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# Bursty magnetic reconnection at Saturn's magnetopause

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[1] We infer the evolution of magnetopause reconnection from simultaneous in situ magnetopause crossings and auroral observations by Cassini on 19 July 2008. Depending on the magnetosheath field, it proceeds from (i) the high-latitude lobe, producing a cusp spot in the aurora, to (ii) lower latitude but north of Cassini, evidenced by an enhancement of the pre-noon auroral arc and escape of magnetospheric electrons during a long boundary layer traversal, to (iii) bursts of reconnection south of Cassini, resulting in bifurcations of the near-noon auroral oval, escape of magnetospheric electrons, and a short boundary layer encounter. The conditions under which the auroral bifurcations associated with this bursty reconnection were observed were examined for this and three other examples. The magnetosphere was strongly compressed with a high magnetosheath field strength in every case. We conclude that reconnection can proceed at different locations on the magnetopause, depending on the local magnetic shear and plasma $\beta$ conditions, and bursty reconnection occurs when the magnetosphere is strongly compressed and can result in significant solar wind-driven flux transport in Saturn's outer magnetosphere.

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## 1. Introduction

[2] Saturn's magnetospheric dynamics are driven by both the planetary rotation and the interaction with the surrounding solar wind [*Mitchell et al.*, 2009]. Plasma and momentum can be transferred to the magnetosphere via reconnection between the interplanetary magnetic field (IMF) and the planetary field at the magnetopause. The occurrence and significance of reconnection at Saturn's magnetopause is a topic of ongoing debate [*Mauk et al.*, 2009; *Grocott et al.*, 2009; *Masters et al.*, 2012; *Lai et al.*, 2012]. Signatures of reconnection, a component of the magnetic field normal to the magnetopause and heated magnetosheath plasma, have been identified by *McAndrews et al.* [2008].

[3] The location of the reconnection site is influenced by the orientation of the IMF with respect to the planetary field [e.g., *Bunce et al.*, 2005]. When the IMF has a northward component, reconnection can occur at low latitudes, resulting in the opening of planetary field lines to the solar wind. Reconnection can also occur at high latitudes between the IMF and the open lobe field regions, expected when the IMF is southward. The plasma conditions at the magnetopause are also expected to influence the occurrence of reconnection. Specifically, a high value of the plasma beta parameter (the ratio of plasma to magnetic pressure) in the magnetosheath could inhibit reconnection when the fields are not anti-parallel [*Swisdak et al.*, 2003; *Phan et al.*, 2010; *Masters et al.*, 2012; *Phan et al.*, 2013].

[4] The signatures of reconnection events at both high and low latitudes have also been modeled and identified in Saturn's auroral observations [*Bunce et al.*, 2005; *Gérard et al.*, 2005]. The interpretation of these features is important because they can provide remote evidence of reconnection events when the spacecraft is not in the right location to measure them directly, making auroral observations a powerful tool for understanding magnetopause reconnection at Saturn. The signature of low-latitude reconnection is an intensification of the near-noon auroral arc, while lobe reconnection is manifest as a distinct spot poleward of the noon auroral arc [*Bunce et al.*, 2005; *Gérard et al.*, 2005]. A similar dependence occurs in the Earth's aurora [*Milan et al.*, 2000a; *Fuselier et al.*, 2002]. Recent analysis of Cassini auroral images has also revealed poleward arc bifurcations in the high-latitude noon sector of the ionosphere, which are interpreted as the signatures of bursty reconnection events [*Milan et al.*, 2000b; *Radioti et al.*, 2011; *Badman et al.*, 2012]. Their size, shape, and motion support this interpretation over other generation mechanisms such as Kelvin-Helmholtz vortices [*Grodent et al.*, 2011].

[5] It is of great interest to examine how the solar wind and IMF conditions affect the occurrence of magnetopause reconnection. Simultaneous observations of the near-magnetopause conditions and the aurora are desirable to achieve this, but the opportunities for such coincident data are rare. Here we present analysis of one such opportunity provided by Cassini.

