Nightside reconnection at Jupiter: Auroral and magnetic field observations from 26 July 1998

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[1] In this study we present ultraviolet and infrared auroral data from 26 July 1998, and we show the presence of transient auroral polar spots observed throughout the postdusk to predawn local time sector. The polar dawn spots, which are transient polar features observed in the dawn sector poleward of the main emission, were previously associated with the inward moving flow resulting from tail reconnection. In the present study we suggest that nightside spots, which are polar features observed close to the midnight sector, are related to inward moving flow, like the polar dawn spots. We base our conclusions on the near-simultaneous set of Hubble Space Telescope (HST) and Galileo observations of 26 July 1998, during which HST observed a nightside spot magnetically mapped close to the location of an inward moving flow detected by Galileo on the same day. We derive the emitted power from magnetic field measurements along the observed plasma flow bubble, and we show that it matches the emitted power inferred from HST. Additionally, this study reports for the first time a bright polar spot in the infrared, which could be a possible signature of tail reconnection. The spot appears within an interval of 30 min from the ultraviolet, poleward of the main emission on the ionosphere and in the postdusk sector planetward of the tail reconnection *x* line on the equatorial plane. Finally, the present work demonstrates that ionospheric signatures of flow bursts released during tail reconnection are instantaneously detected over a wide local time sector.

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1. Introduction

[2] *Vasyliūnas* [1983] proposed that an internally driven major reconfiguration process, similar to the solar wind driven terrestrial substorms, takes place in the Jovian magnetotail, characterized by mass loading of magnetic flux tubes. In the view of *Vasyliūnas* [1983] the tail configuration becomes stretched, magnetic tension can no longer balance the enhanced centrifugal forces and reconnection is initiated. Plasmoids are released downtail and the inner part of the magnetosphere relaxes to a less stretched configuration. Plasma flow bursts are directed away and toward the planet. Galileo detected signatures of tail reconnection in the Jovian magnetotail concentrated beyond 60 R_J in the predawn tail sector, occurring with a characteristic period of 2–3 days [e.g., *Russell et al.*, 1998; *Woch et al.*, 1998; *Kronberg et al.*, 2005; *Ge et al.*, 2007]. This periodicity has led to the suggestion that they are driven by the internal mass loading process described by *Vasyliūnas* [1983]. A recent study based on the analysis of Galileo magnetic field data revealed additional reconnection signatures particularly in the premidnight local times [*Vogt et al.*, 2010]. A statistical analysis of all the reconnection events did not show a distinct periodicity and the authors argued that the reconnection signatures in Jupiter's magnetotail are not necessary triggered by internal processes and they could be at least partly influenced by external factors such as magnetospheric interaction with the solar wind.

[3] Magnetic reconnection at Jupiter's magnetotail produces an auroral signature in Jupiter's ionosphere. The emissions located poleward of the main oval, the polar emissions, are suggested to be magnetically connected to the outer magnetosphere and possibly related to a sector of the Dungey and/or Vasyliūnas cycle flows [*Cowley et al.*, 2003; *Grodent et al.*, 2003b]. Auroral observations have shown the occasional appearance of "multiple dawn arcs" taking the form of parallel arc structures located poleward of the main emission in the dawn sector [*Grodent et al.*, 2003a] and "nightside polar spots," isolated spots appearing in the

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dusk-midnight sector, poleward of the main oval [*Grodent et al.*, 2004]. Given their observed location and properties the multiple dawn arcs and the nightside spots were proposed to be triggered by reconnection processes in the Jovian magnetotail. A recent analysis based on the 2007 Hubble Space Telescope (HST) data set [*Radioti et al.*, 2008] revealed the presence of "polar dawn spots" consisting of transient auroral emissions in the polar dawn region, with a characteristic recurrence period of 2–3 days. Because of their periodic recurrence and observed location, the polar dawn spots were interpreted as auroral signatures of internally driven magnetic reconnection in the Jovian magnetotail. Particularly, the polar dawn spots were associated with the inward moving flow bursts released during magnetic reconnection in Jupiter's tail [*Radioti et al.*, 2010]. The authors based their conclusions on a model adapted from the terrestrial case, according to which moving plasma flow is coupled with the ionosphere by field-aligned currents, giving rise to auroral emissions. The association of the polar dawn spots with tail reconnection was further confirmed by *Ge et al.* [2010]. The authors magnetically mapped tail reconnection events into Jupiter's ionosphere, by tracing field lines using an updated Khurana's Jovian magnetosphere model including the external field and the effects of the swept back configuration of tail field lines.

