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Statistical Behavior of
Quasi-Steady Balanced Reconnection
in Earth’s Magnetosphere

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geophysics and Space Physics

by

Jennifer Eileen Kissinger

2012
Magnetic reconnection between Earth's magnetosphere and the solar wind results in several modes of response, including the impulsive substorm and the quasi-steady mode known as steady magnetospheric convection (SMC). SMC events are theorized to result from balancing the dayside and nightside reconnection rates. The reasons the magnetosphere responds with different modes are not fully known. This dissertation comprises statistical data analysis of the SMC mode to investigate the solar wind conditions and magnetospheric properties during these events. A comprehensive list of SMC events is selected from 1997-2011.

In the first of three studies, an association between SMCs and solar wind stream interfaces (SI) is identified in the declining phase of Solar Cycle 23. SMC occurrence peaks 12-24 hours after an SI if the solar wind is geoeffective. The subset of SI-associated SMCs occurs
during fast solar wind velocity, in contrast to previous results, but the driving electric field imposed on the magnetosphere ($E_y$) is the same for SI-associated and unassociated SMC events. Therefore the magnitude and steadiness of $E_y$ is the most important solar wind parameter for an SMC to occur.

The second study shows that magnetotail convection is significantly different for SMC events, compared to quiet intervals and isolated substorms. Fast flows transporting enhanced magnetic flux are deflected toward the dawn and dusk flanks during SMC. Flow diversion is due to a broad high pressure region in the inner magnetosphere. The interval preceding SMC events is found to set up the magnetotail conditions that assist balanced reconnection. In particular inner magnetosphere pressure before SMCs is enhanced from substorm levels but not as high as SMC levels. The final study shows that nearly all SMCs are preceded by a substorm expansion. In rare cases when an SMC occurs without a preceding substorm, we hypothesize that the distant x-line is able to balance a weak solar wind driver.

These results help explain how quasi-steady magnetospheric convection occurs. A southward turning of the solar wind and positive $E_y$ leads to dayside reconnection and a substorm onset occurs. Plasma injections from the near-Earth nightside x-line increase the pressure in the inner magnetosphere. If positive $E_y$ continues to drive dayside reconnection, the nightside x-line will stabilize to match it. Tail flux is diverted towards the flanks by pressure gradients and returns to the dayside. This convection pattern keeps the magnetosphere in its balanced reconnection mode.
The dissertation of Jennifer Eileen Kissinger is approved.

Margaret G. Kivelson

Larry R. Lyons

Vassilis Angelopoulos

Robert L. McPherron, Committee Chair

University of California, Los Angeles

2012
This dissertation is dedicated to my parents, John and Winona,
who taught me to believe that not even the sky is the limit
and gave me the foundation to reach for the stars.
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Chapter 5 will appear in a paper soon to be submitted for publication.
Figure 5.16 has been reproduced with permission from C. T. Russell from Russell, C. T. (2000), How northward turnings of the IMF can lead to substorm expansion onsets, *Geophys. Res. Lett.*, 27(20), 3257–3259.

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### Selected Presentations


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CHAPTER 1

Introduction

1.1. Modes of magnetospheric response

Transfer of energy from the solar wind to the Earth’s magnetosphere drives geomagnetic activity, and is primarily accomplished by magnetic reconnection. Dungey [1961] first described a system in which the southward-pointing solar wind interplanetary magnetic field (IMF) undergoes magnetic reconnection with the Earth’s northward-pointing dipole magnetic field at the dayside subsolar point of the magnetosphere. This creates two open field lines, each with one end connected to the Earth, allowing solar wind energy into the magnetosphere. The solar wind forces these lines over the polar caps into the tail, stretching out the field lines to form the magnetotail lobes, until they reconnect again on the nightside of the Earth. The newly closed field lines move sunward, then around the Earth, crossing both dawn and dusk terminators to restore dayside flux. Thus there are four main rates of flux reconnection and transport: dayside reconnection, tailward lobe transport, nightside reconnection, and Earthward plasma sheet transport. The relative balance or imbalance of these four flux rates determines the mode of magnetospheric response.

In the near-Earth neutral line model [McPherron et al., 1973; Baker et al., 1996], the distant x-line (> 100 Earth radii) cannot reconnect open field lines quickly enough to balance the rate of dayside reconnection. Lobe flux and magnetic pressure build up, thinning the plasma sheet, until a closer, second near-Earth x-line is formed. This x-line creates a closed Earth field line and an open solar wind field line, reduces the energy in the system by ejecting a plasmoid down the tail, and sends the remaining plasma Earthward. This loading-unloading process, called a substorm, is the most common and well-studied reaction of the magnetosphere to solar wind
driving. It is a transient response, with a timescale of ~1-3 hours, and consists of a significant reconfiguration of the magnetotail and explosive luminous signatures in the auroral oval [Rostoker et al., 1980].

The magnetosphere can respond to driving with other modes, fundamentally different from the substorm. One is sawtooth events, a global oscillation where the magnetosphere is strongly driven and flux is stored and released in quasi-periodic injections [Henderson, 2004]. The other is a directly driven process, commonly termed steady magnetospheric convection (SMC). This name is a bit of a misnomer, as it has been shown that convection during these intervals consists of localized bursty fast flows [Sergeev et al., 1990, Tanskanen et al., 2005] and some events include auroral perturbations similar to pseudo-breakups [Sergeev et al., 1996a]. It is perhaps more correct to say “quasi-steady” or “stable” magnetospheric convection. The term “balanced reconnection intervals” (BRI) has been suggested in order to reference the proposed state of the magnetosphere for these events [DeJong et al., 2008]. Other terms include “convection bays” and “continuous magnetospheric dissipation”, based on the mode’s signature in ground magnetometers and magnetotail pressure, respectively [Pytte et al., 1978; Tanskanen et al., 2005]. However, we will use the term “steady magnetospheric convection” and “SMC” in this dissertation for historical reasons, with the understanding that on large spatial and time scales, the magnetospheric system is steady, but this mode of response includes localized, short-lived, non-steady features.

The study of a disturbed yet stable magnetosphere is extremely important, especially when compared with the unsteady substorm mode. SMC research answers fundamental questions on the magnetosphere’s variability and sensitivity to changing solar wind conditions. Quantifying how the magnetosphere reacts with different modes to various solar wind conditions
is necessary to fully understand driving of the magnetosphere by the solar wind, and crucial to accurate predictions of future activity.

1.2. Brief historical overview of SMC research

Steady magnetospheric convection events are intervals of enhanced convection in the magnetosphere and ionosphere that persist for longer than a substorm recovery phase and have no substorm expansions [Sergeev et al., 1996a]. The possibility of such events was first postulated by Caan et al. [1973], who noted that such intervals often included localized bay disturbances seen at only one or two magnetometer stations. Pytte et al. [1978] carried out a detailed examination of one event and suggested the name “convection bay” to describe such situations, due to the signature of 2-celled convection in the ionosphere. They theorized that such events occur after the formation of a near-Earth x-line during a substorm, which then remains close enough to the Earth to balance the dayside reconnection rate. Erickson and Wolf [1980] argued that steady convection is impossible, because flux tubes convecting adiabatically Earthward would compress and reach unreasonable pressures. This “pressure-balance inconsistency” was resolved by Hau et al. [1989], who showed a deep minimum in the plasma sheet Bz would allow a steady convection configuration to develop.

An extensive study of five SMC events was carried out by Sergeev and associates, with results summarized in Sergeev et al. [1996a]. Their work proved that the magnetosphere could reach a steady state, that SMC is a unique mode of response, and that SMCs commonly occur. They found that the large-scale plasma convection and magnetic field configuration were steady, while shorter time-scale transient activations occurred in the magnetotail and ionosphere. The near-Earth magnetic field was highly stretched, with an intense and thin current sheet, while the
mid-tail had a thick plasma sheet, relaxed lobe field, and enhanced equatorial magnetic field values. Modeling indicated there was indeed a minimum in $B_z$ (~1-2 nT) in the transition region from thin to thick current sheet (~12 Earth radii). The tail neutral line was estimated to be somewhere in the region of 50-100 Earth radii ($R_E$). The polar cap was enlarged and stable, with a broad double auroral oval. This implied a large amount of magnetic flux closed through the plasma sheet. Multiple north-south aligned auroral streamers were observed to correlate with observations of fast flows in the plasma sheet [Sergeev et al., 2001; also Solovyev et al., 1999; Zesta et al., 2002].

The first large statistical survey of SMC events was conducted by O’Brien and his advisor McPherron. They showed that the distribution of SMC duration was subexponential, proving that the magnetosphere has some capacity to remain in a steady state [O’Brien et al., 2002]. They also developed the first statistical characterization of solar wind conditions that produce SMC [McPherron et al., 2005]. SMC events occurred during moderate, steady solar wind driving ($V_t \sim 350$ km/s, IMF $B_z \sim$-3 nT, corresponding $E_y \sim$1 mV/m), with solar wind parameters very stable up to ten hours before the SMC began. Longer SMCs occurred during slower and steadier solar wind velocity, though the IMF $B_z$ magnitude was the same as for shorter SMCs. However, they found that these typical solar wind conditions do not always result in an SMC, as similar conditions produced either an isolated substorm or an SMC [O’Brien et al., 2002].

Further statistical work on solar wind driving of different magnetospheric modes was performed by DeJong et al. [2009a]. They compared histograms of solar wind parameters and their steadiness for sawtooth events, SMCs, substorms that initiate SMCs, and isolated substorms. SMCs and sawteeth occurred under similar parameter steadiness, with sawteeth
occurring under much stronger driving than SMCs. SMCs occurred during weaker solar wind velocity and steadier IMF $B_z$ when compared to substorms. SMCs also had a smaller range of possible conditions compared to the other modes of response. They renamed SMCs as “balanced reconnection intervals” (BRI) to emphasize the proposed cause of this mode. These results concurred with a comparison of solar wind conditions during SMCs, periodic substorms, and sawtooth oscillations, performed by Borovsky (but only published in Clauer [2006]). The solar wind driver ($-VB_z$ integrated over the event) had a similar occurrence distribution for SMC events and periodic substorms, although SMC events had a much lower probability of negative values (positive $B_z$). The SMC occurrence distribution of solar wind turbulence (or steadiness, $\delta B/B$) was much steadier than for periodic substorms, and matched the sawtooth distribution.

Statistical studies continued to reveal new insights into SMC events. Shukhtina et al. [2004] compiled event lists of quiet intervals, SMC events, and substorm onsets and found that the lobe magnetic field, tail flaring angle, and tail radius during SMC were similar to quiet intervals. They estimated the magnetic flux in the tail ($F_T$) and found that it remains nearly constant between 15-35 $R_E$ at an average of 0.7 GWb, similar to quiet time (0.6 GWb) but smaller than substorm onset levels (0.95 GWb). Shukhtina et al. [2010] extended this work and found that the total magnetic flux had a weak dependence on the solar wind driver ($F_T \sim 0.03E_m$, the merging electric field). Dmitrieva et al. [2004] used the same event lists to compare average plasma sheet magnetic flux transfer rates to dayside flux transfer rates. Their results support the hypothesis of balanced reconnection during SMC, as the average dayside flux transfer rate matched the global plasma sheet Earthward convection rate for these events. This was corroborated with individual SMC cases with closely-matched dayside and nightside reconnection rates [Milan et al., 2007].
Recent models have indicated that the entropy parameter ($PV^{5/3}$) plays an important role in the Earthward plasma transport of different modes of response [Wolf et al., 2009]. Fast flows have been related to "bubbles" [Pontius and Wolf, 1990], flux tubes with a lower entropy parameter than their surroundings that therefore move Earthward [Sergeev et al., 1996b]. Estimates of $PV^{5/3}$ in the near-Earth tail ($|X|$ between 8-12 RE) by Yang et al. [2010a] found a near constant value of $0.06 \text{nPa}(\text{RE}/\text{nT})^{5/3}$ for nine SMC events, even when fast flows were observed. By artificially depleting the entropy parameter across the tail, Yang et al. [2010b] simulated an SMC event and reproduced many observed features in the magnetotail and on the ground. They concluded that a low entropy magnetotail could solve the "pressure balance inconsistency" by supplying under-populated flux tubes to the inner magnetosphere. Two scenarios were presented for attaining this low $PV^{5/3}$ boundary: 1) steady near-Earth reconnection at $|X| \sim 20-30 \text{ RE}$ with significantly shorter flux tubes creates low $PV^{5/3}$ across the entire magnetotail; and 2) sporadic midtail reconnection at $|X| \sim 50 \text{ RE}$ with numerous small bubbles cumulatively forms a narrow low-entropy flow channel. Yang et al. [2012] ran a comparison of several simulations for an SMC event and showed that a depleted, low entropy plasma sheet over all local times gave the best agreement with satellite measurements, compared to a low-entropy flow channel centered around midnight.

Most recently, the effect of the ionosphere on the mode of convection was modeled by Brambles et al. [2011]. Weak ion ($O^+$) outflows resulted in quasi-steady convection under various drivers (0.9-3.7 mV/m) as long as the mean fluence rate remained under a threshold ($\sim 1.1 \times 10^{26} \text{ ions/s}$), above which periodic sawtooth oscillations occurred. Increasing the fluence rate caused the location of the tail x-line to retreat tailward.
1.3. A hypothesis for SMC generation

It is thought that steady magnetospheric convection results from balancing the rate of opening flux via dayside reconnection and the rate of closing flux via nightside tail reconnection [Pytte et al., 1978; DeJong et al., 2008]. This harkens back to the original model of magnetospheric reconnection and convection proposed by Dungey [1961]. Dmitrieva et al. [2004] have shown that on average, the dayside reconnection rate and the plasma sheet Earthward flux return rate are equal during SMCs. How does the magnetosphere attain such a balance, especially since its ‘typical’ response to solar wind driving is a substorm?

One clue is that many SMC intervals are preceded by a substorm onset [McPherron et al., 2005], and it has been suggested that this substorm preconditions the magnetosphere to enter a steady state [O’Brien et al., 2002]. This was corroborated by a comparison of solar wind conditions for SMC-preceding substorms and isolated substorms. Precursor substorm conditions are very similar to those during SMC events, and differ significantly from those during isolated substorms [DeJong et al., 2009a]. Sergeev et al., [1996a] state that the configuration required to maintain steady convection might only be able to develop after a substorm.

We hypothesize that a prior substorm onset is necessary to set up the magnetosphere to allow balanced reconnection. A southward turning of the solar wind IMF initiates onset of dayside reconnection. Flux builds up in the lobes, the cross-tail current sheet thins, and the unstable configuration results in a near-Earth x-line and substorm onset. Normally, the IMF turns northward and the substorm recovery phase returns the magnetosphere to its quiet state. However, if the solar wind driving remains southward and steady, dayside reconnection continues, and the magnetosphere settles into a state where the nightside x-line reconnects enough magnetic flux to match the dayside driving. The tail x-line can retreat somewhat tailward
of its initial location due to increased pressure in the inner magnetosphere, but it remains close enough (i.e., not distant) to maintain stability. The balance of flux reconnection rates drives convection such that flux neither accumulates in the tail nor is significantly depleted at the dayside. Most of the flux transport is accomplished with transient fast flows, similar to bursty bulk flows that occur during substorms. These flows do not pile up in the inner magnetosphere as during isolated substorms, since the preceding substorm has increased pressure in that region. Instead, flows are diverted towards the flanks of the tail, carrying flux back to the dayside. The SMC event is ended either by the solar wind IMF turning northward and the nightside x-line gradually retreating tailward, until it reaches far down-tail and activity returns to quiet levels, or some change in the solar wind results in a new near-Earth x-line and new substorm onset.

1.4. Major topics to be addressed in the dissertation

The SMC mode of response is severely understudied, and thus many questions remain to be answered. Some questions have been addressed with single case studies, but never examined in a statistical manner. This dissertation will cover several outstanding questions with the goal of testing our hypothesis of SMC formation as laid out in section 1.3. Our focus will be on statistical studies of multiple datasets to achieve a broad understanding of the physics in question. We will address the following topics:

1. **Solar wind driving of the SMC mode.** Are SMCs associated with recurring structures in the solar wind, such as corotating interaction regions (CIR) and coronal mass ejections (CME)?

2. **Flux transport in the magnetotail.** Assuming SMCs are Balanced Reconnection Intervals, how is the return of closed magnetic flux from the nightside of the
magnetosphere to the dayside accomplished to maintain stability? What is the statistical behavior of the magnetotail plasma during the balanced reconnection mode? How does it compare to the unloading/substorm response and inactive periods? What is the probability that fast flows carrying magnetic flux are seen in the magnetotail during SMC compared to substorms?

3. **Connections between substorms and SMCs.** What is the role of preceding substorms in the formation of SMC events? How often are SMCs preceded and terminated by substorm onsets? Are preceding substorms (and formation of a NEXL) necessary to precondition the magnetosphere to allow quasi-steady convection?
CHAPTER 2
Event Selection

2.1. Previous definitions

Steady magnetospheric convection (SMC) events have been identified by a variety of criteria, but historically they have been selected from their signature in ground magnetometer data. Caan et al. [1973] described an event that consisted of continuous, strong activity in auroral zone magnetograms with non-simultaneous “expansion-like” decreases observed at various stations. This 10-hour long event followed a day of quiet conditions and a global substorm expansion onset. They observed that the tail lobe field strength remained constant, leading them to speculate that:

“Steady flux transfer to the tail can lead to a state of continual geomagnetic activity with no clearly defined substorm phases.”

Subsequently Pytte et al. [1978] described a similar event and coined the name "convection bay" to describe such intervals. Characteristics used to identify these intervals included continuous southward IMF, continuous electrojet activity, absence of the usual indicators of substorm expansion including Pi2 pulsations and mid-latitude positive bays, and an equivalent ionospheric pattern characteristic of the DP-2 convection system.

The first standardized criteria for SMC intervals required (1) auroral electrojet index (AE) ≥ 200 nT, (2) no substorm signatures, current sheet disruptions, or plasmoid releases in the tail, and (3) stable, continuous southward IMF for four to six hours [Sergeev et al., 1996a]. The AE index measures magnetic activity in the auroral zone and enhanced values indicate intensified electrojets and convection in the magnetosphere. O’Brien et al. [2002] pointed out that two of these criteria present problems for selection and study of SMCs. The second criterion
is vague and unquantifiable, and lends itself more to case studies. Selection of thousands of
events for statistical study requires criteria that are consistent, quantifiable, and easily applied to
large datasets. The third criterion presupposes solar wind conditions that lead to SMCs. Defining
SMCs, a magnetospheric process, by solar wind parameters and then asking what different
conditions result in substorms vs. SMCs is circular thinking.

To resolve these issues, O’Brien et al. [2002] used the AE index only, generated from
ground-based magnetometer data, to select SMC intervals. Although their specific goal was to
identify the solar wind conditions typical for SMC events, their criteria are valid for studying all
SMC-related questions, as they define this magnetospheric event using a signature of
magnetosphere convection, not according to outside stimuli. Their criteria or slightly modified
versions have been used in various studies [O’Brien et al., 2002; McPherron et al., 2005;
McWilliams et al., 2008; Partamies et al., 2009a; Yang et al., 2010a] and are as follows:

(1) AE ≥ 200 nT.

(2) the change in AL (auroral lower index) must not decrease by more than 25 nT per
minute, i.e. dAL/dt ≥ -25 nT/min. This quantifies the Sergeev et al. [1996a] second criterion.
Expansion onset typically appears in the AL index as a sharp drop, so requiring that the slope be
less than a certain value rules out most substorm expansions.

(3) Conditions (1) and (2) must persist for 90 minutes or more, in order to be longer than
a typical substorm recovery phase.

Using the same criteria (with a modified minimum duration of three hours), McWilliams
et al. [2008] argued that the AE ≥ 200 nT criterion was insufficient to capture smaller SMCs,
especially in the winter. The AU (auroral upper) index has a seasonal bias due to increased
photoionization during the northern summer months [Kamide and Akasofu, 1983], which allows
stronger currents to close in the northern hemisphere during these times. This leads to a greater selection of events during summer months, while the cutoff criterion eliminates all but the strongest events during northern winter. The authors proposed a variable criterion for AE that depends on the day of the year, \( x \):

\[
AE \geq 90 + 110 \cos \left( \frac{x - 173}{365} \pi \right) nT
\]

Although application of this equation resulted in approximately the same number of events per month throughout the year, the function was chosen specifically to achieve that result, and the physical meaning of the equation is unknown. Instead, we prefer to separate the components that make up the AE index, the auroral upper (AU) and auroral lower (AL) indices, and treat them separately. The AU and AL indices represent the strongest measured magnitude of the eastward and westward electrojets, respectively, while the AE index represents the overall activity of the electrojets \([Davis and Sugiura, 1966]\). The AU and AL indices are influenced by different factors: for example, the AU index, as mentioned, experiences an annual variation, while the AL index undergoes a semiannual variation with peaks at the equinoxes. Thus we chose to separate out the different physical processes that make up the AE index, rather than imposing a variable criterion.

\[\text{DeJong and Clauer [2005]}\] used Polar UVI images to determine the poleward boundary of the auroral oval. This boundary serves as an indicator of open field line flux, which must remain constant if day- and nightside reconnection are balanced. An SMC event was identified as having \( AE \geq 200 \) nT, no substorm signatures, and a steady polar cap area (\(< 10\% \) change) for at least three hours. They found some events with poleward boundary intensifications (PBIs) [also observed by \textit{Lyons et al.}, 1998 and \textit{Zesta et al.}, 2002] and pseudo-breakups \([Elvey, 1957, \text{also observed by Sergeev et al., 1986}]\). The magnetic ground signature of both PBIs and pseudo-
breakups is a sharp break similar to a weak or moderate substorm expansion, but with short duration (~5-15 minutes) [McPherron et al., 1968; Lyons, 2000; McPherron et al., 2008]. The authors concluded that the $\text{dAL/dt} \geq -25$ nT/min criterion from O’Brien et al. [2002] is too strict, excluding large, rapid fluctuations in the AL index that may be due to transient features unrelated to substorms. The steady polar cap criterion led to a suggestion that a steadiness criterion for the AL index would result in a better selection of SMC events that includes transient activations like PBIs [A. DeJong, personal communication, 2009].