## 2. Cassini Observations on 19 July 2008

### 2.1. In Situ Observations of Saturn's Magnetopause

[6] Figure 1a shows observations made by the Cassini magnetometer (MAG) [*Dougherty et al.*, 2004] and electron spectrometer (ELS) [*Young et al.*, 2004] during a magnetopause crossing on 19 July 2008 (Day Of Year 201).

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

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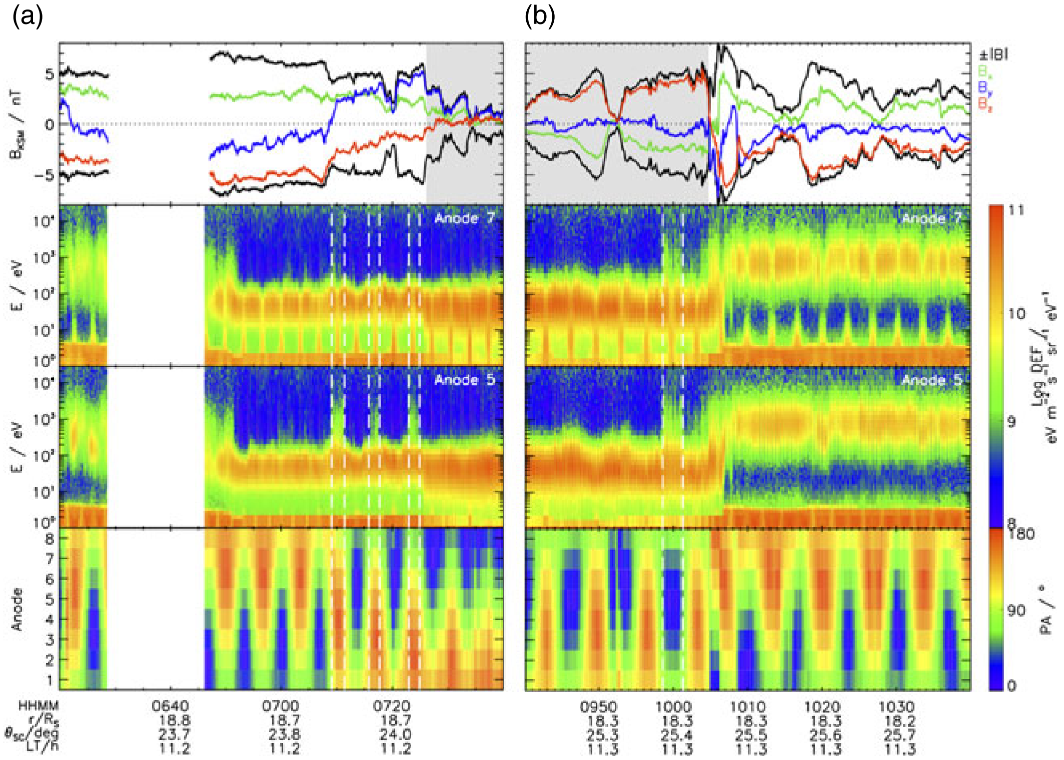

**Figure 1.** Cassini MAG and ELS observations during the (a) outbound and (b) inbound magnetopause crossings on 2008-201. Top panel: Magnetic field components and magnitude in KSM coordinates. The gray shaded regions indicate the magnetosheath excursion. Second and third panels: Electron differential energy flux (DEF) measured by ELS anodes 7 and 5, respectively. Bottom: Particle pitch angles (PA) measured by the ELS anodes. The white dashed lines mark features described in the text.

Cassini was moving inbound at ~ 19 $R_S$ radial distance, ~ 24°N latitude, and 11 local time (LT). Kronocentric Solar Magnetic (KSM) magnetic field coordinates are used, where X is positive towards the Sun, Y is perpendicular to Saturn's rotation axis and positive to dusk, and the X-Z plane contains the rotation axis. Electron fluxes measured by two ELS anodes, 7 and 5, which covered different particle pitch angles (indicated in the bottom panel), are shown. Continuous plasma flow vector measurements are limited by spacecraft pointing, so as in previous studies [*McAndrews et al.*, 2008], we focus on the magnetic field and electron data.

