GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L03104, doi:10.1029/2007GL032460, 2008

Auroral polar dawn spots: Signatures of internally driven reconnection processes at Jupiter's magnetotail

A. Radioti,[1] D. Grodent,[1] J.-C. Gérard,[1] B. Bonfond,[1] and J. T. Clarke[2]

Received 25 October 2007; revised 10 December 2007; accepted 31 December 2007; published 7 February 2008.

[1] We report the presence of polar spots located in the dawn auroral region, based on the HST ACS 2007 campaign. We study the location of these features in the equatorial plane as well as their time scales and periodicities, based on a comprehensive series of images taken between February 21 and June 11, 2007. It is shown that the majority of polar dawn spots magnetically map to the dawn sector. Additionally, they occur quasi-periodically every 2–3 days, a periodicity observed for the first time in auroral features. Because of their mapped location and their periodic cycle, we interpret the polar dawn spots as signatures of internally driven magnetic reconnection in the Jovian magnetotail. **Citation:** Radioti, A., D. Grodent, J.-C. Gérard, B. Bonfond, and J. T. Clarke (2008), Auroral polar dawn spots: Signatures of internally driven reconnection processes at Jupiter's magnetotail, *Geophys. Res. Lett.*, *35*, L03104, doi:10.1029/2007GL032460.

1. Introduction

[2] Analysis of Hubble Space Telescope (HST) ultraviolet images has shown that Jupiter's auroral emissions are divided into three main components characterised by their locations, the physical processes from which they originate, and their time variations [*Grodent et al.*, 2003a, 2003b; *Clarke et al.*, 1998]. With increasing latitude these three components are: the satellite footprints, the main oval and the polar emissions (Figure 1). The satellite footprints are magnetically connected to the positions of the moons Io, Europa and Ganymede and therefore easy to identify. The main auroral oval is associated with the ionosphere-magnetosphere coupling current system which is related to the breakdown of corotation in the middle magnetosphere and maps to the equatorial plane between $\sim$15 and $\sim$40 R_J [e.g., *Cowley and Bunce*, 2001; *Hill*, 2001]. The polar emissions, located poleward of the main oval are magnetically connected to the outer magnetosphere and possibly related to a sector of the Dungey and Vasyliūnas cycle flows [*Cowley et al.*, 2003; *Grodent et al.*, 2003b]. The analysis of previous HST datasets occasionally showed the presence of multiple dawn arcs [*Grodent et al.*, 2003a] and isolated midnight spots [*Grodent et al.*, 2004] located poleward of the main oval. These polar auroral features were suggested to be triggered by reconnection processes in the Jovian magnetotail.

[3] In analogy with the solar wind driven terrestrial substorms, *Vasyliūnas* [1983] proposed that an internally driven major reconfiguration process takes place in the Jovian magnetotail. Mass loading of magnetic flux tubes leads to a stretched tail configuration. At some point the magnetic tension can no longer balance the enhanced centrifugal forces and reconnection is initiated. As a consequence, plasmoids are released downtail and the inner part of the magnetosphere relaxes to a less stretched configuration. Bursty flows are directed away and towards the planet. The Galileo spacecraft detected signatures of such substorm-like events concentrated beyond 60 R_J in the predawn tail region sector, occurring with a characteristic period of 2–3 days [*Krupp et al.*, 1998; *Woch et al.*, 1998, 1999, 2002; *Louarn et al.*, 1998; *Russell et al.*, 1998, 2000; *Kronberg et al.*, 2005, 2007]. This periodicity has led to the suggestion that they are driven by the internal mass loading process described by Vasyliūnas.

2. Characteristics of the Polar Dawn Spots

[4] This work is based on FUV images acquired with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). The dataset includes images between 21 February 2007 and 11 June 2007. Each set of observations (HST orbit) lasts $\sim$45 minutes, during which consecutive images are taken every 2–3 minutes. Occasionally more than one set of sequential observations has been obtained during the same day, and the maximum observational time coverage per day is 3 hours. This dataset makes it possible for the first time to study the timescales and periodicities of the auroral features, ranging from a few minutes to a few days. The angular resolution of the images is 0,08 arcsec FWHM point spread function. We applied a dark count substraction, flat fielding, and geometric correction to all the images [e.g., *Grodent et al.*, 2003a]. The determination of the planetary center on the images required for the polar projections was provided by an automatic limb fitting procedure [*Bonfond*, 2007].