[4] In the present study we examine a unique set of near simultaneous HST (UV) and Galileo (magnetic field) observations on 26 July 1998 in order to determine the triggering mechanism of the nightside spots observed in the UV. We magnetically map the ionospheric locations of the spots to the equator and compare the mapped source location to Galileo's position in the equatorial plane. We additionally take advantage of the simultaneous UV and IR observations to examine for the first time possible IR auroral signatures of tail reconnection. Finally, we discuss the local time extent of the auroral footprints of tail reconnection as it has been revealed by HST.

2. UV and IR Aurora and in Situ Magnetic Field Measurements on 26 July 1998

[5] Figure 1 shows the FUV auroral emissions at the north pole of Jupiter measured by HST/STIS on 26 July 1998. The pixel resolution is 0.024 arcsec and dark count subtraction, flat fielding, and geometric correction have been applied [e.g., *Grodent et al.*, 2003a]. The three images captured on 26 July 1998 are taken within a time interval of ~1 h and ~10 min. Some of the main auroral features such as the main and polar emissions are indicated for reference on the top image. At 1351 UT we do not detect any transient spot which resembles a signature of tail reconnection according to the current knowledge (polar dawn spot or nightside spot). The next two images, however, reveal the presence of three spots, all located poleward of the main emission but in different local time sectors. Spot a is located in the dawn sector and resembles a "polar dawn spot," which according to previous studies is associated with magnetic reconnection at the Jovian magnetotail and particularly with the inward moving flow released during the process [*Radioti et al.*, 2008, 2010]. Moving toward midnight we observe a less discernible spot, spot b. Finally, spot c, located in the premidnight sector resembles the "nightside polar spot," which was reported by *Grodent et al.* [2004] and was related to tail reconnection. The nightside spots in *Grodent et al.* [2004] are estimated to originate from beyond 100 R_J in the premidnight sector of the magnetotail, their emitted power varies between 1.5 and 4 GW and their duration ranges between 5 min and 1 h. The 26 July 1998 data set, presented here, consists only of 3 images and therefore we cannot derive the duration of the spots and the time variations of the emitted power. However, the spots are observed in two images 7 min apart, suggesting that their lifetime is minimum 7 min. The auroral image taken at 1447 UT (Figure 1) shows the spots with the maximum emitted power, which is ~1.8 GW, 0.1 GW, and 0.8 GW, for the spots labeled a, b, and c, respectively. By emitted power we mean the UV power emitted by the H Ly α line and H_2 Lyman and Werner bands.

[6] Figure 2 shows three of the IR images taken on 26 July 1998, with the NSFCAM instrument [*Shure et al.*, 1994] on the NASA Infrared Telescope Facility using a 0.04 μm wide filter centered on 3.43 μm, a strong emission line of the H_3^+ molecular ion. Standard data reduction, including sky subtraction, bad pixel removal and flat fielding, was performed as described by *Satoh and Connerney* [1999]. The images are created from eight subimages dithered on the detector chip, then combined to form a complete image. Here we show 3 images at 1325, 1339 and 1342 UT where the bright spot is evident at 1339 UT. Next to the second panel in Figure 2 we show an enlarged area which is constructed by subtracting the image in the third panel (at 1342 UT) from the image in the second panel (at 1339 UT) and thus bringing up the bright polar spot d. The brightness of the spot is about 114% that of the immediately surrounding main emission and it lasts a couple of minutes, based on the analysis of the subimages taken every 20 s, which are used to create the images shown in Figure 2. The bright spot in IR appears within an interval of 30 min of the UV spots. It is located poleward of the main emission in the postdusk local time sector a couple of hours earlier in local time compared to spot c in UV.