[7] At the start of the interval, the southward magnetic field and higher energy electrons (100 eV–1 keV) are consistent with Cassini being located in the dayside magnetosphere. A ~ 20 min data gap occurred, after which a boundary layer was encountered for ~35 min. In the boundary layer, the $B_Z$ component of the magnetic field became less negative, the $B_Y$ component rotated from negative to positive, and a cooler, denser electron population was detected. At ~07:26 UT, Cassini exited through the magnetopause into the magnetosheath proper (gray shading), where the field magnitude was significantly lower and the electron energy further decreased. This magnetopause crossing was caused by contraction of the magnetopause over the inbound spacecraft.

[8] Shortly before the magnetopause crossing, anode 5 detected some hotter, tenuous electrons (delimited by white dashed lines in Figure 1a). This magnetosphere-like population was detected only while anode 5 sampled electrons anti-parallel to the magnetic field (indicated by the red shading in the pitch angle coverage panel at the bottom of Figure 1a). This population was also measured by other anodes sampling the anti-parallel direction, but not by anode 7, which sampled lower particle pitch angles. The measurement of this anisotropic population is indicative of the escape of magnetospheric electrons on open boundary layer field lines, compared to the bi-directional fluxes observed inside the magnetosphere at the start of the interval. Similar anisotropic electron fluxes were presented as evidence of reconnection by *McAndrews et al.* [2008] and were earlier used to identify reconnected field lines at the Earth's magnetopause [*Onsager et al.*, 2001; *Lavraud et al.*, 2005]. The anti-parallel direction of the detected fluxes inside the magnetopause places Cassini southward of the reconnection site at this time. The suggested configuration is sketched in Figure 2a.

[9] The magnetic field orientation is consistent with this interpretation: the $B_Y$ component was modestly negative in the magnetosphere due to the sweepback of sub–co-rotating closed field lines. The open field lines in the boundary layer would be dragged duskward by the planetary rotation at low altitude and dawnward, around the magnetosphere obstacle, by the solar wind flow in the magnetosheath. The result is an enhanced $B_Y > 0$ component southward of the reconnection site, as measured by Cassini.

[10] The data taken around the time Cassini re-entered the magnetosphere, approximately 2.5 h later, are shown in

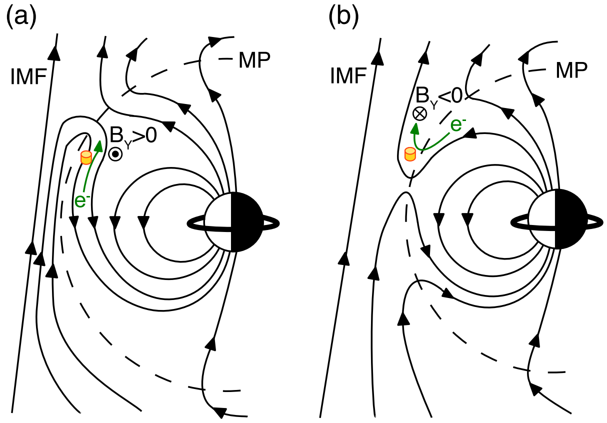

**Figure 2.** Schematic (not to scale) showing the location of Cassini (yellow) relative to the magnetopause reconnection site and open field lines, as inferred from the anisotropic electron fluxes indicated by the green arrow, for the (a) outbound and (b) inbound magnetopause crossings. The dashed line represents the magnetopause, and the arrowed solid lines indicate planetary and interplanetary magnetic field lines. The direction of the enhanced $B_Y$ components detected at Cassini are also labeled. The Sun is to the left.

Figure 1b. At ~10:00 UT, prior to the magnetopause crossing, both anodes 5 and 7 detected a hotter, tenuous electron component, similar to the magnetospheric population (marked by white dashed lines on Figure 1b). This was detected only while the anodes sampled field-parallel electrons, indicated by the blue shading in the bottom panel of Figure 1b. This is again indicative of magnetospheric electrons escaping from an open magnetopause but now with Cassini located north of the reconnection site.

