Comparative statistical analysis of storm time activations and sawtooth events

T. I. Pulkkinen,1,2 N. Partamies,3 R. L. McPherron,4 M. Henderson,1 G. D. Reeves,1 M. F. Thomsen,1 and H. J. Singer5

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[1] Statistical properties of storm time magnetospheric activity are examined using superposed epoch analysis. We show that about half of storm time auroral electrojet activations have signatures that are typical of nonstorm substorms, including geostationary orbit injections and magnetic field dipolarizations. Analysis of a separate data set of sawtooth events shows that they have auroral and inner magnetosphere characteristics that are quite similar to those found generally during storm time activity. Hence it is concluded that the sawtooth events do not represent a specific class of magnetospheric activity. Examination of the solar wind and IMF properties showed that about 30% of storm time substorm-like activations and about 20% of the sawtooth oscillations have associated solar wind or IMF triggers and that triggering is more likely during high solar wind pressure and fluctuating IMF. The solar wind-magnetosphere coupling efficiency is shown to be independent of the solar wind Mach number or level of IMF fluctuations but dependent on the level of driving; when $E_y$ is small, the ionospheric dissipation, ring current intensification, and geostationary field stretching are relatively larger than when the driving $E_y$ is large.


1. Introduction

[2] During magnetic storms the magnetospheric activity is highly complex and the magnetosphere and ionosphere host a variety of activations and dynamic changes that sometimes resemble those found during isolated substorms, while at other times they do not [Pulkkinen et al., 2002, 2004]. The dynamic changes may occur at such rapid succession that identification of individual substorms or injection/dipolarization processes in the tail is very difficult [Reeves and Henderson, 2001]. However, the tail may also enter a quasi-static steady convection state that may last for hours in spite of the enhanced driving [Sergeev et al., 1996].

[3] Owing to the complexity of the storm time magnetospheric activity, there are relatively few studies of the detailed characteristics of the tail and ionospheric processes during magnetic storms. Pulkkinen et al. [2002, 2004] examined auroral electrojet activations during five storm main phases and concluded that not all activations identified from ground magnetometer data corresponded to tail signatures typically associated with substorms. They asserted that there are several distinct types of storm time active events of which only part resemble nonstorm substorms.

[4] Sawtooth events are large-amplitude oscillations of energetic particle fluxes and the magnetic field at geostationary orbit recurring with a period of about 2–4 hours [Belian et al., 1995; Reeves et al., 2004]. These quasi-periodic injections in the particles were originally identified as a separate class of events due to their striking periodicity and the fact that they are often seen nearly simultaneously over a wide region of local times [Henderson et al., 2006]. During these events, the cross-tail current is often close to the Earth and strong, and the partial ring current is strong enough to cause the dusk sector magnetic field to become highly stretched [Pulkkinen et al., 2006a, 2006b]. Recent studies have suggested that rather than a distinct class of activity, the sawtooth events are a subset of large, recurrent substorms [Borovsky et al., 1993; Huang et al., 2003; Henderson et al., 2006; Partamies et al., 2006].

[5] There is some controversy about the driver of the sawtooth oscillations, not unlike the discussion regarding isolated substorm onsets. For example, Lee et al. [2004] argue that each sawtooth in the sequence is triggered by a solar wind pressure pulse, while others claim that the sawtooth oscillation timings arise from dynamics internal to the magnetosphere [e.g., Huang et al., 2003; Henderson et al., 2006]. Furthermore, as pointed out by Henderson [2004], some sawtooth events have been previously analyzed...
as substorms. It also seems that the quasi-periodic 3-hour recurrence interval is similar whether the IMF structure includes modulation at that period [Slavin et al., 1992] or is continuously southward [Huang et al., 2003].

[A] A key feature of the storm evolution is the formation of an intense ring current in the inner magnetosphere. However, the role of substorms or substorm-like activations in the storm development and in the ring current intensification and decay is still an open issue [McPherron, 1997]. While some researchers have argued that convection alone can account for the ring current enhancement [Fok et al., 1996], others have concluded that substorm-like time-dependent and mesoscale variations are necessary for the acceleration of the ring current to the observed energies exceeding 100 keV [Ganushkina et al., 2005].

