Observations of nightside magnetic reconnection during substorm growth and expansion phases

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The temporal and spatial variability of nightside magnetic reconnection is described using two-dimensional ionospheric measurements during the growth phase and early expansion phase of a single substorm. Two techniques (A and B) are used to address both the localized (across ~15° longitude at ~2300 magnetic local time (MLT)) and the large-scale reconnection rate, using ionospheric data that provides the component of the electric field tangential to the polar cap boundary (PCB) in the stationary boundary frame. Technique A uses localized high-resolution measurements derived from 630 nm all-sky imager data at Rankin Inlet and ionospheric convection vectors obtained from line-of-sight velocity data from the Kapuskasing and Saskatoon Super Dual Auroral Radar Network (SuperDARN) HF radars. Technique B uses lower resolution global measurements, obtained by combining Polar VIS imager data and a velocity field derived using SuperDARN global convection mapping. A third technique (C) estimates the nightside reconnection potential from the dayside reconnection potential and the variation in the polar cap area. Technique A reveals standing wave-like variation of period ~16 min in the reconnection rate in the late growth phase (spatial noncontinuity in the x-line). The localized measurements of the reconnection rate vary between 0 and 50 mV/m during both the growth and expansion phases. Technique B shows the expansion of the x-line toward the duskside during the first 15 min of the expansion phase, from a width of ~4 hours of MLT to ~7 hours MLT.

1. Introduction

Many magnetospheric phenomena are explained well by the paradigm of magnetic reconnection [Dungey, 1961]. The coupling between the electric field and particles of the solar wind and the Earth’s magnetosphere that arises from reconnection increases magnetospheric convection and transports solar wind energy into the magnetotail [Cowley, 1980]. The explosive releases of mass, momentum, and magnetic energy involving the entire magnetotail that take place at geomagnetic substorm expansion phase onset [Akasofu, 1964] are often assumed to be signatures of the dominant reconnection process in the magnetotail. However, dayside reconnection sometimes occurs in pulses called “flux transfer events” (FTEs), which were first observed in analyses of spacecraft data located near the magnetopause [Russell and Elphic, 1978, 1979; Haerendel et al., 1978]. Studies of the ionospheric signatures of FTEs [Milan et al., 2000] show that individual FTE events can contain a significant fraction (~10%) of the total open magnetic flux in the polar cap [Lockwood et al., 2001].

On the nightside, in situ observations show that magnetotail convection takes the form of 5–10 min long groups of short (~1 min), high-speed flow events termed bursty bulk flows (BBFs) that account for a significant fraction of the transport of energy, momentum, and magnetic flux through the central plasma sheet (CPS) [Baumjohann et al., 1990; Angelopoulos et al., 1992]. In addition, Nakamura et al. [1994] suggested that there is no phenomenological difference between pseudo-breakups and major expansion onsets, but there may be a difference in the scale size of the magnetospheric source, since pseudo-breakups give rise to weaker and more localized, but otherwise similar signatures to substorm onsets. The importance of BBFs to magnetotail dynamics and of FTEs to dayside reconnection suggests that contributions to the nightside magnetic flux and energy budget on a smaller scale size than that of geomagnetic substorms may be significant. Our aim, in this current study, is to examine the magnetotail x-line for spatial and temporal discontinuities which would result from subsystem scale magnetotail processes. Spatiotemporal variations in the reconnection rate measured in the ionosphere mirror those that are occurring at the site of reconnection in the magnetosphere, so ground-based instrumentation can monitor recon-
connection in the magnetosphere. We measure the nightside magnetic reconnection rate in the growth and early expansion phase of a single substorm, setting observations localized at \( \sim 2300 \) MLT in context by making use of lower-resolution global nightside estimates.

[4] We shall principally use two-dimensional (2-D) ground-based measurements of the nightside reconnection rate by implementing the principle introduced by Vasyliunas [1984] which was applied and refined by de la Beaujardière et al. [1991] and Blanchard et al. [1996, 1997a]. The flow of energy, mass, and momentum across the boundary between open and closed field lines (the separatrix) is controlled by the electric field imposed on the x-line. The latter is called the reconnection electric field \( (E_{\text{rec}}) \) or reconnection rate.

