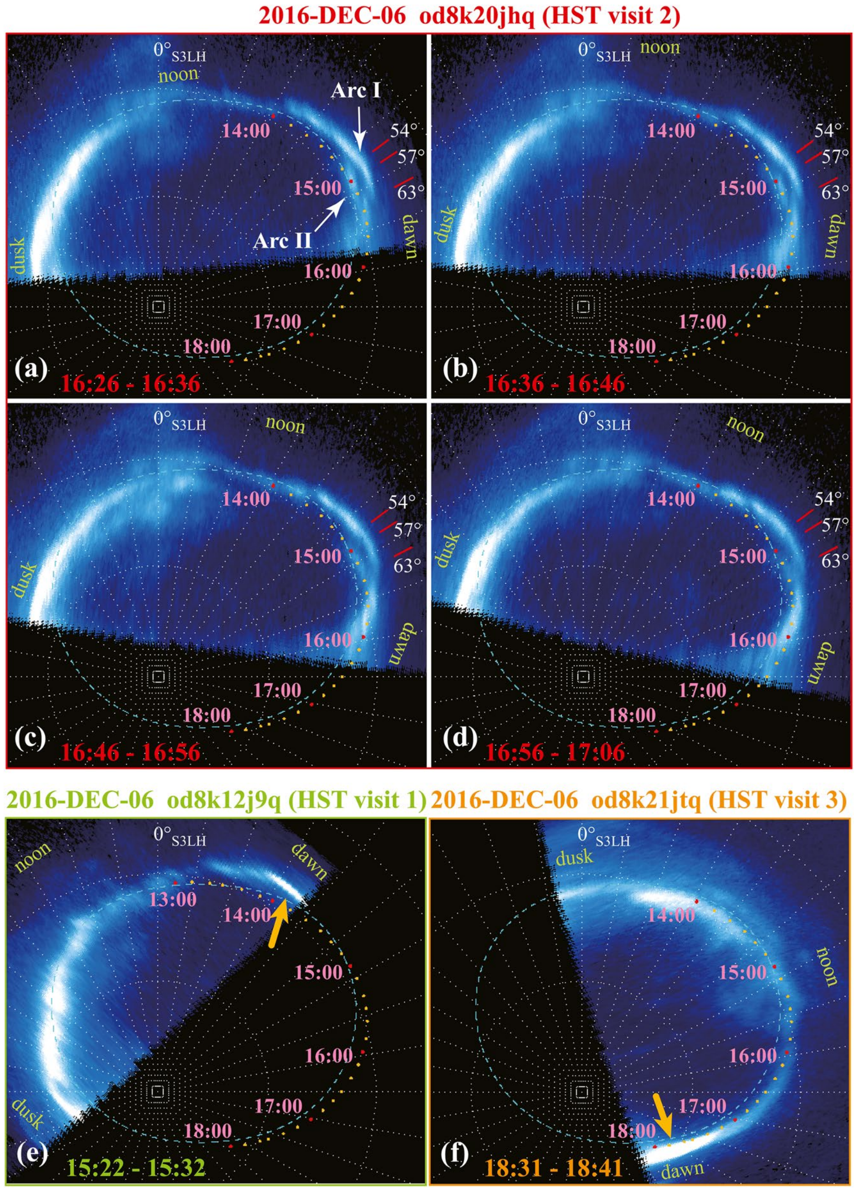

Figure 1. Images of Jupiter's southern aurora recorded by STIS on December 6, 2016. Each image is displayed in the corotating frame. These 10-min images were extracted from three 41-min long Hubble Space Telescope (HST) visits. The longitude is in the left-hand Jupiter System SIII (S3LH) coordinates. The dotted lines and circles are the grids of longitude and latitude and both are separated by 10°. The cyan dashed curve is the statistical average location of the auroral emission in Jupiter's southern ionosphere calculated by Bonfond et al. (2012). The yellow and red dots mark the magnetically mapped trajectory of the Juno spacecraft with a time separation of 10 min. The labeled times for the red footprints are the Universal Time at Jupiter, which was shifted to account for the ~49.3 min one-way light travel time between Jupiter and HST. The three short red lines at longitudes 54°, 57°, and 63° correspond to the three longitudes selected for Figure 2.

at 16:26 UT (Universal Time) and 16:41 UT, corresponding to the two arrows in Figure 2b. The red curve shows that the peak of Arc II was at the latitude of ~−68.9° and the peak of Arc I was at ~−67.2°. The Arc II moved to ~−68.5° within 15 min (blue curve) and then dimmed at this longitude, as shown in Figure 2b. The Arc I also moved equatorward simultaneously.