[7] On 26 July 1998, Galileo was located in the premidnight sector and detected a signature of inward (planetward) moving flow. Figure 3 presents magnetic field measurements taken by Galileo along the inward moving flow released during tail reconnection on 26 July 1998 between 2000 and 2100 UT, a few hours later than the auroral observations. Unfortunately, there are no auroral observations between 2000 and 2100 UT. Figure 3a shows B_θ, the north-south component of the magnetic field, with the reconnection event interval indicated by the vertical dashed lines. The event was identified on the basis of the quantitative criteria of *Vogt et al.* [2010], requiring an increase in $|B_\theta|$. The inferred flow direction is inward because B_θ is positive. Figure 3b shows the radial B_r (dotted) and azimuthal B_ϕ (solid) components of the magnetic field, and Figure 3c shows its magnitude $|B|$. Figure 3d shows the field bend-back angle ($a\tan(\frac{B_\phi}{B_r})$), indicating the field sweep back with respect to the radial direction. The bend-back angle is usually negative since B_r and B_ϕ are of opposite

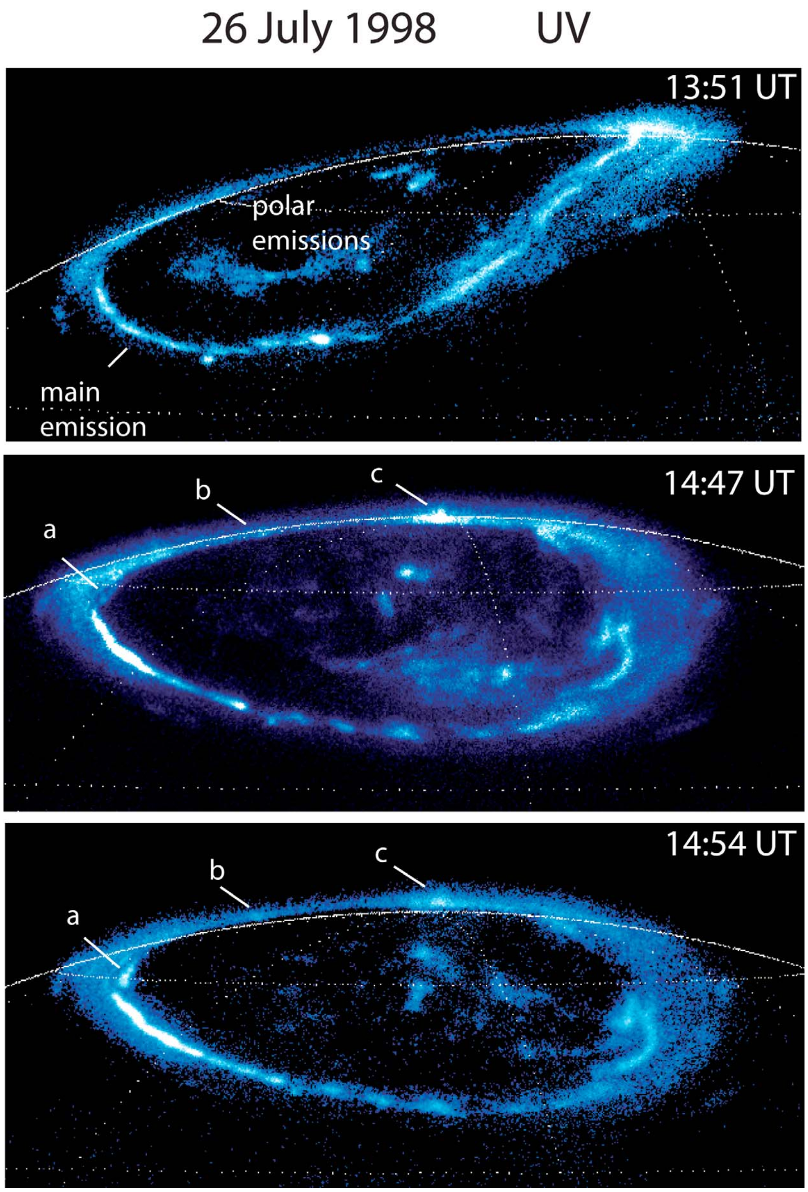

Figure 1. HST-STIS images showing the FUV auroral emission at the north pole of Jupiter between 1351 and 1454 UT on 26 July 1998. The S3 central meridian longitudes (CMLs) are 132° (first panel), 166° (second panel), and 170° (third panel). The main and polar emissions are indicated in the first panel. In the second and third panels, the letters a, b, and c point to polar auroral spots throughout the dawn to premidnight local times.