[5] Figure 1 shows two HST-ACS raw images of Jupiter's northern aurora taken on June 15 and March 5, 2007 at different central meridian longitudes (CML). The main auroral features, i.e., the main oval, Io footprint and the polar emissions are indicated by the arrows. At the dawn side, isolated spots are observed poleward of the main oval and equatorward of the dark region, a region almost devoid of auroral emission. Figure 2 shows polar projections of a sequence of images taken every 7–10 minutes on March 5, 2007. The polar dawn spots are marked by the arrows and are named with the letters a, b, c, d. It is shown that during the 26-minute time interval the existing polar dawn spots disappeared (a and c spots) while a new one appeared

[1]Laboratoire de Physique Atmosphérique et Planétaire, Institut d'Astrophysique et de Géophysique, Université de Liège, Liege, Belgium.
[2]Center for Space Physics, Boston University, Boston, Massachusetts, USA.

0094-8276/08/2007GL032460$05.00

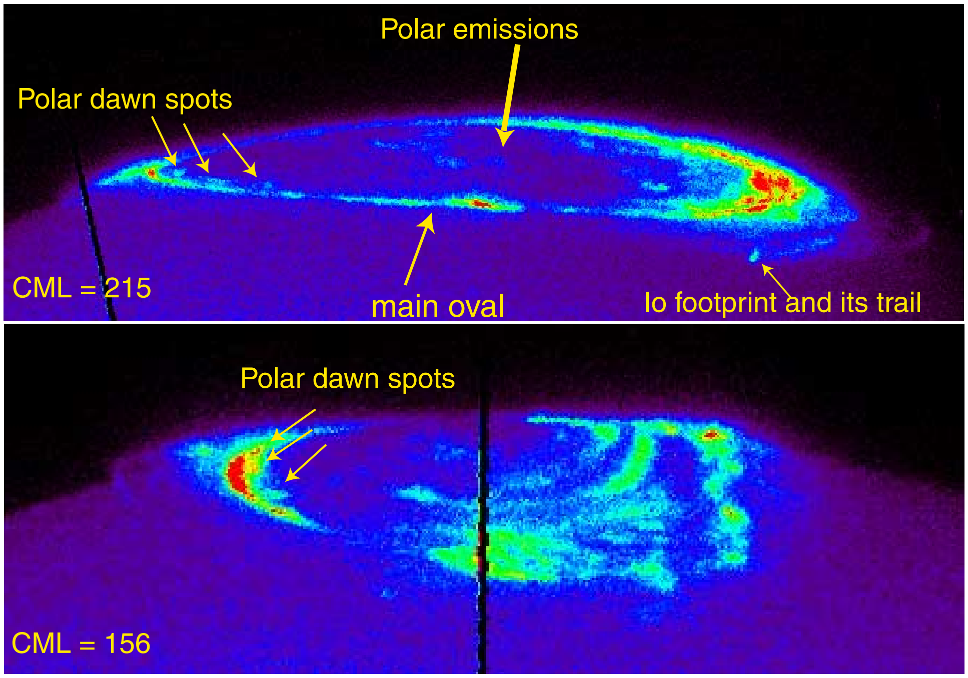

Figure 1. Raw HST-ACS images showing the FUV auroral emission at the north pole of Jupiter, taken (top) on 15 May 2007 and (bottom) on 5 March 2007. The arrows indicate the main auroral features: the main oval, the Io footprint and its trail, the polar emissions and the polar dawn spots.

(d spot). The location of the observed polar dawn spots is close to the theoretical projected location of the Vasyliūnas-cycle tail X-line in the ionosphere as suggested by *Cowley et al.* [2003].