[5] There have to date been far fewer studies of the nightside reconnection rate using ionospheric data than of the dayside reconnection rate, and most of these have conducted their analysis in one dimension [de la Beaujardière et al., 1991, 1994; Blanchard et al., 1996, 1997a; Ostgaard et al., 2005; Watanabe et al., 1998]. de la Beaujardière et al. [1991] derived the temporal variation of the nightside reconnection rate using Sondrestrom Incoherent Scatter Radar (ISR) data, using the plasma velocity across a PCB (polar cap boundary) assumed to be colocated with the steep density gradient of E-region precipitating electrons. Blanchard et al. [1996, 1997a] not only used the E-region electron density gradient to determine the PCB, but also, as in this present study, ground-based observations of 630 nm auroral emissions. Watanabe et al. [1998] studied the reconnection rate just prior to substorm onset utilizing data from SuperDARN HF radars [Greenwald et al., 1995]; the PCB was identified at a single instant using Defence Meteorological Satellite Program (DMSP) satellite particle precipitation data. Ostgaard et al. [2005] combined IMAGE FUV satellite data and EISCAT radar measurements to estimate the reconnection rate in the magnetotail for 48 hours. They found the magnetotail reconnection to be a bursty process with the reconnection rate oscillating between 0 and 80 mV/m with a period of \( \sim 10–15 \) min. Ostgaard et al. [2005] attribute the oscillation in the reconnection rate to wave-like motion of the PCB which they propose is related to a ULF internal cavity mode. They concluded that the magnetotail reconnection was not being directly driven by the solar wind but by an internal magnetospheric process.

[6] In this paper we use three techniques that utilize ionospheric data to examine nightside reconnection. Two of the techniques (A and B) are used to find the temporal and spatial dependence of the localized (across \( \sim 15^\circ \) longitude at \( \sim 2300 \) MLT) and global nightside reconnection rate, respectively. Both sets of reconnection rates are determined from ionospheric data that provide the component of the electric field tangential to the polar cap boundary (PCB) in the stationary boundary frame. Technique A combines measurements of a 2-D PCB derived from 630 nm all-sky imager (ASI) data at Rankin Inlet and 2-D ionospheric convection velocities obtained from line-of-sight velocity data from the Kapuskasing and Saskatoon SuperDARN HF radars. Technique B, less accurate than technique A, estimates the 2-D nightside reconnection rate using a PCB obtained from the VIS instrument [Frank et al., 1995] on board the Polar satellite, and 2-D Super-DARN map potential ionospheric convection velocities. As an additional check, a third technique (C) is used to obtain a global overview of the event using Advanced Composition Experiment (ACE) satellite data [McComas et al., 1998] to estimate the dayside reconnection potential and Polar VIS images to define the area of the polar cap. We combine these measurements to estimate the nightside reconnection potential. This estimate of the nightside potential is compared with the estimate obtained using technique B.

[7] We start by estimating the time of the substorm expansion phase onset for this case study. In section 3 we present the method and results for techniques A and B. The 2-D reconnection rate measurements localized at \( \sim 2300 \) MLT are examined in detail using technique A. The time variations in the extent of the x-line and in the nightside reconnection potential are examined using technique B. In section 4 we present a second technique (C) for obtaining the nightside reconnection potential and compare the results of this technique with those of technique B. We compare our localized values for the reconnection rate derived from technique A with those of previous studies, and discuss the nature of its temporal and spatial variability in section 5. Conclusions are presented in section 6.

2. Substorm Onset Identification

2.1. Method

[8] Our main identification of the substorm expansion phase onset time will be made using global images of the auroral oval provided by the Ultra Violet Imager (UVI) instrument aboard the Polar satellite [Torr et al., 1995], which has a time resolution of 37 s for the interval studied. We identify the onset time by the sudden brightening of the equatorward part of the auroral oval in the midnight sector that is followed by a rapid poleward and azimuthal expansion of aurora [Rostoker et al., 1980]. This identification is supported by other well-established substorm indicators, such as the timing of negative H-bays [Akasofu et al., 1965] and Pi2 pulsation onsets, as measured by ground-based magnetometers across a range of magnetic latitudes in Canada [Rostoker, 1967]. Figure 1 shows the location of the magnetometer stations as triangles. Marked are four Canadian Auroral Network for the Open Project Unified Study (CANOPUS) stations: Rankin Inlet (r), Eskimo Point (e), Fort Churchill (c), and Gillam (g), and two Geological Survey of Canada stations: Ottawa (o) and St John’s (j).