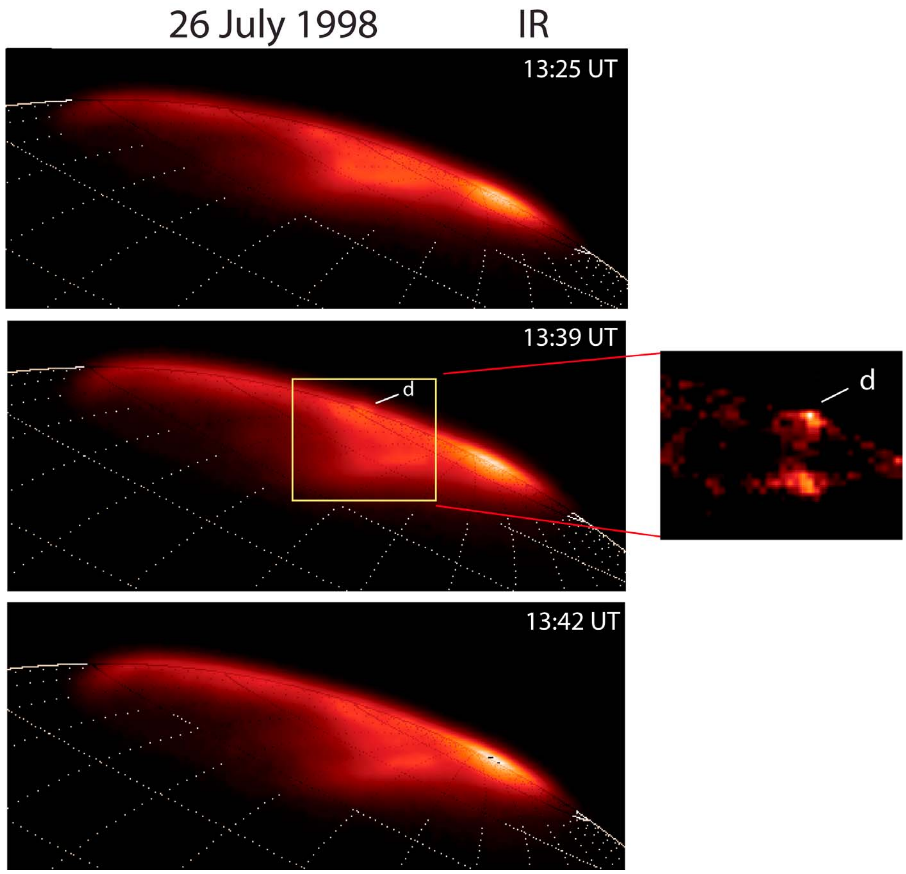

Figure 2. IR images taken with the NSFCAM instrument on the NASA Infrared Telescope Facility showing the auroral emission at Jupiter's northern hemisphere between 1325 and 1342 UT, on 26 July 1998. The S3 CML is ~130° for all three images. The second panel shows an enhancement at the midnight sector poleward of the main emission, possibly due to the appearance of a bright polar spot (indicated by d). The enlarged area from the second panel is constructed by subtracting the image in the third panel (at 1417 UT) from the image in the second panel (at 1413 UT), bringing up the bright polar spot (indicated by d).

sign, because the field is typically swept back. We can use changes of the bend-back angle as a proxy to the flow [*Vogt et al.*, 2010] through angular momentum conservation arguments. In the present example the dotted lines mark the increase of the bend-back angle (becomes more positive) during the event, indicating inward flow. The same interval indicates the region of upward field-aligned currents (FAC) possibly associated with auroral emissions.

[8] We magnetically map the location of the auroral spots on the equatorial plane in order to determine their equatorial origin. For the magnetic mapping we use a model described by *Vogt et al.* [2011]. The model is based on an iterative method to map equatorial field lines to the ionosphere assuming magnetic flux conservation between the equator and the ionosphere. It assumes an internal field model which includes a magnetic anomaly in the northern hemisphere [*Grodent et al.*, 2008] and accounts for the field bend-back in the equator using the bend-back model of *Khurana and Schwarzl* [2005]. The locations of the spots a, c, and d observed in UV and IR on 26 July 1998 are represented by the solid diamonds. Spot b according to the model of *Vogt et al.* [2011] maps approximately to the premidnight distant magnetotail. Specifically, the spot maps to beyond 150 R_J, which is the upper limit of the model's applicable range, and therefore its location cannot be precisely defined. Therefore, we do not present the mapped location of spot b in Figure 4. The extended boxes around the diamonds show an estimate of the uncertainty in defining the location of the spot on the original image. Thus they do not represent the exact size of the source region but the region within which the spots is likely to originate. The equatorial source region of the UV auroral spots (spots a and c) covers a large local time sector from predawn to premidnight (~8 h) and the bright spot in IR is located a bit earlier, between midnight and dusk. We additionally draw in Figure 4 a statistical *x* line derived by *Vogt et al.* [2010] based on a distribution of reconnection events with positive and negative B_θ signatures, indicative of inward and outward moving flow, respectively. The location of the *x* line seems to be consistent, especially in the post-midnight rather than in the premidnight sector, with previ-