The labels below Figure 2d show the magnetically mapped positions in the equatorial plane along the cuts in the ionosphere at the longitude of 57°. The second and third rows are the values of the MLT and the distance (D) to Jupiter's center in the equatorial plane at 16:26 UT, and the fourth and fifth rows at 16:41 UT.

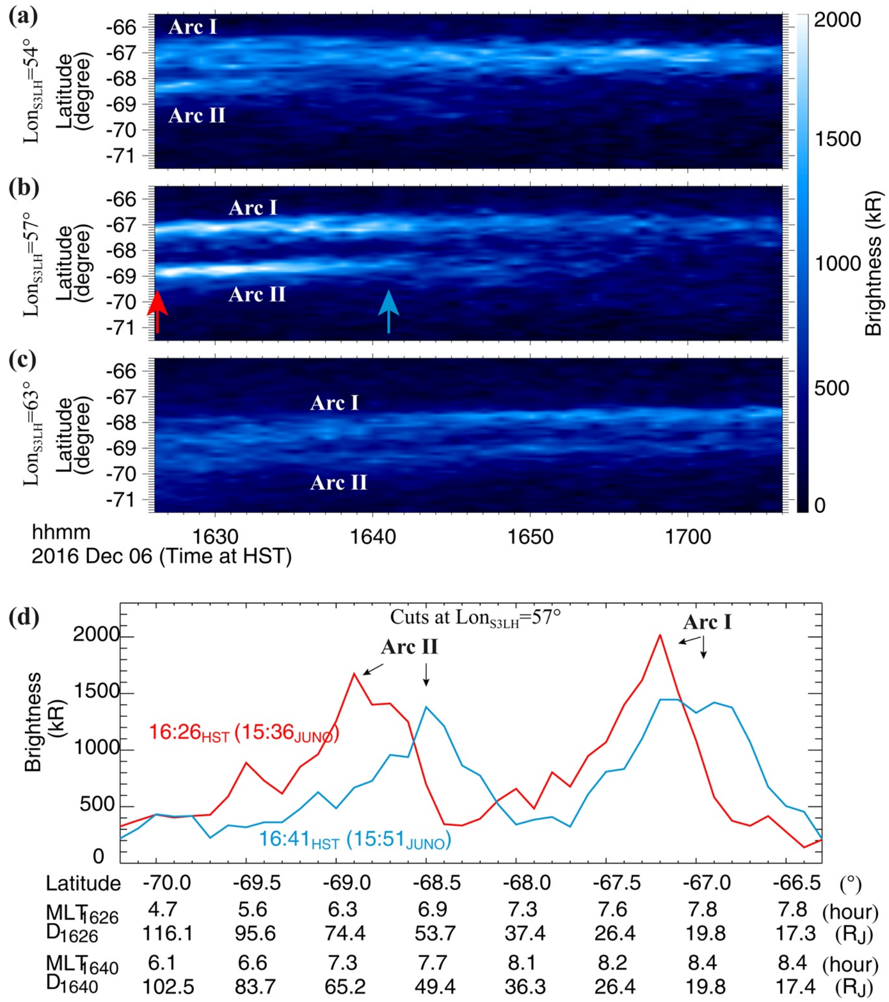

Figure 2. Brightness profiles of the double-arc auroral emission. (a–c) The keograms showing the auroral brightness varying with time as a function of latitude for SIII longitudes 54°, 57°, and 63°. (d) The brightness profiles at the longitude of 57° at two Hubble Space Telescope (HST) times of 16:26 UT (red) and 16:41 UT (cyan) as highlighted by the two arrows in panel (b). The labels below panel (d) are the magnetically mapped equator positions in the equatorial plane along the cuts in the ionosphere at the two HST times.