[7] Largely based on ground magnetic observations, it is generally assumed that the ring current consists of a symmetric part (quantified by the Dst or SYM-H indices) and an asymmetric part maximizing in the evening sector (quantified by the ASY-H index). This view is further supported by the high-energy ion drift paths that carry the majority of the ring current; as they convect inward from the plasma sheet, they are adiabatically energized and start drifting duskward in the quasi-dipolar magnetic field. However, recent energetic neutral atom observations from the IMAGE satellite [Brandt et al., 2002] found a peak intensity in the imager energy range in the postmidnight sector. While the formation mechanism has not been conclusively pinned down, it is most likely a result of the interplay of convection and magnetic drifts in this intermediate energy range.

[S] The energy driving magnetospheric activity comes from the solar wind. The energy flow from the solar wind into the magnetosphere-ionosphere system is dominantly controlled by the direction and magnitude of the interplanetary magnetic field (IMF) and to lesser extent governed by the solar wind velocity and pressure [Akasofu, 1981]. Enhanced dayside reconnection during times when the IMF has a southward component increases convection in the ionosphere and causes structural changes in the magnetotail, often leading to a substorm [Baker et al., 1996]. While the overall driving of the solar wind and IMF is widely accepted, it is still an open question to what extent, e.g., substorm onsets or other dynamic events in the magnetosphere are directly driven by variations in the IMF and solar wind parameters [Lyons et al., 2003]. This is especially true for storm-associated activity, when, e.g., the sawtooth oscillations and steady convection periods can be driven by qualitatively similar drivers but are associated with vastly different magnetotail dynamics.

[9] While the average convection speed in the magnetotail is a fraction of the solar wind electric field imposed on the magnetosphere, at any given time and location the convection is bursty and the mean velocity is small compared to the distribution of observed particle velocities [Angelopoulos et al., 1992]. Thus characterizing periods as steady convection events does not necessarily mean that the plasma flow in the magnetotail would be laminar and steady but that, averaged over the tail cross section, the amount of plasma and flux transport does not vary over time scales of several hours [Sergeev et al., 1996]. The characteristics that discern the steady convection periods from, e.g., substorm growth or expansion phases is the frequency and amplitude of the bursts, not necessarily the characteristics of the individual bursts as observed by single spacecraft [Tanskanen et al., 2005].

[10] The prototypical substorm, defined for the most part by observations during nonstorm substorms, consists of a growth phase, expansion phase, and recovery phase [Baker et al., 1996]. The growth phase is a slow reconfiguration initiated by the onset of enhanced dayside reconnection, and its signatures are increased convection in the ionosphere, formation of a thin current sheet embedded in the inner and midtail plasma sheet, and often (but not always) increase of the amount of open magnetic flux in the tail lobes [Dmitreva et al., 2004]. At substorm onset, a rapid reconfiguration takes place during which the auroral bulge is formed and expands poleward, energetic particles are injected to the inner magnetosphere, and fast flows eject plasma and magnetic flux in the form of a plasmoid or a flux rope in the antisunward direction. During any given substorm, many of these signatures may not occur or may not be observable with the few measurement points we have available, and there is no accepted definition of what is the required minimum set of observations to call an active event in the magnetosphere a substorm.

[11] During storms, the magnetosphere is strongly driven, and dynamic events follow in rapid succession. The purpose of this paper is to examine these dynamic events, here called “activations” to emphasize the fact that we are not claiming that all or any of these activations are “substorms” as defined based on non-storm-time observations. We consider observations in the solar wind, in the inner magnetosphere, and in the ionosphere. We take “typical substorm signatures” to be (1) an injection at geostationary orbit, (2) a dipolarization of the inner magnetotail field, and (3) a rapid enhancement of the westward electrojet in the auroral ionosphere. While auroral observations are often used to time substorm onsets, those data were not included in this study and hence are not part of our definition. Section 2 describes the data sets and analysis methods. In sections 3 and 4 we present a statistical analysis of storm time activations. Section 5 presents a similar statistical analysis of sawtooth events and compares those results with a subset of the storm time activation statistics showing similar characteristics. Section 6 discusses the effects of solar wind and/or IMF triggering, and section 7 discusses the effects of solar wind properties on the magnetospheric activity. Sections 8 and 9 end with discussion and conclusions.