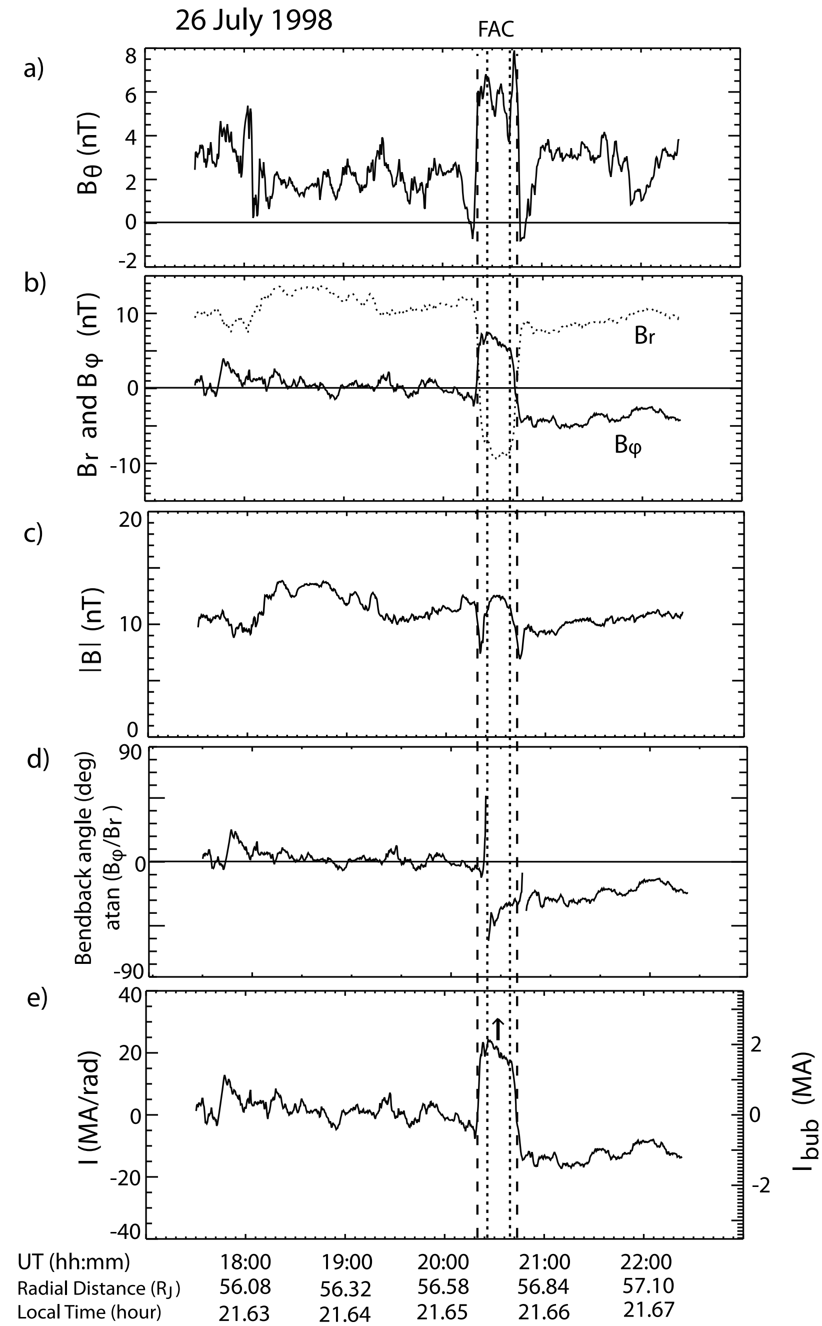

Figure 3. (a) North-south B_θ, (b) radial B_r (dotted line) and azimuthal B_ϕ (solid line) component of the magnetic field, and (c) its magnitude $|B|$ as a function of time on 26 July 1998 at ~56 R_J and at ~2139 local time. (d) Bend-back angle as a function of time for the same time interval. (e) Left axis shows the equatorward directed height-integrated Pedersen current per radian of azimuth I derived from the B_φ. The scale on the right axis indicates the equatorward directed height-integrated Pedersen current integrated over the size of the flowing bubble I_{bub} for 5 R_J azimuthal extent of the bubble. The dashed lines show the interval where Galileo measures the inward moving flow, the dotted lines indicate the field-aligned region, and the arrow indicates the direction of the field-aligned current (upward).