The minimum duration of SMCs continues to be an area of some debate. The methods detailed here use various values: 4-6 hours [Sergeev et al., 1996a], 1.5 hours [O’Brien et al., 2002; McPherron et al., 2005], and 3 hours [McWilliams et al., 2008; DeJong et al., 2005]. The purpose of a minimum duration criterion is to eliminate substorm recovery phases, which on average are about 90 minutes long [Baker et al., 1994]. Many researchers prefer to double this value to three hours, ensuring exclusion of substorm recovery phases. However, O’Brien et al. [2002] plotted the distribution of intervals that satisfied SMC criteria, with durations from one minute up to 700 minutes, and found a continuum with no obvious minimum duration. Thus, they selected the shortest possible duration that would still be longer than the average substorm recovery.

2.2. Selection of SMCs

Our goal is to test each question posed in this dissertation with datasets from a large, comprehensive SMC event list. By modifying the auroral index criteria of O’Brien et al. [2002], we have identified 3001 SMC events in the interval 1997-2011. Events were selected by visual inspection of daily Kyoto auroral electrojet indices, AL and AU. All limits were selected to be
larger than the magnitude of different quantities observed on a quiet day, but low enough so that we would detect small SMCs. Our criteria are:

1. \( \text{AL} < -75 \text{ nT} \).

2. \( \text{AU} > 50 \text{ nT} \). This condition was allowed to be violated up to 50% of the time during events in the winter months due to the seasonal variation of AU [McWilliams et al., 2008]. The combination of conditions 1 and 2 results in an effective AE > 125 nT criteria, which is smaller than those discussed above. Lower limits were chosen in order to select weak SMCs.

3. \( \text{AL} \) steadiness \( \leq 20\% \). Steadiness is defined as the standard deviation divided by the mean (coefficient of variance) [DeJong et al., 2009a]. A running average and standard deviation is found for a 30 minute period, advanced by 1 minute increments. A value of 0.0 indicates a completely steady interval (flat line), while higher values are less steady. This condition was developed through collaboration with Anna DeJong. Up to 50% of a given event was allowed to have steadiness larger than 20%. This permitted selection of SMCs that included larger AL fluctuations as observed by DeJong and Clauer [2005].

4. Event duration must be longer than 90 minutes in order to be longer than a typical substorm recovery period [McPherron et al., 2005; O’Brien et al., 2002], following the reasoning laid out in section 2.1.

5. The start time of the SMC is selected when all of the above criteria are met. Often, this occurred after a substorm onset, seen as a sharp decrease in the AL index. At times, there was an obvious substorm recovery (increase in AL) before the SMC (stable AL). In this case, the SMC start was selected at the beginning of the stable AL, after the partial recovery. In other cases, it was impossible to distinguish the 'recovery' from the SMC.
(Figure 2.1 below includes an example of such a situation). Thus we selected the start of these SMC events after the expansion phase of the preceding substorm was complete. The end time of the SMC corresponds to another substorm expansion onset, or when one or more of the above three criteria go outside of threshold values.

During event selection, we also examined the time series of dAL/dt, a 15 minute sliding derivative operator that represents the rate of change in the AL index (similar to the slope of AL in O'Brien et al. [2002]). While there was no specific limit for this parameter, we used it in our visual selection to better define the onset of a substorm or the end of an SMC. Peaks in this

![Figure 2.1](image)

**Figure 2.1.** Two SMC intervals occurred on 08-09 June 2007. The first panel plots AU and AL, as well as AE (red). The second panel plots dAL/dt, a fifteen-minute running average representing the rate of change of AL. The third panel plots AL steadiness. Overlaid green lines in each panel show where each parameter’s criterion is met. The first SMC (blue region) begins with a substorm expansion, and consists of a long period of enhanced convection (five hours), while the second SMC (purple region) does not begin with an obvious substorm, but still meets all of our criteria. Adapted from Kissinger et al. [2011].
parameter do not necessarily correspond to substorms, as PBIs or pseudo-breakups would produce a similar break, but their occurrence encouraged closer examination of a particular interval to determine whether or not it was an SMC.

An example of two selected SMC intervals on 8-9 June 2007 can be seen in Figure 2.1 (16:32 to 21:34 and 02:22 to 05:48). Green segments of the plotted lines show when each parameter fits the given criteria. The first event is a ‘typical’ SMC that begins and ends with a substorm expansion, while in the second event no beginning or ending substorm is seen. For both events, the AL index is consistently below -75 nT, AU is above 50 nT, and AL steadiness is below 20%. In the first event, the sliding derivative operator dAL/dt has small peaks that correspond to transient AL fluctuations, with a larger negative peak at the time of the concluding substorm expansion. This helps us define the end of the SMC.

2.3. Validation of selected events

It should be emphasized that the auroral indices suffer from numerous problems due to changes in the number of contributing stations [Rostoker, 1972], irregular distribution of AE stations in latitude relative to the dynamic movement of the auroral oval [Kamide and Akasofu, 1983], and the small number of contributing stations [Akasofu et al., 1983; Newell and Gjerloev, 2011]. The AL index can miss substorm onsets, particularly in UT sectors of poor coverage (i.e., Siberia during the rising phase of the solar cycle [McPherron et al., 2009]); therefore it is important to verify that there are no substorm expansions within our SMC intervals. However, since our goal for this dissertation is statistical data analysis of a large number of events, it would be unrealistic to scrutinize numerous datasets for each individual event to completely ensure lack of substorm expansions. Instead, we used several methods to approximate the percentage of false
positives in our SMC event list. First, we compared our events to a list of substorm onsets and eliminated any suspect intervals with an onset in the middle. This substorm list of 24061 onsets was visually selected with AL data from 1997 to May 2011 [Hsu et al., 2012]. Second, we examined a subset of events for peaks in the GOES-8 or GOES-12 magnetic inclination angle (in the meridian plane from H to Z axis) and electron flux enhancements at LANL, both signatures of substorm injections at geosynchronous orbit. We found that 11% of this subset had these substorm signatures within the SMC interval. However, the inclusion or removal of this subset does not change the statistical results presented in the rest of this dissertation. Therefore, we conclude that our selection criteria are adequate, for our statistical purposes, to identify intervals of enhanced, stable convection without substorms.

Our hypothesis states that SMCs result from balanced dayside and nightside reconnection, which should lead to stable open flux and steady polar cap boundaries. Ideally, one would select SMC events from images of the polar cap and auroral oval, as in DeJong and Clauer [2005]. Unfortunately, visually determining the polar cap boundary for the entire set of Polar images, spaced 37 seconds apart, for 12 years would take an excessive amount of time. In addition, satellite orbital constraints would limit the number of events that could be confirmed. We must validate whether our events can be considered balanced reconnection intervals in other ways.

First, we compare our SMC event list with 51 SMCs identified using Polar by DeJong et al. [2009b]. They found that the O’Brien et al. [2002] criteria would only identify 27 of their 51 SMCs. Our improved method selects 38 of their 51 SMCs. For two of their events, AE data were unavailable. In each of the remaining 11 intervals, we did not identify it as an SMC due to some combination of AL steadiness and another parameter going outside of our limits. In an effort to
automate selection of SMC events, DeJong et al. [2009b] suggested that the steadiness parameter should allow for more variation. However, this method is still undergoing validation. On average, our method selects the start of an SMC around the same time as DeJong et al. [2009b], but tends to select the end of the SMC before the DeJong and Clauer [2005] method.

Since the 51 SMC events from DeJong et al. [2009b] were selected by steady polar cap area with Polar images, they were able to rename their events "balanced reconnection intervals", as matching dayside and nightside reconnection rates result in stable open flux in the polar cap. Although it would be unreasonable to measure the polar cap area for our 3001 events, we can compare the auroral indices during our events to the DeJong et al. [2009b] events. If these parameters are similar for our SMCs and their BRIs, we can safely say that we are studying similar events, and can assume that statistically, our events are also caused by balanced reconnection.

Figure 2.2 shows a comparison of cumulative probability distributions for AL, AU, dAL/dt, and AL steadiness. The red lines in each plot show the distributions for our SMC events. The black lines show the distributions for each parameter during the DeJong et al. [2009b] BRI events. Since we had a strict AL cutoff, we have removed any data points during the BRIs in which AL went above -75 nT. It is clear that our SMCs have similar AL, AU, and dAL/dt distributions to BRIs. Our SMCs tend to be steadier in AL than the BRIs, due to our AL steadiness cutoff; in fact, about 20% of the data points in the BRIs fall outside of the steadiness cutoff. This discrepancy explains why some of the BRIs were not selected as SMCs. Our steadiness criterion is stricter in order to be certain we are selecting steady intervals. Therefore, we conclude our assumption that we are studying balanced reconnection intervals is statistically valid.
Figure 2.2. Cumulative probability distributions of AL, AU, dAL/dt, and AL steadiness compared for our SMCs (red lines) and DeJong et al. [2009b] BRIs.

As further validation of our method, we applied our criteria to the five events from Sergeev et al. [1996a] and summarize the results in Table 2.1. We successfully identified three out of five events, although a small portion of event 5 was missed due to exceeding the steadiness criterion. Similarly, most of event 4 was missed due to the AL becoming too unsteady for selection. Finally, the AL index during event 3 was very small and almost always under our -75 nT threshold. The data from Sergeev et al. [1996a] shows that the average AE was 190 nT, a little less than their typical AE >= 200 nT. At some points, the AE is almost entirely due to the
contribution from AU. It is clear that there are no substorms during this time, and this is probably a very weak SMC event.

When compiling thousands of events for statistical study, one would prefer to select intervals automatically. One outstanding problem with automated detection is the exclusion of very active SMCs; examples include Event 4 in Table 2.1 from Sergeev et al. [1996a] and Event 4 in DeJong et al. [2008]. An automated SMC detection method is being developed [DeJong et al., 2009b], specifically focusing on refining the AL steadiness criteria. When these criteria are finalized, our extensive visually-selected SMC list will enable validation of the automated methods. Unfortunately this method was not completed in time for this dissertation.

Finally, we would like to justify our 90-minute minimum duration. We compare solar wind parameters during 'short' SMCs (<3 hours) with 'long' SMCs (>3 hours). Figure 2.3 shows

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>UT</th>
<th>Avg AE</th>
<th>Avg Bz</th>
<th>Avg Vsw</th>
<th>Percent Found</th>
<th>Problem Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1981-11-24</td>
<td>01-12</td>
<td>360</td>
<td>-4.3</td>
<td>342</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1978-02-19</td>
<td>16-22</td>
<td>340</td>
<td>-6.0</td>
<td>381</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1980-04-24</td>
<td>03-14</td>
<td>190</td>
<td>-2.5</td>
<td>318</td>
<td>18%</td>
<td>AL</td>
</tr>
<tr>
<td>4</td>
<td>1988-01-25</td>
<td>15-23</td>
<td>200</td>
<td>-3.9</td>
<td>287</td>
<td>38%</td>
<td>Steadiness</td>
</tr>
<tr>
<td>5</td>
<td>1988-04-27</td>
<td>15-22</td>
<td>250</td>
<td>-3.8</td>
<td>303</td>
<td>89%</td>
<td>Steadiness</td>
</tr>
</tbody>
</table>

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![Cumulative probability distributions of AL index and solar wind E_s during short (blue dashed lines) and long (red solid lines) SMCs.](image)

**Figure 2.3.** Cumulative probability distributions of AL index and solar wind E_s during short (blue dashed lines) and long (red solid lines) SMCs.
cumulative probability distributions of AL index and $E_s$ ($V_{SW} * B_z = E_y$; $E_s$ is only positive values of $E_y$ to correspond to negative IMF $B_z$). Shorter SMCs (blue dashed line) occur during slightly smaller AL values, as well as faster solar wind velocity and weaker IMF $B_z$ (not shown), which combined results in weaker $E_s$ values. These results concur with McPherron et al. [2005], who found that slow, more southward solar wind causes longer duration SMC events in the magnetosphere. If we approximate the magnetosphere as a driven system, the input to the system is the solar wind driver $E_s$, and the output is the measure of the convection, the AL index. We can estimate the coupling efficiency between the solar wind and the magnetosphere by assuming that $E_s$ and AL are constant during the course of a particular SMC (this method is detailed further in section 3.4). Then the coupling strength is the output divided by the input, or $AL / E_s$, shown in Figure 2.4. Here, we see that there is very little difference in the distributions of coupling strength between short and long SMCs. This correlates with Figure 2.3, where the weaker $E_s$ distribution for shorter SMCs results in a corresponding weaker AL distribution. Therefore, we can be assured that we are examining physically similar intervals between short and long SMCs.

![Figure 2.4](image-url)  

**Figure 2.4.** Cumulative probability distributions of the coupling coefficient $AL/E_s$ for short (blue dashed lines) and long (red solid lines) SMCs.
2.4. SMC event statistics

With this large list of SMC intervals, we can examine their typical duration and recurrence rate. Figure 2.5 shows histograms of the SMC recurrence rate and SMC duration. Both distributions fall off with increasing duration. While the average separation between successive SMCs is 43 hours, the median value is 18 hours, and the peak of the distribution occurs at 4 hours. The peak SMC duration occurs at 100 minutes, just over our minimum duration threshold of 90 minutes. This correlates with the findings of O’Brien et al. [2002], who demonstrated that the distribution of SMC duration follows a subexponential curve. The average SMC duration is 180 minutes (3 hours).

![Figure 2.5. Distributions of SMC recurrence rate (left; the separation between two successive SMC events) and SMC duration (right). The most probable value (black), median (blue), and mean (red) are marked with vertical dashed lines.](image)

2.5. Conclusions

As with substorms, identification of SMC intervals can be accomplished with numerous datasets and various criteria. Most methods of identification are ideal for case studies only. The single comprehensive statistical selection method for SMCs made use of the auroral indices [O’Brien et al., 2002], the only dataset consistently available over all years of interest to this
study. Building on this method, we have formalized a set of criteria for identifying large numbers of SMC events using auroral indices. Such criteria could be used to automatically detect SMCs, but we recommend visual inspection of potential intervals to ensure their validity.

Our selection process does not guarantee that each event is an interval of balanced reconnection. Unfortunately no continuous set of auroral observations is available to confirm the events selected with our formal constraints. However, we show that our criteria did select more than 75% of events identified as balanced reconnection intervals with auroral imagers. Furthermore, statistical properties of auroral indices for our events are virtually identical to those during BRIs. Finally, we have used a variety of methods to assure ourselves that only a small percentage of our events have substorms within them, and we confirmed that inclusion of problematic events does not significantly alter our statistical results. On this basis, we are confident that our list of SMC events is dominated by events similar to those chosen in the past as SMC, and similar to those identified as BRIs. In Chapter 4, we will demonstrate that the magnetotail conditions during the events we selected differ in statistically significantly ways compared to quiet intervals, substorm growth phases, expansion phases, and recovery phases.
CHAPTER 3

Solar Wind Driving

3.1. Introduction

Steady magnetospheric convection (SMC) events are thought to be a consequence of balanced reconnection at the day and night sides of the magnetosphere [Sergeev et al., 1996a; DeJong et al. 2008]. This process is sometimes referred to as the “Dungey Cycle” [Milan et al., 2007] since it is the situation originally envisioned by Dungey [1961] to explain auroral activity. An outstanding question remains as to why the magnetosphere sometimes responds to solar wind driving with a substorm, and at other times with an SMC, even under similar conditions [O’Brien et al., 2002]. Pulkkinen et al. [2007] used simulations to show the magnetosphere becomes less steady as solar wind speed increases. The effect of solar wind speed was confirmed with a statistical study of sawtooth events, isolated substorms, and SMCs by Partamies et al. [2009b]. They found that overall, solar wind conditions during SMCs are similar to substorms, but that SMCs occur during lower solar wind speed.

When regions of fast solar wind impact on slow solar wind, a stream interface is created [Gosling et al., 1978]. Seen at the Earth, the region of slow solar wind occurs before the interface, velocity increases as the interface passes the Earth, and peak velocity occurs after the interface. Since SMCs have been previously found to occur during slow, steady solar wind conditions, one might expect to see an increase in SMC events before stream interfaces. Kissinger et al. [2010] did find a correlation between SMC occurrence and stream interfaces (SI) during Dec 2007-2009; however, SMC occurrence peaked 0.5-1 day after a stream interface, not before. In addition, a minimum in SMC occurrence was observed 3-1.5 days before the stream interface. The solar wind conditions during SMCs associated with stream interfaces were
different from those reported previously [DeJong et al., 2009a, Partamies et al., 2009b, McPherron et al., 2005], including faster solar wind velocity and weaker interplanetary magnetic field (IMF) $B_z$ than expected, seeming to contradict previous results. The events of DeJong et al. and Partamies et al. were from the rising phase of the solar cycle (1997-2002 and 1998-2001 respectively) while those of McPherron et al. covered an entire solar cycle, but they did not examine the differences in SMC by solar cycle phase. Since the events of Kissinger et al. occur during the declining phase, this may explain the discrepancy between their results and the other studies.

In this chapter, we set out to study events from Solar Cycle 23, years 1998-2009 inclusive, to determine the effect of the solar cycle on the SMC-SI relationship. The primary question we will answer is: Are SMCs associated with recurring structures in the solar wind, such as corotating interaction regions (CIR) and coronal mass ejections (CME)?

3.2. Analysis procedure

Stream interfaces occur when regions of faster solar wind interact with and overtake slower solar wind streams [Gosling et al., 1978]. As they corotate with the Sun, they are also known as corotating interaction regions (CIRs). We identified 396 stream interfaces from 1998 to 2009. Stream interfaces were visually identified by requiring that all of the following qualitative signatures were seen in conjunction: an increase in solar wind velocity from slow (less than 500 km/s) to fast (greater than 500 km/s); an increase in density followed by a sudden drop; a bipolar variation in the azimuthal flow angle ($\arctan(V_y/V_x)$); a peak in the magnetic field strength; increased magnitude of $E_y$ fluctuations; and often (60% of the time) a crossing of the heliospheric current sheet as seen in the IMF spiral angle. Figure 3.1 shows an example of a
stream interface on 19 June 1995 (not used in the study). The time of the interface was selected as the zero crossing of the azimuthal flow angle.

**Figure 3.1.** Example of a stream interface. Solar wind OMNI data is plotted during June 1995: total velocity, east-west flow angle, IMF magnitude (pink) and density (blue), spiral angle, and GSM E_y. The time of the interface (10:05:19) was selected at the zero crossing of the flow angle. Velocity increases sharply from ~380 km/s to over 600 km/s. An increase is seen in density before the interface, followed by a sudden drop, and B_{total} increases after the interface. The spiral angle shows that there is a crossing of the heliospheric current sheet. From Kissinger et al. [2011].

To compare our lists of SMCs and SIs, we use a technique of time delay superposed epoch analysis [Kissinger et al., 2010]. For each stream interface \( n \), we selected the SMC events that occurred after the preceding interface \((n-1)\) and before the subsequent interface \((n+1)\). We calculated the delay between the SMCs and the \( n \)th stream interface, and accumulated the delays for each SI. A histogram of the time delays was generated, separated into 0.5 day (12-hour) bins, and spanning -20 days (before a stream interface) to +20 days (after a stream interface). To
construct a probability density function (PDF), we divided the time delay histogram by the total number of events times the bin width:

$$\text{PDF} = \frac{\text{Histogram}}{\text{number of events} \times \text{bin width}}$$

Plotting the probability density function histogram results in a superposed epoch analysis of SMC occurrence with respect to the time of stream interfaces ($t = 0$, see Figure 3.2).

This procedure introduces artifacts into the analysis. First, delays are found only for SMCs that occur between the preceding and following SIs; therefore, any SMCs outside this range are ignored. If our SIs were evenly spaced by seven days, for example, this means it would be impossible to get a delay of more than ± seven days. Although stream interfaces have a typical recurrence rate (seven days over the entire solar cycle), they are irregularly spaced, and thus SMC events are seen past this average SI recurrence time. The delays in the histogram fall off rapidly after seven days, and because there are few events there we ignore anything near the outskirts of the graph.

Second, an SMC event with a positive delay for the $n$th interface (event occurring after the stream interface) will in turn have a negative delay for the $(n+1)$th interface (event before the stream interface). This effectively doubles the number of events—an SMC will appear twice, once on either side of the $t=0$ line. Combining this with the above “average SI recurrence time” can result in a secondary peak at around -7 days. This is an effect of the analysis and does not appear when the relationship is examined using other methods.

### 3.3. Dependence of the SMC-SI relationship on solar cycle

Plots of SMC occurrence using time delay superposed epoch analysis were examined for each year from 1998 to 2009. A comparison of these yearly graphs revealed that SMC
occurrence with respect to SIs showed two types of behavior—correlated and uncorrelated—and that these were organized by solar cycle phase. Figure 3.2 displays the superposed epoch analysis of the probability density for an SMC to occur with respect to a stream interface (epoch time = 0, thick vertical dashed line) in 12-hour bins, with the two traces corresponding to different phases of the solar cycle. The rising phase of solar cycle 23 (1998-2003, blue line), shows a weak correlation between SMCs and stream interfaces, while the declining phase (2004-2009, red line) shows a significant organization of SMC with respect to stream interfaces. In this case, SMC occurrence peaks sharply -1 day before to +2.5 days after a stream interface, and there is a minimum in SMC occurrence -3 to -1 days before the interface. This is similar to the result found by Kissinger et al. [2010] for a smaller set of data. The gray bar graph is a histogram of separation between successive SI. The most probable separation between SI is between six and

![SMC Relative to Stream Interfaces](image)

**Figure 3.2.** SMC intervals are compared with stream interfaces using time delay analysis. Epoch t=0 marks a stream interface (thick vertical black line). The probability density of SMC occurrence in the days before and after an interface is plotted in 12-hr bins. The rising phase of the solar cycle (1998-2003) is plotted in the blue line and the declining phase (2004-2009) is the red line. The separation of successive stream interfaces in days is shown as a grey histogram, and the most probable separation (6-7 days) is plotted before and after t=0 as a thin vertical dashed line. Adapted from Kissinger et al. [2011].
seven days, shown as a thin dashed line before and after epoch zero. Again, the secondary SMC peak at -6 days is an artifact of the analysis.