[11] There was a sharp transition between the $B_Z > 0$, $B_Y \sim 0$ field in the magnetosheath (gray shading) and the $B_Z < 0$, $B_Y < 0$ field in the magnetosphere. Although differences in the speed of the spacecraft with respect to the magnetopause boundary region may partly explain the different signatures, the data are consistent with a thinner boundary layer at this later encounter. The negatively enhanced $B_Y$ component measured just inside the magnetopause is consistent with these being open field lines, following similar arguments to those made above. The suggested configuration is sketched in Figure 2b. The field magnitude just outside the magnetopause was elevated to ~ 5 nT, and dominated by the $B_Z > 0$ component, compared to ~ 3 nT at the earlier outbound crossing.

[12] The magnetospheric electron populations encountered before both the outbound and inbound crossings showed no evidence of acceleration. These are therefore not encounters with a reconnection jet, like that presented for a close encounter with the reconnection site by *McAndrews et al.* [2008], but are interpreted as escape of magnetospheric electrons on magnetospheric field lines which were opened at a reconnection site some distance from the spacecraft.

### 2.2. Auroral Observations

[13] During the magnetosheath excursion described above, Cassini Ultraviolet Imaging Spectrograph (UVIS, *Esposito* [2004]) observed the northern aurorae by scanning its narrow slit across the auroral region. A selection of pseudo-images constructed by combining the slit scans using the method described by *Grodent* [2011] are shown in Figure 3. The auroral region was covered every ~ 10 min.

[14] Figure 3a shows the presence of an intense cusp spot poleward of the main oval at local noon while Cassini was inside the magnetosphere at 05:34 UT. Poleward cusp spots at Saturn appear when the IMF is southward and lobe reconnection occurs [*Bunce et al.*, 2005; *Gérard et al.*, 2005]. This spot is short lived: it is present in only one scan.

[15] The observations around the time Cassini exited the magnetosphere (07:25 UT), exemplified by Figure 3b, show a prolonged enhancement of the pre-noon main oval aurora. This is consistent with the occurrence of low-latitude (i.e., not lobe) reconnection and enhancement of poleward flow near noon, i.e., the poleward motion of newly opened field lines [*Bunce et al.*, 2005; *Gérard et al.*, 2005].

[16] Soon after this, the pre-noon arc began to bifurcate and an intense arc moved poleward. When Cassini re-entered the magnetosphere at ~10:05 UT, a second bifurcation was developing post-noon, shown at its most intense in Figure 3c. These auroral features are associated with bursts of reconnection and subsequent motion of the newly reconnected field line [*Milan et al.*, 2000b; *Radioti et al.*, 2011; *Badman et al.*, 2012]. The full sequence of auroral

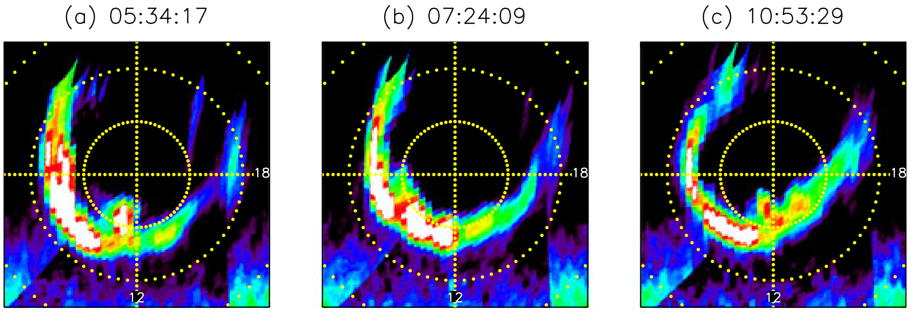

**Figure 3.** Selection of polar-projected Cassini UVIS observations of Saturn's northern FUV aurorae on 2008-201. Local noon is to the bottom and dusk to the right. The data are projected to the peak emission altitude of 1100 km above the 1 bar level [*Gérard*, 2009]. FUV emissions at 115.5–191.2 nm wavelengths are shown. The grid shows latitudes at intervals of 10° and the noon-midnight and dawn-dusk meridians. The start time of each scan of the auroral region is labeled at the top, and the duration of the scans shown was ~ 10 min.