2. Data Sets and Analysis Method

[12] In order to statistically examine the storm time magnetic activations, storms exceeding Dst = −75 nT during the year 2004 were examined. For each storm, ground magnetic records from the Scandinavian sector IMAGE [Viljanen and Hakkinen, 1997] and Canadian sector CARISMA [Rostoker et al., 1995] were visually examined to identify rapid electrojet enhancements exceeding about 200 nT. These chains are latitudinally extended, but cover only a limited portion of longitudes. Thus the event selection was limited to those where one or the other chain was in the night sector. This analysis produced a list of 150 activations, tagged with onset times defined from the
Table 1. Storms Included in Statistics

<table>
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<td>11</td>
<td>10</td>
<td>1100</td>
<td>289</td>
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*Day and hour of minimum Dst and the value of minimum Dst are based on preliminary provisional Dst data from the World Data Center C2 in Kyoto.*

ground magnetic records. The list of storms included in the study is shown in Table 1. For easy comparison of the events with one another, a quasi-AL index was created from the longitudinally limited magnetometer chains [Kauristie et al., 1996].

[13] In order to characterize the ring current dynamics, the SYM-H and ASY-H indices obtained from the World Data Center in Kyoto were examined at 1-min temporal resolution. These indices are computed as weighted averages (SYM-H) and maximum differences (ASY-H) of 4–6 longitudinally distributed midlatitude stations [Yermolaev, 1990; Sugirara and Kamei, 1991]. SYM-H and ASY-H can be used as proxies of the symmetric and asymmetric parts of the inner magnetosphere ring current, respectively, although both indices are sensitive also to other current systems such as the tail current, the magnetopause current, field-aligned currents, and currents induced within the conducting Earth [Turner et al., 2000].

[14] The Los Alamos Synchronous Orbit Particle Analyzer (SOPA) data from the geostationary satellites 1990–095, 1991–080, 1994–084, LANL-97A, LANL-01A, and LANL-02A [Belian et al., 1992] were used to examine the energetic (50–350 keV) electron flux enhancements and injections. An onset was judged to have an energetic electron injection associated with it if the 30-min average of differential energy flux in the lowest-energy channel (50–75 keV) before the onset was a factor of 2 lower than the 30-min average after the onset. While this method does not guarantee that the flux levels after the injection are higher than those prior to the growth phase, visual examination showed it to be a quite robust method for picking up the onset-associated injections.

[15] The Magnetospheric Plasma Analyzer (MPA) data [Bame et al., 1993] on board the same satellites were used to derive the magnetic field inclination at geostationary orbit. The field inclinations were inferred from the pitch angle distribution symmetry properties for electrons in the energy range 0.03–40 keV. In case the ion distribution showed stronger anisotropy, the ion data in the energy range 0.1–40 keV were used for the anisotropy determination [Thomsen et al., 1996]. Furthermore, the GOES-9, GOES-10, and GOES-12 magnetic field observations [Singer et al., 1996] were also used. In this study we examine the field inclination angle in solar magnetic (SM) coordinates, in which the Z axis is aligned with the dipole axis (positive northward), X axis is contained in the plane defined by the dipole axis and the Sun-Earth line, and Y completes a right-handed triad. This coordinate system was selected to remove effects that arise from the dipole tilt variations associated with different seasons and universal times. Both data sets are combined in one in our studies to get the best local time coverage for each individual event.

[16] The use of multiple geostationary satellites made it possible to examine activity in different local time sectors. For that purpose, the magnetospheric data were binned to five local time sector bins: prenoon (0600–1200 MLT), afternoon (1200–1800 MLT), evening (1800–2200 MLT), midnight (2200–0200 MLT), and morning (0200–0600 MLT). In binning geosynchronous data to the different local time bins, data from one spacecraft for a particular event is included only in one local time bin based on the onset time, even though the satellite moves during the 6 hours of the epoch time. Therefore the superposed epoch results for the geostationary satellite data reflect to some extent also the motion of the spacecraft.