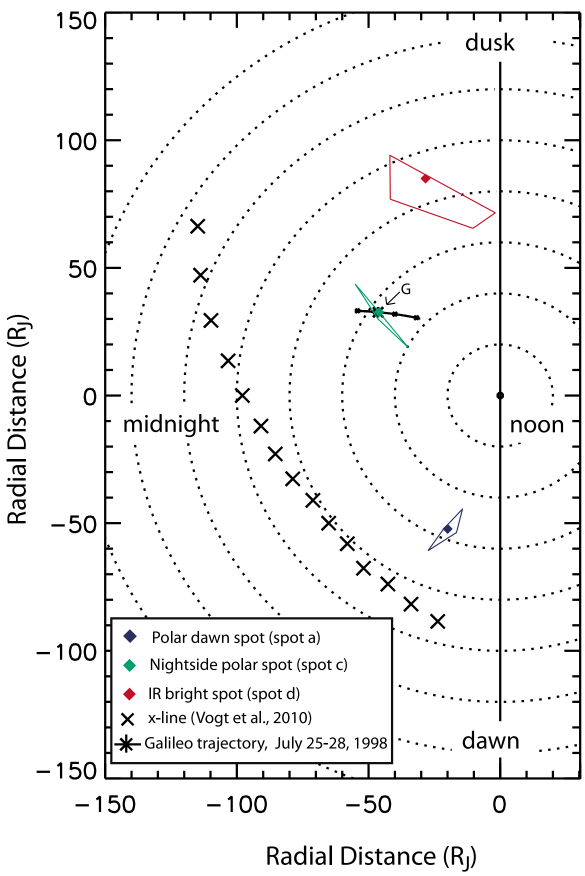

Figure 4. The solid line shows Galileo trajectory on the equatorial plane on 25–28 July 1998, with the Sun to the right and Jupiter in the center. The asterisk marked with "G" indicates the location of Galileo on 26 July 1998 at 2000–2100 UT when it detected the inward moving flow. The solid diamonds indicate the equatorial magnetically mapped locations of the auroral spots observed in UV and IR on 26 July 1998, and the boxes around them represent an estimate of the uncertainty in defining the location of the spot on the original image. For the magnetic mapping we use a model described by *Vogt et al.* [2011]. The crosses indicate the statistical x line derived by *Vogt et al.* [2010] based on a distribution of reconnection events with positive and negative B_θ signatures, indicative of inward and outward moving flow, respectively.

ous estimations based on energetic particle measurements from Galileo [*Woch et al.*, 2002]. Planetward of the x line Galileo observed signatures of inward moving flow bursts [*Woch et al.*, 2002; *Kronberg et al.*, 2008; *Vogt et al.*, 2010]. The equatorial origin of the auroral spots under study is located planetward of the x line supporting the scenario that these auroral emissions are associated with the inward moving flow released during tail reconnection. We also project Galileo's trajectory during 25–28 July 1998 on the equatorial plane in Figure 4, in order to compare the auroral observations with the in situ near simultaneous Galileo measurements. The asterisk marked with G shows the position of Galileo when it measured the flow burst event on 26 July 1998. The nightside polar spot magnetically maps very close to the observed flow suggesting that the auroral emission was triggered by the inward plasma flow.