2.2. Results

[9] The substorm studied in this paper occurred at \( \sim 0521 \) universal time (UT) on 12 December 2001. An examination of data from the CANOPUS and Greenland ground magnetometers indicates that this is a small, isolated substorm occurring after at least 5 hours of no substorm activity. Figure 2 shows the \( H \) component of the ground magnetic field in Canada for the interval 0400–0700 UT, the magnetic latitude of the stations decreasing from the top panel downward. At \( \sim 0415 \) UT, the rise in the \( H \) component of the ground magnetic field at Rankin Inlet and Eskimo Point indicates the formation of the eastward electrojet which accompanies the growth phase
of this substorm. The H-bays seen in this case study at Rankin Inlet and Eskimo Point at 0530 UT are a global feature; H-bays are also seen in ground magnetometer data obtained in Western Canada (2030 MLT) and in Scandinavia (0230 MLT). The ground magnetometer data from Geological Survey of Canada and Greenland West stations are not shown in this paper. A burst of Pi2s (not shown) initiates at 0522 UT in the H component of the Ottawa data.

We use the timing of the optical onset observed in 170 nm UVI images from the Polar satellite as the definitive timing for the substorm expansion phase onset. Figure 3 presents every other available Polar UVI image during the interval 0502–0530 UT. An estimate of the location of the PCB (as determined from Polar VIS data by the method detailed in the following section) is marked by crosses. Between ~2100 and 2400 MLT, the PCB is located at ~71°N Altitude-Adjusted Corrected Geomagnetic Coordinates (AACGM). From 0502 UT, pseudo-breakup-like auroral intensifications [Nakamura et al., 1994; Rostoker, 1998] that are well equatorward of the PCB (~66-70°N AACGM) are present between ~2100 and 2400 MLT. An auroral intensification at midnight MLT that commences at 0520:23 UT spreads poleward and azimuthally in subsequent images. We identify this intensification with the ionospheric substorm expansion phase onset. Considering the evidence from ground magnetometers and the Polar UVI images, we estimate that the time of the substorm expansion phase onset is 0521 UT ±1 min.

3. Direct Measurements of the Nightside Reconnection Rate

3.1. Methods for Techniques A and B

Under the assumption of frozen-in magnetic field lines, Vasyliunas [1984] showed that the reconnection electric field $E_{\text{rec}}$ (or reconnection rate) maps into the ionosphere along the field lines of the separatrix. The rate of flux transfer across an element of the separatrix of length $dl_{\text{sphere}}$ (or reconnection potential) is given by

$$E_{\text{rec}}dl_{\text{sphere}} = -[B \times (V - U)]dl_{\text{sphere}},$$

where $B$, $V$, $U$, and $dl_{\text{sphere}}$ are the magnetic field, the plasma velocity, the PCB velocity, and an element of the PCB in the frame of reference of the measuring instruments in the ionosphere. We can estimate the ionospheric reconnection rate from $-B \times (V - U)$ using discrete ionospheric measurements (see Chisham et al. [2004a] for more details of this method). The ionospheric reconnection rate relates to the magnetospheric reconnection rate by the ratio of the elements $dl_{\text{m}}/dl_{\text{sphere}}$.

Figure 1. A map showing the locations of the ground-based instrumentation used in this study. Marked by orange triangles are the CANOPUS stations: Rankin Inlet (r), Eskimo Point (e), Fort Churchill (c), and Gillam (g), and the two GSC stations: Ottawa (o) and St John’s (j). The field-of-view of the Aqsaniq all-sky imager at Rankin Inlet is represented by the red circle, while those of the SuperDARN HF radars at Kapuskasing and Saskatoon are represented in blue and green, respectively. Here 60°, 70°, and 80°N AACGM are marked by the thick black arcs.