[17] Finally, the ACE magnetic field [Smith et al., 1998] and solar wind [McComas et al., 1998] data were used to characterize the driver conditions for these events. In addition to the interplanetary magnetic field components \( B_x, B_y, B_z \) in GSM coordinates we examine the solar wind speed \( V \), density \( n \), dynamic pressure \( p \), the Alfvénic Mach number \( M_A \), the solar wind electric field \( E_y = -VB_z \), and the \( \epsilon \) parameter. The Alfvénic Mach number is defined as

\[
M_A = V/V_A = \frac{V}{B} \sqrt{\rho/\mu_0},
\]

where the Alfvén speed is \( V_A = B/\sqrt{\rho/\mu_0} \), \( \rho \) is the mass density, \( B \) is the IMF magnitude, and \( \mu_0 \) is the vacuum permeability. The \( \epsilon \) parameter is given by

\[
\epsilon = 4\pi V B^2 l_0^2 \sin^4 (\theta/2)
\]

where \( l_0 = 7 R_E \) is an empirical scaling parameter and \( \tan(\theta) = B_y/B_z \) defines the IMF clock angle [Perreault and Akasofu, 1978; Akasofu, 1981]. The solar wind measurements were propagated to the dayside magnetopause using the \( X \)-distance of the satellite and the average solar wind speed during the interval.

[18] The effects of the IMF fluctuations were estimated by computing two measures of solar wind turbulence given by [Borovsky and Funsten, 2003]

\[
\delta B = \sqrt{\sigma_{Bx}^2 + \sigma_{By}^2 + \sigma_{Bz}^2},
\]

\[
\frac{\delta B}{B} = \sqrt{\sigma_{Bx}^2 + \sigma_{By}^2 + \sigma_{Bz}^2}/(\langle B \rangle)
\]

where the standard deviations (\( \sigma \)) and average magnetic field magnitudes (\( \langle B \rangle \)) are computed over the entire epoch time. These fluctuations are evaluated from the 64-s ACE data and thus do not include the high-frequency component that one would obtain using full resolution data. However, we assume that the lower-frequency variations dominate the magnetospheric coupling processes.
In order to extract the general characteristics of the storm time activations, a superposed epoch analysis was performed using the ground onset time as zero epoch. For each activation, a period of 3 hours before and after the ground onset was considered, and medians were evaluated at 1-min temporal resolution for the geostationary data, SYM-H and ASY-H indices, at 64-s resolution for the ACE data, and at 10-s resolution for the auroral electrojet indices. In the following, we will examine the full data set as well as separate the data set into subsets with various characteristics at geostationary orbit.

3. Storm Time Activations

Figures 1, 2, and 3 show a summary of the solar wind and IMF parameters, the magnetospheric indices, and the magnetotail observations for the full data set of 150 activations (thin line with shading) together with a subset of events which were associated with nightside (1800–0600 MLT) geostationary orbit energetic electron injection (thick line). The superposed epoch curves were computed as medians of the quantities.

[21] It was found that about half (71 events) of the ground onsets could be identified with simultaneous energetic particle injections, and about two thirds of the events (101 events) showed simultaneous magnetic field dipolarizations. Because of the rapidly recurring onsets, the time delays allowed for these to occur were limited to ±30 min; thus events may have been misidentified as not having an injection or dipolarization due to errors caused by delays associated with particle drift times and/or substorm current wedge expansion times in the tail. For the same reason, the energetic particle injection study was limited to the rapidly drifting electrons.

[22] Almost half of the events (68 events) showed a distinct decrease in the geosynchronous satellite field inclination measurements (field inclination less than 40°) prior to the onset. These events were interpreted to be associated with an intensifying cross-tail current near or slightly
associated with a tailward of geostationary orbit. Furthermore, in a substantial part of these events the magnetic field stretching extended from the night sector toward the evening and/or morning sectors, implying that the cross-tail current was sufficiently close to the Earth to be partially colocated with the ring current.

The driver properties (Figure 1) show typical storm time conditions: southward field, enhanced field magnitude, and slightly enhanced solar wind density for those events that showed geostationary orbit injections. The data also hint that solar wind and IMF triggers may be present, as there is a small increase in pressure at the time of the onset as well as a maximum in both the $\epsilon$ and $E_Y$ associated with a northward turning of the IMF $B_Z$.