[9] We follow the procedure suggested by *Radioti et al.* [2010] to derive the emitted power from the magnetic field measurements along the flow bubble, measured by Galileo. The analysis is based on the bubble model, which was initially introduced for the Earth [*Chen and Wolf*, 1993] and adapted for Jupiter [*Radioti et al.*, 2010]. According to this model a moving flow bubble (plasma flow burst released at the reconnection site) is coupled with the ionosphere by field aligned currents (FACs), giving rise to auroral emissions. The configuration of the FAC responsible for auroral emissions and the currents flowing along the bubble have been previously illustrated by *Radioti et al.* [2010, Figure 4]. We use Ampére's law in order to estimate the equatorward height-integrated Pedersen current per radian of azimuth, I (Figure 3e), flowing in the ionosphere at the feet of the field lines from the azimuthal component B_ϕ (Figure 3b). Because of current continuity I is equal to the net FAC per radian of azimuth flowing into the ionosphere between the pole and the observation point. A decrease in I while the observation point moves toward the equator implies that a similar amount of FACs leaves the ionosphere. Thus, we indicate with an arrow the direction of the FAC identified as upward (directed out of the ionosphere). We integrate the current I over the azimuthal size of the flowing bubble, in order to derive the current flowing at its flank, I_{bub}. This estimation is made for a 5 R_J azimuthal extent of the flow, derived from the mean V_ϕ = 236 km/s [*Vogt et al.*, 2010] and the duration of this event, ~25 min. The right axis of Figure 3e shows the value of I_{bub} for an azimuthal extent S = 5 R_J. During the time interval of the flow burst, the FAC at the flank of the bubble I_{bub} decreases from 2.14 to ~1.5 MA, meaning that a net FAC amount (ΔI_{bub}) of ~0.64 MA leaves the ionosphere (upward current). The upward directed FAC is carried by downward moving electrons and can power auroral emissions. Similarly to *Radioti et al.* [2010] we derive the voltage across the bubble, the available (generated) power, the dissipated power and finally the auroral emission. We assume that 1% to 10% of the total available power is dissipated in the ionosphere and 10% efficiency for converting injected power into FUV auroral power [*Grodent et al.*, 2001]. The derived values are summarized in Table 1. The emitted auroral power ranges between 0.44 and 4.4 GW for azimuthal extent of 5 R_J. The estimated power based on the concept of the bubble model has the

Table 1. Auroral Emitted Power Derived Based on the Bubble Model

Azimuthal Extent of Bubble	5 R_J
ΔI_{bub} (MA)	0.64
Voltage (KV)	700 ± 450
Available power (GW)	448 ± 228
Dissipated power[a] (GW)	4.48 ± 2.28 to 44.8 ± 22.8
Auroral emission[b] (GW)	0.44 ± 0.22 to 4.48 ± 2.28

[a]One percent to ten percent of the available power is assumed to be dissipated.
[b]Assuming 10% efficiency for converting injected power into FUV auroral power [*Grodent et al.*, 2001].

Table 2. Dates When We Observe Possible Signatures of Tail Reconnection Through the Midnight to Dawn Local Time Sector in the Northern Hemisphere

Date[a]	Polar Dawn Spots Seen	Nightside Spots Seen
26 Jul 1998	yes	yes
13 Aug 1999	yes	yes
21 Sep 1999	yes	no
14 Nov 2000	yes	no
14 Dec 2000	no	yes
16 Dec 2000	yes	yes
18 Dec 2000	no	yes
28 Dec 2000	no	yes
15 May 2007	yes	no
23 May 2007	yes	yes

[a]Only those data are considered whose geometry allows the study of the nightside aurora.

same order of magnitude as the observed nightside spot (~0.8 GW).

3. Discussion

[10] Nightside spots in UV have been previously associated with tail reconnection [*Grodent et al.*, 2004]. Here we take advantage of this unique set of near simultaneous HST (UV images) and Galileo (magnetic field observations) to confirm such an association and to determine the triggering mechanism of the nightside spots. Galileo observed the inward moving flow ~6 h after HST detected the auroral feature. We assume that the observed flow serves as an indication that reconnection initiated in that region and resulted in consecutive flow release. In other words, we propose that reconnection was initiated at ~56 R_J, ~21.6 LT and we detected first with auroral images a signature of tail reconnection, the inward moving flow, and then with Galileo when Galileo's trajectory took it through the right place. This assumption is based on previous Galileo observations, according to which the configuration that favors reconnection in the Jovian magnetotail is observed to last between 10 and 30 h [*Woch et al.*, 1999; *Kronberg et al.*, 2005]. All reconnection events do not have the same duration and thus long events are reported to last up to two Jovian rotations, during which several short-duration flow bursts are reported [*Krupp et al.*, 1998]. The nightside spot, spot c in the present example, magnetically maps very close to the location of the inward moving flow detected by Galileo on the same day. Additionally, the estimated auroral power based on magnetic field measurements along the flow event has the same order of magnitude as the observed emitted auroral power of the nightside spot. Accordingly, we suggest that the nightside spots, like the polar dawn spots, are triggered by the inward moving plasma flow released during magnetic reconnection at Jupiter's tail.

[11] It should be noted that the polar dawn spots have been observed with a characteristic recurrence period of 2–3 days and therefore associated with internally driven reconnection process [*Radioti et al.*, 2008]. However, from the example presented in the current study we cannot distinguish between internal or external driving of the reconnection associated with the nightside auroral spot. There are not daily auroral images during this time interval in order to detect a periodic recurrence of the nightside spot, neither is there further evidence that the near-simultaneous magnetospheric event observed by Galileo has internal or external origin.