Figure 2. The H component of the ground magnetic field as measured by ground magnetometers located at (a) Rankin Inlet, (b) Eskimo, (c) Churchill, (d) Gillam, (e) St John’s, and (f) Ottawa. The locations of these instruments are marked in Figure 1. The dashed vertical line marks the substorm expansion phase onset time which occurs at ~0521 UT. Note that the scales used in the bottom two panels are different to the scales used for the top four panels.
the Institute for Space Research at the University of Calgary. The field-of-view of the Aqsaq ASI is represented by the red circle in Figure 1. We subtract the appropriate dark frame, apply a flat-field correction, and only use data with an elevation angle of greater than 70° where 90° is at zenith. We locate the PCB at an intensity threshold of 300 R at 630 nm as determined by the meridional scanning photometer (MSP) at Rankin Inlet. We determine the PCB from the ASI data at the same time resolution as the convection velocity data, that is, every 2 min. The PCB derived from ASI data agrees to within ~1° with three other proxies in the interval examined. The first is the threshold value of 130 R/degree in the latitudinal gradient in the intensity of 630 nm Rankin Inlet MSP data. The second proxy is the PCB derived from 130.4 nm Polar VIS data at the longitude bin containing the location of Rankin Inlet. Third, we interpolate the 200 m/s spectral width boundary (SWB) [Chisham and Freeman, 2003; Chisham et al., 2004b] of meridional beam data from the SuperDARN radars, Kapuskasing and Saskatoon to the longitude of Rankin Inlet. The fields-of-view of the the Kapuskasing (k) and Saskatoon (s) SuperDARN radars are shown in blue and green, respectively, in Figure 1.

[13] The overlapping fields-of-view of the Saskatoon and Kapuskasing SuperDARN HF radars allow merging of the the line-of-sight Doppler velocities from each radar to produce 2-D velocity vectors of the plasma flow in the F-region ionosphere, in this case with a time resolution of 2 min [Hanuise et al., 1993]. In selecting the velocity data, we use a minimum of 3 dB power and assume a virtual F-region height of 400 km. The reconnection electric field is then calculated using equation (1) for each velocity vector within 0.75° latitude of the PCB and within 2° longitude of Rankin Inlet.

[14] Technique B uses the SuperDARN global convection mapping (or map potential) technique to provide an estimate of the ionospheric convection velocity field every 2 min. This is achieved by fitting line-of-sight velocity information measured by the SuperDARN radars to an expansion of an electrostatic potential function expressed in terms of spherical harmonics [Ruohoniemi and Baker, 1998]. We can derive the nightside reconnection potential, by using equation 1 for each map potential velocity vector within 1° latitude of the PCB provided by Polar VIS data interpolated to a time resolution of 2 min. Following the method of Carbury et al. [2003], we determine the PCB location by fitting a Gaussian-like function to latitudinal profiles of global satellite images (we also use this global PCB in section 4 as part of technique C to find the global nightside reconnection rate). We use 130.4 nm images from the VIS instrument [Frank et al., 1995] on board the Polar satellite which are available at ~5 min resolution (application of this method to Polar UVI data could only provide the PCB location for a limited range of MLT). The Polar VIS data are binned into 1 hour of MLT by 1° of MLAT bins and each binned latitudinal profile is fitted by the following function:

$$F(\lambda) = A_0 \exp\left[\frac{-0.5(\lambda - A_1)^2}{A_2^2}\right] + A_3 + A_4\lambda + A_5\lambda^2,$$

where $\lambda$ is the magnetic latitude in degrees. A PCB for a given latitudinal profile is obtained if the curve-fitting routine converges and the following criteria are satisfied: the absolute intensity of the Gaussian, $A_0$, exceeds 5 photons/cm²/s; the center of the auroral oval, $A_1$, exceeds 50° AACGM and is less than 85° AACGM; the ratio of the peak value of the Gaussian $A_0$ to the value of background at the center of the oval ($A_1 + A_4A_1 + A_5A_1^2$) exceeds 0.2; the Gaussian width ($\Delta \lambda = 2.354A_1$) exceeds 1°; the Gaussian halfwidth spans less than 30% of the latitude bins with finite intensity; the fractional standard deviation of the fit is less than 0.2 and the latitude of the PCB is under 84° AACGM.