Not surprisingly, the geostationary orbit field stretching and dipolarization (Figure 2) is much clearer for the subset showing the injections. The dipolarization is clear in the midnight and evening sectors and shows as a slight increase at the onset time also in the morning sector; the dayside data do not show changes in the field inclination associated with the onsets. On the other hand, the evening and night sector fields show only weak signatures of the substorm growth phase, the decreasing trend in the evening sector data is in part due to the motion of the spacecraft toward midnight and lower inclination values. (As the subset showing the injections is not identical to the subset showing growth phase signatures, the morning and evening sector growth phase signatures are averaged out from this data set). Furthermore, the ionospheric currents do not show growth phase-associated enhancement; the AL index even recovers slightly during the hour prior to the onset. On the other hand, as all these events were observed in the middle of a storm, the magnetic activity level both before and after the activations was already at much higher level than during nonstorm times. This is caused by the solar wind electric field driving the ionospheric electrojet currents. The symmetric ring current index shows a slight flattening of the negative trend of the index, whereas there is a clear positive signature in the asymmetric ASY-H index.

The electron fluxes (Figure 3) for the data set having injections show a clear decrease in the fluxes during the hour preceding the onset and an increase of the fluxes at zero epoch time. The injections were observed at all local times almost simultaneously but with a discernible dispersion from the nightside toward dayside. The injections are especially clear in the midnight and dawn sectors and qualitatively resemble those found during isolated substorms, maybe with the exception of the rapid drift times and therefore near-simultaneous response in multiple local time sectors.

Both the field inclination and the electron fluxes recover within 1.5–2 hour of the onset, which is slightly faster than typically found during isolated substorms [Pulkkinen et al., 1994]. Furthermore, both data sets show, in multiple local time sectors, an indication of a 2–3-hour periodicity in the magnetospheric activity. Both before and after the zero-epoch time, the flux and field inclination variations indicate a prior and subsequent activation.

4. Evening and Morning Sector Activity

The field stretching at geosynchronous orbit is not always symmetric with respect to the midnight meridian: sometimes the stretching is strongest in the evening sector, at other times smallest field inclination values (most stretching) was observed in the morning sector. Figures 4 and 5 show the superposed epoch results for two subsets of onsets, those that had field inclination less than 40° in the local time sector 0200–0600 MLT (red line) and those that had field inclination less than 40° in the local time sector 1800–2200 MLT (blue line). Note that both data sets contain a few events where the field was stretched over the entire night sector.

The driver characteristics (Figure 4) are not very different for these events, although the driving electric field is slightly larger for the morning sector stretching events, which can be deduced from the large velocity and more negative $B_Z$. Maybe surprisingly, there is no IMF $B_Y$-dependence characterizing where the strongest stretching occurs; the average $B_Y$ was close to zero for both sets of events. The morning sector stretching events were characterized by a higher solar wind speed, which, however, was associated with a slightly lower solar wind density, which
led to almost identical solar wind pressure values (not shown). Also the Mach numbers for the two subsets of events were quite similar (not shown).

[29] The midnight sector field inclination (Figure 5c) is slightly larger for the cases where the field is stretched in the evening sector, while the minimum field inclination in the dusk sector is slightly smaller than that for the morning sector. The morning sector stretching events are associated with more intense storm activity as shown by the larger SYM-H index. Furthermore, these events show a clear positive excursion of the SYM-H index at onset, which is not seen in the dusk-sector stretching events or in the full data set. There are no marked differences between either the ring current asymmetry (ASY-H indices) or auroral activity (AL indices) either between these two data sets or with these as compared to the full data set.

5. Sawtooth Events

[30] In this section we examine a data set of 138 individual sawtooth oscillations recorded in the time period from beginning of 1999 to the end of 2002 and compare the results with the other types of storm time activations. The sawtooth events were selected based on visual examination of geosynchronous energetic electron and proton measurements and by requiring that successive, relatively dispersionless injections were observed by multiple satellites at different magnetic local times. Differently from the storm time activation event data set, the sawtooth events were timed based on the proton injection times. Figure 6 shows the solar wind and IMF observations in a format similar to Figure 1. Comparison of the two data sets shows that the sawtooth oscillations are associated with quite a similar level of driving, with $E_y \sim 3-4$ mV/m and IMF $B_z$ slightly below $-5$ nT. On the other hand, the solar wind speed during the sawtooth oscillations is substantially lower (by more than 100 km/s) than during other storm time activations, the density is higher than for the full data set (although similar to the data set having geostationary orbit injections), and the Alfvén Mach number is slightly lower. Furthermore, the indications of the solar wind pressure trigger and IMF northward turnings as onset triggers present in the storm time activation data set are not visible in the sawtooth event data set.