[6] We analysed the data obtained between February 21 and June 11, 2007. Polar dawn spots are observed on 17 out of 37 days. The spots last from 10 minutes to ~1 hour. Within this time period the emitted power of a typical spot, such as spot "c" in Figure 2 can reach 1 GigaWatt above the background emission. The maximum brightness is ~250 kR above the background emissions, which corresponds to an input energy flux of 25 mWm^{-2}. The spatial dimensions of the spots, are typically ~3000 × 1000 km and they are located ~1200 km poleward of the central position of the main oval. The spots are corotating with the planet, since their position in S3 longitude and latitude remains almost constant over the observed time period.

[7] Earlier studies of polar spots such as the multiple dawn arcs [*Grodent et al.*, 2003a] and the midnight spots [*Grodent et al.*, 2004], were limited to single cases, because of the restricted HST data coverage. With the 2007 HST dataset we can now examine several cases of polar dawn spots, locate their magnetospheric source region, and describe their occurrence with time, essential for defining their origin.

3. Interpretation

3.1. Equatorial Plane Mapping

[8] We map the position of the polar dawn spots from the ionosphere to the equatorial plane using the VIP4 magnetic field model [*Connerney et al.*, 1998], even though it is known to become inaccurate beyond the orbit of Io, especially for the radial distance rather than the longitude. Given the inaccuracy of the VIP4 model we consider the mapped position as an approximation. The histogram in Figure 3 shows the local time interval to which the spots map, during each day of observation. Since the polar dawn spots are corotating with the planet, their position in local time changes with time. The histogram shows the local time interval the polar dawn spots cover during each day of observation. The majority of the spots are observed between 04:00 and 09:00 LT.

[9] The bottom plot of Figure 3 shows an equatorial view of the source region of the polar dawn spots presented by the dashed area. The region is constrained by the 04:00 and 09:00 LT meridians, the range to which the majority of these events maps. It can not be ascertained whether spots appear before 04:00 LT (dashed line meridian) or not, because of the limited HST viewing geometry. Since the main oval is thought to map to 15–40 R_J [*Cowley and Bunce*, 2001], the polar dawn spots located poleward of the main oval are expected to be magnetically connected to the equatorial plane beyond these distances. The dotted region in Figure 3 shows the local time sector, where Galileo measurements in the equatorial plane revealed evidence of spontaneous reconnection. Signatures of these substorm-like events are predominantly observed in the predawn region between 00:00 and 04:00 LT beyond 60 R_J [*Krupp et al.*, 1998; *Woch et al.*, 1998, 2002; *Russell et al.*, 1998, 2000; *Kronberg et al.*, 2005]. However, given the limitation of the Galileo coverage in the dawn sector beyond 40 R_J, it can not be ascertained whether substorm-like events occur in the dawn sector after 04:00 LT. Figure 3 shows that the region magnetically connected to the polar dawn spots is located near the observed substorm-like events.