**Table 1.** Details of Magnetopause Crossings Studied

| Time of MP Crossing<br>Time of Auroral Obs. | Location | MP Model | Partial $\beta$ | Sheath Field |
|---|---|---|---|---|
| 2008-193 20:00 UT | LT $\sim$ 11 | $R_{ss} \sim 19\ \mathrm{R_S}$ | $\beta_{\mathrm{sheath}} \sim 6$ | $3 < \lvert B \rvert < 5$ nT |
| 2008-195 04–10 UT | $\theta_{SC} \sim 19°$ | $P \sim 0.05$ nPa | $\beta_{\mathrm{sphere}} \sim 2$ | $B_z < 0$ |
| | | | $\Delta\beta \sim 4$ | shear $\sim$ 50° |
| **2008-201 10:05 UT** | LT $\sim$ 11 | $R_{ss} \sim 17\ \mathrm{R_S}$ | $\beta_{\mathrm{sheath}} \sim 32$ | $1 < \lvert B \rvert < 4$ nT |
| 2008-201 03–13 UT | $\theta_{SC} \sim 25°$ | $P \sim 0.08$ nPa | $\beta_{\mathrm{sphere}} \sim 4$ | $B_z > 0$ |
| | | | $\Delta\beta \sim 28$ | shear $\sim$ 150° |
| 2008-242 18:40 UT | LT $\sim$ 11 | $R_{ss} \sim 19\ \mathrm{R_S}$ | $\beta_{\mathrm{sheath}} \sim 26$ | $1 < \lvert B \rvert < 4$ nT |
| 2008-239 02–04 UT | $\theta_{SC} \sim 1°$ | $P \sim 0.04$ nPa | $\beta_{\mathrm{sphere}} \sim 3$ | $B_z < 0$ |
| | | | $\Delta\beta \sim 23$ | shear $\sim$ 115° |
| 2008-319 10:20 UT | LT $\sim$ 11 | $R_{ss} \sim 18\ \mathrm{R_S}$ | $\beta_{\mathrm{sheath}} \sim 4$ | $\lvert B \rvert \sim 4$ nT |
| 2008-320 22 UT | $\theta_{SC} \sim 33°$ | $P \sim 0.07$ nPa | $\beta_{\mathrm{sphere}} \sim 1$ | $B_z < 0$ |
| | | | $\Delta\beta \sim 3$ | shear $\sim$ 50° |

observations can be seen in the movie in the Supporting Information.

## 3. Discussion and Conclusions

[17] During the interval presented above, the evolution of the reconnection site can be tracked using the combined auroral and in situ observations, from (i) the high-latitude lobe, producing a cusp spot in the aurora, to (ii) lower latitude but north of Cassini (at 24°N), evidenced by an enhancement of the near-noon auroral arc and escape of magnetospheric electrons during a long boundary layer encounter, to (iii) bursts of reconnection south of Cassini, resulting in bifurcations of the near-noon auroral oval, escape of magnetospheric electrons, and a much shorter boundary layer traversal.

[18] The inferred thinning of the boundary layer suggests that the flux was being efficiently transported away from the low-latitude dayside magnetosphere during the interval of bursty reconnection. The detection of significant flux transport is contrary to some predictions made regarding a decrease of reconnection efficiency in the generally high magnetosonic Mach number environment at Saturn [*Scurry and Russell*, 1991]. We therefore characterize the conditions at the later, inbound magnetopause crossing in this example, when bursty reconnection was occurring, and compare to typical conditions presented by *Masters et al.* [2011, 2012].

[19] The conditions for the inbound magnetopause crossing at ~10:05 UT are summarized in Table 1 (date highlighted in bold). The sub-solar magnetopause standoff distance during the final crossing was estimated using the *Kanani et al.* [2010] model of Saturn's magnetopause. Measurements of the electrons detected by ELS, the cold ions detected by IMS, and the suprathermal (> 3 keV) particles detected by the MIMI instrument were used to determine the plasma pressure in the magnetosphere and the magnetosheath. The measurement of the cold ion contribution is limited by spacecraft pointing, meaning that the ion densities may be underestimated if the peak flow direction is not captured in the field of view, which is the case in this interval. However, we use these values to provide reasonable lower limits for the plasma pressures and beta values. We include the contribution of energetic water group ions to the plasma pressure in the magnetosheath because they can escape the magnetosphere into the magnetosheath even in the absence of magnetopause reconnection due to their large gyroradii (N. Sergis, private communication, 2013).