[31] The magnetic field inclination for the sawtooth events (Figure 7) shows quite similar behavior to the subset of events where the evening sector field inclination was chosen to be below 40°: Stretching in the evening and midnight sectors, and less so in the morning sector. Comparison of the magnetic indices shows that the sawtooth events are associated with slightly less auroral activity (AL index) but quite similar level of ring current enhancement (Dst or SYM-H index). However, in this case the SYM-H index shows a response at injection onset, while there is no
Finally, the geostationary orbit injections (Figure 8) are strong and show clearer signatures of the growth-phase associated dropout than is evident in the subset consisting of events with evening sector field inclination below 40°. This is partly a consequence of the selection criterion: the sawtooth oscillations were timed based on the geosynchronous orbit particle data, whereas the storm time activations were timed based on ground magnetic indices. However, if the storm time activation data set is further limited to very high degree of geostationary orbit stretching, the dropouts associated with the growth phase become clear in the nightside magnetotail (not shown). The 2–3 hour periodicity is also evident in the set of sawtooth oscillations, similar to that found in the storm time activation data set (the fluxes begin to increase after about 2 hours of the zero epoch in the midnight sector data, while the signatures are less clear in other local time sectors).

6. Effects of Triggering

[33] In order to examine the effects of solar wind and/or IMF triggers on the storm time activations and sawtooth oscillations, the events that had plausible triggers were analyzed separately. The events were judged to have a trigger if the IMF B_Z changed by at least 3 nT or the solar wind dynamic pressure changed by more than 1 nPa from 30 min prior to the zero epoch time to 30 min after the zero epoch time. Thirty-minute averages were used to eliminate effects of timing errors either related to the onset on ground and in the magnetosphere or related to the solar wind travel time from the satellite location to the subsolar magnetopause. Furthermore, the triggering criteria were selected to be simple enough that they could be derived for a large number of events without the need to analyze each event individually. The same triggering criteria outlined above"
were applied to both the storm time activation and sawtooth oscillation data sets.

Figure 9 shows a composite of the results for the triggered events identified from the storm time activation data set (44 events, shown with red line) and for the sawtooth event data set (138 events, shown with blue line). Both data sets show a clear northward turning of the IMF $B_Z$ around the onset time as well as a pressure enhancement. Other than that, the only change in the average solar wind and IMF properties was that the solar wind pressure, as well as velocity and density (not shown) were larger than for the full data sets. Thus triggering seems to be more likely during conditions when the solar wind compression on the magnetosphere is stronger. Furthermore, the numbers of events show that 30% of the storm time activations have associated triggers, while only 20% of the sawtooth oscillations have associated triggers. Thus triggering is not favored under conditions that produces the sawtooth oscillations.

Figure 8. Superposed epoch analysis results for the geostationary orbit energetic electron fluxes in the range 50–350 keV in units of $1/cm^2/s/sr/keV$ for a subset of storm time activations with evening sector field inclination $< 40^\circ$ (59 events, left) and for the sawtooth event data set (138 events, right). (a) Energetic electron fluxes for storm time activations in the (a) 1800–2200 MLT, (b) 2200–0200 MLT, (c) 0600–1200 MLT, and for sawtooth events for (d) 1800–2200 MLT, (e) 2200–0200 MLT, (f) 0600–1200 MLT.

Figure 9. Superposed epoch analysis results for the triggered events from the storm time activation data set (44 events, red line) and from the sawtooth event data set (27 events, blue line). (a) IMF $B_z$, (b) solar wind dynamic pressure; Geostationary orbit field inclination in degrees for (b) 1800–2200 MLT and (f) 2200–0200 MLT; Geostationary orbit energetic electron flux (50–350 keV) in units of $1/cm^2/s/sr/keV$ for (c) 1800–2200 MLT and (g) for 2200–0200 MLT; (d) AL index and (h) SYM-H index.
however, there is a clear field signature in the evening sector, which would imply that the current systems in that local time sector are affected by the injection process.

7. Effects of IMF and Solar Wind Characteristics

[36] The IMF fluctuations were examined by evaluating the standard deviations of the IMF components using the 64-s data. Both measures of turbulence are somewhat lower for the sawtooth events than for the full set of storm time activations ($\sigma B = 3.7$ nT and $4.3$ nT; $\sigma B/\langle B \rangle = 0.5$ and 0.8, respectively). This would imply that the sawtooth events are associated with a more steady driver than other types of storm time activations. The numbers for the storm time activation subset having night sector injections are very similar to those for the full data set.