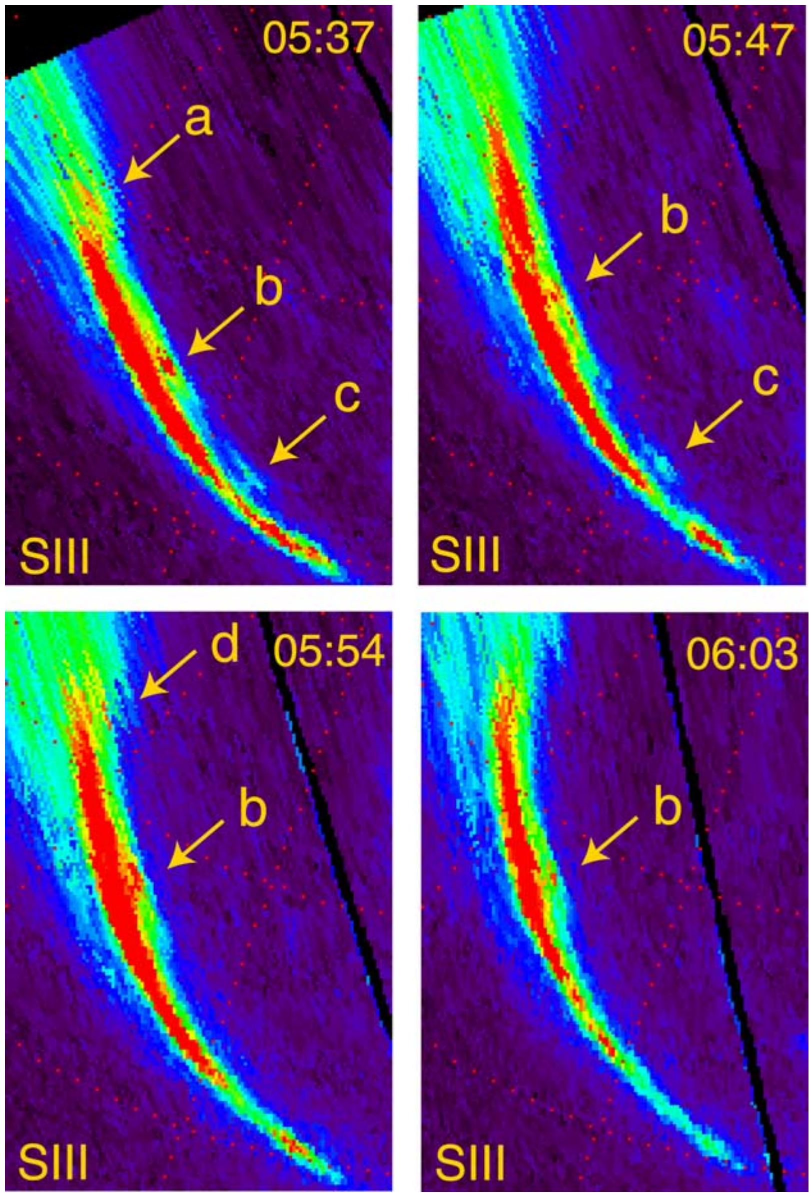

Figure 2. Polar projections of a time sequence of auroral images at the north pole of Jupiter, taken on 5 March 2007, showing the evolution of the polar dawn spots. The spots are marked with the letters a, b, c, d. The limb brightening is not taken into account for the image projection.