Figure 3. Images from the UVI instrument aboard the satellite Polar. The CANOPUS magnetometers stations Rankin Inlet, Eskimo Point, Fort Churchill, and Gillam are marked on this figure as triangles. The vertical line is midnight MLT and the black arcs lie at 60°, 70°, and 80° N AACGM. The crosses mark the PCB as estimated from Polar VIS data.
The PCB latitude at a given MLT ($\chi_{PCB}$) is assumed to be displaced poleward of the center of the auroral oval by the Gaussian halfwidth.

$$\chi_{PCB} = A_1 + \Delta \chi$$  \hspace{1cm} (3)

For any given global image, the PCB may be defined for some MLTs and not others. We fill any gaps in the PCB in MLT by determining the Fourier transform of the PCB as a function of MLT, and by using the first six terms as a series expansion to represent the boundary, as was done by Milan et al. [2003]. For example, the asterisks in Figure 4a give the latitudinal profile of Polar VIS data from the 2200–2300 MLT bin at 0532 UT. The fit of this latitudinal profile to equation (2) is given by the solid line in Figure 4a, and the PCB latitude (vertical dotted line) can then be estimated from equation (3). All 19 of the successful PCB determinations at this UT, shown as diamonds in Figure 4b, are used to determine the global PCB which is the solid line in Figure 4b.

15 Technique A allows us to investigate the localized reconnection rate in high detail (uncertainty of $\sim 7$ mV/m), with no smoothing other than that resulting from the 2 min time resolution of the SuperDARN radar data. It utilizes merge velocity vectors which are completely independent of each other. Technique B (uncertainty of $\sim 24$ mV/m) has the ability to provide the total nightside potential; however, there is a greater degree of smoothing in the results. The technique uses a SuperDARN map potential velocity field, where there exists a degree of dependence between adjacent velocity vectors. Technique B also uses Polar VIS data, resulting in a PCB of poorer spatial and temporal resolution than the PCB derived from ASI data.

3.2. Localized Results From Technique A

The data used to estimate the reconnection rate local to Rankin Inlet during the 20 min either side of the substorm expansion phase onset is displayed in Figures 5–7. Rankin Inlet is marked by a yellow triangle in these three figures, which cover the interval 0502–0536 UT. In each figure, the velocity merge vectors derived from the SuperDARN HF radars are superimposed on Aqsaqin 630 nm ASI data in geomagnetic coordinates. The local reconnection rate for seven different longitude ranges is presented in Figure 8 for the same time period. In each panel, the diamonds mark single point measurements of the reconnection rate and the thick line is the 6-min running mean. Positive reconnection rates are not expected on the nightside (they would imply the convection of flux from closed to open field line regions) and their appearance is an indication of the size of the uncertainty in the reconnection rate calculation at that time. The greatest contribution to the uncertainty is from the PCB velocity term. The uncertainty is typically $\sim 7$ mV/m by applying standard error analysis techniques [e.g., Bev-ington and Robinson, 2003] to equation (1), but this value does vary with time.

17 There is an enhancement of the local nightside reconnection rate between 0504 and 0506 UT of $\sim 20–40$ mV/m around the location of and to the east of Rankin Inlet (Figures 8d–g and Figures 5b and 5c), some 16 min or so before onset. The PCB is relatively stationary in the Earth frame, except in the east of the field-of-view, where it moves poleward and ionospheric flow is directed out of the polar cap. To the west of Rankin Inlet, the ionospheric flow is parallel to a relatively static PCB. Consequently, the average nightside magnetic reconnection rate there is small (Figures 8a–8e). At $\sim 0512–0514$ UT (Figure 5f) there is a burst of reconnection of $\sim 40$ mV/m resulting from poleward motion of the PCB between 327 and 337$^\circ$E (see also Figures 8a–8e). At 0516 UT (Figure 6b) there is an increase in the equatorward convection across a relatively stationary
PCB which maintains the reconnection rate around the longitude of Rankin Inlet (Figures 8d–8e). To the east of Rankin Inlet (Figures 8e–8g), the reconnection rate is nonzero from 0502 to 0508 UT, close to zero from 0508 to 0514 UT and nonzero from 0514 to 0520 UT. To the west of Rankin Inlet (Figures 8a–8c), the reconnection rate time variation is in antiphase with that to the east of Rankin Inlet. The reconnection rate varies in a standing-wave-like fashion, with a period of ~16 min in the 20 min leading up to substorm onset.