[37] On the other hand, the triggered events show markedly larger fluctuations with $\sigma B = 6.3$ nT and $6.7$ nT and $\sigma B/\langle B \rangle = 1.3$ and 1.2, for the triggered storm time activations and sawtooth injections, respectively. This indicates that the triggered events occur during periods when there are plenty of fluctuations in the IMF parameters and therefore also numerous candidates for possible triggers.

[38] The Alfvén Mach numbers for the storm time activations averaged about 5 before the activation and about 6 following the activation. For the sawtooth events, the Mach numbers were slightly above 4 before the activation. Analysis of the individual events show that the sawtooth event data set has only very few high Mach number events, whereas the high Mach number tail in the storm time activation data set is much larger. However, both of these numbers are below average solar wind properties, where the Alfvén velocity is of the order of 50 km/s and hence the Mach numbers typically approaching 10.

[39] We further examined events that had low Mach number ($M_A < 4$) and high Mach number ($M_A > 8$) in the impinging solar wind. As the Mach number is largely controlled by the IMF magnitude, this divided the data set effectively to low-$E_Y$ and high-$E_Y$ events. Therefore we limited the $E_Y$-values to below 4 mV/m (but larger than 0) to get a more equal level of driving for the high-Mach number and low-Mach number event sets. When the driving levels are comparable, also the magnetospheric and ionospheric properties were almost identical, indicating that the level of activity both in the ionosphere and in the inner magnetosphere is independent of the Alfvén Mach number in the solar wind.

[40] Dividing the data set to low and high level of fluctuations again separated the data set to low-$E_Y$ and high-$E_Y$ sets, indicating that stronger fluctuations are associated with a stronger driver. Limiting the $E_Y$-values between 0 and 4 mV/m yielded almost identical results in the ionosphere, but slightly stronger stretching and clearer injection signatures for the events with high level of fluctuations as compared to those with low level of fluctuations. Also the SYM-H index was slightly more negative and ASY-H index slightly larger for the high-fluctuation events than the low-fluctuation events. However, as the driver had stronger solar wind pressure and larger $\epsilon$ caused by a larger $B_Y$, these differences are more likely to be related to the driver intensity than the level of fluctuations. In conclusion, the fluctuations could not be shown to play any role in determining the level of activity either in the magnetosphere or in the ionosphere.

[41] The solar wind-magnetosphere-ionosphere coupling efficiency seems to be mostly a function of the driver intensity: dividing the data set to $E_Y < 4$ mV/m and $E_Y > 4$ mV/m shows that in the ionosphere, the average ratio $A_L/E_Y$ after the onset is much larger for low-level driving than it is for high-level driving (Figure 10h). Similarly, the deviation of the field inclination angle from the dipole value scaled by $E_Y ((90^\circ - \theta)/E_Y)$ is larger for low-level driving than it is for higher level of driving. Thus more moderate driver couples more efficiently with the ionosphere and magnetosphere.

[42] Finally, if the data set is divided into low-pressure ($P < 3$ nPa) and high-pressure ($P > 3$ nPa) events, it is noted that even though the driver intensity is only somewhat larger for the high-pressure events than for the low-pressure ones, the high-pressure events show clearly larger ionospheric activity, more depressed SYM-H, and larger ASY-H (Figure 10). Comparing the ratios of response versus driver intensity, it is seen that the pressure has no effect on the coupling efficiency of the geostationary orbit field inclination, as the high- and low-pressure curves essentially overlap. For the magnetic indices, the high- and low-pressure events behave very similarly to the high and low $E_Y$-events, showing larger activity for larger values but lower coupling efficiency.

8. Discussion

[43] We examine storm time activations using superposed epoch analysis timed based on ground magnetic onsets. The results are compared with a set of sawtooth oscillations timed with respect to the geostationary orbit injection time.

[44] About half of the storm time electrojet enhancements are coincident with inner magnetosphere dynamics typically associated with substorm processes: geostationary orbit field stretching followed by dipolarization and energetic particle injections. These activations tend to recur every 2–3 hours, which is similar to the repetition period of recurrent substorms obtained by Borovsky et al. [1993]. Although we have not used magnetotail data in this analysis, it would seem based on this analysis that these activations resemble isolated substorms, being associated with current sheet intensification and thinning prior to the onset and midtail reconnection and current disruption at onset.