The mapped position of the peak of Arc II was at $D \sim 70\ R_J$ at 16:26 UT and shifted to $D \sim 49\ R_J$ at 16:41 UT. The mapped D-value of Arc I changed from ~22 R_J to ~20 R_J. It is worth noting that the mapping results are sensitive to the longitude of the subsolar position which is changing with time. The variation of the mapped D-value partially results from the changing of the subsolar point, that is, the different shape of the magnetosphere at different local times, for example, from 16:26 to 16:41 UT, the subsolar longitude changed from 1° to 10°, resulting the D-value variations from 74.4 (53.7) R_J to 65.2 (49.4) R_J at the latitude of −69.0° (−68.5°). The mapping position of the two arcs suggests that the radial distance in the magnetosphere between the sources of the two auroral arcs is larger than 20 R_J.

2.3. Analyzing In Situ Observations to Investigate the Magnetospheric Dynamics

Figure 3 shows in situ observations of the magnetosphere by the Juno spacecraft (see longer interval in Figure S1). Figure 3a provides the three magnetic components (B_r, B_θ, and B_φ) in spherical coordinates. The red (yellow) horizontal bar above Figure 3a marks the time interval of the second (third) HST visit. The one-way light travel time of ~49.3 min from Jupiter to HST during this interval has been taken into account. In the period of the second HST visit, the B_θ component showed an enhancement in magnitude from <2 nT to

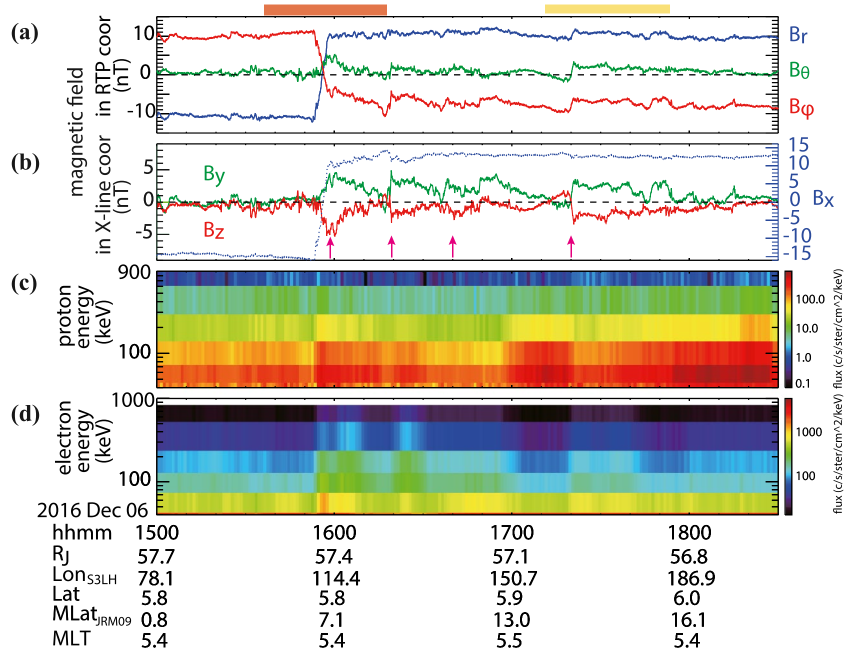

Figure 3. The magnetic field and energetic charged particles in Jupiter's magnetosphere observed by the Juno spacecraft. (a and b) Three components of the magnetic field in the RTP (Radius-Theta-Phi) spherical coordinates and the current sheet (or *X*-line) coordinates. (c and d) The ion and electron flux spectra obtained from the JEDI instrument.

>5 nT while the spacecraft crossed the current sheet as indicated by the sign reversals of B_r and B_φ. Before the current sheet crossing, the magnitude of $|B_\varphi|$ had an average of ∼10 nT that was comparable to $|B_r|$. $|B_\varphi|$ reduced to ∼7 nT on average after the crossing while the B_r component was still ∼10 nT. Both the large enhancement of the B_θ component and the rapid decrease of the $|B_\varphi|$ in a short time interval indicate the rapid reconfiguration of the magnetic morphology in the current sheet. A plausible interpretation is that magnetic reconnection was freshly triggered and produced reconnection fronts (Fu et al., 2013; Guo et al., 2019).

