Auroral signatures of multiple magnetopause reconnection at Saturn

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Received 23 July 2013; revised 20 August 2013; accepted 20 August 2013; published 6 September 2013.

[1] Auroral observations capture the ionospheric response to dynamics of the whole magnetosphere and may provide evidence of the significance of reconnection at Saturn. Bifurcations of the main dayside auroral emission have been related to reconnection at the magnetopause and their surface is suggested to represent the amount of newly opened flux. This work is the first presentation of multiple brightenings of these auroral features based on Cassini ultraviolet auroral observations. In analogy to the terrestrial case, we propose a process, in which a magnetic flux tube reconnects with other flux tubes at multiple sites. This scenario predicts the observed multiple brightenings, it is consistent with subcorotating auroral features which separate from the main emission, and it suggests north-south auroral asymmetries. We demonstrate that the conditions for multiple magnetopause reconnection can be satisfied at Saturn, like at Earth. **Citation:** Radioti, A., D. Grodent, J.-C. Gérard, B. Bonfond, J. Gustin, W. Pryor, J. M. Jasinski, and C. S. Arridge (2013), Auroral signatures of multiple magnetopause reconnection at Saturn, *Geophys. Res. Lett.*, *40*, 4498–4502, doi:10.1002/grl.50889.

1. Introduction

[2] Magnetic reconnection, the breaking and topological rearrangement of magnetic field lines in a plasma, is one of the most fundamental processes in planetary magnetospheric physics. Even though the investigation of magnetopause reconnection at Saturn started in the Voyager era, its significance is still under debate. Voyager observations showed reconnection signatures at Saturn's magnetopause [*Huddleston et al.*, 1997] and suggested that bursty reconnection similar to flux transfer events at Earth [*Russell and Elphic*, 1979] is not a significant mechanism at Saturn, because of the high magnetosonic Mach numbers which are reached close to Saturn. However, *Grocott et al.* [2009] demonstrated that reconnection is not suppressed by high magnetosonic Mach number at Earth. Additionally, Cassini plasma and magnetic field observations revealed signatures of reconnection at Saturn's magnetopause [*McAndrews et al.*, 2008]. On the other hand, *Masters et al.* [2012] suggested that only a limited fraction of the magnetopause surface can become open. Finally, recent studies indicated that reconnection plays a smaller role at Saturn than at Earth, in large-scale transport near the subsolar region of the magnetopause [*Lai et al.*, 2012].

[3] Auroral observations provide evidence of the significance of magnetopause reconnection at Saturn, as they capture the ionospheric response to dynamics of the whole magnetosphere. Theoretical and observational studies suggested that the quasi-continuous main UV auroral emission at Saturn is produced by magnetosphere-solar wind interaction, through the shear in rotational flow across the open closed field line boundary (OCFLB) [e.g., *Bunce et al.*, 2008]. Saturn's auroral morphology is, to a large extent, controlled by the balance between the magnetic field reconnection rate at the dayside magnetopause and the reconnection rate in the nightside tail [*Cowley et al.*, 2005]. Intensification of the prenoon auroral emission is suggested to be related to low-latitude reconnection, while a distinct spot-like emission poleward of the main auroral emission is associated with lobe reconnection [*Gérard et al.*, 2005; *Bunce et al.*, 2005]. Recently, Cassini's Ultraviolet Imaging Spectrograph (UVIS) revealed the presence of bifurcations of the main dayside auroral emission, which are interpreted as signatures of consecutive reconnection events at Saturn's magnetopause [*Radioti et al.*, 2011] and suggested that magnetopause reconnection can lead to significant increase of the open flux within a couple of days. Cassini multi-instrumental studies confirmed that the auroral arcs are related to newly reconnected field lines and suggested that bursty reconnection at Saturn is efficient at transporting flux [*Badman et al.*, 2013].