Why are SMCs correlated with stream interfaces during the declining phase of the solar cycle, but not during the rising phase? One possibility is that the stream interfaces themselves are different during different parts of the solar cycle. Figure 3.3 again shows the probability density of SMC occurrence with respect to stream interfaces, now separated by phase (rising phase on the left column, declining phase on the right) and by geoeffectiveness of the streams according to the Russell-McPherron effect [Russell and McPherron, 1973a] (rows). Effectiveness of the solar wind to reconnect with the Earth’s magnetosphere depends on the changing orientation of the solar magnetospheric coordinate system relative to the solar equatorial system. It can be determined by the IMF magnetic spiral angle according to the rule “Spring To, Fall Away” [Russell and McPherron, 1973a]. That is, near the spring equinox, the solar wind is geomagnetically effective when the magnetic field $B_y$ component points toward the Sun along the spiral angle of 45 deg (negative), and ineffective when it points away from the Sun (positive); during the fall the opposite is true. A stream interface separates two solar wind sectors, and the solar wind can be Ineffective or Effective both before and after the interface, resulting in four categories: effective before, effective after (EE, first panels, black lines); ineffective before, effective after (IE, second panels, red lines); effective before, ineffective after (EI, third panels, green lines); and ineffective before and ineffective after (II, fourth panels, blue lines). The type of interface and the number associated are displayed on each plot.

In the rising phase of cycle #23, IE interfaces were the most likely to occur, while all other types have around the same occurrence rate. Relative to IE interfaces, there is an increase in SMC occurrence just before the interface, while EE, EI, and II show no increased SMC
Figure 3.3. SMC probability density before and after stream interfaces is plotted in 12-hour bins by rising phase (left column) and declining phase (right column), and by stream effectiveness: EE (black, first row), IE (red, second row), EI (green, third row), and II (blue, fourth row). The number of interfaces for each case is displayed on the respective plot. Adapted from Kissinger et al. [2011].

correlation. In the declining phase, the number of EI and II interfaces nearly doubled, while the number of EE and IE interfaces is around the same; thus IE, EI, and II have the same occurrence rate. Since six years of data goes into both the rising phase and declining phase plots, this means
that the number of SIs per year increases between the solar cycle phases. Both EE and IE show a peak in SMC occurrence at/after the interface, especially IE. This SMC peak after EE interfaces is not seen in the rising phase. SMC occurrence near EI interfaces does not peak in either phase, although there is a tendency for increased SMC occurrence 4-7 days before the interface due to the effective solar sector. Finally, although occurrence at II interfaces is relatively flat, it shows a small peak in SMC right at the interface in the declining phase.

During the declining phase, three types of interfaces (IE, EE, and II) show some or significant correlation with SMC occurrence, while in the rising phase, only one interface type (IE) does. Averaging all the interfaces together results in the overall behavior seen in Figure 3.2. The association for SMC events with EE and II changes between the phases, and even the SMC peak and shape for IE interfaces changes significantly. This suggests there is still an unknown difference for stream interfaces between phases.

Figure 3.4 shows a superposed epoch analysis of solar wind and ground station parameters, where stream interfaces occur at t=0 days. The interfaces are separated by effectiveness type, as evidenced by the first panel, spiral angle (Psi). This angle results from a coordinate system rotated +45° about Z GSE, so that angles near -90° are “toward” the Sun (effective in Spring) and angles near +90° are “away” (ineffective in Spring). The spiral angle has been flipped for data in the fall in order to agree with this convention. Here it is easy to see that EE interfaces are effective before and after the interface; IE interfaces are ineffective before and switch to being effective just before the interface, and so on. The remaining panels display solar wind dynamic pressure \( p_{\text{dyn}} = 1.67 \times 10^{-6} \times n_p \times v^2 \), solar wind GSM E_y, AE index, and Sym-H index. There is a higher dynamic pressure peak associated with the two interface types that include an IMF sector crossing, IE and EI, which occurs during ~60% of stream interfaces.
This results from the crossing of the heliospheric current sheet (HCS), which is a region of enhanced density separating the two different regions of magnetic polarity [Bavassano et al., 1997]. Note that geoeffective high speed streams (EE, black and IE, red) result in higher geomagnetic activity after the interface (AE and Sym-H) than ineffective. The largest increase in activity is caused by IE, and the smallest by EI. This is due to the fact that the two types which

![Comparison of Four Classes of Stream interfaces 1998-2009](image)

**Figure 3.4.** Superposed epoch analysis with respect to stream interfaces of IMF spiral angle, dynamic pressure, GSM E_y, AE index, and Sym-H. Interfaces are separated by effectiveness: II (blue), EI (green), IE (red), and EE (black). Adapted from Kissinger et al. [2011].
are effective after the interface, IE (76 interfaces) and EE (42 interfaces), show positive $E_y$ afterwards, while streams which are ineffective after (69 II and 69 EI) have negative $E_y$ GSM. In fact, effective-after interfaces (EE, IE) result in stronger $E_y$ signatures after the stream interface than effective-before interfaces (EE, EI) show before the event, owing to the increase in velocity. This is consistent with the Russell-McPherron statement that geomagnetic activity is organized by effectiveness of the IMF. EE and IE interfaces correlate with SMC activity because their effective solar wind orientation after the interface results in more negative $B_z$/more positive $E_y$, resulting in reconnection, and a higher probability of SMCs.

To show the effect of the changing solar wind driver for each type of interface, we rectify solar wind $E_y$, such that only positive values remain (corresponding to negative IMF $B_z$) and negative values are flagged as "not-a-numbers". This is called "E south" ($E_s$), referring to its dependence on southward $B_z$. Then we calculate a running hourly sum of $E_s$ (Int $E_s$), which represents the total amount of driving applied to the magnetosphere in one hour. Figure 3.5 shows a superposed epoch analysis of Int $E_s$ separated by solar cycle phase and stream interface effectiveness type, in the same manner as Figure 3.3. The light blue lines represent Int $E_s$ averages for each minute with respect to the time of the interfaces. Thick colored lines are a 12-hour running average of these values. The general effectiveness of the solar wind before and after each stream type is easy to see: for example, Int $E_s$ is near zero before IE interfaces since the solar wind is ineffective due to positive $B_z$, and becomes large after the interface during the effective/negative $B_z$ solar wind sector. This also helps explain the peak in SMC occurrence with respect to declining phase II interfaces seen in Figure 3.3: although in general, Int $E_s$ is near zero on both sides of the II interfaces, there is a small organized increase just after the II interfaces. In general, it is apparent that there is more scatter in Int $E_s$ levels during the rising phase compared
Figure 3.5. Average ensembles of the total hourly $E_s$ (Int $E_s$) are plotted with respect to stream interfaces in the same manner as Figure 3.3. Light blue lines show averages every minute, and overlaid thick colored lines are a 12-hour running average of these values.

to the declining phase. The patterns of Int $E_s$ changes at stream interfaces are more clear and organized in the declining phase. This may be due to the fact that coronal holes that generate fast solar wind streams are more developed during the declining phase. Thus, the three organized Int $E_s$ peaks in the declining phase for EE, IE, and II interfaces result in associated SMC occurrence
peaks, while the variable and disorganized behavior of Int E, in the rising phase results in only IE interfaces causing a systematic enhancement in SMC occurrence.

The increase in reconnection during a geoeffective high-speed stream affects other types of activity as well. Using a list of over 20000 substorm onsets [Hsu and McPherron, 2012], we compared the number of substorms that occur before and after a stream interface. This is shown in Figure 3.6 as substorm number versus time. The smoothed number of substorms that occur within seven days before each interface is plotted in blue, and those occurring within seven days after an interface in red. Smoothing was accomplished by creating a NaN (not a number) time series with one day resolution. For each SI onset, the substorm number occurrence before and after was filled into the time series, and then a running average using a ±40 days time window was calculated. There are always more substorms after a stream interface than before it. The upward trend suggests that there are more substorms in the declining phase of the solar cycle than in the rising phase. There seems to be a periodicity in the number of substorms on the order of 1-1.5 years which should be explored in the future.

Figure 3.6. Smoothed number of substorms vs. time over a solar cycle. Substorms that occur within seven days before a stream interface are plotted in blue; substorms that occur within seven days after are in red. Adapted from Kissinger et al. [2011].
Figure 3.7. Number of substorms per day relative to stream interfaces (t=0).

The increased number of substorms at a stream interface is obvious in Figure 3.7. Substorm occurrence reaches a minimum at -1 day before stream interfaces, then increases sharply at the boundary, peaking ~12 hours after SI arrival. If the formation of a near-Earth neutral line and substorm onset are necessary to allow the magnetosphere to enter an SMC state, then the increased substorm occurrence would also contribute to the increased SMC occurrence.

3.4. Solar wind–magnetosphere coupling

The solar wind causes geomagnetic activity in the form of a half-wave rectifier [Murayama et al., 1980]. When the IMF points southward, it couples to the Earth’s magnetic field via reconnection. Solar wind-magnetosphere coupling is more efficient during SMC events than other modes of response [Partamies et al., 2009a]. The magnetosphere can be thought of as a driven system, with the solar wind rectified $E_y$ as the input ($E_y > 0$, corresponding to $B_z < 0$ since $E_y \sim V_x B_z$; also called $E_s$), and the convection in the magnetosphere, approximated by $AL$
index, as the output. If we assume that the filter is causal, the impulse response of the magnetosphere can be represented as

\[ O(t) = (I * g)(t) \overset{\text{def}}{=} \int_{-\infty}^{\infty} I(\tau)g(t-\tau)d\tau \]

where \( O \) is the output of the system, \( I \) is the input of the system, \( g \) is the impulse response function integrated over time, and \( \tau \) is the variable of integration in the convolution equation. To attain an estimate of the coupling between \( E_s \) and \( AL \), we assumed that the input \( I = E_s(t) \) and the output \( O = AL(t) \) during an event were constant. This allows us to take \( I(t) \) outside the integral. The integral then becomes the area under the impulse response function \( g(\tau) \) which we call the coupling coefficient. This coefficient is the ratio of average \( AL \) to average \( E_s \). If the coupling coefficient increases, this means that for the same unit \( E_s \) applied to the magnetosphere, a larger \( AL \) response results; thus, the coupling is more “efficient.” To examine the coupling efficiency of our dataset, we selected SMC events that were at least two hours long and required that \( E_y \) was positive 95% of the time. We averaged all data after the first hour of the SMC to partially remove any transient effects. The smoothed probability density function (calculated in the same manner as Figure 3.2) of the coupling coefficient \( = \frac{AL_{\text{avg}}}{E_s_{\text{avg}}} \) is shown in Figure 3.8. The rising phase is in blue, and the declining phase is in red. The most probable value for each phase is plotted as dashed lines.

The measure of the coupling is greater during the declining phase SMCs than during the rising phase SMCs. This means that the same \( E_s \) value (input) resulted in a larger \( AL \) index value (output) during the latter part of the solar cycle. This concurs with a similar result found by McPherron et al. [2009] using a more robust analysis of time dependent linear prediction filters. They suggest various explanations, including low quality of \( AL \) index during the rising phase or the increase of CMEs during the rising phase and at maximum with different properties than
CIRs. In fact, Turner et al. [2009] found that CIR-driven storms are more efficient than those driven by CMEs. Since CME occurrence decreases during the declining phase [Webb and Howard, 1994], we may be seeing the effect of CIR efficiency becoming more prominent. While this may explain the results for overall coupling efficiency, we found no significant correlation between SMCs and CMEs (see section 3.6), so it is difficult to determine how the lack of CMEs affects the coupling efficiency of SMCs in the declining phase. A third option for increased coupling offered by McPherron et al. [2009] is that some of the AL variance is due to viscous interaction, dynamic pressure, or electron precipitation. Energetic electrons in the magnetosphere [Vassiliadis et al., 2002, paragraph 42] and solar wind dynamic pressure [Fairfield and Jones, 1996, Figure 6] do peak during the declining and minimum phases of the solar cycle. This increase in declining phase coupling may also explain why there are more substorms during the

**Figure 3.8.** Probability density function of coupling coefficient ($\text{AL}_{\text{avg}}/\text{ES}_{\text{avg}}$), separated by phase (rising, blue line; declining, red line). The most probable value for each phase is displayed as a vertical dashed line. Adapted from Kissinger et al. [2011].
declining phase (Figure 3.6). The particular mechanisms that cause increased coupling in the declining phase should be examined in future studies.

3.5. SMCs Associated and Unassociated with stream interfaces

SMCs selected by Kissinger et al. [2010] were found to occur during very different solar wind conditions than in previous studies [O’Brien et al., 2002; DeJong et al., 2009a]. To examine solar wind and geomagnetic conditions for our list, we divided our SMCs into Associated (occurring between -1 to +2.5 days with respect to a stream interface) and Unassociated events (all other times). The probability of Associated events changed significantly between solar cycle phases: 251 out of 1725 SMCs were associated with stream interfaces during the rising phase (~14.6%), but 535 out of 1020 SMCs were associated during the declining phase (~52.5%). This reiterates the result that SMCs are significantly associated with stream interfaces in the declining phase.

We used 1-minute OMNI and Kyoto data to compare the two types of events. For each parameter, a cumulative probability distribution function (cdf) was calculated for Associated SMCs, Unassociated SMCs, All SMCs, and Background (all other data). In order to determine whether two different distributions are significantly different, we utilized the Kolmogorov-Smirnov test (KS test) [Press et al., 1986]. The KS statistic is the maximum value of the absolute difference between two cdfs $S_{N1}(x)$ and $S_{N2}(x)$:

$$D = \max_{-\infty<x<\infty} \left| S_{N1}(x) - S_{N2}(x) \right|$$

To find the significance of $D$, one uses the following sum:

$$Q_{KS}(\lambda) = 2 \sum_{j=1}^{\infty} (-)^{j-1} e^{-2j^2 \lambda}$$

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This is a monotonic function with limiting values. If $\lambda = 0$, then $Q_{KS} = 1$; if $\lambda = \infty$, $Q_{KS} = 0$. The significance level of $D$ is given by

$$
Pr(\text{obability}(D > \text{observed}) = Q_{KS} \left( \sqrt{\frac{N_1 N_2}{N_1 + N_2}} D \right)
$$

where $N_1$ is the number of data points in the first distribution, and $N_2$ is the number in the second. Small probability values show that the cdfs are significantly different. This becomes asymptotically accurate as the two $N$s grow large. Since we are dealing with one minute data over a period of several years, we have a very large number of samples that make up each cdf. Using the KS test to compare our cdfs, we never resulted in a probability larger than $1 \times 10^{-7}$—in fact, for many comparisons the exponential grew so large that the probability was evaluated to 0. Due to our large sample numbers, even small differences between two cdfs are significant.

Figure 3.9 shows the cumulative probability distribution functions of solar wind total velocity $V_t$ (top left), IMF $B_{z,GSM}$ (top right), dynamic pressure $P_{\text{dyn}}$ (bottom left) and rectified $E_y$ or $E_s$ (only positive values to correspond to negative $B_z$; bottom right). Red thick lines represent Associated SMCs, blue dashed lines represent Unassociated SMCs, green lines represent data from all SMCs, and black thin lines plot all other data, which can be considered the solar wind background. Figure 3.10 plots the cumulative probability distribution functions in the same convention and for the same parameters as in Figure 3.9, but for their steadiness (standard deviation/mean). A larger steadiness parameter means that the data is less steady, and a smaller parameter is steadier. Data with steadiness parameter = 0 would be a straight line. Associated SMCs occur during much faster and slightly less steady solar wind speed compared to Unassociated SMCs. This is due to the definition of a stream interface as a jump from slower to
faster velocity. In addition, Associated SMC events, compared to Unassociated, occur during weaker, less steady $B_z$, as well as slightly higher pressure and lower density (not shown). These differences match conditions expected after a stream interface, but represent a departure from typical SMC conditions [McPherron et al., 2005, DeJong et al., 2009a]. However, the driver of activity, $E_s$, is statistically the same for Associated and Unassociated SMCs, and $E_s$ steadiness is below the background distribution for both types of SMCs. For the remaining parameters, when we combine both types of SMCs (green line), the solar wind parameters are similar to results from prior studies, so Associated SMC events may be averaged out in other research.

Figure 3.9. Cumulative probability distributions of solar wind total velocity, IMF $B_z$, dynamic pressure, and $E_s$. Blue dashed lines correspond to unassociated SMCs, red solid lines correspond to associated SMCs, green lines include all SMCs, and the thin black line is all other data (background). Adapted from Kissinger et al. [2011].
Conditions during Unassociated SMCs occur during slow and steady solar wind velocity, and for moderately negative, steadier $B_z$ and positive, steadier $E_y$ compared to the background. For the most part, this agrees with previous studies [O’Brien et al., 2002, McPherron et al., 2005, DeJong et al., 2009a]; however, both DeJong et al. and O’Brien et al. found that solar wind velocity during SMCs is slower compared to the background, while for our Unassociated SMCs the velocity is in fact comparable to or slightly faster than the background. What could cause this difference in velocity behavior, especially given that DeJong et al. used BRIs during 1997-2002, which overlaps our rising phase period (1998-2003)? When we compare velocity cdfs by year, the only year in which Unassociated SMC velocity is faster than the background is
in 2003. Solar wind velocity during 2003 was unusually high [Gibson et al., 2009, Figure 3a], and this abnormal year increases the overall average of the Unassociated SMC velocity.

DeJong et al. [2009a] found that occurrence of different modes of magnetospheric response depended most on the magnitude of the solar wind velocity (<450 km/s for SMCs) and the magnitude (~4 nT) and steadiness (steady) of the IMF Bz. Our Unassociated SMCs agree with these figures, while Associated SMCs occur during faster solar wind (due to their appearance after stream interfaces) and have less steady IMF Bz than the background. E\textsubscript{s} steadiness during Associated SMCs is lower than the background, and thus steadier. This suggests that it is the magnitude and steadiness of E\textsubscript{s} that results in SMCs.

**Figure 3.11.** Cumulative probability distributions of AL, AU, AL steadiness, and AU steadiness, following the same convention as Figure 3.9.
The cumulative probability distribution functions for geomagnetic AL and AU are plotted in Figure 3.11, along with their steadiness. These plots also follow the conventions of Figure 3.9. Both types of SMCs, by nature of their selection criteria, have enhanced, steadier AL and AU indices compared to all non-SMC data. Associated SMCs have slightly stronger AL values than Unassociated. The steadiness of AL is about the same for either type of SMC, but Associated SMCs have slightly less steady AU than Unassociated.

3.6. SMCs and CMEs

Finally, we compare our SMC events to another type of organized structure in the solar wind, coronal mass ejections (CME). We use a subset of events from 1998-2009 from a CME list published by Jian et al. [2006]. Although the median separation between CME events is ~9 days, the most probable separation is less than two days. This means we are unable to use the same procedure as in section 3.2. Instead, we compare the two lists using point process analysis. A point process is a series of points in a set, in this case on a timeline. With two such series, we can attain a measure of the correlation between the two types of events. We treat the start time of SMC events and the start time of CME events as point processes. As a comparison, we also perform the point process analysis to compare SMC start times and SI events. Figure 3.12 shows the conditional probability that a CME (top row) or an SI (bottom row) occurs with respect to the start time of an SMC. The thick horizontal dashed line is the mean probability well away from the origin, and the thin dashed lines are twice the standard deviation (σ) from the mean. We have further separated the events by solar cycle phase, with rising phase on the left and declining phase on the right.
Figure 3.12. Comparison of CME start times (top row) and stream interfaces (bottom row) to SMC start times using point process analysis. Events during the rising phase (1998-2003) are on the left and during the declining phase (2004-2009) on the right.

This type of analysis confirms our result from Figure 3.2: stream interfaces are strongly correlated with SMC events during the declining phase and are not correlated during the rising phase. Declining phase stream interface occurrence peaks just before SMC start times, rising above the $2\sigma$ line two days before. Rising phase CME events are uncorrelated with SMC events. For declining phase CMEs, there is a small peak above the $2\sigma$ line one day before SMC start, but it is much smaller than the declining phase SI peak. Therefore, we conclude that SMCs have little to no correlation to CME events.
3.7. Conclusions

We have found a correlation between steady magnetospheric convection events and stream interfaces in the solar wind. SMC occurrence peaks -1 to +2.5 days with respect to a stream interface. A minimum in SMC events is seen -3 to -1 days before the interface. This correlation is present in the declining phase of solar cycle 23, but during the rising phase little change in SMC occurrence is seen with respect to stream interfaces.

There are several factors that contribute to the different correlation between phases. First, the IMF geo-effectiveness of the stream influences SMC occurrence. Streams that are effective after the interface (EE and IE) tend to have higher positive $E_y$ values that will result in reconnection, and correspondingly larger geomagnetic activity. In the declining phase, three types of interfaces show a correlation with SMC occurrence, particularly EE and IE. In the rising phase, only IE interfaces exhibit a correlation. This appears to determine which association is seen in the aggregate. A second factor for SMC-SI correlation is the occurrence of substorms. More substorms occur after a stream interface than before, and substorm occurrence increases during the declining phase. Since most SMCs occur after a substorm onset (see more in Chapter 5), therefore there is a greater chance of SMCs occurring after a stream interface in the declining phase. Third, solar wind-magnetosphere coupling is stronger during the declining phase.

These factors result in SMCs that are associated with stream interfaces. This is the first time such a sub-population of SMCs has been identified. The subset occurs during different solar wind conditions than previous studies reported [O’Brien et al., 2002, DeJong et al., 2009a], but we suggest that they have been averaged out in other research. In particular the solar wind velocity is very high, far beyond the ranges expected for SMC, and all parameters are less steady. This is due to the SMCs’ following a stream interface, but is unexpected since
McPherron et al. [2005] show that slow, steady solar wind results in SMCs. We show that the magnitude of the solar wind driver, $E_s$, is the same for both Associated and Unassociated SMCs, and thus it is $E_s$ that is most important solar wind factor for driving an SMC. The declining phase SMC-SI relationship and its causes above must be further studied.
4.1. Introduction

When the solar wind Interplanetary Magnetic Field (IMF) has a negative $B_z$ component, i.e. is southward, it can reconnect with the Earth's northward-pointing dipole magnetic field. Reconnection drives geomagnetic activity by opening dayside magnetic flux and transporting it to the nightside. Open field lines are pulled back by the solar wind to form the magnetotail lobes. The north and south tail lobes reconnect on the nightside and create the closed field lines of the plasma sheet. The pressure gradient between dayside and nightside causes Sunward flow, driving convection back toward the Earth, in a process known as the Dungey cycle [Dungey, 1961]. The Earth's magnetosphere responds to solar wind driving in various ways. One of the most well-studied modes of response is the substorm, a loading-unloading process in which energy builds up in the magnetotail during a growth phase [McPherron, 1970], is suddenly released in an expansion phase, and declines back to quiet values in the recovery phase [Russell and McPherron, 1973b]. Other times, the magnetosphere can respond with a quasi-steady response known as steady magnetospheric convection (SMC). These events are characterized by enhanced, stable convection, persisting longer than a typical recovery phase, with no substorm expansions [Pytte et al., 1978; Sergeev et al., 1996a].