To examine the details of magnetic reconnection process, the magnetic field was transformed to current sheet coordinate system (the same as the *X*-line coordinate system that was used in reconnection regions on Saturn; Arridge et al., 2016; Guo, Yao, Wei, et al., 2018). The bend-back effect in the giant planetary magnetosphere gives rise to a permanent B_φ, which often leads to an ambiguity in identifying the Hall effect of reconnection. The new coordinates remove the bend-back effect by rotating the original axes with the bend-back angle, which is the arctangent of B_φ/B_r. The current sheet frame is obtained using the interval between 15:00 and 15:50 UT where the magnetic field was not highly perturbed (more information in Figure S2). The result is plotted in Figure 3b. The B_y component was anti-correlated to the B_z component, corresponding to the Hall magnetic field generated by the reconnection process (Arridge et al., 2016; Guo, Yao, Wei, et al., 2018; Øieroset et al., 2001). The energized ions and electrons accelerated by magnetic reconnection are shown in Figures 3c and 3d. As highlighted by the red arrows in Figure 3b, the enhanced $|B_z|$ and the corresponding Hall magnetic field B_y near the current center and in the "lobe" region (out of the current sheet, i.e., after the current sheet crossing) indicate that the spacecraft successively encountered the magnetic reconnection sites and recorded reconnection fronts. The pitch angle distribution of the accelerated electrons (see Figure S3) shows that the perpendicular flux is lower than those with small pitch angles, which could be the feature generated by the Fermi acceleration process in the reconnection jet front (Fu et al., 2013).

The spacecraft is located at ∼57 R_J, which is within the limits of the mapped location of Arc II (∼50–70 R_J). The MLT of Juno is ∼5.4 h, corresponding to the edge of the double arc region, as shown in the ionospheric footprint of Juno's trajectory around 16:00 UT in Figure 1. Although Juno did not penetrate the flux tube connecting the center of the double-arc region, we could infer that the reconnection process took place at the region mapped to Arc II. The respective perturbations of the B_θ (or B_z) component (as highlighted by red arrows Figure 2b) and multiple enhancements of electron energy fluxes after the current crossing indicate that the reconnection is drizzle-like or unsteady (Fu et al., 2013; Guo et al., 2019), which may lead to the motion of the edge of Arc II. Especially at the distinct B_z reversal marked by the fourth red arrow (Figure 3b), the dawn aurora significantly brightened along Juno's trajectory, as highlighted by the yellow arrow in Figure 1f, revealing a strong relationship between the aurora and reconnection. Considering the equatorward motion of the aurora, the B_θ reversal between 13:20 and 14:20 UT (see Figure S1) may also contribute to the auroral emission equatorward of Juno's footprints as highlighted by the yellow arrow in Figure 1e.

3. Discussion and Summary

We present observational evidence that a reconnection process resulted in the formation of an auroral arc poleward of a relatively stable aurora, together forming a double-arc auroral structure. During the observation, both arcs moved equatorward. Arc I was relatively stable compared to Arc II. Arc I was probably more mature than Arc II when the observation was made. Considering that Arc I was equatorward and its mapping position at equator plane was closer to the planets, one of the possible scenarios is that Arc I was generated by some magnetospheric activities before 16:00 UT, which was short-lived and not observed by Juno, or by activities that were observed ~10 h earlier in which magnetic reconnection participated as well (see Figure S1).

The signatures of the reconnection process, that is, the enhancement of energetic particles (Figures 3c and 3d) and the anti-correlation between B_y and B_z (Figure 3b), lasted for tens of minutes. During this interval, as indicated by the mapped trajectory in Figure 1, the spacecraft passed through the flux tubes linked to the auroral region within a large longitude range. The contemporaneous observations provide a direct connection between the drizzle-like magnetic reconnection process and the transient auroral arc.