[4] At Earth, the reconnection process evolves in a transient manner with the occurrence of quasiperiodic bursts, known as flux transfer events [e.g., *Russell and Elphic*, 1979]. Ionospheric signatures of bursty magnetopause reconnection at Earth have been observed in the form of poleward-moving auroral structures (PMAF) [e.g., *Milan et al.*, 2000; *Sandholt and Farrugia*, 2008] and have been associated with mixed magnetospheric and magnetosheath plasma connected to field lines of newly opened flux produced by reconnection [*Lockwood and Wild*, 1993]. *Fasel* [1995] performed a statistical study of the properties of these auroral events, including a classification of the different types based on their brightenings history. They discussed the origin of multiple auroral brightenings in the context of multiple reconnection on the same flux tube. The present study provides the first report on multiple brightenings of the auroral bifurcations at Saturn, similar to those reported at Earth. However, it should be noted that the scales and dynamics

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0094-8276/13/10.1002/grl.50889

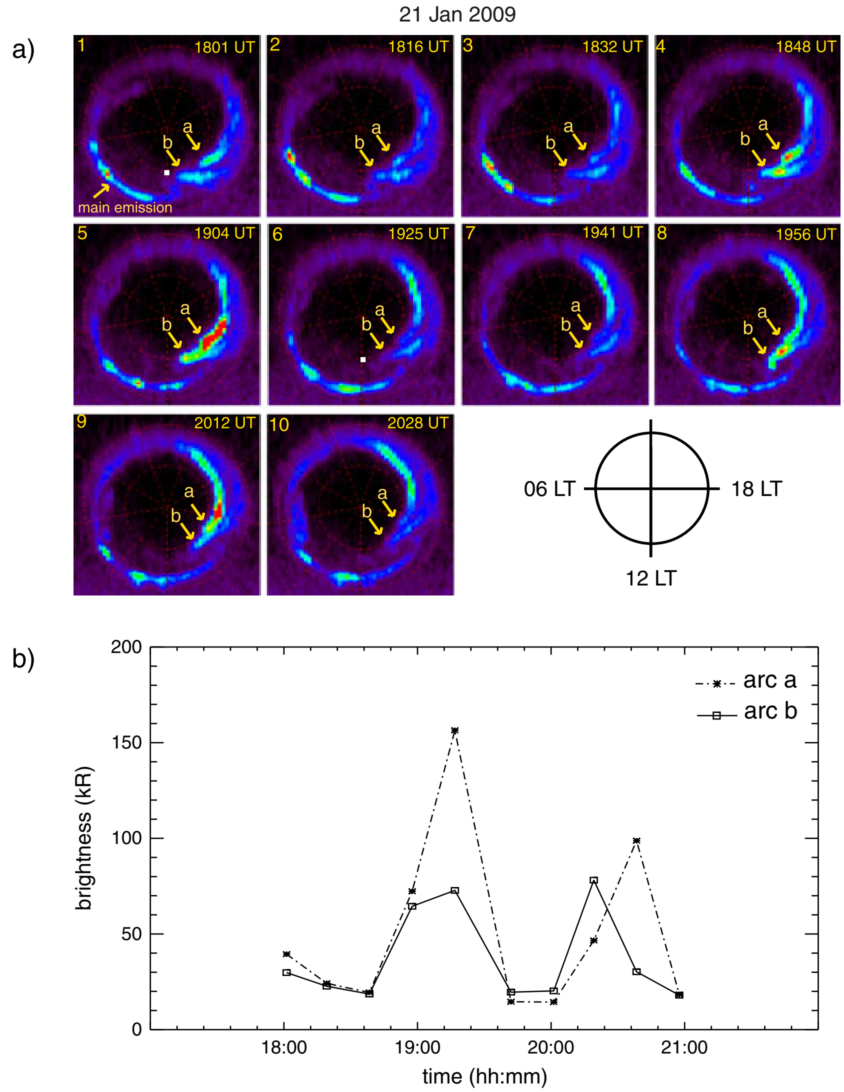

Figure 1. (a) A sequence of polar projections of Saturn's northern aurora obtained with the FUV channel of UVIS onboard Cassini. The first image starts at 1800 UT and the last one at 2025 UT on DOY 021, 2009. Noon is to the bottom and dusk to the right. The grid shows latitudes at intervals of 10° and meridians of 40°. The main emission associated with OCFLB is indicated on the first image. Arrows indicate the auroral structures (bifurcations) a and b which are discussed in the text as auroral signatures of reconnection. White squares on images 1 and 6 indicate the magnetically mapped location of Cassini at 1801 and 1925 UT. (b) Maximum brightness in kR (of total H_2) [*Gustin et al.*, 2012] of bifurcations a and b as a function of time during the displayed interval in Figure 1a.