Why the magnetosphere sometimes responds with an isolated substorm and sometimes with an SMC event is still unknown. One possible factor that could contribute to the response is preconditioning of the magnetosphere. O'Brien et al. [2002] identified two cases where the solar wind velocity and IMF $B_z$ were similar, but one resulted in an isolated substorm and the other in an SMC. They pointed out that before the SMC occurred, the magnetosphere was already
undergoing enhanced activity, while before the isolated substorm, the magnetosphere was quiet. In fact, about 80% of SMCs are associated with an obvious substorm expansion onset just before the start of the SMC [McPherron et al., 2005]. In most statistical SMC studies, events without a preceding substorm onset are the exception [DeJong et al., 2009a; Dmitrieva et al., 2004]. This preceding substorm may change the conditions in the magnetosphere to allow an SMC to occur.

SMC events are thought to occur from balanced reconnection rates between the dayside and nightside reconnection x-lines. Dmitrieva et al. [2004] showed this balance by comparing average dayside merging electric field and average plasma sheet electric field during SMCs and substorms. They found that the two flux transport rates were equal during SMC events; by comparison, the plasma sheet convection was reduced during substorm growth phases and twice as large during substorm expansions, compared to the dayside flux transport rate. In studying flux transport rates, statistical averages of multiple events are necessary because plasma sheet convection consists of both "quiet" convection and fast short-duration flows [Baumjohann et al., 1989, 1990]. These variations were identified during substorms as bursty bulk flows (BBFs), a series of fast-moving plasma bursts a few Earth radii (R_E) wide that carry closed magnetic flux from the nightside tail reconnection region [Angelopoulos et al., 1992, 1994]. Earthward BBFs concurrent with positive B_z are a signature that enhanced reconnection has occurred tailward of the flow. Similarly, BBFs moving tailward with negative B_z indicate enhanced reconnection Earthward of the observation. During substorms, BBFs are decelerated in the inner magnetosphere, where the dipole field strength increases. As more BBFs are slowed and stopped, a "pile-up region" of magnetic flux is formed and grows radially outward [Baumjohann et al., 1999; Baumjohann, 2002]. The occurrence of BBFs increases as the auroral electrojet index (AE) increases [Angelopoulos et al., 1994], and BBFs can account for a majority of observed
Earthward flux transport [Angelopoulos et al., 1994; Schödel et al., 2001]. Fast flows are even observed when the magnetosphere is quiet [Angelopoulos et al., 1993].

Although we refer to "steady convection" for SMCs, in reality these events also consist of fast plasma flow bursts that can carry 11-84% of the mass flux in a given event [Sergeev et al., 1990, 1996a]. Tanskanen et al. [2005] also found BBFs during periods of relatively steady magnetotail total pressure (called continuous magnetospheric dissipation (CMD) events). Compared to an unloading mode (substorm expansion), BBFs during CMD events are not as fast but occur more often. Recent models also indicate strong flows during SMC events, with Earthward flowing plasma diverted to the dawn and dusk flanks, leaving the inner magnetosphere undisturbed [Goodrich et al., 2007]. Using a set of nine events, Yang et al. [2010a] indicated that during SMC-associated fast flows, the events entropy parameter remains nearly constant, indicating midtail (40-60 \( R_\oplus \)) reconnection.

During substorms, the flux pile-up region keeps a portion of tail-reconnected flux from returning to the dayside reconnection region. In an SMC, the tail-reconnected flux should return to the dayside in order to continue balancing the dayside reconnection rate for hours at a time, but how the tail accomplishes this flux return remains unknown. To investigate this question, we perform a detailed statistical analysis of fast flows and plasma conditions in the magnetotail during SMC events. The results are compared to flows and plasma during quiet intervals, pre-SMC intervals, and substorm phases.

In this chapter, the primary question we will answer is: How is the return of closed magnetic flux from the nightside of the magnetosphere to the dayside accomplished to maintain stability during SMC? Secondary questions include: What is the statistical behavior of the magnetotail plasma during the balanced reconnection mode? How does it compare to the
unloading/substorm response and inactive periods? What is the probability that fast flows carrying magnetic flux are seen in the magnetotail during SMC compared to substorms?

4.2. Selection of substorms and quiet intervals

All modes of response were identified with auroral index data, AL (auroral lower) and AU (auroral upper), from the World Data Center for Geomagnetism, Kyoto AE index service. SMC events were visually selected between 1997-2010 according to the criteria of Chapter Two. We found 2853 intervals satisfying these criteria. To investigate the role of magnetospheric preconditioning in SMCs, we also look at the two hour interval before the start of an SMC, hereafter dubbed Pre-SMC.

Substorm onsets were selected visually from auroral indices, characterized by a sharp drop in the AL index [Hsu and McPherron, 2012]. The subset of onsets we examine here occurred during 1997-2010. To be certain that the substorm was distinct from the SMC, it was required that the onset occurred more than 75 minutes before the start of an SMC; i.e., not a substorm associated with SMC. Further, we attempted to select "isolated" substorms by requiring that for a given onset, there could not be another onset within +/- 2.5 hours [Borovsky et al., 1993]. This resulted in 8600 substorm onsets. Using the time of the onset, we identified the three phases of a substorm: growth, expansion, and recovery. We began the growth phase intervals -30 minutes before the onset and set the end of the growth intervals as the onset. Expansion phase intervals were chosen by setting the onset as the start of the event, and setting the end of the interval +30 minutes after the onset [McPherron, 1970]. Finally, recovery phase intervals were selected from onset+45 minutes to onset+120 minutes [Baker et al., 1994; Baumjohann et al.,
Although this is a crude measure of substorm phases, the authors are not aware of a current, large list of substorms separated by their phases.

Quiet intervals were selected automatically with auroral indices by requiring that $\text{AL} > -75 \text{ nT}$ and $\text{AU} < 50 \text{ nT}$ for at least 90 minutes. The quiet events spanned the interval 1997-2010. The identified events resulted in far more data than necessary, so every fifth event was selected. The final list included 1422 quiet events.

We used datasets from two missions for this study: the Geotail satellite and all five THEMIS probes. Geotail data was supplied by the CDAWeb website. Magnetic field components came from the Magnetic Field Instrument (MGF), and plasma moments came from the Low-Energy Particles Instrument (LEP), which measures an energy range of 60 eV to 40 keV for ions. The temporal coverage of available Geotail data is from 1997-2006. Geotail provides two types of data: Editor-A, which is transmitted in real-time to the Usuda Deep Space Center in Japan, and Editor-B, which is recorded continuously onboard the satellite and then downloaded daily to the NASA JPL Deep Space Network [Nishida, 1994]. We used Editor-A when it was available, since it is considered more reliable, and Editor-B at all other times [Mukai et al., 1994]. The magnetic field components were downloaded in Geocentric Solar Magnetospheric (GSM) coordinates at 3-second cadence, and a $B_z$ offset correction was applied based on values from the Geotail website. This was interpolated to 12-second cadence to match the plasma data. The THEMIS magnetic field data consists of Level 2 fluxgate magnetometer spin fit (FGS) components in GSM coordinates. Plasma moments from the lower energy electrostatic analyzer (ESA, ranging from a few eV to 30 keV for electrons and 25 keV for ions) and higher energy solid state telescope (SST, ranging from 25 keV to 6 MeV) instruments were computed on the ground and then added together to obtain combined moments. All parameters were interpolated
to the same 12-sec cadence as Geotail plasma data. THEMIS data was used for events during 2007-2010.

By combining these two datasets, we were able to obtain results from over an entire solar cycle (Geotail from 1997-2006, THEMIS from 2007-2010), as well as greater coverage of radial distances. THEMIS data was limited to an inner radial distance ($\rho$) boundary of $\rho \geq 5 \, R_E$. The majority of THEMIS data points occur within $12 \, R_E$, the apogee of three of the spacecraft, but data farther out was also obtained from the B (apogee of $30 \, R_E$) and C (apogee of $20 \, R_E$) spacecraft. We restricted Geotail data to a radial distance of $\rho \geq 12 \, R_E$, since we did not have the high energy particle data that could affect the moments inside this region. Beyond this distance, the energetic particle contribution is small. Thus we obtain greater temporal and spatial coverage than could be obtained by either mission alone.

In sections 4.3 and 4.4, we present results from ion flows and moments. One exception to our method is the total pressure, which was calculated differently between Geotail and THEMIS. For Geotail, only ion LEP data was available, and thus the electron pressure component is not included in the total pressure. Geotail dominates outside of $13 \, R_E$, where electron pressure is very small, yet THEMIS dominates inside of $13 \, R_E$, where electron pressure starts becoming considerable. Therefore both the electrons and ions were used to calculate the pressure for the THEMIS dataset. This means that we might underestimate the average total pressure in the region where Geotail dominates the coverage, though the relative differences between the modes of response in this region should be the same. In order to confirm that we can legitimately combine the two datasets, we compared plasma moments between Geotail and THEMIS from the region of comparable overlap, $\rho=13-16 \, R_E$. Histograms of the moments were in agreement between the two missions; in particular, the total pressure histograms were very similar. This
confirms that the electron pressure contribution is small beyond 13 R_E and validates our combination of the two datasets.

4.3. Earthward fast flow bursts

We set out to identify fast flow patterns in the magnetotail, and thus limited our dataset to times when a spacecraft was within X_{GSM} <= 0 R_E and |Y_{GSM}| <= 20 R_E. Furthermore, we attempted to remove data within the magnetosheath by excluding points when the following was true: |Y_{GSM}| >= 11 R_E, ion temperature (T_i) < 0.5 keV, and ion density (n_i) > 1 cm^-3. Data was restricted to the plasma sheet by requiring that beta (β), the ratio of the plasma pressure (P_{th} = nkT) to the magnetic pressure (P_{mag} = B_T^2/2\mu_0), be greater than 0.5. Finally, the time-averaged velocity vector was separated into parallel and perpendicular vectors based on the magnetic field. Hereafter when we refer to the velocity, we are referring to the perpendicular velocity vector (V_\perp) unless otherwise stated.

Fast Earthward flows were defined when V_{x-y} >= 200 km/s, where V_{x-y} is the total speed in the GSM x-y plane, and V_x > 0 km/s. The start of the flow was selected when the equatorial speed exceeded 200 km/s, and the end selected when the speed fell below 200 km/s. An example of fast flows during SMC observed by Geotail is presented in Figure 4.1. The spacecraft passed in and out of the plasma sheet (β, panel 5) throughout the interval, and whenever it was in the plasma sheet, it saw fast Earthward flows (V_\perp, panel 3). Although the AL index was weak and steady (panel 1), there was significant transient activity in the tail. Geotail was located at |X| ~ 28 R_E, indicating nightside reconnection occurred tailward of this point. The fast plasma flows are responsible for a significant transport of magnetic flux (panel 4). Before the SMC began, a fast tailward flow (-350 km/s) carrying negative B_z was observed. This indicates that before this
event, the x-line was Earthward of Geotail's location, and that once the SMC started the x-line shifted to tailward of Geotail.

**Figure 4.1.** An example of fast Earthward flow bursts that occurred during an SMC event on 06 May 2006. The SMC began at 0846 UT (vertical black line) and ended at 1208 UT. The panels show AL index, magnetic field components in GSM coordinates from Geotail, perpendicular velocity components from Geotail, flux transport (\(\text{flux} = V_{x-y} \times B_z\)), and beta (\(p_{th} / p_{mag}\)). Beta is marked in green when the spacecraft was in the plasma sheet (\(\beta > 0.5\)).

Table 4.1 compiles the number of events and the number of Earthward fast flows observed during quiet, Pre-SMC, SMC, and substorm phase intervals. SMCs have the highest occurrence rate of Earthward fast flows (3.8%), followed by Pre-SMC (2.5%), substorm recovery (1.8%), substorm expansion (1.5%), and substorm growth (1.1%). As expected, quiet
periods show the lowest occurrence of fast flows (0.3%), although they are still observed [Angelopoulos et al., 1993]. The occurrence of SMC fast flows correlates to Tanskanen et al. [2005], who found that more fast flows occurred during intervals of relatively steady tail total pressure (termed continuous magnetospheric dissipation) compared to unloading intervals. Previous study of BBFs has shown that in regions of the largest occurrence rates, they can comprise more than 80% of Earthward magnetic flux transport [Angelopoulos et al., 1994]. In the last column of Table 4.1, we show the overall average of Earthward flux transport accomplished by Earthward fast flows for each type of activity. Earthward magnetic flux transport rate is defined as the equatorial speed \( V_{x,y} \) times \( B_z \) when the velocity has an Earthward component \( (V_x > 0 \text{ km/s}) \). The amount of transported flux is the time integral of this rate. To obtain the percentage of flux transport, we integrate the flux observed by the spacecraft during Earthward fast flows and divide it by the total Earthward flux transport observed throughout the event. Note that this encompasses our entire dataset, from radial distances spanning 5-30 \( R_E \). In the region of largest occurrence rates, near midnight and at maximum radial distance from the Earth, fast flows carry 50-60% of the total Earthward flux transport, comparable to prior research [Angelopoulos et al., 1994; Schödel et al., 2001]. The largest percentage of fast flow Earthward magnetic flux transport is during Pre-SMC and SMC cases, with \(~15\%\) and \(~20\%\) of the total Earthward flux transport accomplished by fast flows, respectively. These values are consistent

<table>
<thead>
<tr>
<th>Response</th>
<th># Events</th>
<th>Earthward flows (#)</th>
<th>Occurrence rate (%)</th>
<th>Earthward Transport (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>1422</td>
<td>1045</td>
<td>0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Pre-SMC</td>
<td>2853</td>
<td>2692</td>
<td>2.5</td>
<td>15.4</td>
</tr>
<tr>
<td>SMC</td>
<td>2853</td>
<td>5653</td>
<td>3.8</td>
<td>20.1</td>
</tr>
<tr>
<td>Substorm Growth</td>
<td>8600</td>
<td>1337</td>
<td>1.1</td>
<td>9.0</td>
</tr>
<tr>
<td>Substorm Expansion</td>
<td>8600</td>
<td>1859</td>
<td>1.5</td>
<td>12.2</td>
</tr>
<tr>
<td>Substorm Recovery</td>
<td>8600</td>
<td>5349</td>
<td>1.8</td>
<td>13.4</td>
</tr>
</tbody>
</table>
with prior SMC case studies that found individual event fast flow occurrence rates of 2-27% and fast flow flux transport levels of 11-84% [Sergeev et al., 1996a]. This is also comparable to the event in Figure 4.1, in which fast Earthward flows are observed during 23% of this event, carrying 68% of the magnetic flux during the SMC interval.

The probability of observing fast Earthward flows is further illustrated in Figures 4.2 and 4.3. Figure 4.2 plots the probability of observing a fast Earthward flow vs. radial distance during each of the six types of activity: quiet (purple), Pre-SMC (orange), SMC (black), substorm growth (green), substorm expansion (blue), and substorm recovery (red). All probabilities have been normalized to the time spent in each 0.2 \( R_E \) bin by the satellites. SMC events show the highest probability of fast flows in the mid-tail (distance > 21 \( R_E \)), followed next by substorm recovery. The probability of observing fast Earthward flows during SMCs increases approximately linearly as radial distance increases, with the highest probability occurring at 31 \( R_E \), the apogee of the Geotail and THEMIS B spacecraft. This indicates that during SMCs, the

![Probability of Earthward Fast Flows vs. Radial Distance](image)

**Figure 4.2.** The probability of observing fast (\( V_{x,y} > 200 \) km/s) Earthward flows in the magnetotail by radial distance. Occurrence of flows was normalized by the amount of time spent by spacecraft in each bin. Each plot represents a different level of geomagnetic activity: quiet (purple, top left); Pre-SMC (orange, top middle); SMC (black, top right); substorm growth (green, bottom left); substorm expansion (blue, bottom middle); and substorm recovery (red, bottom right).
average statistical location of the tail x-line is beyond 31 \( R_E \), the maximum distance of our available observations. The probability during substorm recovery likewise increases in a mostly linear fashion as radial distance increases. In contrast, Pre-SMC and substorm expansion intervals show more variation, with peaks and troughs in probability. This indicates that the location of the x-line for these intervals varies within our observable range. Thus, in general, before SMC events (Pre-SMC) the x-line is statistically somewhere within 30 \( R_E \), and then during SMC events the x-line moves to a statistical location beyond 30 \( R_E \); the same shift in x-line location occurs between substorm expansion and substorm recovery. In the inner magnetosphere (within 15 \( R_E \)), the probability of seeing a fast Earthward flow during SMC is smaller than the probability during substorm expansion or recovery. We examined the probability of observing rapid flux transport events (> 2 mV/m, after Schodel et al. [2000]) with no speed criterion and found that the occurrence rate for SMC is comparable to substorm expansion and recovery within 15 \( R_E \). Thus, even though few fast flows are observed above our threshold level, the enhanced flux transport is comparable. Finally, the quiet and growth phases have lower overall probabilities of seeing fast flows.

Figure 4.3 displays fast Earthward flow probability vs. local time (LT) in 0.5 hour bins, similar to Figure 4.2. For all types of activity, the probability of observing fast Earthward flows has approximately the same distribution shape versus local time, with the highest probabilities near midnight and the lowest on the dawn and dusk flanks, in agreement with previous statistical results [Angelopoulos et al., 1994]. SMC and Pre-SMC flow probabilities are peaked at midnight (2400 LT), while the substorm growth distribution is centered at 2300 LT and substorm expansion and recovery distributions are centered at 2330 LT. McPherron et al. [2011] found a similar result during substorms with inner magnetosphere fast flows peaking at 2300 LT.
Figure 4.3. The probability of observing fast ($V_{x-y} > 200$ km/s) Earthward flows in the magnetotail by local time (same layout as Figure 4.2).

To create patterns of fast flows for each type of activity, fast Earthward flows were averaged in 3x3 $R_E$ bins, and an equatorial map created of the average binned vectors in the GSM x-y plane. Figure 4.4 shows the average Earthward fast flow vectors for substorm expansions (left) and SMC events (right). We only compare two of these panels to avoid visual confusion, and selected substorm expansion intervals to highlight the most significant differences from the SMC pattern. The dashed semi-circle line represents geosynchronous orbit (6.6 $R_E$), and the solid semi-circle line represents the apogee of THEMIS D and E, two of the inner probes. The arrow key on the right is 200 km/s. This figure is a visual average over all events, and does not imply that for any single event, that fast flows are seen throughout the entire tail. Lack of vectors indicates that no fast flows were observed in that bin.

Fast Earthward flows during SMC events show a very clear pattern of deflection towards either the duskward or dawnward flank. This deflection is small along the midnight line, but is seen on either side of midnight and increases with $|Y|$. Flow deflection also appears to increase as radial distance decreases. This statistical pattern concurs with two SMC events in Sergeev and Lennartsson [1988], who showed strong flankward components on both the duskward and
Figure 4.4. Average fast Earthward flow vectors during substorm expansions (left) and SMCs (right). Flows were averaged into 3x3 $R_E$ bins and are plotted in the GSM x-y plane. The dashed semicircle represents geosynchronous orbit (6.6 $R_E$) and the solid semicircle represents the apogee of the THEMIS D and E spacecraft (11.9 $R_E$). Flows are scaled to 200 km/s (right arrow key).

dawnward side of the tail, following modeled contours of constant flux tube volume. This pattern is much more symmetric around midnight compared to previous studies of average flow patterns, such as Angelopoulos et al. [1993] and Hori et al. [2000]. These studies found that the average flow pattern displayed a dawn-dusk asymmetry, with smaller and sunward-directed flows in the dawn flank and larger, duskward-directed flows in the dusk flank. However, fast flows were removed in Angelopoulos et al. [1993] and averaged in Hori et al. [2000]. The larger duskward component in these slower flow patterns was due to the diamagnetic drift of ions due to the inward pressure gradient, which has a magnitude on the order of 25 km/s [Angelopoulos et al., 1993]. Since this duskward drift is much smaller than our 200 km/s fast flow cutoff, it has a negligible effect on our flow patterns.

The strong deflection of fast flows is further illustrated in Figure 4.5. Here, we add light blue vectors that represent quartiles of flow direction in each bin. No vectors are added if there
were too few flows to identify flow direction quartiles. This is a measure of the 'spread' of the fast flows. Along midnight and at farther radial distances, the spread of fast flows is large, and many flows are directed either Earthward, duskward, or dawnward. During SMC, along the dawn and dusk flanks and in the inner magnetosphere region, the spread of fast flows is small compared to the average vector. This indicates that fast flows in these areas are strongly directed along the average flow vector, deflected away from the inner magnetosphere. In contrast to the SMC case, during substorm expansions fast Earthward flows show a pattern of more directly-Earthward flow, especially in the midnight region of the tail ($|Y| < 7 \text{ RE}$). There is some deflection toward the flanks away from the midnight region, although the pattern is more chaotic and the spread of flow directions is not as organized as the SMC pattern.

![Figure 4.5](image)

**Figure 4.5.** The same as Figure 4.4, with the addition of light blue lines to represent the quartiles (25% and 75%) of flow direction within each spatial bin.