[18] Around onset itself, reconnection rates of ~20–40 mV/m occur at most longitudes. The intense convection equatorward across the relatively stationary PCB around substorm expansion phase onset (Figures 6d and 6e) has fallen away by 0524 UT (Figure 6f). The reconnection rate increases at 0528 UT (Figure 7b and Figures 8c, 8e, and 8f) when swift poleward movement of the PCB commences. We have few measurements of the local reconnection rate after 0532 UT, since the PCB has moved poleward of the region of radar backscatter. The rapid poleward surge of the PCB continues across the field-of-view of the ASI in the interval 0534–0536 UT (Figures 7e–7f) and beyond (not shown).

[19] The median of the reconnection rate over the longitude range 327–341\(^\circ\)E is plotted in Figure 9d. The median of the point measurements of the reconnection rate over

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**Figure 5.** Merged velocity vectors, derived from Kapuskasing and Saskatoon SuperDARN radars, superimposed on the Aqausiq ASI 630 nm emission data in geomagnetic coordinates. The black dots mark the location of the radar data observations. The PCB derived from the 630 nm data is shown as a solid black line and the location of the ASI at Rankin Inlet is marked by the yellow triangle. The times written after the letters “SD” and “ASI” in each of the plots (a)–(f) are the start time of the 2 min radar scan and the time stamp of the ASI 630 nm image. The color bar shows the emission intensity in digitized units of emission intensity.

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**Figure 6.** As for Figure 5 but for the interval 0514–0524 UT.
hour of MLT varies between ~0–15 mV/m before onset, rises to ~22 mV/m at onset, and peaks just under 40 mV/m within the following 10 min.

3.3. Large-Scale Results From Technique B

Figures 10a and 10b show the reconnection rate as a function of MLT at (a) 0520 UT and (b) 0536 UT, derived using technique B. The MLT extent of the nightside reconnection x-line in the ionosphere increases from ~4 hours MLT at 0520 UT (1 min before substorm onset) to at least 7 hours MLT at 0536 UT (some 15 min after onset). The spread in the MLT extent of the x-line occurs mainly in the premidnight sector.

The time variations of the reconnection rate using technique B for the longitude ranges examined in Figure 8 are all similar to that shown in Figure 10c, which shows the time variation of the reconnection rate between 335° and 337° E AACGM. A comparison with the time variation of the reconnection rate in this longitude range using technique A (Figure 8e) shows that the minimum observed at ~0510 UT using technique A is not present when technique B is applied, due to the higher level of smoothing used in technique B than in technique A.

The variation of the reconnection potential, as given by the integral along the x-line of equation (1) throughout the whole interval using technique B, is shown as the dotted line in Figure 9c. This represents the reconnection potential from the available data which covers ~6–7 hours of MLT. The nightside reconnection potential increases in an intermittent fashion from 0500 UT reaching a peak at 0536 UT (of ~100 ± 10 kV) and falling close to zero at about 0545 UT. The nightside reconnection potential then increases as the substorm undergoes an intensification, about the time when H bays in the ground magnetic field are observed at Rankin Inlet and Eskimo Point (see Figure 2). This is consistent with the picture presented by Morelli et al. [1995] in which substorm intensifications, following an

![Figure 7](image-url)  
As for Figure 5 but for the interval 0526–0536 UT.