of the two planets are different, and thus, a PMAF at Earth that lasts several minutes would correspond to a feature at Saturn which could last a few hours, considering the time is required for the newly opened field line to move across the magnetopause.

2. Multiple Reconnection Along the Same Flux Tube

[5] Figure 1a shows a sequence of polar projections of Saturn's northern aurora obtained with the FUV channel of the UVIS instrument [*Esposito et al.*, 2004] onboard Cassini on 21 January 2009. The projections are constructed by combining the slit scans using the method described by *Grodent et al.* [2011]. In the present sequence, the bifurcations (indicated by the arrows) rebrighten twice during the 2.5 h and reach their maximum quasi-simultaneously (Figure 1b). The brightenings are observed about 1 h apart, and the intensity varies by at least a factor of 10 over the 20 min interval between images 5 and 6. Additionally, the radial distance between the extremity of bifurcation b and the dayside emission is observed to slightly increase as a function of time from ~4.5° to 6° of latitude, while the motion and morphology of the bifurcations are also influenced by the rotation of the planet. The bifurcations here are observed to subcorotate with ~15% of the full planetary rotation (see additional material), consistent with their interpretation of being related to opened field lines. The motion of the bifurcations and that of the main emission are also discussed on the basis of a 6 h sequence in *Radioti et al.* [2011]. Bifurcations of the main emission at Saturn are observed in 6/16 dates analyzed so

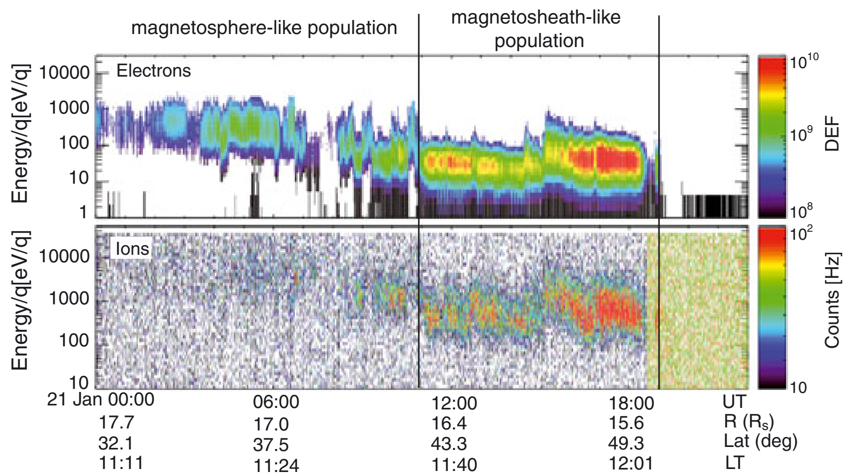

Figure 2. In situ Cassini Plasma Spectrometer observations for the 21 January 2009. (top) Electron differential energy flux (DEF) measured by ELS. (bottom) Ion counts measured by IMS.

far (37 data sets) [*Radioti et al.*, 2011]. Here we report that multiple brightenings occur in 3/6 dates when bifurcations are observed, all three cases in the northern hemisphere and the time intervals between two consecutive brightenings range between 60 to 75 min.