Fewer fast flows are observed in the inner magnetosphere (within the solid curved line at 11.9 RE) for SMCs compared to substorms. This agrees with the radial flow probabilities from Figure 4.2, as well as results from McPherron *et al.* [2011]. The lower probability of observing a
fast flow during SMC events is shown numerically in Table 4.2. For each type of activity we show the total number of Earthward fast flows that occur within 15 R_E, their occurrence rate, and the percentage of Earthward magnetic flux transport they contribute. Fewer fast flows are observed during SMC than for Pre-SMC or substorm intervals, with the most Earthward fast flows observed during substorm expansion phases.

<table>
<thead>
<tr>
<th>Response</th>
<th>Earthward flows (#)</th>
<th>Occurrence rate (%)</th>
<th>Earthward transport (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>151</td>
<td>0.06</td>
<td>1.6</td>
</tr>
<tr>
<td>Pre-SMC</td>
<td>230</td>
<td>0.41</td>
<td>4.5</td>
</tr>
<tr>
<td>SMC</td>
<td>156</td>
<td>0.18</td>
<td>1.6</td>
</tr>
<tr>
<td>Substorm Growth</td>
<td>242</td>
<td>0.22</td>
<td>6.8</td>
</tr>
<tr>
<td>Substorm Expansion</td>
<td>521</td>
<td>0.50</td>
<td>3.8</td>
</tr>
<tr>
<td>Substorm Recovery</td>
<td>415</td>
<td>0.20</td>
<td>2.8</td>
</tr>
</tbody>
</table>

To quantitatively illustrate the visual result of flow deflection during SMC, we examine the deflection angle of the fast flows. For each flow burst near midnight (within 2300-0100 LT), we measured the absolute angle between the X-GSM axis and the flow (so that an angle of 0° would be directly along the X-GSM axis or Earthward, while 90° would be along the Y-GSM axis or flankward). Figure 4.6 plots the cumulative probability distributions of deflection angle for flows during SMC (black), Pre-SMC (orange), substorm expansion (blue) and substorm recovery (red) within radial distances of (top left) 5-15 R_E, (top right) 15-20 R_E, (bottom left) 20-25 R_E, and (bottom right) 25-30 R_E. Starting with the outer-most radial distances (lower panels), in the mid-tail, the distributions of deflection angle are similar. Flows are equally Earthward or flankward for all four types of activity. As we move radially inward to within 20 R_E (upper right), substorm expansion fast flows are slightly less deflected, SMC and substorm recovery fast flows are more deflected, and Pre-SMC fast flows experience the most deflection. Within 15 R_E (upper left), the situation changes dramatically. Substorm expansion and recovery fast flows
have the least deflection, Pre-SMC fast flows have become significantly more Earthward-directed to match the substorm distributions, and SMC fast flows experience very significant deflection toward the flanks. In fact, there is a 0% probability that SMC fast flows are within 20° of the X-GSM line (Earthward), and only 5% probability that they are within 35°.

**Figure 4.6.** Cumulative probability distributions of the absolute azimuthal deflection of fast Earthward flows. The deflection is measured with respect to the X-GSM axis, such that 0° is along the X-axis (Earthward) and 90° is along the Y-GSM axis (dawnward or duskward). Four types of activity are shown: substorm expansion (blue long dashed lines), substorm recovery (red dash-dotted lines), Pre-SMC (orange short dashed lines) and SMC (black solid lines). Only fast flows within 2300-0100 LT are included. The plots represent different radial distances: 5-15 R_E (top left), 15-20 R_E (top right), 20-25 R_E (bottom left), and 25-30 R_E (bottom right).
In the next section, we will explore further what causes the diversion of fast flows during SMC events.

4.4. Plasma conditions in the magnetotail

In this section, we examine the average behavior of plasma density, temperature, pressure, and Earthward flux transportation rates in the magnetotail during the six types of activity. All plasma sheet ($\beta > 0.5$) data from the Geotail and THEMIS satellites were compiled to create spatial event ensembles. Note that this section includes all plasma sheet samples, not just fast flows from the previous section. We will show that the average conditions in the magnetotail are very different depending on the mode of magnetospheric response.

Figure 4.7 shows contours of average ion density (cm$^{-3}$) in the GSM equatorial plane for quiet, Pre-SMC, SMC, substorm growth, substorm expansion, and substorm recovery. All plots

![Figure 4.7](image)

**Figure 4.7.** Contour maps of average density values in the X-Y GSM plane by type of activity: (top row) quiet, Pre-SMC, SMC; (bottom row) substorm growth, expansion, and recovery. All plots are to the same color scale.
are to the same color scale. The green circle in the middle of each plot represents Earth, and the larger dashed circle is geosynchronous orbit (6.6 $R_E$). In each case, the density is highest in the inner magnetosphere and lowest in the tail. The SMC and Pre-SMC cases have a smaller region of enhanced density and lower values than for substorm phases. The density is also depleted in the tail during SMC, similar to the substorm recovery case.

Figure 4.8 shows contours of average ion temperature (keV) in the same manner as Figure 4.7. Generally, the highest temperatures are in the near-Earth region. Quiet intervals show low temperatures in the outer region of the tail, while enhanced geomagnetic activity correlates with higher temperatures in the tail [shown statistically by Baumjohann et al., 1989; Huang and Frank, 1994]. There is also evidence for dawn-dusk asymmetry, although it is counterintuitive to the asymmetry previously reported by Wing and Newell [1998] and Wang et al. [2006], who found higher temperatures on the duskward side of the tail. This may be due to the absence of energetic particles in the Geotail dataset, which dominates beyond 12 $R_E$. The temperature in the tail increases through the substorm phases, from growth to expansion to recovery. This agrees with Baumjohann et al. [1991], who used superposed epoch analysis to show that temperature increases during substorm onset and peaks during the recovery phase. Here we see a very significant difference between the Pre-SMC and SMC states versus the substorm phases. The temperature in the tail during Pre-SMC and SMC is much hotter, and the hot region is broader in azimuthal extent, compared to the temperature in all three of the substorm phases. Substorm recovery averages 7-8 keV in the mid-tail compared to $>10$ keV for the SMC state.

Figure 4.9 shows contours of average total pressure ($P_{\text{total}} = nkT + B^2/2\mu_o$ nPa), again in the same manner as Figure 4.7. Each case shows that pressure is higher in the inner magnetosphere and lower in the tail. The falloff of pressure as the radial distance increases down
Figure 4.8. Contour maps of average temperature in the same format as Figure 4.7.

Figure 4.9. Contour maps of average total pressure in the same format as Figure 4.7.
the tail has been shown previously in numerous studies [e.g., Spence et al., 1989; Kistler et al., 1992; Huang and Frank, 1994; Hori et al., 2000]. This high pressure region is largest in the SMC case, extending out radially to ~12-15 R_E. Similarly, the Pre-SMC high pressure region extends out to 10-12 R_E. In contrast, the high pressure region during substorm recovery only extends to ~8-10 R_E. The gradient between high inner magnetosphere pressure and low tail pressure is much steeper in the substorm growth, expansion, and recovery cases than for Pre-SMC and SMC.

Figure 4.10 shows contours of average Earthward flux transport rate in the same format as Figure 4.7. The average Earthward flux transport rate was calculated by multiplying the equatorial speed, V_{x,y}, by B_z when the flow had a positive V_x. Thus, this is an average measure of how much magnetic flux is transported Earthward. During the quiet case, flux transport rates are low in the tail. The other five cases show higher rates of flux transport at various locations in

![Figure 4.10](image_url)

**Figure 4.10.** Contour maps of average Earthward magnetic flux transport in the same format as Figure 4.7.
the tail. During SMCs, the highest rates of flux transport are observed on the dawn flank and throughout a broad azimuthal extent of the tail region. The Pre-SMC state is similar, with higher rates of flux transport on the dawn flank and in the tail dawnward of midnight. The substorm expansion case has a channel of higher flux transportation rate in the inner magnetosphere, extending radially outward along midnight. Substorm recovery also has increased flux transportation rate in the tail region, similar to the SMC case, but narrower in azimuthal extent.

To compare the plasma conditions between types of activity in a quantitative manner, we divide the magnetosphere into two regions: tail ($\rho \geq 15$ RE) and inner magnetosphere ($\rho < 15$ RE). We chose this distance since it is at 15 RE that fast flows during SMC experience more significant deflection (seen in Figure 4.6) and where the high pressure contours extend in the SMC case (Figure 4.9). All data within each region are then compiled into cumulative probability distribution functions (cdfs). Figure 4.11 shows four cdf plots for density (top left), total pressure (top right), temperature (bottom left), and Earthward magnetic flux transport rate (bottom right) within the tail region. The colored lines represent types of activity in the same way as Section 4.3: quiet (purple), substorm growth (green), substorm expansion (blue), substorm recovery (red), Pre-SMC (orange), and SMC (black). In all four of the plasma parameters, there is a clear separation of behavior by type of activity. SMC intervals have the lowest density, highest temperature, highest total pressure, and highest rates of Earthward flux transport out of all the modes of response.

The tail region is most dense during quiet intervals. The density distributions for substorm growth and expansion are very similar, as are the Pre-SMC and substorm recovery distributions. Higher density values are more likely to be observed during substorm growth/expansion than during substorm recovery/Pre-SMC. The lowest density distribution
Figure 4.11. Cumulative probability distributions of density (top left), total pressure (top right), temperature (bottom left), and Earthward magnetic flux transport (bottom right) in the tail region ($\rho > 15$ RE). Colored lines represent each type of activity: quiet (purple dotted), substorm growth (green dotted long-dashed), substorm expansion (blue long-dashed), substorm recovery (red dotted short-dashed), Pre-SMC (orange short-dashed), and SMC (solid black).

occurs during SMC. The temperature cdfs are similarly separated by the type of activity, but in reverse order: the distribution during quiet times shows the lowest temperatures, increasing through the substorm phases, with the Pre-SMC and then the SMC case showing the highest distribution of temperatures. Pre-SMC and SMC have a higher probability of higher temperatures. This concurs with the behavior in the contour plots of Figure 4.8, but illustrates the ordering of temperature in the tail region by type of activity. This is partially a consequence of the greater occurrence of fast flows during SMC, as the temperature increases sharply at the time of a fast flow (e.g., Angelopoulos et al., [1992]), in particular at times just behind dipolarization
fronts observed within the fast flow interval [Runov et al., 2009, 2011]. The increased occurrence of fast flows and the amount of magnetic flux they transport during SMC (Table 4.1) also influences the cdfs of Earthward flux transport rate, which are also very well ordered by type of activity in the same pattern as temperature. Quiet times have the lowest rates of Earthward flux transport, and the distributions increase from substorm growth/expansion, substorm recovery/Pre-SMC, to the SMC distribution with the largest probability of enhanced Earthward flux transportation rate. Finally, the total pressure in the tail region increases with the mode of response, with the lowest pressure distribution during quiet intervals, higher pressure during substorm phases, and the highest pressure during Pre-SMC and SMC.

Figure 4.12 shows cdfs of plasma conditions in the same manner as Figure 4.11, but in the inner magnetosphere region ($\rho < 15$ Re). The density in the inner magnetosphere is the nearly same for all types of activity (quiet and substorm growth distributions have been removed for clarity). The inner magnetosphere total pressure shows the same type of ordered behavior by type of activity as the tail pressure did in the previous figure. The lowest pressure distributions occur during quiet time, pressure increases through the substorm phases, and the SMC case has the highest pressure distributions. Interestingly, the Pre-SMC distribution most closely matches the substorm recovery distribution. This result matches well with the pressure contours shown in Figure 4.9, and shows quantitatively that the region of high pressure in the inner magnetosphere during SMCs is not just larger in extent, but also in magnitude. The temperature in the inner magnetosphere shows the same order, increasing slightly through the substorm phases from growth to recovery. Pre-SMC and SMC distributions have the highest temperatures. Finally, the distributions of Earthward flux transport rate are similar for substorm expansion, substorm recovery, Pre-SMC, and SMC states, enhanced from quiet and substorm growth levels.
Figure 4.12. The same as Figure 4.11 except within the inner magnetosphere region ($\rho < 15$ RE).

To illustrate the relative changes between the tail region and the inner magnetosphere by type of activity, Figure 4.13 displays radial cuts along midnight of density, total pressure, temperature, and Earthward flux transport rate. Only cuts for SMC (black), Pre-SMC (orange), substorm expansion (blue), and substorm recovery (red) are shown for clarity. These figures reiterate the previous results but show where in the tail region transitions in plasma parameters occur. The ordering of density is difficult to discern in this plot, but in general the SMC case has the lowest average density values from $\sim 16$ RE outward. The pressure increases above substorm levels for Pre-SMC and SMC states starting as far out as 20 RE and is significantly higher by 16 RE. The temperature in the tail region is significantly enhanced for Pre-SMC and SMC states compared to the two substorm phases. Note that the sharp drop in temperature at 12 RE is not
Figure 4.13. Average plasma parameters along the midnight meridian (within $|Y| < 5$ \(R_E\)): density (top left), total pressure (top right), temperature (bottom left), and Earthward magnetic flux transport (bottom right). Four types of activity are shown: substorm expansion (blue), substorm recovery (red), Pre-SMC (orange), and SMC (black).

real, but is due to which satellite dominates the coverage (Geotail beyond 12 \(R_E\), THEMIS within 12 \(R_E\)), and the fact that the satellites cover different time ranges (Geotail includes the rising phase and solar maximum, while THEMIS measurements occur during solar minimum). Earthward flux transport rate is highest for SMCs in the tail region and substorm expansions in the inner region, with a transition between the two occurring at ~18 \(R_E\).

4.5. Discussion

This is the first statistical survey of magnetotail conditions during steady magnetospheric convection. Our goal was to investigate how the return of closed flux from the nightside to the dayside during SMC is accomplished. To do so, we identified the relative differences in the magnetotail according to the mode of magnetospheric response, particularly focusing on SMC events and substorms. Previous case studies on SMCs have shown that during such events the
magnetotail exists in a hybrid state, with a thin near-Earth current sheet (similar to the growth phase) and thick midtail plasma sheet (resembling the substorm recovery phase) [Sergeev et al., 1994]. We have examined the magnetic field $B_z$ component in the magnetotail for our events (not shown) and our statistical result agrees with these case studies. The average SMC $B_z$ matches substorm growth phase values within 8 $R_E$ and matches substorm recovery phase values outside of 13 $R_E$, with a transition region between 9-12 $R_E$.

SMC events are intervals of balanced reconnection [DeJong et al., 2008] in which the opened and closed magnetic flux of the magnetosphere remains stable [Milan et al., 2007]. The dayside reconnection rate and the day-to-night flux transport rate are controlled by the solar wind. If the solar wind driver is enhanced and stable, the nightside x-line can match the dayside reconnection rate for hours [McPherron et al., 2005]. This balance of flux reconnection rates drives convection such that flux neither accumulates in the tail nor is significantly depleted at the dayside. Closed flux must return to the dayside in order for this to occur. More than 80% of SMC events occur within 75 minutes after an obvious substorm expansion (explored further in Chapter 5), suggesting that such events occur after the formation of a near-Earth neutral line that remains in the near- to midtail for the duration of the SMC, reconnecting tail lobe flux. Our results can be understood in terms of the balanced reconnection model and explain how the return of magnetic flux is accomplished.

SMC events have the highest occurrence rate of fast Earthward flows (~4%) and these fast flows transport a larger percentage of the total magnetic flux observed (~20% on average), compared to the other modes of activity (Table 4.1). This confirms that during SMC, magnetotail reconnection occurs throughout the events in a bursty manner. Since fast-moving plasma is responsible for a larger percentage of the total Earthward magnetic flux transport, this implies
that enough flux returns to the dayside "quickly enough" to balance the rate of dayside reconnection. Additionally, the probability of observing an Earthward fast flow during SMC increases with radial distance. This suggests that the statistical location of the nightside x-line is in the midtail beyond 31 \( R_E \), in agreement with previous studies [Sergeev et al., 1996a].

Fast flows during SMC experience a pattern of diversion toward either the dawn or dusk flank (Figures 4.4 and 4.5). This pattern is fairly symmetric around midnight, and the deflection of flows increases as radial distance decreases. Fewer flows penetrate the inner magnetosphere (within 15 \( R_E \)) for SMC than any other active mode of response. Those that are observed show extreme flankward deflection. This stands in marked contrast to the pattern during isolated substorms, in which closed flux from the near-Earth neutral line is injected into the nightside inner magnetosphere and forms a "pile-up region" [Baumjohann et al., 1999]. Instead, fast flows carrying recently closed magnetic flux are forced away from the inner magnetosphere and the flux is returned to the dayside by way of the dawn and dusk flanks. This return allows for the continued balance of reconnection rates.

SMCs show higher levels of pressure than substorms, particularly in the inner magnetosphere where a broad region of enhanced total pressure extends to >15 \( R_E \). This enhanced pressure region is responsible for the diversion of fast flows observed during SMC events. Consider two Earthward fast flows, one during SMC and the other during a substorm expansion. The substorm flow moves radially inward until it reaches the strongly dipolar region of the inner magnetosphere, where the total pressure increases sharply. The flow is braked in this region [Shiokawa et al., 1997]. The incoming SMC flow will experience a force exerted by the pressure gradient at farther radial distances. This gradient is more gradual than the sharp gradient during substorms, and is not strong enough to stop the flow completely. Instead, it deflects the
flow in the direction of lower pressure (duskward if the flow is on the dusk side of midnight, dawnward if the flow is on the dawn side). The elevated inner magnetosphere pressure diverts magnetic flux to the flanks, after which flux returns to the dayside.

Of the six modes of response we studied SMC events have the lowest densities and highest temperatures in the tail region. This is particularly evident for temperature, which is significantly ordered by the mode of response throughout the entire plasma sheet. The temperature is lowest and the density is highest during quiet times; temperature increases and density decreases during substorm growth/expansion and substorm recovery. The Pre-SMC temperature lies between substorm recovery and SMC levels while Pre-SMC density is similar to the substorm recovery phase. Beyond ~12 RE, temperature during SMC events averages ~7-10 keV, well above other modes of response. In the inner magnetosphere, the temperature values remain higher than the substorm phases. The differences in density and temperature can be described in terms of the near-Earth neutral line model [McPherron et al., 1973; Russell and McPherron, 1973b], as follows: During the substorm growth phase, reconnection has begun in the near-Earth plasma sheet, but it occurs on closed field lines containing higher-density plasma. The substorm expansion phase begins when the x-line "eats through" the plasma sheet field lines and reaches the lower-density lobe field lines. In the recovery phase, reconnection continues on lobe field lines and the x-line retreats down the tail. Now, consider the SMC case. The magnetosphere responds to driving with a preceding substorm (Pre-SMC), but instead of the x-line retreating to the distant tail, reconnection continues in the near- to mid-tail for hours at a time. This x-line is reconnecting lobe field lines across the tail, and so continuously sends lower-density plasma into the plasma sheet. If the nightside x-line is reconnecting lower-density lobe plasma, it must heat the plasma in order for the plasma pressure to remain the same.
The rate of Earthward transportation of magnetic flux is enhanced during all active modes of response compared to quiet time. During substorm expansions, enhanced flux transport rate occurs predominantly along the tail in a region offset duskward from the midnight meridian by about 3 RE. During SMC and substorm recovery phases, significant Earthward flux transportation rates are seen across the tail region, with the broadest region and highest levels occurring during SMC. In the inner magnetosphere, flux transport rate distributions are the same for substorm expansion, recovery, Pre-SMC, and SMC cases. Increased Earthward flux transport rates across the entire tail during SMC results in more magnetic flux to be returned to the dayside and allows for balance of the solar wind driving rate.

We examined the two hours before SMCs and found that the occurrence rate of fast flows during Pre-SMC times is slightly larger than during substorm recovery, while the radial probability distribution is comparable to that during substorm expansion phases. The density, temperature, pressure, and Earthward flux transport rates in the tail region and the inner magnetosphere region for Pre-SMC lie between the SMC state and the substorm phases. In particular, the inner magnetosphere high pressure region extends farther out during Pre-SMC, as in the SMC case, although the values are not quite as high. As most SMCs occur after a substorm, it seems that this preceding substorm expansion sets up the state of the magnetotail to assist the occurrence of SMCs.

4.6. Conclusions

We have shown how the magnetotail accomplishes night-to-day transport of magnetic flux during balanced reconnection. During SMC events, few fast flows penetrate the inner magnetosphere; most are diverted to either flank of the magnetotail due to strong pressure
gradients in the inner magnetosphere. These fast flows carry a significant portion of magnetic flux, and presumably then return to the dayside to balance the rate of reconnection at the dayside subsolar point and allow the SMC event to continue. The broad high pressure region in the inner magnetosphere is the likely result of the preceding substorm during the Pre-SMC interval, which causes the initial buildup of pressure.
5.1. Introduction

Substorms and steady magnetospheric convection are mutually exclusive modes of response. While it is possible to have a storm and a substorm occur at the same time, by definition a substorm cannot occur during an SMC. The transition to and from SMCs and substorms can be difficult to determine from auroral indices. In our selection criteria (see Chapter 2), if an SMC was preceded by a substorm, we selected the start time of the SMC event after the obvious substorm expansion was complete, and at times after a clear partial recovery phase. However, the AL signature of a preceding substorm was not a requirement for SMC selection.

*O'Brien et al.* [2002] showed that the magnetosphere has some capacity to resist transitioning from an SMC to a substorm. In other words, reconnection rates can remain balanced until some threshold or instability occurs, whether in the solar wind or internally. In Chapter 4, we reviewed the conditions in the magnetosphere that contribute to this quasi-stable state: near- to midtail reconnection across the tail closing significant lobe flux; a broad high-pressure region in the inner magnetosphere that diverts plasma away from the pile-up region; and flux return to the dayside via fast flow bursts. In studying the two hours before SMCs (Pre-SMC), we found that the plasma conditions typical of SMCs were already enhanced compared to isolated substorm levels. This suggests that the preconditioning of the magnetosphere, in combination with certain solar wind conditions [*McPherron et al.*, 2005; *DeJong et al.*, 2008; see also Chapter 3], allows the magnetosphere to enter a state of balanced reconnection.
Rather than spontaneously entering a steady state, the magnetosphere tends to transition directly from a substorm to an SMC interval. In a superposed epoch analysis of AL with respect to the start time of 2365 SMC events, McPherron et al. [2005] observed a sharp decrease in AL before the SMC, reaching a minimum at the start of the SMC. They also found that about half of their events were terminated by a substorm. DeJong et al. [2008] found only one case out of 51 balanced reconnection intervals that did not follow a substorm. Sergeev et al. [1996a] suggested the possibility that the magnetic field configuration required to allow steady magnetospheric convection could only occur after the unloading of tail flux in a substorm expansion. After the expansion, the plasma sheet would thicken as it does in a substorm recovery, while continuing southward IMF $B_z$ would thin the near-Earth tail similar to a new growth phase.