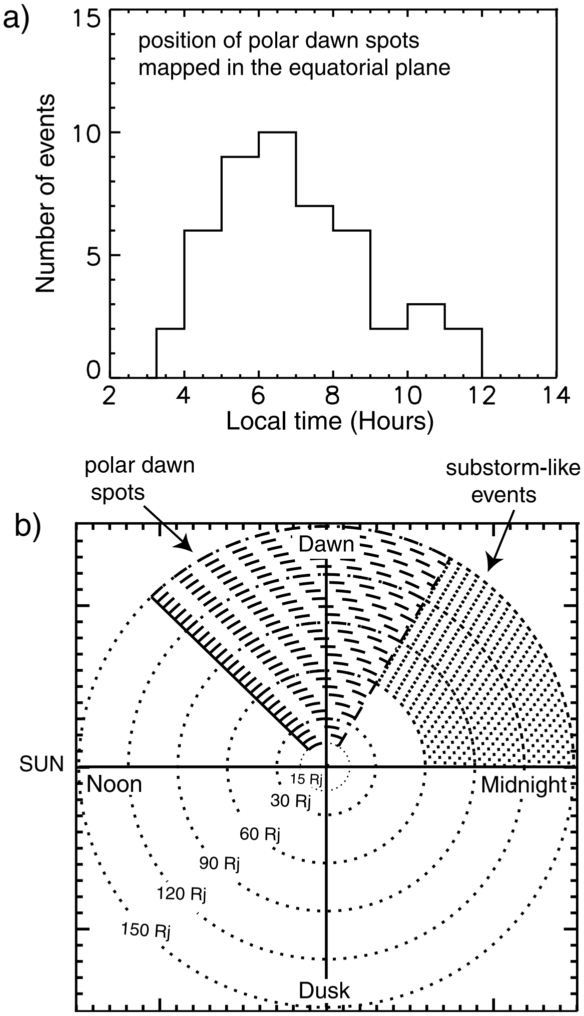

Figure 3. (a) Histogram showing the local time interval to which the polar dawn spots map during each day of observation. The statistical analysis is based on images taken on 17 different days between 21 February and 11 June 2007. The VIP4 magnetic field model [*Connerney et al.*, 1998] is used for the magnetic mapping from the ionosphere to the equatorial plane. (b) The dashes show the equatorial view of the polar dawn spots' source region. The local time meridians that define the boundaries of this region are 09:00 and 04:00 LT, between which the majority of the spots map, according to the histogram (Figure 3a). Due to the limited HST viewing geometry, it can not be ascertained whether polar spots are observed before 04:00 LT (meridian by dashed line). The dotted region shows the local time sector beyond 60 R_J where signatures of reconnection events (substorm-like events) are observed in the equatorial plane [*Krupp et al.*, 1998; *Woch et al.*, 1998, 2002; *Russell et al.*, 1998, 2000; *Kronberg et al.*, 2005]. Given the limitation of the Galileo coverage in the dawn sector beyond 40 R_J it can not be ascertained whether substorm-like events occur after 04:00 LT.

[10] Galileo measurements of the ion and electron energy spectra during the Jovian substorms showed evidence of heated and accelerated plasma during the reconnection process [*Woch et al.*, 1999]. Plasma heated in the reconnection process could be the source population of the polar dawn spots. Part of the heated plasma is carried away by the plasmoid release, and part of it is directed towards the planet. A statistical study based on Galileo observations revealed the presence of inward and outward burst flows beyond 60 R_J, associated with the reconnection x-line [*Woch et al.*, 2002]. The plasmoid cannot be directly related to the polar auroral features, because it is magnetically disconnected from the planet. However, heated plasma precipitating in field-aligned current sheets, which couple the changing angular momentum of the flux tubes between the magnetosphere and the ionosphere, could drive auroral emissions, by analogy with terrestrial substorms [*Baker et al.*, 1996]. We suggest that the polar dawn spots magnetically connected to 04:00–09:00 LT are related to precipitated heated plasma that resides on flux tubes which take part in the relaxation process governing the region planetwards of the x-line.

3.2. 2–3 Day Periodicity and Timescales

[11] Figure 4 shows the days (including the average hour of day) that polar spots are observed as a function of time between 20 February and 10 March 2007. The interval during which polar dawn spots are observed has a characteristic recurrence period of 2–3 days. Between March 10 and June 11 there are not data available on every day. However, polar dawn spots were also observed during this time interval and their frequency does not rule out the 2–3 day periodicity. Such a periodicity has not been observed within the interplanetary medium and therefore can not be attributed to the solar wind - magnetospheric interaction. On the other hand, Galileo observations revealed a 2–3 day quasi-periodic occurrence of internally driven substorm-like events [*Woch et al.*, 1998; *Krupp et al.*, 1998; *Louarn et al.*, 1998; *Kronberg et al.*, 2005]. This periodicity was linked to the quasi-periodic transition between two basic states of the Jovian magnetosphere: the mass-loading phase characterised by a thick and quiet plasma sheet and the mass-release phase, associated with a thin plasma sheet and magnetic reconnection. The 2–3 days quasi-periodic cycle of the polar dawn spots, never observed before for auroral features, strongly supports a relation between the auroral spots and the internally driven processes in the Jovian magnetosphere.

[12] Apart from the periodicity, the timescales of the polar dawn spots and the substorm-like events show many similarities. The intervals during which polar dawn spots are observed can last up to 29 hours, based on the available observations (Figure 4). Similarly, the configuration that favors reconnection in the Jovian magnetotail is observed to vary between 10 and 30 hours [*Woch et al.*, 1999; *Kronberg et al.*, 2005]. Additionally, during a major reconfiguration event, smaller scale reconnection events lasting from minutes to few hours can occur [*Russell et al.*, 2000]. Similarly the polar dawn spots can last between 10 minutes and ~1 hour.