[6] We propose that the auroral bifurcations presented in Figure 1 are related to newly opened field lines generated by magnetopause reconnection. This is supported by simultaneous Cassini Plasma Spectrometer [*Young et al.*, 2004] observations which detected plasma originating from ongoing reconnection occurring along the magnetopause of Saturn at the time the auroral bifurcations are observed (Figure 2). Between ~1100 and 1900 UT Cassini passed through the magnetospheric cusp region. Reconnection creates newly opened magnetospheric field lines allowing magnetosheath plasma to enter the magnetosphere, through the cusp. The Electron Spectrometer (ELS) observed cold dense electrons, properties similar to that seen in the magnetosheath. The ion mass spectrometer (IMS) observed multiple "stepped" ion energy-latitude dispersions. An ion energy-latitude dispersion is a signature of the terrestrial cusp and is direct evidence for reconnection. Multiple dispersions with a "stepped" signature are indicative of the occurrence of multiple reconnection at the magnetopause. After 1900 UT, Cassini enters a region devoid of plasma. A multi-instrumental study supporting these conclusions is presented in detail by Jasinski et al. (in preparation, 2013). The evolution of magnetopause reconnection based among others on electron measurements and auroral bifurcations was also studied by *Badman et al.* [2013]. We magnetically map the location of Cassini on the ionosphere at 1801 and 1925 UT (white squares on images 1 and 6 of Figure 1) using a current sheet model, considering a magnetopause standoff distance of 22 R_S, a current sheet half thickness of 2.5 R_S and the current sheet scaling laws from *Bunce et al.* [2007]. The used model does not consider the reconfiguration of the magnetic field lines due to reconnection. At 1800 UT, Cassini's position was close to the auroral bifurcation, when the spacecraft observed signatures of multiple reconnection. At 1925 UT, the location of Cassini was beyond the region of the auroral bifurcations, indicative of a region devoid of plasma, as suggested by the electron and ion measurements. If the bifurcations existed a few hours earlier, based on their subcorotating motion (15%, which corresponds to ~5°/h), one would expect them to be located in the prenoon-noon sector during 1200–1600 UT, when Cassini crossed the reconnection region.

[7] We suggest that the multiple brightenings of the bifurcations are related to multiple reconnection along the same flux tube (Figure 3) as suggested for the terrestrial case [*Fasel et al.*, 1993]. Reconnection at site X1 results in the formation of new flux tubes CE and E′C′ which move away from the reconnection point. Because of the velocity of the newly created flux tubes, an induced electric field leads to the presence of polarized charges. Thus, a pair of field-aligned currents are generated by the discharge of polarization charges and flow along the sides of the flux tubes. Here we indicate only the upward currents (flowing from the ionosphere to the equator) associated with the auroral emissions $J_1^{||}$ flowing along the newly created flux

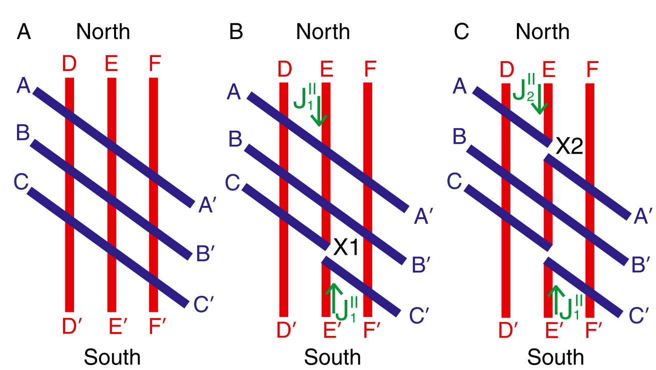

Figure 3. Schematic representation of time evolution of multiple reconnection along the same flux tube, adapted to Saturn from the terrestrial case [*Fasel et al.*, 1993]. Red and blue thick lines represent the planetary magnetic flux tubes and interplanetary magnetic flux tubes, respectively, as viewed from the Sun. X1 and X2 indicate two reconnection sites. $J_1^{||}$ and $J_2^{||}$ represent the upward field-aligned currents generated by the discharge of polarization charges and associated with auroral emissions.