In this chapter, the primary question we will answer is: What is the role of preceding substorms in the formation of SMC events? Secondary questions include: How often are SMCs preceded and terminated by substorm onsets? Are preceding substorms (and formation of a NEXL) necessary to precondition the magnetosphere to allow quasi-steady convection? We will investigate the relationship between SMCs and substorms, with a particular focus on preceding substorms. First, we determine the correlation between the two types of events. Next, we will identify SMC cases without an observed preceding substorm and characterize the solar wind conditions that drive such events. Finally, we will use several cases to describe the state of the magnetosphere, concluding with a suggestion of how these events can occur.

5.2. Probability that a substorm precedes or follows an SMC

We begin by determining the statistical probability that a substorm occurs before or after an SMC. We treat the start and stop time of SMC events and substorm expansion onsets as point
processes. A point process is a series of points in a set, in this case on a timeline. With two such series, we can attain a measure of the correlation between the two types of events. Figure 5.1 shows the conditional probability that a substorm onset occurs with respect to a) the start time of an SMC and b) the end of an SMC. The thick horizontal dashed line is the mean probability well away from the origin, and the thin dashed lines are twice the standard deviation from the mean. There is a high probability for substorms to occur both just before and just after SMC intervals. The correlation of substorms with the start time of an SMC begins to increase above the mean level at $\sim 75$ minutes, rises above the $2\sigma$ line at about -50 minutes, and peaks at 0.066 16 minutes before an SMC begins. This peak precedes SMC start because we require at least the expansion phase to complete before the SMC begins. As we expect, the correlation drops sharply once the SMC event occurs, and rises back to the mean level after $\sim 90$ minutes, our minimum SMC event duration. In comparison, the peak correlation of substorms with the end of SMC is smaller (0.054 peak at 4 minutes after), but is still very significant. The peak width covers 0 to 25 minutes after the end of the SMC. In a similar comparison of substorm onsets to the start time of quiet intervals from Chapter 4, there is no peak in occurrence probability (not shown).

![Figure 5.1. Point process correlation between substorm expansion onsets and a) the start of SMC events and b) the end of SMC events.](image-url)
5.3. SMCs with no preceding substorm

5.3.1. Selection of events

Using the numbers found in section 5.2, we perform a one-to-one comparison of substorm onsets and the start times of SMCs. Substorm onset times were selected visually from auroral indices by a sharp drop in the AL index [Hsu and McPherron, 2012]. The temporal coverage of the substorm onsets list nearly overlaps our SMC event list, allowing us to directly compare 2924 SMCs. An SMC is said to begin with a substorm if an onset is identified within -75 minutes before SMC start, and an SMC is ended by a substorm if an onset is identified within +25 minutes after SMC end. We find that:

- 2353 SMCs begin with an AL substorm onset (80.5%)
- 1138 SMCs end with an AL substorm onset (39%)

Thus, most SMC events occur after a clear substorm, and less than half end in a substorm. The ~20% of SMC events that did not have an associated preceding AL onset signature were examined in more detail. Closer examination showed many of these events did in fact have a preceding AL onset. Such onsets could have been missed due to the selection process of AL substorms, as Hsu and McPherron [2012] used a 24-hour window that preferentially misses substorms during 2300 UT and scaling that could miss small onsets. When these events are included, we find that 92% of SMC events occur after a substorm onset. In other cases, we identified a preceding pseudo-breakup, or prior enhanced AL activity that did not conform with usual substorm signatures, but could possibility help set up the magnetotail in a similar manner.

Table 5.1 summarizes the types of activity that preceded the 20% of SMC events unassociated with a Hsu and McPherron AL onset. The second column shows the percentage of each type
relative to the subset (571 events), while the third column shows the overall percentage of each type compared to all SMCs (2924 events).

<table>
<thead>
<tr>
<th>Type</th>
<th>Percentage of 20% subset</th>
<th>Percentage of all SMCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL onset missed by Hsu</td>
<td>56.5%</td>
<td>11.0%</td>
</tr>
<tr>
<td>Pseudo-breakup/small onset</td>
<td>7%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Active, not organized or steady</td>
<td>22%</td>
<td>4.3%</td>
</tr>
<tr>
<td>No AL signature</td>
<td>14%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

The last row of Table 5.1 shows the percentage of SMCs that did not have any prior signature in the AL index. Compared to our entire SMC list, this corresponds to 2.8% of events. We closely examined these events and identified a subset of SMCs in which no preceding substorm signature could be identified in any available dataset, including: electron flux injections at the LANL satellites; dipolarization at geosynchronous GOES satellites; expansions in auroral imagers on the Image satellite [onset list from Frey et al., 2004], the Polar satellite [onset list from Liou, 2010], and the THEMIS ground all-sky imagers (ASI); sharp negative breaks at high latitude magnetometers; and positive bays in mid-latitude magnetometers [list provided by Xiangning Chu]. The final subset comprises 32 SMC events, corresponding to 1% of our entire list. Clearly these events are rare. We conclude that statistically most SMCs are preceded by the formation of a near-Earth neutral line that unloads the magnetosphere and sets up the pressure distribution to sustain the SMC state. In the remaining portion of the chapter, we turn our attention to the 32 anomalous SMCs with no observed preceding substorm, with the goal of illuminating if and how balanced reconnection could initiate in the magnetosphere without a prior substorm.
5.3.2. Solar wind conditions

An example of an SMC/BRI that did not appear to have an initiating substorm was presented by DeJong et al. [2008]. The event occurred on December 22-23, 2000 and consisted of a slow increase and decrease in the AE and AL indices, respectively, over more than six hours. The polar cap flux was steady throughout the event with a value of 0.76+/−0.05 GWb. The BRI was ended by a large substorm (AL ~−1100 nT) which did not seem to be caused by a northward turning of the IMF. Strangely, the solar wind magnetic field and density were not steady for this event, showing fluctuations larger than typical for SMCs. The IMF Bz was strongly southward (~−15 nT) except for a large northward turning at 2330 UT which did not result in the typically expected substorm expansion. Instead, aurora data indicated that only a pseudo-breakup occurred. Since the y- and z-components of the solar wind velocity also underwent an enhancement at this time, the authors hypothesized that this northward turning was deflected away from the Earth's magnetosphere. The only steady parameter was Vx, remaining slow and level at −318 km/s. Their conclusion was that the magnetosphere was already in a state that allowed the reconnection rates to balance without the need for an expansion phase.

Figure 5.2. Superposed epoch analysis of average |AL| with respect to the start time of SMCs with no preceding substorm.
The slow and steady enhancement of the AL index is typical of SMCs without an obvious preceding substorm. An ensemble average of |AL| is plotted in Figure 5.2 and shows the average behavior of increasing |AL| throughout the events. The magnitude of the AL index begins to increase \( \sim 1.5 \) hours before we select the start of the events due to our AL minimum criterion. Only data through the end of each SMC goes into the ensemble, which is why the average |AL| index goes unstable and cuts off at +4 hours.

Solar wind conditions during the subset of atypical SMC events are compared to the average solar wind conditions during all other SMCs. Figure 5.3 shows a superposed epoch analysis of solar wind speed, IMF \( B_z \), and \( E_y \) on the left column, with the corresponding steadiness for each parameter on the right column. The behavior with respect to the start time of all SMCs is plotted in blue, while the subset of 32 anomalous SMC events is plotted in red. As in

![Figure 5.3](image)

**Figure 5.3.** Superposed epoch analysis of solar wind speed, \( B_z \), \( E_y \), and the steadiness of each, relative to the SMC start times. Conditions during SMCs without a preceding substorm are plotted in red, and all other SMCs are in blue.
the previous figure, data past the end of each SMC was truncated. The most obvious difference is that the solar wind velocity is slower than the average SMC levels. Further, B\textsubscript{z} values are less negative prior to the start of non-initiated SMCs. The decrease in B\textsubscript{z} occurs at around the same time for both types of SMCs (-3 hours) and reaches the same magnitude at the start (-3 mV/m). The combination of V\textsubscript{sw} and B\textsubscript{z} results in weaker E\textsubscript{y} for non-initiated SMCs than the average before t=0, though E\textsubscript{y} reaches the average SMC level ~1 hour after SMC start. Although the average ensembles of V\textsubscript{sw}, B\textsubscript{z}, and E\textsubscript{y} show more variance for non-initiated SMCs, the corresponding steadiness parameters (right column) are actually slightly lower compared to all other SMCs. E\textsubscript{y} steadiness varies more, but since it varies around the typical level for all other SMCs, this is likely due to small number of events comprising the ensembles.

The effect of the reduced electric field is easier to see in Figure 5.4. We calculate a running hourly sum of E\textsubscript{s} (only positive values of E\textsubscript{y} correspond to negative IMF B\textsubscript{z}), which we call the hourly integrated rectified E\textsubscript{y}, or Int E\textsubscript{s}. This represents the total amount of solar wind driving applied to the magnetosphere during one hour prior to each sample. We also looked at integration times of 30 minutes and 90 minutes, and obtained similar results. The ensembles of Int E\textsubscript{s} in Figure 5.4 show that the average behavior of the driver for all SMCs (blue line) is to steadily increase -2 hours before SMC start, reaching a stable level at the start of the SMC of about 55 (mV/m * hr). In contrast, for non-initiated SMCs (red line) the driver takes a longer time to increase. Before the SMC and at its start, Int E\textsubscript{s} is consistently lower than the average level for all other SMCs. The increase in the driver is slower, beginning -3 hours before and taking >4 hours to reach the peak level, which occurs 1.5 hours after the start of the SMC. After this point, the driver remains enhanced but more variable. This might be due to the fact that we do not include data past the end of each SMC. Since our minimum SMC duration is 1.5 hours,
Figure 5.4. Superposed epoch analysis of the running hourly sum of solar wind $E_s$ (Int $E_s$) relative to the start time of SMCs without a preceding substorm (red), and all other SMCs (blue).

After this time fewer SMC events contribute to the ensembles. It appears that the average driving is smaller for these longer SMCs. The behavior of Int $E_s$ suggests that the solar wind turns on dayside reconnection at a slow enough rate, possibly allowing for the nightside reconnection rate to achieve balance without tail unloading.

Note that there is a minimum in Int $E_s$ for the SMCs without preceding substorms -3 hours before SMC start. This means that there was almost no solar wind input to drive dayside reconnection for at least one hour prior to this point. This agrees with the general behavior of $E_y$ in Figure 5.3, where $E_y$ is weakly negative (corresponding to weakly positive IMF $B_z$) two to four hours before SMC start. We speculate that this period of little to no driving may be important in 'resetting' the magnetosphere into a quiet state (as evidenced by low AL and AU indices) before slow enhancement of solar wind driving and magnetospheric convection.

While we would like to statistically determine the state of the magnetotail during these events, there is not enough satellite coverage with only 32 SMCs. We must turn to case studies to illuminate any differences from average SMC conditions. In the next section, we present three SMC events which have no preceding substorm signatures, and with satellite coverage in the magnetotail.
5.3.3. Case studies

Typical SMC on 2008-03-09

As a comparison, we first present an example of magnetotail and aurora behavior during a 'typical' SMC event with a preceding substorm. This SMC occurred on 09 March 2008 and is just under three hours long. Figure 5.5 shows the auroral indices, AU and AL, and propagated solar wind conditions from the OMNI 1-minute dataset during this event, including the velocity components, IMF components, \( E_y \), and dynamic pressure. The SMC begins at 0216 UT after a substorm onset and is ended by another, larger substorm at 0506 UT. The AL index is large for

![Figure 5.5. Kyoto auroral indices (AU and AL), AL steadiness, OMNI solar wind velocity, magnetic field, \( E_y \), and dynamic pressure during a 'typical' SMC on 09 March 2008. Vertical dashed lines show the start and stop times of the SMC.](image-url)
this SMC, averaging ~600 nT, and is very stable (average AL steadiness is 0.10). The solar wind velocity increases over the course of the event, from ~450 km/s to ~500 km/s. The IMF B_z component is southward before and during the event, except for a couple of brief northward excursions. B_z decreases to more negative values during the course of the event, and is most strongly southward (-16 nT) at the end of the SMC. The resulting E_y is therefore positive for most of the interval and reaches up to 8 mV/m at the end of the SMC.

Figure 5.6 shows that all five THEMIS spacecraft were aligned along the dusk side of the magnetotail during this SMC, although THEMIS A does not enter the plasma sheet until the end of the event. THEMIS D and E are in the inner magnetosphere at |X_GSM| ~9-10 R_E, C is further out at 16 R_E, and B is at 20 R_E. The right panel of Figure 5.6 shows that all four spacecraft observe fast Earthward flow bursts during the SMC. THEMIS B sees the most flows and the fastest (max V_x-y = 458 km/s), followed by THEMIS C (max V_x-y = 273 km/s). THEMIS D and E only see one and two flows respectively, which just meet our threshold of 200 km/s (203 km/s for D, 215-229 for E). This event is a good summary of our statistical findings in Chapter 4.

![Figure 5.6](image_url)

**Figure 5.6.** Left panel: Alignment of THEMIS spacecraft in the GSM x-y plane during a 'typical' SMC on 09 March 2008. Right panel: Directions of fast flow bursts in the GSM x-y plane observed by THEMIS spacecraft during this SMC.
farther radial distances, Earthward flows are faster, more frequent, and directed in various
directions (dawnward, Earthward, and duskward). Closer in, few fast flows reach the inner
magnetosphere, and those that do have large deflections (dawnward at E, duskward at D).

Since we present this SMC as a comparison to the following three events, we are not
focused on the specific behavior of the magnetotail for this SMC and do not detail the spacecraft
flow and plasma measurements in this chapter (see Appendix). Instead, Table 5.2 summarizes
the observations of the five THEMIS spacecraft during this SMC event. The satellites are
ordered by farthest radial distance. The second column shows the number of fast flows observed
by each satellite. The next three columns display the average density (cm\(^{-3}\)), temperature (keV),
and total pressure (nPa) observed. The second number in these three columns represents the
average level found in our statistical work from Chapter 4, for the region in which each satellite
is located. At all locations for this SMC event, THEMIS measured densities that are larger than
the expected statistical values. The temperature is slightly colder in the tail region (B and C) but
hotter in the inner magnetosphere (D and E). The observed total pressure is larger for all five
spacecraft compared to the statistical levels. Since the statistical levels combine data from
numerous SMC events, such differences for individual events are to be expected.

<table>
<thead>
<tr>
<th>Probe</th>
<th># Flows</th>
<th>Density (cm(^{-3}))</th>
<th>Temperature (keV)</th>
<th>Pressure (nPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THM B</td>
<td>32</td>
<td>0.35 / 0.20</td>
<td>6.0 / 7.0</td>
<td>0.53 / 0.3</td>
</tr>
<tr>
<td>THM C</td>
<td>14</td>
<td>0.44 / 0.28</td>
<td>6.0 / 8.5</td>
<td>0.73 / 0.48</td>
</tr>
<tr>
<td>THM D</td>
<td>1</td>
<td>0.74 / 0.36</td>
<td>9.2 / 7.3</td>
<td>1.8 / 0.85</td>
</tr>
<tr>
<td>THM E</td>
<td>2</td>
<td>0.80 / 0.30</td>
<td>9.4 / 6.5</td>
<td>2.0 / 0.8</td>
</tr>
<tr>
<td>THM A</td>
<td>0</td>
<td>2.40 / 0.75</td>
<td>11.1 / 12.8</td>
<td>5.9 / 3.0</td>
</tr>
</tbody>
</table>

In addition to the good satellite measurements, there was also good coverage of the
auroral oval from the THEMIS All-Sky Imagers (ASI), with 14 white-light cameras available by
Figure 5.7. Mosaics of THEMIS ASI images during the 09 March 2008 SMC.
the end of the SMC. Several auroral mosaics throughout the SMC are presented in Figure 5.7. The auroral expansion began at around 0143 UT (not shown), in agreement with the AL index in Figure 5.5. At the start time of the SMC (0216 UT, top left panel), there is already evidence of the formation of a double oval, with a stable, very bright diffuse equatorward arc and an active poleward region. This concurs with the behavior detailed by Yahnin et al. [1994] and Sergeev et al. [2001]. The aurora is extremely active during the entire SMC. Many eddies (examples at 0234 UT, 0417 UT) and loops (example at 0251 UT) are observed. Multiple bright arcs appear in the poleward region, rotate into north-south aligned streamers, and feed into the diffuse equatorward aurora (examples at 0251 UT, 0428 UT, 0444 UT). Towards the end of the event some of these streamers seem to lead to formation of omega bands (examples at 0444 UT, 0506 UT) that drift eastward (first observed during SMC by Solovyev et al. [1999]). The connection between streamers and torches/omega bands has been previously shown by Henderson et al. [2002]. The large bright equatorward arc is what we expect to observe, based on the statistical large pressure levels in the inner magnetosphere from Chapter 4 [Lyons et al., 1998], and the multiple discrete poleward boundary intensifications (PBIs) and streamers are consistent with the observations of fast Earthward flow bursts.

Overall, this SMC is a good example of a 'typical' case, as it highlights many of the behaviors detailed in Chapter 4. The substorm onset beforehand assists SMC formation by increasing the total pressure in the inner magnetosphere (not shown; see Appendix). We now describe the magnetotail conditions observed during three SMCs without preceding substorm onset signatures, with satellite coverage in three different regions: the tail region (∼27 R_E), the inner magnetosphere region (<10 R_E), and the midtail region (∼46 R_E).
Event 1: Tail region during Non-Initiated SMC on 2000-04-09

This SMC event is 3.4 hours long. Figure 5.8 plots auroral indices and solar wind conditions in the same manner at Figure 5.5. The SMC begins at 0951 UT, when the AU index condition is satisfied. It is clear that there is no AL substorm onset. As seen in the statistical behavior of Figure 5.2, the AL index slowly and steadily increases over the duration of the event. The SMC is ended by a moderate substorm onset at 1313 UT. In this case the lack of a preceding substorm was confirmed with LANL SOPA data, in which no onset signature was observed until the concluding substorm. The solar wind velocity is fast but steady ($V_x \sim -546$ km/s), and the IMF $B_z$ is weak but consistently southward during the event ($B_z \sim -2.1$ nT), resulting in a weak

![Figure 5.8](image)

**Figure 5.8.** Auroral indices and solar wind conditions during Event 1 in the same manner as Figure 5.5.
but consistent driver \((E_y \sim 1.18 \text{ mV/m})\).

During Event 1, Geotail was in the midtail at around \(|X_{\text{gsm}}| = 27 \text{ RE}\) on the duskward side of the tail. Figure 5.9 shows the magnetic field and plasma data recorded by the satellite; from top to bottom: magnetic field components in GSM, \(B_{\text{total}}\), perpendicular velocity components, the perpendicular velocity in the GSM equatorial plane \((V_{\perp x-y})\), flux transport rate \((V_{\perp x-y} \ast B_z)\), density, temperature, total pressure and its components (plasma and magnetic), and plasma beta \((P_{\text{pl}} / P_{\text{mag}})\). The start and end times of the SMC are plotted in dashed vertical lines. Looking at the beta parameter, we can see that Geotail is in the plasma sheet (marked in green and defined as \(\beta > 0.5\)) during most of the SMC. In the \(V_{\perp x-y}\) panel, we have marked data points in green when a fast Earthward flow \((V_{\perp x-y} > 200 \text{ km/s}, V_x > 0 \text{ km/s})\) in the plasma sheet was observed by Geotail. An hour before the SMC starts, some fast flows \((V_{\perp x-y} \sim 400 \text{ km/s})\) are observed, mostly in the dawnward (-\(V_y\)) direction with small tailward components. These fast flows do not accomplish very much transportation of flux. After the start of the SMC and within its first hour, fast flows are again observed, this time with Earthward components and mostly directed to the duskward flank. Still, the rate of flux transport is similar to what it was before the SMC started. Enhanced temperature values occur around 20 minutes after the SMC starts, averaging 12 keV, accompanied by decreased density. After 1100 UT the spacecraft moves out of the plasma sheet, possibly into the mantle or low-latitude boundary layer (note the higher density, cold plasma, and low beta).

The second part of the SMC event is quite different from the first. Geotail suddenly re-enters the plasma sheet at around 1140 and observes very fast Earthward BBFs. The total equatorial speed goes as high as 900 km/s, mostly in the duskward direction but with \(V_x\) reaching \(\sim 400 \text{ km/s}\). These flows also carry a lot of magnetic flux, up to \(\sim 3.4 \text{ mV/m}\), and the first BBF
Figure 5.9. Geotail magnetic field and plasma conditions during Event 1.
includes a sharp dipolarization in $B_z$. For the rest of the SMC event, fast Earthward/duskward flow bursts continue to occur, each transporting a significant amount of flux. In total, 28 fast Earthward flows bursts are observed during this SMC, with an occurrence rate of 18% and accomplishing 54% of the Earthward flux transport. This entire portion of the SMC has very high temperature values, averaging 20 keV and peaking above 30 keV, and very low density at around 0.03 cm$^{-3}$. The density is even lower than prior plasma sheet values. This might indicate that reconnection, much more tailward than 27 $R_E$, is closing underpopulated flux tubes from the lobe. This then results in the significant heating of the plasma to maintain pressure balance. Just after the SMC ends, one very brief, strong tailward flow occurs, presumably from the formation of a near-Earth neutral line located Earthward of Geotail, that produces the substorm onset. After this the plasma sheet thins and Geotail moves into the lobe.