4. Conclusions

[13] Based on the HST ACS 2007 campaign we report the presence of polar dawn spots, auroral emissions located at ~1200 km poleward of the central position of the main oval

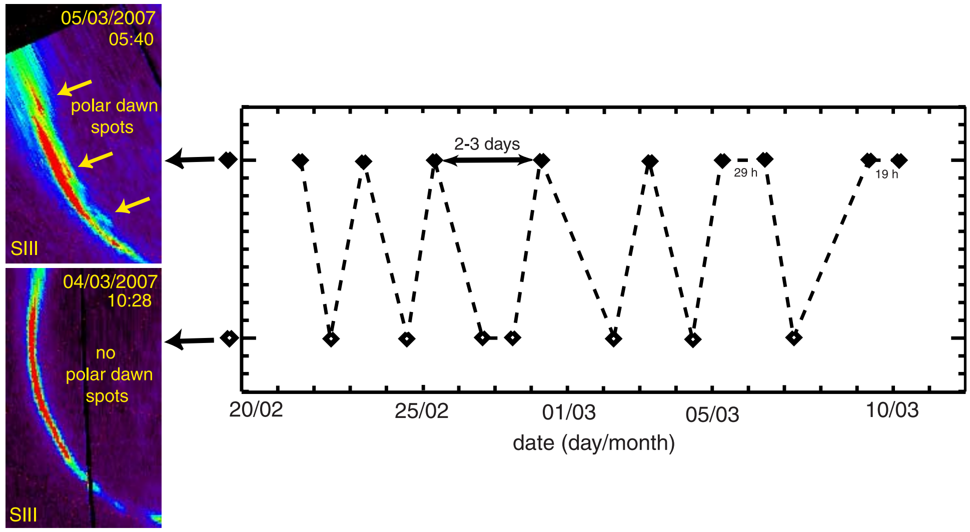

Figure 4. 2 to 3 days periodic occurrence of the polar dawn spots for the time frame of 20 February to 10 March 2007 with daily observations. The dates (day/month) along which auroral polar dawn spots are observed are indicated with filled diamonds, and those along which no auroral polar dawn spots are observed are shown with empty diamonds. The polar projections to the left demonstrate two representative examples during this time frame. The span intervals of 19 and 29 hours during which polar dawn spots are observed are also indicated.

and in corotation with the planet. It is shown that the majority of polar dawn spots magnetically map to the dawn sector, near the region of the observed location of the reconnection signatures. The 2–3 day quasi-periodic occurrence of the polar dawn spots matches the observed 2–3 day periodicity of the Jovian substorms and strongly suggests their association with the internally driven processes. Because of their observed location and their periodic cycle, we suggest that the polar dawn spots are related to the precipitated heated plasma during the reconnection process, and we interpret them as signatures of internally driven magnetic reconnection in the Jovian magnetotail.

[14] **Acknowledgments.** This work is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute (STScI), which is operated by AURA, Inc. for NASA under contract NAS5-26555. The research was supported by the Belgian Fund for Scientific Research (FNRS) and the PRODEX Programme managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office. Support is also acknowledged on grant HST-60-10862,01-H from the STScI to Boston University.

References

Baker, D. N., T. I. Pulkkinen, V. Angelopoulos, W. Baumjohann, and R. L. McPherron (1996), Neutral line model of substorms: Past results and present view, *J. Geophys. Res.*, *101*, 12,975–13,010.

Bonfond, B. (2007), The Io footprint: Analysis of Hubble Space Telescope observations of Jupiter's aurorae, M. S. thesis, Univ of Liege, Liege, Belgium.

Clarke, J. T., et al. (1998), Hubble Space Telescope imaging of Jupiter's UV aurora during the Galileo orbiter mission, *J. Geophys. Res.*, *103*, 20,217–20,236.

Connerney, J. E. P., M. H. Acuña, N. F. Ness, and T. Satoh (1998), New models of Jupiter's magnetic field constrained by the Io flux tube footprint, *J. Geophys. Res.*, *103*, 11,929–11,939.

Cowley, S. W. H., and E. J. Bunce (2001), Origin of the main auroral oval in Jupiter's coupled magnetosphere-ionosphere system, *Planet. Space Sci.*, *49*, 1067–1088.