![Figure 8](image-url)  
The local reconnection rate in the 20 min either side of substorm expansion phase onset for seven different longitude ranges. Each vertical bar is the local reconnection rate calculated according to equation (1) using data within 0.75° latitude of the PCB. The thick line marks the 6-min running mean. As in previous plots, the vertical dashed lines marks expansion phase onset.
4. Indirect Measurement of Nightside Reconnection Potential

4.1. Method for Technique C

We can also indirectly estimate the nightside reconnection potential \( \Phi_n \) given the rate of change of the area \( A \) of the polar cap and the dayside reconnection potential \( \Phi_d \) from the relation

\[
B_2 dA = (\Phi_d - \Phi_n) dt, \tag{4}
\]

which gives the change in the total polar cap flux in a period of time \( dt \). We determine the polar cap area as a function of time by using the global measurements of the PCB location obtained in section 3. We use an estimate of \( B_2 = 5 \times 10^4 \) nT for the flux density threading the polar cap. Reiff et al. [1981] proposed the following parameterization of the dayside reconnection potential (in kV)

\[
\Phi_d = 6.1 \times 10^{12} \times \epsilon + 30 \tag{5}
\]

in terms of the solar wind function

\[
\epsilon = v_x B^2 \sin^4 (\theta/2), \tag{6}
\]

where \( B \) is the magnitude of the IMF, \( v_x \) is the \( x \) component (GSM) of the solar wind velocity, and \( \theta \) is the IMF clock angle (\( \theta = \arctan(B_y/B_z) \)).

[24] The solar wind function \( \epsilon \) is the Poynting flux on the magnetopause [Pudovkin et al., 1986] and represents the energy transfer from the solar wind into the magnetosphere, across the boundary between open and closed magnetic field lines [Perrault and Akasofu, 1978; Akasofu, 1981]. We use solar wind velocity and IMF data from the Solar Wind Experiment (SWE) and MAG instruments on board the ACE satellite [McComas et al., 1998] to evaluate \( \epsilon \). Reiff et al. [1981] found that the correlation coefficient between the dayside reconnection potential and \( \epsilon \) is 0.89, if the value of \( B \) used is the smaller of the IMF magnitude or 7.5 nT. We also apply this criterion. The mean-square deviation of the data points from the line of best fit in the work of Reiff et al. [1981] (\(~15\) kV) provides us with an estimate of the uncertainty in our dayside potential.

4.2. Results for Technique C

[25] Figure 11 presents the following time-lagged solar wind variables in GSM coordinates: the three components of the IMF \((a) B_x, (b) B_y, (c) B_z\), and \( (d) x \) component of the solar wind velocity \( v_x \); for the period 0400–0700 UT on 12 December 2001. The IMF clock angle (\( \arctan(B_y/B_z) \)) is such that low-latitude reconnection is expected throughout the interval [Freeman et al., 1993]. The delay between the satellite and the magnetopause is taken as the ratio of the distance along the \( x \) axis between the Earth and the spacecraft and \( v_x \). The estimated uncertainty in the time lag is \(~8\) min [Ridley, 2000]. The dayside reconnection potential \( \Phi_d \), estimated from equations (5) and (6), is shown in Figure 9a. It increases in value at \(~0500\) UT, when IMF \( B_z \) changes from positive to negative, though it is significant before that time.

[26] The time development of polar cap area is determined from the global PCB measurements provided by the Polar VIS images. Figure 9b shows that the polar cap area increases rapidly in the interval 0445–0455 UT, peaks at \(~0455\) UT, then decreases in the interval leading up to expansion phase onset. From the estimate of \( \Phi_n \) and the variation in the polar cap area, equation (4) can give an estimate of the nightside reconnection potential (shown as the solid line in Figure 9c). Since the dayside potential \( \Phi_d \) increases at \(~0500\) UT, a significant nightside reconnection potential exists from \(~0500\) UT onward. The largest nightside reconnection potential occurs at \(~0535\) UT, some 15 min after expansion phase onset. The variation of the nightside potential given by technique C is similar to that given by technique B, except that the magnitudes are higher.
This may be a result of the limited MLT coverage of the SuperDARN map potential vectors used in technique B.