The total pressure rises throughout the entire event. A minimum in total pressure occurs at the beginning of the SMC and total pressure reaches a peak at the end of the SMC, dropping off rapidly as the tail is unloaded by the concluding substorm. Total pressure should remain relatively constant during SMC-like intervals [Tanskanen et al., 2005], and increasing total pressure is more typical of substorm growth phases in which the dayside reconnection rate is faster than the nightside reconnection rate [Milan et al., 2007]. Still, the average total pressure for this event is 0.11 nPa, which is similar to the statistical value found in Chapter 4 for SMC in this region (0.14 nPa). The event resembles our statistical SMC results in other ways: the large temperatures (especially in the second portion of the event) are characteristic of the SMC mode; the average $B_z$ (1.6 nT) indicates a thick plasma sheet and is similar to the statistical value for the same region (1.8 nT); and the strong Earthward flow bursts carrying significant magnetic flux imply that nightside reconnection occurs tailward of 27 $R_E$. Therefore this event, though not
initiated by a substorm, shows similar behavior in the tail to typical SMCs and is comparable with the statistical results from Chapter 4. The pressure behavior will be addressed further in the Discussion section.

**Event 2: Inner Magnetosphere region during Non-Initiated SMC on 2011-07-01**

Event 2 is almost four hours long. In contrast to Event 1, this event occurs during strong solar wind driving. Figure 5.10 plots auroral indices and solar wind conditions in the same manner at Figure 5.5. The event begins at 1056 UT, when AL steadiness falls below 20%. As in Event 1, the AL index slowly grows for hours, and though its behavior shows more variability,

![Figure 5.10](image.png)

**Figure 5.10.** Auroral indices and solar wind conditions during Event 2 in the same manner as Figure 5.5.
these variations are not strong enough to increase AL steadiness above our threshold. The event is ended by either a brief substorm or a pseudo-breakup at 1453 UT. The solar wind velocity is steady at around 400 km/s. For most of the event, IMF $B_z$ is moderately negative at around -6 nT, but there is some variability in which it increases to positive levels. This results in an average $E_y$ of ~1.7 mV/m, which is positive except for a few data points.

This is an example of an event where there is clearly no substorm according to the auroral indices, but signatures typical of substorm onsets occur in the magnetotail. During Event 2, two THEMIS satellites (D and E) cross through the inner magnetosphere on an inbound pass. Figure 5.11 shows plasma and magnetic parameters for THEMIS D (left column) and E (right column). The figures are arranged in the same manner as Figure 5.9. At the start of the SMC, both spacecraft are located at $X_{GSM} \sim -9 R_E$. Before the start of the event, both satellites observe increases in $B_{total}$ and decreases in plasma beta, indicating that the satellites are going into the lobe due to plasma sheet thinning. The total pressure increases to a peak level and then suddenly drops coincident with very fast (~600 km/s) flow bursts carrying large amounts of magnetic flux (8-10 mV/m). This occurs as the plasma sheet suddenly expands to engulf the satellites (seen as a sharp $B_x$ reduction and moderate $B_z$ enhancement). These are typical signatures of a substorm expansion, but no reaction is observed in the AL index or other ground magnetometers.

The satellites reenter the plasma sheet at the beginning of the event and cross the neutral sheet in the middle of the event, as shown by $B_x$ (blue traces, top panel). The fast flows (panels three and four) are strongly in the Earthward direction, but also have a significant duskward component. THEMIS D, farther out in radial distance, sees nine fast flows bursts, while THEMIS E sees five. THEMIS A (data not shown), which is separated from the other two by less than 1 $R_E$ in the $X_{GSM}$ direction, only observed small enhancements in velocity. At the time
of the flow bursts and for the remainder of the event, the temperature increases to \(~5\) keV, higher than the value beforehand \((\sim 4\) keV\). Temperature and density are fairly constant for the rest of the event, while the total pressure is more variable. After the initial flows, the total pressure in the plasma sheet generally increases during the course of the event. This is partially due to the spacecraft moving inward toward the Earth. There is a sudden increase in total pressure at \(\sim 1330\)
UT observed by both spacecraft as they suddenly move to the outer plasma sheet. The event ends with another series of fast flows (~200 km/s) and a very sharp dipolarization in $B_z$, observed particularly at THEMIS E (as well as THEMIS A). This corresponds with the AL onset in Figure 5.10. During this event, the average pressure measured by THEMIS D and E is similar to the statistical SMC value in Chapter 4 for the same region. The average measured density is higher and the average measured temperature is lower compared to the corresponding statistical levels.

This event highlights conflicting behavior in the inner magnetosphere and on the ground. No substorm onset is observed at the beginning of the event in the AL index or in various magnetometer stations. Yet at the same time signatures of a substorm onset are observed in the magnetotail, including sudden expansion of the plasma sheet and fast Earthward flows associated with a decrease in total pressure. This may indicate that the substorm onset was missed by the available magnetometer stations, or that plasma sheet reconnection initiated, but was quenched before it could reach lobe field lines and result in a full substorm expansion. This event does agree with the statistical behavior of SMCs, since the observed fast flows with significant flux show strong deflection toward the duskward flank. In addition, the measured total pressure levels are comparable to those expected from our statistical results. The plasma sheet is stable during the remainder of the event, even as the AL index measures increasing electrojet activity.

Event 3: Midtail region during Non-Initiated SMC on 2011-05-16

The last SMC, which lasts for 2.8 hours, is a weak event that just meets our thresholds for selection. Auroral indices and solar wind conditions are shown in Figure 5.12 in the same way as Figure 5.5. The IMF $B_z$ is mostly southward during the event (-2.25 nT on average), although several brief northward turnings occur in the middle. The solar wind velocity is fast ($V_x \sim -525$
km/s), and so the average electric field $E_y$ is around 1.2 mV/m. Yet, the AL index response to this driving is weaker than expected, averaging -120 nT (the corresponding average AE is 208 nT). One reason for the weak AL response is the IMF $B_y$. It is strongly positive (~6 nT) during the entire interval, and since the event occurs in May, it is ineffective according to the Russell-McPherron rule [Russell and McPherron, 1973a].

**Figure 5.12.** Auroral indices and solar wind conditions during Event 3 in the same manner as Figure 5.5.

During this event, three THEMIS probes (A, D, and E) move inward through the inner magnetosphere on the dawnward side. In addition, two THEMIS probes, reclassified as ARTEMIS B and C, are in the midtail at around $X_{GSM} \sim 46 R_E$. The ARTEMIS spacecraft provide a good opportunity to explore the conditions of the midtail during an SMC event. Figure
5.13 presents magnetic and plasma conditions at ARTEMIS B (left column) and C (right column) in the same manner as Figure 5.11. Due to a change in the survey mode of the two spacecraft, only data within the start and stop times of the SMC event is shown.

Figure 5.13. ARTEMIS B (left) and C (right) magnetic field and plasma conditions during Event 3.

For most of the event, ARTEMIS B and C are in the southern lobe. In the middle of the event from 1725 to 1800, the plasma sheet expands and the satellites dip into the outer plasma
sheet. Both spacecraft observe flow enhancements, including three fast Earthward flows that meet our 200 km/s threshold. These flows also have significant duskward (positive $V_y$) components and include an increase in magnetic flux transport. The presence of fast flows carrying positive $B_z$ indicates that reconnection is occurring beyond 46 $R_E$. The inner magnetosphere satellites (not shown) observe small flow and flux transport enhancements around the same time as B and C, although not strong enough to meet threshold levels. As expected, the outer spacecraft observe higher density and temperatures within the outer plasma sheet compared to the lobe. The total pressure is reduced within this region compared to what one might expect from lobe values before and after the excursion. This is partially due to the degradation in the SST instruments and the possible presence of heavy ions that the spacecraft cannot detect [V. Angelopoulos, private communication, 2012]. We assumed that heavy ions would contribute a total pressure increase of 25% and then extrapolated a total pressure envelope based on lobe values. We found that SST contribution to the total pressure is underestimated by a factor of 10 on ARTEMIS B and a factor of 4 on ARTEMIS C.

Although we have no statistics with which to compare the observations of ARTEMIS B and C, we can compare the plasma conditions in the inner magnetosphere. THEMIS D and E observe average temperatures of ~4.5 keV and ~4.2 keV, and average total pressure levels of ~1.2 nPa and ~1.5 nPa, respectively. These values are very low compared to the statistical averages we expect from Chapter 4 (11.5 keV and 3.8 nPa in the comparable region). This is a weak event, but the results from the ARTEMIS spacecraft show that some reconnection activity occurs tailward of 46 $R_E$. 
Summary of case study results

By examining three SMC events without preceding substorm onset signatures, we show that the magnetotail conditions in the inner magnetosphere, tail region, and midtail are similar to our statistical findings for SMC events. Still, there are some discrepancies. In Event 2, satellites in the inner magnetosphere observe signatures of a substorm, while no substorm signatures are observed on the ground. In general, the total pressure is reduced at the beginning and increases over the course of the SMC events. Increasing total pressure is expected to occur during substorm growth phases.

5.4. Discussion

Our hypothesis of SMC development relies on the prior establishment of a near-Earth x-line (NEXL). When the solar wind IMF turns southward, a NEXL forms, and once reconnection reaches the last closed plasma sheet field line and begins to reconnect lobe flux, a substorm occurs. Flux is removed from the tail via a plasmoid, and Earthward convection increases. Fast Earthward flows carrying enhanced magnetic flux encounter the sharp pressure and magnetic field gradients in the inner magnetosphere, and the flows are slowed. A pile-up region forms, with enhanced pressure levels [Xing et al., 2010a]. It is then that the SMC event begins, if the IMF remains steady and southward and continues to drive dayside reconnection. We suggest that the NEXL retreats partially down-tail to "make room" for the newly closed flux [Baker et al., 1996], but it does not fully retreat. It must remain close enough, at least at midtail distances (50-70 R_E) [Sergeev et al., 1996a], where it continues reconnecting open lobe flux, matching the dayside reconnection rate. This configuration is stable for hours, until the solar wind turns northward, becomes unsteady, or an internal magnetospheric process unbalances the system.
This is the statistical sequence of events we have observed. The question then becomes, is such a sequence always necessary for the SMC mode of response?

Thirty-two SMC events, corresponding to 1% of our overall list, were found to have no preceding substorm onset signatures. We cannot rule out the possibility that a small substorm onset occurred, unrecorded by the available datasets. The auroral indices can miss small substorm signatures in regions of poor station coverage, and supplementary datasets have varying availability. Event 2 is an example wherein no substorm is observed by ground magnetometers, but satellites within 10 RE see typical substorm signatures. For this subset, since we cannot definitively say that a preceding substorm onset occurred, we choose to treat these events as rare outliers that must be explained within our premise. Without an initial NEXL and pressure build-up in the inner magnetosphere, how do the magnetotail reconnection rates remain balanced for hours at a time?

One possibility is that a localized x-line forms in the region beyond 30 RE, at a location sufficient to balance the solar wind driver. Its location is far enough away from the Earth and its formation slow enough that typical substorm ground signatures (explosive brightening of the aurora, sharp decrease in auroral zone magnetometers) do not occur. Nagai et al. [2005] found that the location of magnetotail reconnection depends on the solar wind, such that low solar wind energy input (-Vx*Bx < 1 mV/m) corresponds to "midtail" reconnection (in their case, 25-31 RE). This agrees with our finding that the solar wind Ey (Figure 5.3) and hourly total Es (Figure 5.4) before and at the beginning of these SMC events are lower than the average levels for all other SMCs. Nagai et al. further conjectured that the efficiency of energy input primarily controls the location of reconnection, not the total amount of energy input. Thus in this scenario we would assume that the efficiency is low for these events. For example in Event 3, the large IMF By...
reduced the efficiency of dayside reconnection according to the Russell-McPherron effect [Russell and McPherron, 1973a]. However, in this scenario it is not clear how the large inner magnetosphere pressure distribution is created to divert plasma toward the flanks and return to the dayside.

A second possibility relies on the distant x-line (DXL). Russell [2000] proposed a magnetotail configuration in which both the DXL and the NEXL could exist under stable conditions. His goal was to explain how a northward turning of the IMF could result in a substorm, but the scenario could apply to these rare SMC events. Figure 5.14, reproduced from Russell [2000], shows a schematic of the magnetosphere during such a configuration. The hypothesis required continuous southward IMF to keep driving the dayside reconnection or merging rate, M, leading to increased reconnection at the DXL, R_D. The DXL creates new plasma sheet and returns flux Earthward. If the reconnection rate at the NEXL, R_N, is slow, it would be unable to reach the lobe open flux tubes due to the continued feeding in of plasma from the DXL. Convection (C) would be enhanced, but without a substorm expansion phase. The plasmoid would be "quasi stagnant", trapped between the two x-lines [Nishida et al., 1986]. SMCs without initiating substorms would take place between the southward IMF turning (S) and the northward turning (N), which would be separated by several hours (as seen in Figure 5.3 and the case studies). If the solar wind E_y increases at a slow enough rate, the DXL could balance enough of the driving to impair the NEXL from fully forming. This again agrees with Figure 5.3, in which we see lower E_y values for SMCs without a preceding substorm. Finally, this scenario agrees with the case study results in the magnetotail. Two of the events began with a decrease in total pressure and fast Earthward flows. This could be due to the initiation of the NEXL, which then fails to fully develop due to the effect of the DXL. Then, total pressure slowly increases
over the events, due to the steadily increasing solar wind driver. The magnetosphere stays balanced as long as the DXL keeps reconnecting fast enough and the NEXL reconnects slowly.

Figure 5.14. A possible configuration of two active reconnection sites in the magnetotail during SMC events without preceding substorms. From Russell [2000].
In Chapter 3, we approximated the magnetosphere as a driven system, with $E_s$ as the input and AL as the output. Assuming a linear system, we attained a measure of the coupling between the solar wind and the magnetosphere during SMC events. In section 3.4, we assumed that AL and $E_s$ were constant during the event, but Figure 5.2 and Figure 5.4 show this is not necessarily the case for non-initiated SMCs. Still, the behavior of the two is very similar. The driver of dayside reconnection, hourly total $E_s$, slowly increases for these events, as does the convection measured by the AL index, with the two curves offset in time. Int $E_s$ begins increasing -3 hours before SMC start, while AL begins to increase at around -1.5 hours. If we assume that the DXL is able to balance the dayside reconnection rate, how long after the initial enhancement of M would it take to see a reaction in the ionosphere (measured by the AL index)? Let us assume the dayside x-line is located at 15 $R_E$ and the DXL is at -150 $R_E$ [Slavin et al., 1985; Nishida et al., 1996]. The average solar wind velocity during these SMC events, according to Figure 5.3, is about 380 km/s. So the time it takes a newly-reconnected flux tube to go from the dayside x-line to the DXL is:

$$T = \frac{D}{V} = \frac{165 \text{ RE}}{380 \text{ km/s}} = 46 \text{ minutes}$$

This is in agreement with previous studies [30-40 minutes in Baker et al., 1996]. Now, the newly-closed flux tube moves Earthward, increasing convection. We assume it travels at the minimum speed of our fast Earthward flow threshold from Chapter 4, 200 km/s. The time it takes for the ionosphere at -1 $R_E$ to observe the enhanced convection, via the AL index, is:

$$T = \frac{149 \text{ RE}}{200 \text{ km/s}} = 79 \text{ minutes}$$

Therefore, we expect to see a reaction in the AL index from DXL reconnection due to enhanced solar wind driving in ~125 minutes. This is in good agreement with the delay seen in the superposed epoch analysis in Figures 5.2 and 5.4. The enhancement in Int $E_s$ begins 1.5-2 hours
before the enhancement in AL, indicating that it takes the magnetosphere about two hours to respond to solar wind driving in these cases. With the same simple analysis for a midtail x-line at 60 R_E, we would expect to see a reaction in the AL index 52 minutes after the initial enhancement of dayside reconnection.

Figure 5.15. Superposed epoch analysis, relative to the start time of non-initiated SMCs, of running hourly summed |AL| index, running hourly summed solar wind E_s, and the coupling between these two parameters. The integrated E_s and the corresponding coupling has been time shifted by two hours.
Figure 5.15 shows the strong relationship between the input driver and the output response by plotting the total AL index over one hour (Int AL) and the total Es over one hour (Int Es). Int Es has been time shifted by 120 minutes in accordance with our calculations. The third panel shows the ensemble of a measure of the coupling, dividing Int AL by the time-shifted Int Es. The time-shifted coupling efficiency is low before t=0, then sharply increases at the start of the SMCs. Although there is some variation, the coupling remains mostly constant at around 200 nT / (mV/m), slowly decreasing toward the end of the ensemble (where there are fewer events). The magnetospheric output is clearly able to match the solar wind driver, with a delay of two hours. This supports the hypothesis of the distant x-line responding to and balancing the slow and steady increasing dayside reconnection during these rare SMC events.

One problem with this scenario is the "pressure balance inconsistency" [Erickson and Wolf, 1980]. The entropy in the magnetotail can be approximated by the entropy parameter $PV^{5/3}$, where P is the plasma pressure and V is the flux tube volume $\int ds/B$ [Wolf et al., 2009]. Since $PV^{5/3}$ increases down the tail [Xing and Wolf, 2007], the DXL would be located at a region of large $PV^{5/3}$. Earthward adiabatic convection of this large $PV^{5/3}$ is expected to thin the plasma sheet in the near-Earth region. In fact, this is the case during the substorm growth phase [McPherron, 1970]. Recent RCM models have shown this stretched field and a $B_z$ minimum during the growth phase [Yang et al., 2010b], obtaining $B_z$ levels below 5 nT between $|X| = 8-10$ RE. Still, this does not preclude the possibility that an SMC could occur during such a configuration--in fact, such a $B_z$ minimum was initially modeled by Sergeev et al. [1994] for an SMC event. Furthermore, such low $B_z$ values are observed during Event 2. Both THEMIS D and THEMIS E are located at $|X| = 8-9$ RE and cross the neutral sheet ($B_x \sim 0$ nT), between 1200-1300 UT (D) and 1250-1310 UT (E). Both satellites observe low values of $B_z$ (8 nT and 6.5 nT
respectively) at stable levels for the entire crossing. Although usually $PV^{5/3}$ is low during SMCs [Yang et al., 2010a], it is possible that the DXL is not creating too large $PV^{5/3}$. The inner magnetosphere thins enough to accommodate larger $PV^{5/3}$ levels and yet remains stable (no substorm unloading) for hours. This supports our hypothesis that these rare SMC events can be driven by weaker solar wind electric field without a prior substorm expansion.

5.5. Conclusions

In Chapter 4, we demonstrated that during the two hours before an SMC (Pre-SMC), the magnetotail is reaching the configuration that allows balanced reconnection. In this chapter, we have shown that the majority of SMCs occur after a substorm onset. We conclude that the observed inner magnetosphere pressure buildup is due to the preceding substorm and near-Earth neutral line [Baker et al., 1996]. The NEXL, a result of the IMF turning southward, injects lobe-reconnected plasma and flux into the inner magnetosphere. This causes the pressure to increase and the NEXL may retreat to midtail distances [Sergeev et al., 1996a]. Continued southward driving by the solar wind causes this x-line to remain close enough to continue reconnecting lobe flux, maintaining Earthward convection at enhanced levels. Subsequently, flux encountering the enhanced inner magnetosphere pressure gradient is diverted toward the tail flanks, where it continues to the dayside and hinders dayside flux reduction due to reconnection.

A small subset of SMCs do not occur after a substorm. They occur during lower solar wind driving than is typical for SMCs and are characterized by slowly increasing $|AL|$ index. The magnetotail for these events agrees with our statistical SMC description for the most part, although the total pressure slowly increases over the course of several events. We suggest that
this subset of events can be explained by the presence of a DXL that reacts to slow solar wind driving, and that any NEXL does not reach lobe plasma during the course of the SMC.
CHAPTER 6

Conclusions and Future Work

Solar wind driving produces a variety of responses by the magnetosphere, one of which is steady magnetospheric convection. Although they occur often (~100-300/year), SMCs have been neglected compared to substorm research. Study of this stable, yet active, state is important to fully understand the magnetospheric response to the solar wind. Our goal for this dissertation was to perform comprehensive statistical analysis on solar wind and magnetosphere parameters with multiple data sources in order to address several outstanding questions on SMC events. The main result is a clearer and more detailed picture of the magnetosphere’s response to the solar wind with steady magnetospheric convection.

In the course of this dissertation we identified a large number (3001) of SMC intervals during 1997-2011, using auroral indices, a consistently available dataset. We chose not to refer to these events as balanced reconnection intervals (BRI) [DeJong et al., 2008], since without global auroral imaging we cannot prove conclusively that our SMC events occur when the dayside and nightside reconnection rates are balanced. However, we performed several comparisons in Chapter 2 to assure ourselves that, statistically, our selected events match expected behavior for BRIs. Therefore, in this dissertation we assume that we are studying events during which dayside and nightside reconnection rates are balanced. Obviously, such a balance between opening flux at the dayside and closing flux on the nightside does not occur instantaneously, but is understood to occur over some period of time. Hubert et al. [2009] showed that during SMC an intensification of the dayside opening voltage was matched by the nightside closing voltage 20-40 minutes later. Brief brightenings of the aurora or enhancements in the AL index on the order of 10-15 minutes are often observed during our events and have
been reported by others [Sergeev et al., 1996a, DeJong et al., 2008], and can be caused by a temporary slight mismatch between dayside and nightside reconnection rates [Hubert et al., 2010].

Our objectives were to determine: 1) if organized, often-occurring structures in the solar wind tend to cause SMC events; 2) how flux is returned in the plasma sheet from the nightside x-line to the dayside to sustain balanced reconnection; and 3) if a substorm onset and near-earth neutral line are necessary before the magnetosphere can enter the SMC state. Here we summarize our findings, and conclude with suggested avenues of future study.

6.1. Solar wind driving of the SMC mode

In Chapter 3, we compared SMC events to two types of organized structures in the solar wind: stream interfaces within corotating interaction regions and coronal mass ejections. Such structures occur often and are relatively easy to identify. We found no correlation between coronal mass ejections and SMC intervals, indicating that these solar wind structures may be too brief and unsteady to drive balanced reconnection.