[12] The present study reports for the first time a bright transient polar spot in IR, observed during the same time interval that transient polar spots are detected in UV. The short-lived bright spot (spot d) could be the ionospheric counterpart of inward moving plasma flow released during magnetic reconnection at Jupiter's tail. In the present study we show that the bright IR spot is observed poleward of the main emission in the ionosphere (Figure 2) and at pre-midnight sector planetward of the x line on the equatorial plane (Figure 4). The IR spot appears 30 min before the UV observations. This does not exclude a relation with the UV spots, since the lifetime of the UV spots can range between 10 min and 1 h [*Radioti et al.*, 2008]. While the UV emissions are excited directly, the IR emissions are thermal emissions and their intensity is proportional to the number density and temperature. H_3^+ is formed in the auroral ionosphere by impact ionization of molecular H_2 followed by conversion to H_3^+ via a rapid ion–molecule reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$. A sudden, localized influx of energetic electrons would cause a local increase in H_3^+ production, resulting in local brightening of the IR aurora. New, higher-resolution IR images will be needed to determine more conclusively whether similar bright spots in the IR could be signatures of reconnection.

[13] Auroral observations provide the opportunity to study the footprint of several magnetospheric processes simultaneously. While Galileo can observe local signatures of tail reconnection, auroral observations are able to reveal signatures of tail reconnection linked to magnetospheric regions far apart, giving information on the nature and the extent of the process. In the example under study, auroral footprints of tail reconnection (spots a, c, and possibly b) are observed simultaneously in a wide local time sector, which corresponds to ~8 h (~117 R_J arc length) in the equatorial plane. 26 July 1998 is not the only example where footprints of tail reconnection appear simultaneously in a large local time sector. In a previous work *Grodent et al.* [2004] reported on the simultaneous presence of bright (1.5 to 4 GW) transient spots in the midnight (nightside spots) and dawn (polar dawn spots) sector on 16 December 2000 and proposed that they are associated with the similar magnetospheric events which took place at different locations. Could this mean that tail reconnection at Jupiter occurs simultaneously across an extended local time sector? In order to examine the statistical significance of these observations we investigated all available HST data collected between 1998 and 2007. Only the data whose geometry allows the study of the nightside aurora are considered. Table 2 summarizes the dates when we observe possible signatures of tail reconnection through midnight to dawn local time sector in the northern hemisphere. In 3 out of 10 dates we detect spots only in the dawn sector, in 3 out of 10 dates we detect spots only in the nightside sector, and in 4 out of 10 dates we detect several spots in the nightside to dawn local time sector, like in the case presented here. It should be noted that both the polar dawn spots and the nightside spots are transient. The fact that we do not see them in a given interval when we have available observations it does not necessarily mean that they do not appear in that date. Even though a

preliminary look at the statistics shows that there is occasionally instantaneous release of moving flows along the extent of the *x* line at Jupiter's tail, our sampling is not statistically significant enough and therefore we cannot draw any firm conclusions. More observations favoring the nightside of the Jovian aurora could shed light on the extent of the *x* line and its physical implications.

4. Summary and Conclusions

[14] In the present study we suggest that nightside spots, like polar dawn spots, are related to inward moving flow released during tail reconnection. We base our conclusions on the unique set of HST-Galileo observations of 26 July 1998, during which HST observed a nightside spot magnetically mapped close to the location of an inward moving plasma flow, detected by Galileo on the same day. The emitted power derived from the magnetic field measurements along the flow bubble based on the concept of the bubble model has the same order of magnitude as the observed auroral power of the nightside spot, supporting an association of the moving plasma flow with the nightside auroral spot. Additionally we report for the first time a bright polar spot in IR. Even though further evidence is required in order to establish an association of the IR bright spot with tail dynamics, the present work shows that the spot appears during the same time interval in which the UV spots are observed, poleward of the main emission in the ionosphere and at premidnight sector planetward of the *x* line on the equatorial plane. Finally, the present work demonstrates that ionospheric signatures of moving plasma flows released during tail reconnection are detected over a wide local time sector. However, whether reconnection at Jupiter's tail can result in simultaneous release of flow bursts over a large local time sector, is a question still to be resolved by future missions to Jupiter and/or remote observations.

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