5. Discussion

[27] We first compare our values for the reconnection rate with those of previous studies. de la Beaujardière et al. [1991] found the ionospheric projection of the reconnection electric field to be less than 15 mV/m during the substorm recovery phase and 30–40 mV/m during the expansion phase. Blanchard et al. [1996, 1997a] found that the ionospheric projection of the magnetotail reconnection electric field varied between 0 and 60 mV/m. The ionospheric projection of the reconnection electric field from in situ Polar satellite measurements [Ober et al., 2001] during the expansion phase of a substorm were 20–70 mV/m. Ostgaard et al. [2005] found that the reconnection rate oscillated between 0 and 80 mV/m during a 48-hour period. The values we have determined using technique A, for the reconnection rate over 1 hour of MLT in the 20 min before and after substorm expansion phase onset, are similar to those of previous studies around the time of substorms (0–15 mV/m before onset, ~22 mV/m at onset, with peaks of just under 40 mV/m within the following 10 min).

[28] We find, from our localized measurements (technique A), that the reconnection rate varied between 0 and 50 mV/m during both the growth and expansion phases and displayed temporal and spatial variability. Watanabe et al. [1998] also identified flow burst features in the ~10–20 min before substorm onset, which they associated with activation of the distant tail neutral line approximately 1 hour after growth phase onset. Part of the variability that we observe is due to wave-like motion of the PCB. The localized reconnection rate results reveal that the reconnection rate was modulated by a standing wave pattern in the PCB of period of ~16 min, in the 20 min leading up to substorm onset. Ostgaard et al. [2005] also found that the magnetotail reconnection rate oscillated with a period of ~10–15 min, due to the wave-like motion of the PCB, from which Ostgaard et al. [2005] concluded that the magnetotail reconnection was not being directly driven but was an internal ULF magnetospheric process. The oscillatory nature of the reconnection rate does not extend into the expansion phase, during which we also see evidence of a noncontinuous x-line in the localized reconnection rate measurements.

[29] Blanchard et al. [1997a] found that the median reconnection rate from an ensemble of 24 substorms did not begin to increase until 20 min after onset which they attributed to the spatial variation in the development of the magnetotail reconnection during substorms. Ober et al. [2001] also found a 20-min delay between substorm onset and a decrease in the total magnetic flux of the polar cap which they propose is the time that elapses before reconnection of open lobe flux occurs along a near-Earth x-line. We find that the magnetotail reconnection rate increases soon after onset near 2300 MLT and the extent of the x-line increases in MLT during the following 15 min in agreement with Blanchard et al. [1997a].

[30] Our key finding is that the x-line for nightside reconnection has been shown to be spatially noncontinuous using high-resolution ionospheric measurements of the reconnection rate. The existence of small gaps (at least ~0.5 hours MLT) in the x-line may not have a major impact on the total reconnection potential but has major implica-
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6. Conclusions

Continuous 2-D measurements of the ionospheric proxy of the reconnection rate during the late growth phase and expansion phase onset of an isolated substorm have been presented using two techniques. Technique A provides localized reconnection rate measurements by using SuperDARN merge velocity vectors and a PCB derived from 630 nm ASI data. Global nightside reconnection rate measurements are provided by technique B which uses the SuperDARN map potential velocity field and a PCB derived from the Polar satellite’s VIS instrument. The variation in the nightside potential using technique B is similar to that obtained using the rate of change of the area of the polar cap and a proxy of the dayside reconnection potential derived from ACE satellite data (technique C). We find the following:

1. The nightside reconnection potential increases in an intermittent fashion during the late growth phase, reaching a peak of approximately 100 kV some 15 min after expansion phase onset.
2. Intermittent temporal and spatial variations in the reconnection rate are modulated by a standing wave of period approximately 16 min during the late growth phase. This is due to wave-like motion of the polar cap boundary which may indicate the modulation of directly driven reconnection by internal magnetospheric processes [Ostgaard et al., 2005].
3. The localized measurements of the reconnection rate varied between 0 and 50 mV/m during both the growth and expansion phases.
4. Nighttime reconnection occurs both as a result of PCB motion (e.g., Figure 5f) and accelerated plasma flow across a stationary PCB (e.g., Figures 6d and 6e).
5. Global nightside measurements of the reconnection rate indicate that the MLT-extent of the x-line increases from approximately 4 hours MLT at expansion phase onset to at least 7 hours MLT, 15 min after onset.
6. The degree of smoothing that occurs in producing the large-scale reconnection rates using technique B means that this technique is unable to show whether the x-line is continuous or not.

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