[20] Despite the relatively high field strength in the magnetosheath (1–4 nT), the average plasma pressure across the excursion was also high, such that beta was estimated to be $\beta \sim 32$. The magnetic shear angle across the magnetopause was ~ 150°. According to the results of *Masters et al.* [2012], reconnection is likely to be locally suppressed by the high $\Delta\beta \sim 28$ across the magnetopause. However, at other locations where the value of $\beta$ in the near-magnetopause magnetosheath is lower or the shear angle is higher, the *Swisdak et al.* [2003] condition for reconnection onset may have been satisfied, leading to the occurrence of reconnection. This is consistent with the measurements made at the magnetopause crossings shown here, where evidence of an open magnetopause is detected without identification of a local X-line.

[21] We have identified several other examples when the distinctive auroral bifurcation signatures associated with bursty reconnection occurred. The event studied in detail here suggests that they occur under solar wind compression conditions. Solar wind co-rotating interaction region or coronal mass ejection structures, which cause magnetospheric compression, persist for several days at Saturn [*Jackman et al.*, 2004]. We therefore select three other auroral bifurcation events when Cassini crossed the magnetopause within 4 days of the auroral observation, as we can assume that the measured magnetopause conditions will be generally representative of those which occurred at the time of the auroral observations. The conditions for these crossings are also summarized in Table 1. The corresponding auroral observations were previously presented by *Radioti et al.* [2011] and *Badman et al.* [2012].

[22] The crossings occurred at ~ 11 LT and at low latitude, $\theta_{SC} \sim 1°$–33°. During all four crossings the magnetosphere was very compressed: $R_{SS} \sim 17$–19 R$_{\mathrm{S}}$, compared to the typical range of 22–27 R$_{\mathrm{S}}$ [*Achilleos et al.*, 2008]. These correspond to particularly high solar wind dynamic pressures of 0.04–0.08 nPa, such as observed in strong solar wind compression regions [*Crary et al.*, 2005]. The magnetosheath field magnitude was also generally high (few nT).

[23] On two occasions (2008-193 and 2008-319), $\beta$ in the magnetosheath was low suggesting reconnection could proceed even where the magnetic shear was low. The locally measured shear was indeed low, ~ 50°, in both cases, and possible evidence of ongoing reconnection was accordingly identified at these crossings (see Figures in Supporting Information). In the other two intervals, the magnetosheath

$\beta$ was higher, suggesting that reconnection could occur at locations where the magnetic shear angle was high. On 2008-201 (described above), the local magnetic shear angle was ∼ 150° and evidence of reconnection was identified. On 2008-242, the magnetic shear angle was ∼ 115° and there was no obvious in situ evidence of reconnection, suggesting that the shear was not sufficiently high at this time and location, although it could have been at the time of the auroral observations 3 days previously.

[24] We infer that bursty reconnection at Saturn's magnetopause occurs when the magnetosphere is significantly compressed by the solar wind, associated with high solar wind dynamic pressure and IMF magnitude. The compressed magnetosheath field can pile up at the dayside magnetopause boundary and cause a reduction in the local $\beta$. This makes it possible for reconnection to proceed efficiently wherever there is sufficient shear in the field across the magnetopause, influencing the location of the reconnection site.

[25] *Radioti et al.* [2011] used one sequence of observations of the associated bifurcations in the aurora to estimate the magnetopause reconnection rate. They estimated ∼ 250 kV, which is typical of rates determined under compression regions [*Jackman et al.*, 2004; *Badman et al.*, 2005], in agreement with our analysis. The auroral signatures were present in ∼ 37% of the UVIS auroral observation sequences studied [*Radioti et al.*, 2011], while the high (1–5 nT) magnetosheath field strengths were present in ∼ 10–50% of magnetopause crossings [*Masters et al.*, 2011]. Under these not uncommon conditions, significant solar wind-driven flow layers are expected in Saturn's outer magnetosphere [*Badman and Cowley*, 2007].

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