Cowley, S. W. H., E. J. Bunce, T. S. Stallard, and S. Miller (2003), Jupiter's polar ionospheric flows: Theoretical interpretation, *Geophys. Res. Lett.*, *30*(5), 1220, doi:10.1029/2002GL016030.

Grodent, D., J. T. Clarke, J. Kim, J. H. Waite Jr., and S. W. H. Cowley (2003a), Jupiter's main auroral oval observed with HST-STIS, *J. Geophys. Res.*, *108*(A11), 1389, doi:10.1029/2003JA009921.

Grodent, D., J. T. Clarke, J. H. Waite Jr., S. W. H. Cowley, J.-C. Gérard, and J. Kim (2003b), Jupiter's polar auroral emissions, *J. Geophys. Res.*, *108*(A10), 1366, doi:10.1029/2003JA010017.

Grodent, D., J.-C. Gérard, J. T. Clarke, G. R. Gladstone, and J. H. Waite Jr. (2004), A possible auroral signature of a magnetotail reconnection process on Jupiter, *J. Geophys. Res.*, *109*, A05201, doi:10.1029/2003JA010341.

Hill, T. W. (2001), The Jovian auroral oval, *J. Geophys. Res.*, *106*, 8101–8107.

Kronberg, E. A., J. Woch, N. Krupp, A. Lagg, K. K. Khurana, and K.-H. Glassmeier (2005), Mass release at Jupiter: Substorm-like processes in the Jovian magnetotail, *J. Geophys. Res.*, *110*, A03211, doi:10.1029/2004JA010777.

Kronberg, E. A., K.-H. Glassmeier, J. Woch, N. Krupp, A. Lagg, and M. K. Dougherty (2007), A possible intrinsic mechanism for the quasi-periodic dynamics of the Jovian magnetosphere, *J. Geophys. Res.*, *112*, A05203, doi:10.1029/2006JA011994.

Krupp, N., J. Woch, A. Lagg, B. Wilken, S. Livi, and D. J. Williams (1998), Energetic particle bursts in the predawn Jovian magnetotail, *Geophys. Res. Lett.*, *25*, 1249–1252.

Louarn, P., A. Roux, S. Perraut, W. Kurth, and D. Gurnett (1998), A study of the large-scale dynamics of the Jovian magnetosphere using the Galileo plasma wave experiment, *Geophys. Res. Lett.*, *25*, 2905–2908.

Russell, C. T., K. K. Khurana, D. E. Huddleston, and M. G. Kivelson (1998), Localized reconnection in the near Jovian magnetotail, *Science*, *280*, 1061–1064.

Russell, C. T., K. K. Khurana, M. G. Kivelson, and D. E. Huddleston (2000), Substorms at Jupiter: Galileo observations of transient reconnection in the near tail, *Adv. Space Sci.*, *26*(10), 1499–1504.

Vasyliūnas, V. M. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. Dessler, pp. 395–453, Cambridge Univ. Press, New York.

Woch, J., N. Krupp, A. Lagg, B. Wilken, S. Livi, and D. J. Williams (1998), Quasi periodic modulations of the Jovian magnetotail, *Geophys. Res. Lett.*, *25*, 1253–1256.

Woch, J., et al. (1999), Plasma sheet dynamics in the Jovian magnetotail: Signatures for substorm-like processes?, *J. Geophys. Res.*, *26*, 2137–2140.

Woch, J., N. Krupp, and A. Lagg (2002), Particle bursts in the Jovian magnetosphere: Evidence for a near-Jupiter neutral line, *Geophys. Res. Lett.*, *29*(7), 1138, doi:10.1029/2001GL014080.

J. T. Clarke, Center for Space Physics, Boston University, 25 Commonwealth Avenue Room 506, Boston, MA 02215, USA.

B. Bonfond, J.-C. Gérard, D. Grodent, and A. Radioti, Laboratoire de Physique Atmosphérique et Planétaire, Institut d'Astrophysique et de Géophysique, Université de Liège, Alle du 6 Aôut, 17 Sart-Tilman, B-4000 Liège, Belgium. (a.radioti@ulg.ac.be)