We identified a strong association between SMCs and stream interfaces (SI). The probability of an SMC event occurring significantly increased -1 to +2.5 days after a stream interface arrived at the Earth during the declining phase of solar cycle 23 (2004-2009). This enhanced occurrence did not appear in the rising phase (1998-2003). We explored several contributing factors for this difference in SMC-SI association by solar cycle phase. First, we found that the IMF geo-effectiveness of the streams strongly affects the association with SMC occurrence. Since stream interfaces separate two solar wind streams, both of which can be effective or ineffective, there are four pairs: effective before, effective after (EE), ineffective
before, effective after (IE), and so on. In the declining phase, three types of interfaces show a correlation with SMC occurrence, particularly EE and IE, while in the rising phase, only IE interfaces exhibit a correlation. Streams that are effective after the interface (EE and IE) tend to have higher positive $E_y$ values that will result in reconnection, and correspondingly larger geomagnetic activity. Second, as shown in Chapter 5 (and discussed further in section 6.3), most SMCs are preceded by a substorm. We found that more substorms occur after a stream interface than before, and substorm occurrence increases during the declining phase. With the increased chance of substorms occurring after a stream interface in the declining phase, there is also a greater chance for SMCs to occur in the same interval. Finally, SMCs in the declining phase showed more efficient coupling ($AL / E_s$) than SMCs in the rising phase. This agrees with the general behavior of stronger solar wind-magnetosphere coupling during the declining phase [McPherron et al., 2012, in prep], which means that the same $E_s$ driver in both phases will result in a larger response in $AL$ during the declining phase.

The association of SMC with the interval after stream interfaces runs counter to expected results based on previous work. Some researchers have found that slow solar wind speed (~400 km/s) is the most important factor associated with SMCs [Partamies et al., 2009b], and others indicate the combination of slow solar wind speed (<450 km/s) and steady IMF $B_z$ distinguishes SMCs from other modes of response [DeJong et al., 2009a]. Since stream interfaces mark the boundary between slow and fast solar wind sectors, associated SMCs therefore occur during faster (>500 km/s) solar wind than expected. In comparing SI-Associated SMCs (those occurring -1 to +2.5 days after stream interfaces) with all other SMCs, we found that the common parameter was the magnitude of the solar wind driver of activity, $E_s$. Further, the steadiness of $E_s$ was lower (steadier) than the typical solar wind distribution for both types of
SMCs. Since this parameter is a combination of solar wind speed and IMF $B_z$, it is true that speed plays a role in the occurrence of SMCs. However, we emphasize that it is the strength and steadiness of $E_x$, the driver of dayside reconnection that is most important for SMC occurrence.

6.2. Flux transport in the magnetotail

Most of the statistical research on SMCs has focused on the solar wind conditions that drive such events. Our knowledge of how the magnetosphere behaves during SMC results from a handful of events. In Chapter 4, we performed the first large statistical survey of magnetotail plasma conditions during SMC. We further extended this work by comparing magnetospheric SMC conditions to those during quiet intervals, isolated substorm phases, and Pre-SMC intervals (two hours before SMC start).

In every parameter we examined, SMCs displayed significantly different behavior from quiet and substorm intervals. Out of all examined modes of response, SMCs had the largest occurrence rates of fast Earthward flows, the largest Earthward transport rates of magnetic flux, the lowest densities and highest temperatures in the tail, and the highest, broadest region of enhanced pressure in the inner magnetosphere. Our research showed just how the magnetosphere can return newly closed flux from the magnetotail x-line to the dayside. Fast flows carrying enhanced magnetic flux are diverted away from the inner magnetosphere to the dawn and dusk flanks. This deflection is strong compared to substorms, symmetric about midnight, and increases both with decreasing radial distance and increasing $|Y_{GSM}|$. The diversion of flux is due to the broad region of high total pressure in the inner magnetosphere, which extends out beyond 15 $R_E$. The hot, tenuous plasma sheet in the tail region and the radially-increasing occurrence
rates of fast earthward flow bursts indicate that tail reconnection is closing lower-density open flux from the lobes at a distance farther out than 31 R_E.

In examining the Pre-SMC intervals, we showed that the magnetosphere is being preconditioned toward the SMC state before SMCs occur. Plasma conditions and flows are more similar to those during SMCs rather than isolated substorms, but not quite as enhanced as SMCs. This also corresponds to the findings of DeJong et al. [2009a], who found that solar wind conditions in the two hours prior to SMCs more closely resembled SMC conditions than isolated substorm conditions. The Pre-SMC intervals seem to be a hybrid between isolated substorms and SMCs.

6.3. Connections between substorms and SMCs

In Chapter 3, we showed that both SMC and substorm occurrences increase after a stream interface (Figures 3.2 and 3.6). In Chapter 4, we saw that during the two hours before SMCs (Pre-SMC), the magnetospheric plasma conditions (occurrence of fast flows, temperature, total pressure, earthward flux transport) are enhanced from isolated substorm levels, but not quite as enhanced as SMC levels. This shows that prior to the start of the SMC, the magnetospheric conditions needed for these events are already being established. Previous research has indicated that substorm expansions precede many SMC events [McPherron et al., 2005] and it has been suggested that the unloading of the tail through a substorm may be necessary before balanced reconnection can occur [Sergeev et al., 1996a]. On the basis of these conclusions, in Chapter 5 we completed a direct comparison of SMC and preceding substorms.

We found that most (80%) SMCs are associated with a clear substorm onset identified in the AL index, and that nearly all (99%) SMCs are preceded by substorm signatures in other
datasets, small onsets/pseudobreakups, or strong unstable convection. In this last category, we could not identify the typical signatures of a clear substorm, but we assume that this preceding activity could result in the same pressure build-up in the inner magnetosphere seen in Chapter 4. Therefore we conclude that nearly all SMCs occur after the solar wind IMF turns southward and the magnetosphere responds with a substorm onset. If the IMF continues to be steady and southward and drive dayside reconnection, the magnetosphere will stabilize into the SMC state.

We determined that a small subset of SMC events (1%) do not occur after a substorm or enhanced activity. These events are characterized by steadily increasing AL over many hours, and are driven by steadily increasing solar wind $E_s$. We find that the magnetotail responds to the enhancement in driving after two hours, and suggest that this is due to the distant x-line balancing the slowly increasing dayside reconnection rate.

6.4. Future Research

As previously stated, we could not fully classify our selected events as balanced reconnection intervals. The method to identify such events requires a view of the entire auroral oval to measure the stability of the open flux in the polar cap [DeJong and Clauer, 2005]. This is done with a global auroral imager as on the Polar or IMAGE satellites. Unfortunately, no such global imager has been in operation since 2006, and the author does not know of any prospective future satellites with such instrumentation. SMC research is by no means the only beneficiary of such a mission, and so along with many others we support the implementation of a new spacecraft with global auroral imaging.

Still, even without global imagers, much work can be done with the available ground auroral imagers. In particular, an extensive network of white-light All-Sky Imagers (ASI) spans
the North American continent as part of the overall THEMIS mission. Although the general forms and features of the auroral oval have been detailed for several SMC cases [Yahnin et al., 1994; Lyons et al., 1998; Sergeev et al., 2001], there has not yet been any statistical study on the behavior of the aurora during SMC events. A comparison of the auroral forms between SMC and isolated substorms could be particularly illuminating, especially given the recent advancement on auroral behavior during substorms. Nishimura et al. [2010a] have shown that several minutes prior to many substorm onsets, a poleward boundary intensification (PBI) leads to a north-south streamer, which moves equatorward, and that the contact of this streamer with the preexisting arc results in a substorm. However, it remains an outstanding question as to why some streamers (and their associated plasma sheet fast flow bursts [Sergeev et al., 1999; Lyons et al., 1999; 2010]) lead to a substorm and others do not [Nishimura et al., 2010b]. It has been suggested that the effectiveness of a flow/streamer to cause a substorm onset may depend on enhanced pressure levels in the inner magnetosphere [Nishimura et al., 2011] and/or low entropy parameter $PV^{5/3}$ of the flow/streamer compared to its surroundings [Xing et al., 2010b]. We have shown that many fast Earthward flows are deflected away from the inner magnetosphere during SMC events, the pressure in the inner magnetosphere is large compared to substorms, and others have shown that the entropy parameter during SMC fast flows remains low [Yang et al., 2010a]. With these new findings in mind, it would be interesting to examine the behavior of PBIs and streamers during SMC and compare them to those that initiate substorm onsets.

The factors that contribute to the end of an SMC event are still unknown. We found that less than half of our SMCs are concluded by a clear substorm expansion in the AL index. A comparison could be done of the SMC-concluding substorms and isolated substorms to see how the changed magnetotail state affects typical substorm dynamics. In many other events,
convection suddenly ends or slowly decreases to quiet levels, and it has not been determined if this is simply due to the quenching of dayside reconnection by the solar wind, or if it is influenced by some other condition.

We showed that the association of SMC to stream interfaces changes between the rising and declining solar cycle phases, and that one component of this is due to the stream interfaces themselves differing by solar cycle phase. It is outside the goals of this dissertation to further examine the changes of stream interfaces within corotating interaction regions (CIR) by solar cycle, but such a study would be important given the strong effect of CIRs on relativistic electron enhancements during magnetic storms [Paulikas and Blake, 1979; Baker et al., 1986].

In Chapter 5, we hypothesized that a small number of SMC events occur when the distant x-line closes enough flux to keep the near-Earth neutral line from evolving into a substorm onset. Although we cannot prove this idea since we have no way to remotely identify x-line locations, magnetospheric modeling could indicate if such a situation is possible. A global simulation of an SMC event with a slowly increasing driver and distant x-line could indicate if the magnetosphere could potentially remain balanced in such a state. Simulations could also determine if there is a certain input threshold beyond which the magnetosphere can no longer remain balanced.

Finally, some magnetic storms have been found to occur during SMC intervals [Sergeev et al., 1996a; Zhou et al., 2003; Tsurutani et al., 2004]. Although such storms have been identified, it is not known how quasi-stable convection affects the storm-time radiation belts and relativistic particle energization. We have shown that statistically, fast flows are diverted away from the inner magnetosphere during SMC, potentially robbing this region of seed electrons that are thought to lead to enhancements in relativistic electron flux [Horne and Thorne, 1998; Bortnik and Thorne, 2007]. An association between storms and SMCs might explain why some
storms do not result in relativistic electron flux enhancements [Reeves et al., 2003]. A survey of the effects of SMC on storms and whether or not SMCs help or hinder energetic particle acceleration in the radiation belts would be especially timely in the next several years due to the good magnetotail coverage from THEMIS and the upcoming Radiation Belt Storm Probes (RBSP) mission.

6.5. Final summary

The usual magnetospheric response to southward solar wind IMF is a substorm. We have shown that, except for rare cases, the stable SMC mode of response occurs only after this instable substorm mode has occurred. The near-Earth neutral line during the substorm expansion phase preconditions the magnetosphere toward high inner magnetosphere pressure during SMC events, causing diversion of fast flows toward the tail flanks and back to the dayside. The enhanced pressure causes the nightside x-line to partially retreat, but it remains somewhere in the near- to midtail region and continues to drive convection. Enhanced and steady solar wind driving ($E_s$) continues to open flux during SMCs, which the nightside x-line in turn closes. In this manner, the magnetosphere system can remain for hours in the steady magnetospheric convection mode.
APPENDIX A

Magnetotail and Aurora During a Typical SMC

We present an example of an SMC event that highlights many of the behaviors evident from our statistical description in Chapter 4. This event is the same SMC presented in Chapter 5 as a 'typical' case. Here we go into greater detail about the observations from the THEMIS satellites and All-Sky Imagers (ASIs) during this SMC.

The 2.83-hour-long SMC was strong (average AL -600 nT, average AE 800 nT) and was both preceded and concluded by substorm onsets. The solar wind (presented in Figure 5.5) was steadily changing over the interval before and during the SMC. The solar wind speed increased and, except for a few northward data points, the IMF B_z became more negative throughout the event. The corresponding E_y was therefore also increasing, from ~3 mV/m at the start of the SMC to ~8 mV/m at its end.

The THEMIS satellites were aligned on the duskward side of the magnetotail (Y_GSM ~5-7 R_E), with THEMIS B farthest from the Earth (|X_GSM| ~ 20 R_E), then THEMIS C (|X_GSM| ~ 16 R_E), with THEMIS D and E closest (|X_GSM| ~ 10 R_E and ~9 R_E respectively).

Figure A.1 shows the magnetic field and plasma parameters recorded by THEMIS B. From top to bottom, we plot: magnetic field components in GSM, total magnetic field, velocity components perpendicular to the magnetic field, the total speed in the GSM equatorial plane (V⊥x-y), the magnetic flux transport rate (V⊥x-y*B_z), ion density, ion temperature, total pressure and its components (plasma and magnetic pressures), and the beta parameter (β, plasma pressure divided by magnetic pressure). The start and stop times of the SMC are marked with dashed vertical lines. In the two hours before the SMC, THEMIS B is in the lobe (large B_x, small B_z, low beta). The total pressure steadily grows during this time, indicating loading of the
Figure A.1. THEMIS B magnetic and plasma conditions during a typical SMC.
magnetotail. Around the time of the substorm onset (~0140 UT), a flow enhancement is observed along with a slight reduction in total pressure. Around the start time of the SMC, more fast flows ($V_{\perp x-y} > 200$ km/s) directed Earthward (positive $V_x$) and dawnward (negative $V_y$) are observed, carrying enhanced magnetic flux. After the SMC begins, the satellite enters the plasma sheet (identified when $\beta > 0.5$) and observes many fast Earthward flows with enhanced magnetic flux levels (up to 12 mV/m) throughout the entire SMC. The first 'set' of flows are accompanied by a reduction in the total pressure. Two later flow bursts (just before 0400 UT and ~0420 UT) are associated with large dipolarizations in $B_z$ (and therefore large flux transport levels). These flows also have strong flankward ($V_y$) components. For most of the SMC, the density and temperature remain fairly constant. The average temperature (6 keV) and density (0.35 cm$^{-3}$) are in fairly good agreement with the statistical values in this portion of the tail (7 keV and 0.2 cm$^{-3}$). The total pressure tends to slowly increase over the interval, and the average observed total pressure (0.53 nPa) is larger than the statistical value of 0.3 nPa. The end of the SMC coincides with the peak total pressure, which decreases in the ensuing substorm.

THEMIS C, located at $|X_{GSM}| \sim 16$ RE observes similar behavior to THEMIS B. Figure A.2 shows the magnetic and plasma conditions at THEMIS C in the same manner as Figure A.1. Before the SMC, the spacecraft is also in the north lobe. At the time of the substorm onset, when THEMIS B observes only a small flow enhancement and brief magnetic field changes (~0140 UT), THEMIS C suddenly enters the plasma sheet and observes many fast Earthward flows carrying large amounts of magnetic flux. These flows continue through the beginning of the SMC and occur at the same time as the first set of fast Earthward flows observed at THEMIS B, though THEMIS C observes both tailward and Earthward components. The fast flows during the SMC carry similar or even more amounts of magnetic flux compared to those during the
Figure A.2. THEMIS C magnetic and plasma conditions during a typical SMC.
substorm. In agreement with the observations by THEMIS B, the magnetotail settles down and no fast flows are seen for around an hour, until two fast Earthward flows are observed at ~0400 UT and ~0420 UT. Again, these two flow bursts are associated with $B_z$ dipolarizations and thus enhanced magnetic flux transport levels. The density and temperature remain stable after the start of the SMC, though the average values (0.44 cm$^{-3}$ and 6.0 keV) differ slightly from the statistical levels (0.28 cm$^{-3}$ and 8.5 keV). However, the total pressure is level for most of the SMC (average of 0.73 nPa) and higher than the statistical level (0.48 nPa). The total pressure increases during the second half of the SMC, and the peak is reached at or just after the end of the SMC, when it reduces due to the concluding substorm. Except for slight differences, the behavior at THEMIS C is in good agreement with THEMIS B. The one significant difference is the fast Earthward flows and $B_z$ enhancement/$B_x$ reduction seen by THEMIS C during the substorm onset.

The final two THEMIS spacecraft, D and E, are located close to each other in $X_{GSM}$ and $Y_{GSM}$ (D $\sim$ (-10 $R_E$, 5.8 $R_E$); E $\sim$(-9 $R_E$, 6.3 $R_E$)). They are located in the inner magnetosphere region (identified in Chapter 4 as radial distance $\rho < 15 R_E$). Figures A.3 and A.4 show magnetic field and plasma conditions observed at D and E, respectively. Both spacecraft are in the outer or inner plasma sheet for the entire interval. At the preceding substorm onset and around the same time as the flow enhancements at B and C, both D and E observe fast Earthward flow bursts, carrying enhanced magnetic flux up to 4 mV/m. These flow bursts seem to enhance the previously-level total pressure. The total pressure observed by D and E increases until the SMC starts, after which it remains level for most of the SMC. Once the SMC begins, only one fast flow is observed by both THEMIS D and E. There are several flow enhancements that exceed 100 km/s, occurring around the same time as the fast Earthward flow set seen in the tail region by THEMIS B and C. These flows are faster at THEMIS D (farther out in $X_{GSM}$) than THEMIS
Figure A.3. THEMIS D magnetic and plasma conditions during a typical SMC.
Figure A.4. THEMIS E magnetic and plasma conditions during a typical SMC.
E. This suggests that the fast flows have been slowed below our 200 km/s threshold by the time they reach THEMIS D and continue to be slowed as they reach THEMIS E in the inner magnetosphere region. Additionally, the flows have flankward components comparable to the Earthward components, and the $V_x$ component alternates between Earthward and tailward. They also carry a large amount of Earthward magnetic flux (~2-3 mV/m). In the remainder of the event, the total speed fluctuates up and down with some regularity on the order of ~7-8 minutes.

At the start of the SMC, density decreases and temperature increases, and remains fairly level after that. In this region, the average measured density, temperature, and total pressure are all larger than the levels found from our statistics. In particular the average total pressure is 1.8 nPa at THEMIS D and 2.0 nPa at THEMIS E, both larger than the statistical levels for this region of 0.8 nPa. The total pressure increases during the substorm expansion and then remains mostly steady at both THEMIS D and E until the last hour of the SMC, when it increases again. As seen at the outer two spacecraft, the total pressure peak nearly coincides with the end of the SMC and the concluding substorm onset.

Complementing the satellite data, 14 THEMIS ASI white-light cameras observed the aurora during this SMC event. The behavior of the aurora was briefly summarized in Chapter 5. Substorm onset occurs at ~0143 UT. During the SMC there are two different auroral regions: a bright, stable, diffuse equatorward arc and an active poleward region with many poleward boundary intensifications (PBIs), arcs, and streamers. The poleward aurora is particularly active from ~0230-0300 UT, the same time range in which the four THEMIS spacecraft observed a set of fast flow bursts and enhanced magnetic flux transport levels. Figure A.5 shows mosaics of the auroral images from 0230-0235 UT. While the equatorward diffuse arc remains stable, a prominent eddy forms at around 70° geographic latitude. After 0235 UT the eddy loses cohesion
Figure A.5. THEMIS ASI mosaic images from 0230-0235 UT during a typical SMC.

and several auroral streamers are formed. These can be seen in Figure A.6, which shows mosaic images from 0240-0247 UT. In place of the eddy, a roughly north-south aligned streamer has formed, which brightens and extends down to contact the equatorward auroral region at 0245 UT. The streamer extends over ten degrees of geographic latitude for several minutes. The equatorward portion of the aurora brightens where it connects with the streamer. In the last panel of Figure A.6, an auroral loop begins to form to the west of the streamer. The development of this loop can be observed in images covering 0249-0256 UT in Figure A.7. This loop brightens
Figure A.6. THEMIS ASI mosaic images from 0240-0247 UT during a typical SMC.
Figure A.7. THEMIS ASI mosaic images from 0249-0256 UT during a typical SMC.
over a couple minutes, then rotates westward and fades away by 0256 UT. We can also see that the original streamer from Figure A.6 fades away, and two more north-south streamers form and move equatorward to contact the lower portion of the oval.

After this point, from 0300 UT until 0355 UT, the aurora is relatively stable. Several poleward arcs brighten at this time and rotate into north-south streamers, but they are brief and do not continue down to the equatorward aurora. This corresponds with the stable magnetotail observed by the THEMIS spacecraft.

At 0355 UT, the aurora becomes more active, in association with satellite observations of more fast flows in the tail. For the remainder of the SMC event, multiple eddies, arcs, and streamers form and dissipate over the span of several minutes. Figure A.8 shows a sequence of auroral image mosaics from 0414-0421 UT in which two prominent eddies form in the westward imagers. These forms only last <5 minutes before they dissipate. The westward eddy moves further westward as it dissipates, while an arc brightens poleward of the eastward eddy and becomes a roughly north-south streamer by the last panel. In Figure A.9, we can see the formation of multiple streamers and their effect on the equatorward portion of the aurora from 0426-0433 UT. Two bright, prominent streamers form in the middle of the mosaic images and extend equatorward to feed into the equatorward arc. The arc brightens upon contact, and the streamers form auroral torches that thicken and move toward the east. These torches or omega bands can be seen in the last four panels of Figure A.9, as well as Figure A.10, which shows the last minutes of the SMC from 0459-0506 UT. One omega band forms from the equatorward arc in the eastern most imager over this time, with a coherent structure by the end of the SMC. A second torch/omega band is fed by somewhat diffuse streamers (compared to those in previous figures) and drifts eastward. Additional thin streamers can be observed with a lifetime of several
Figure A.8. THEMIS ASI mosaic images from 0414-0421 UT during a typical SMC.
Figure A.9. THEMIS ASI mosaic images from 0426-0433 UT during a typical SMC.
Figure A.10. THEMIS ASI mosaic images from 0459-0506 UT during a typical SMC.
minutes. After the SMC, another substorm onset occurs (see AL index for this event in Figure 5.5), and the equatorward arc thins from its previous diffuse and latitudinally-wide state (not shown). This corresponds with the total pressure decrease observed by the THEMIS D and E satellites in the inner magnetosphere.

While this appendix only details the magnetotail conditions and aurora behavior for one SMC event, we emphasize that such observations as we describe are common during SMC events. We chose to present this case since it had ideal multi-spacecraft coverage at different radial distances and good imaging of the auroral oval without any obscuring clouds. Other events were examined alongside this case and all of the signatures of fast flows, total pressure, and auroral activity for this SMC were observed in many events with similar coverage. The statistical conclusions from this dissertation describe well the general behavior of the magnetosphere during steady magnetospheric convection.
BIBLIOGRAPHY