tubes after reconnection at X1. These upward field-aligned currents create auroral brightening in the ionospheric end (E and E′) of the flux tubes in the northern and southern hemispheres. The auroral emission associated with these field-aligned currents is expected to fade unless there is an additional injection of field-aligned currents. A successive reconnection at site X2, (Figure 3c), will result in the formation of new flux tubes AE and CA′. The upward field-aligned currents $J_2^{\|}$ flowing along flux tube AE will create an additional brightening of the same auroral emission, as flux tube AE and the previous formed CE have the same ionospheric end (E). This would correspond to the bifurcations' brightening shown in panel 4 and 5 of Figure 1. The newly created flux tube CA′ is not connected to the ionosphere and thus is not expected to create auroral emission. In the southern hemisphere, an additional brightening of the bifurcation is not expected since the successive reconnection at site X2 does not result in the formation of new flux tubes with the same ionospheric foot at the previously formed flux tube E′C′.

[8] We propose that both bifurcations shown in Figure 1 are related to neighbor flux tubes where the conditions for multiple reconnection are met quasi-simultaneously. Additionally, the bifurcations gradually separate from the main dayside emission and substantially subcorotate, which is consistent with the combined effect of magnetic tension and antisunward magnetosheath flow forcing the newly opened field lines to move away from the subsolar magnetopause reconnection site. The main emission does not move to lower latitudes during the observed interval, in accordance with our interpretation of the multiple brightenings, which does not involve entry of new flux, but re-reconnection of a newly opened flux tube.

[9] Our scenario suggests localized north-south auroral asymmetries predicting multiple brightenings in one or another hemisphere depending on the order in which the field lines reconnect as well as on how many times they re-reconnect. Simultaneous north- south observations obtained from Hubble Space Telescope data when Saturn was at equinox revealed that the UV auroral power is larger in a global scale in the north than in the south [*Nichols et al.*, 2009], which could be partly attributed to reconnection being favored on field lines connected to the northern hemisphere. *Meredith et al.* [2013] also proposed that north-south symmetry in auroral intensity could be broken on newly opened dayside flux tubes as a result of reconnection depending on the direction (positive or negative) of the east-west component of the interplanetary magnetic field.

[10] We consider that the auroral bifurcations at Saturn are related to newly opened field lines as suggested here and in previous studies [*Radioti et al.*, 2011; *Badman et al.*, 2013]. However, if the bifurcations at Saturn were related to closed field lines due to shear flow in the magnetodisk (for example, shear flow driven Kelvin-Helmholtz instabilities at the magnetopause), the multiple auroral brightenings could be explained by bouncing of Alfvén waves on closed field lines [*Kan et al.*, 1996]. Enhanced dayside reconnection at patchy reconnection sites launches Alfvén waves. The bouncing of Alfvén waves between the magnetosphere and ionosphere on closed field lines could result in multiple auroral brightenings of dayside arcs which appear to converge on the equatorward boundary of the cusp region at Earth.

3. Summary and Conclusions

[11] We report for the first time on multiple brightenings of auroral bifurcations of the main dayside emission at Saturn, based on Cassini UVIS observations. We propose a simple schematic representation of the process adapted from the terrestrial case [*Fasel et al.*, 1993] in which a magnetic flux tube reconnects with other flux tubes at multiple sites. Field-aligned currents flowing along the newly formed flux tubes will create auroral emissions at their ionospheric foot. We predict that these auroral emissions fade with time until an additional injection of field-aligned currents occurs at a newly formed flux tube with the same ionospheric foot. Additionally, the auroral bifurcations subcorotate and depart from the main dayside auroral emission consistent with the motion of newly opened field lines because of the combined effect of magnetic tension and antisunward magnetosheath flow. North-south asymmetries are also predicted in the auroral emissions at Saturn related to magnetopause reconnection. With the present report, we demonstrate that the conditions for multiple magnetopause reconnection at Saturn could be satisfied like at Earth.

[12] **Acknowledgments.** This work is based on observations with the UVIS instrument onboard the NASA/ESA Cassini spacecraft. The research was supported by the Belgian Fund for Scientific Research (FNRS) and the PRODEX Program managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office. A.R. and B.B are funded by FNRS. J.M.J. is supported by an STFC Studentship.

[13] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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