As revealed by comprehensive observations from in situ spacecraft and ground auroral cameras at Earth, the connection between magnetic reconnection and auroral brightening is rather complicated. A double oval auroral distribution is a typical feature during a terrestrial substorm (Elphinstone et al., 1995). The terrestrial equatorial oval is associated with magnetospheric current disruption, while the poleward auroral oval is associated with the open-closed magnetic field line boundary, where magnetic reconnection takes place. Coordinated remote observations of auroras and in situ measurements in the magnetosphere show direct connections between auroral intensification and magnetic reconnection (Borg et al., 2007; Fuselier et al., 2007; Matar et al., 2020; Øieroset et al., 1997; Phan et al., 2003; Sergeev et al., 2019; Varsani et al., 2017). Although terrestrial substorms are traditionally caused by magnetospheric current disruption (Lui, 1996), reconnection may directly drive pseudo-breakup substorms (Pu et al., 2010). A recent study by Bonfond et al. (2021) has shown a Jupiter auroral process very similar to terrestrial pseudo-breakup. All in all, the intensification of the poleward auroral in the planetary ionosphere is a common feature of magnetic reconnection, and the present study provides direct evidence of such a process at Jupiter. Additionally, as suggested in Section 2.3, the single arc features at the dawn sectors (labeled by "dawn" in green in each plot) around 15:30 UT (Figure 1e) and around 18:40 UT (Figure 1f) can also be mapped to magnetic reconnection regions. Because of the mapping uncertainty and Alfvénic travel time, we do not expect an accurate correspondence between the observed reconnection and the auroral arc (Yao et al., 2021). However, the occurrence of successive reconnection events in a short time interval does indicate an ongoing magnetospheric activity at about the same time when the auroral arc was observed. The auroral structures and reconnection site are also roughly magnetically connected. Therefore, these observations are suggestive evidence of the connection between magnetic reconnection and the observed auroral arc, although the connection could be either direct or indirect (e.g., reconnection front or injection).

The equatorward motion of the auroral arc could be caused by two possible processes. The first possible natural cause is that the location of the source of the auroral arc moves toward the inner region of the magnetosphere. The second plausible mechanism is that reshaping of the magnetic configuration (e.g., by stretching of the magnetic field lines, which results in a poleward motion of the auroral structures; Chu et al., 2014; Haerendel, 2010; Liu et al., 2007; Radioti et al., 2017). Following the mapping, the equatorial footprint of Arc II moved more than 10 R_J (after considering the changing of the subsolar longitude) in the 15 min from 16:26 to 16:41 UT, which is significantly larger than the typical Alfvén speed (less than 300 km/s which corresponds to moving <4 R_J within 15 min) in Jupiter's magnetosphere (Bonfond et al., 2021; Kim et al., 2020). Based on the mapping, it is therefore unlikely that the change of auroral source location in the magnetosphere is the major reason for the equatorward motion of auroral arcs. Particularly, we would like to point out that the double-arc auroral structure may correspond to drizzle-like or localized magnetic reconnection, but not to a large magnetic field collapse which would lead to a dawn storm and potentially auroral injections (Bonfond et al., 2021; Yao, Bonfond, Clark, et al., 2020). Besides, the weakening of the bend-back effect by the reconnection process can result in a sub-corotation auroral as shown at Saturn (Yao et al., 2018), which may contribute to the motion of the edge of Arc II but hard to be ascertained by the limited information in this event. How the reshaping of the magnetic configuration affects the reconnection sites and results in the auroral arc motion in latitude is still an open question.

In summary, by analyzing the coordinated observations from the HST and Juno spacecraft, we, for the first time, investigate the evolution of the double-arc auroral structure on Jupiter. The poleward auroral arc was dynamically developing and both arcs were moving equatorward. Juno recorded unsteady reconnection sites in the magnetosphere that can account for the formation and rapid evolution of the auroral arc. This study highlights the importance of magnetic reconnection on driving transient auroral evolution near the main auroral emission.

Data Availability Statement

The HST data are publicly available at STScI (https://archive.stsci.edu/proposal_search.php?mission=hst&id=14634). All Juno data presented here are publicly available from NASA's Planetary Data System as part of the JNO-J-3-FGM-CAL-V1.0 (https://pds-ppi.igpp.ucla.edu/search/view/?f=yes&id=pds://PPI/JNO-J-3-FGM-CAL-V1.0), and JNO-J-JED-3-CDR-V1.0 (https://pds-ppi.igpp.ucla.edu/search/view/?f=yes&id=pds://PPI/JNO-J-JED-3-CDR-V1.0) data sets for the MAG, and JEDI instruments.

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