[45] It is to be noted that the other half of the events, which did not meet our criteria for having geostationary orbit injections, include a wide range of inner magnetosphere dynamic configurations and dynamic evolutions. In some (small) portion of the events there were no associated flux variations at all. Other events in this category include injections where the timings did not meet our criteria, and hence the association between the auroral electrojet activation and geostationary orbit injection could not be made. Furthermore, there were several events where the fluxes oscillated rapidly without clear increase of the fluxes; such events also fall out of our selection criteria. Thus the fact that 50% of the events fall out of our “typical substorm” category does not mean that the other 50% would not be associated with any kind of inner magnetosphere energetic particle flux variations.
Figure 10. Superposed epoch analysis results for the geostationary orbit field inclination and ground magnetic indices for the data set for which \( E_y < 4 \text{ mV/m} \) (110 events, blue line), \( E_y > 4 \text{ mV/m} \) (40 events, red line), \( P < 3 \text{ nPa} \) (97 events, green line), and \( P > 3 \text{ nPa} \) (53 events, orange line). (a) Solar wind motional electric field for high-\( E_y \) and low-\( E_y \) events, (b) field inclination Theta in SM coordinates for 2200–0200 MLT, (c) AL index (d) SYM-H index, (e) ASY-H index, (f) solar wind motional electric field for high-pressure and low-pressure events, (g) tail field stretching efficiency at geostationary orbit \( (90^\circ - \theta)/E_y \), (h) ionospheric coupling efficiency \( \text{AL}/E_y \), (i) ring current coupling efficiency \( \text{SYM-H}/E_y \) and (j) asymmetric ring current coupling efficiency \( \text{ASY-H}/E_y \).

[46] The sawtooth oscillations, which were identified separately and form an independent data set, show many similarities but also some differences as compared to the storm time activations. While the driving conditions (IMF \( B_z \) and \( E_y \)) are comparable to the storm time activations, the solar wind speed is significantly lower, which makes the Alfvén Mach number lower for this data set. On the other hand, if one selects a subset of storm time activations that have field stretching in the evening sector (a typical signature of sawtooth events [Pulkkinen et al., 2006a]) the average properties in the inner magnetosphere as well as in the auroral ionosphere of that subset of events are very similar to those observed during sawtooth events. Thus it seems that the dynamics of the sawtooth events are not different from (a subset of) other storm time activations.

[47] Comparison of the sawtooth events and storm time activations clearly indicates that both types of activations recur every 2–3 hours. Thus it would seem that the periodicity during the sawtooth oscillations is determined by internal magnetospheric processes or the solar wind-magnetosphere interaction that are present during all times and is not characteristic of the sawtooth oscillations alone. The multiple recurrence of the oscillations would seem to be a consequence of the steady and not too intense solar wind driver (lower level of IMF fluctuations than in the storm time activations data set), which allows for the magnetosphere to go through several complete activity cycles in succession.

[48] What is it then in the magnetosphere that would lead to a 2–3 hour recurrence period? Taking an average solar wind speed of 500 km/s and a typical tail length of 100 \( R_E \) gives a timescale of about 20 min for a solar wind structure to pass the magnetosphere. Typical time for the substorm growth phase to set up a thin current sheet in the inner magnetosphere is about 30–60 min [McPherron, 1970]. Substorm recovery times vary depending on the magnetospheric region: the midtail plasma sheet recovers in about 20 min, while the inner magnetosphere magnetic field configuration is restored in about 90 min, and the AE indices return to quiet levels in 2–3 hours [Pulkkinen et al., 1994]. Plasmoids reach the solar wind speed usually quite rapidly [Slavin et al., 1984]; even allowing for a slower travel speed of a few 100 km/s yields timescales below 1 hour for the plasmoid to leave the magnetosphere. The drift periods of energetic ions in the inner magnetosphere range from about 3 hours (tens of keV particles at dipolar orbits at 4 \( R_E \) distance) downward, depending on particle energy and the magnetic field configuration. Thus only the ionospheric recovery time and the peak ring current ion drift times or a sum of the growth and recovery times are comparable to the recurrence period, and it is not self-evident how any of these would affect the substorm recurrence, leaving the periodicity in the magnetosphere an open issue.

[49] Earlier studies have qualitatively indicated that more fluctuating solar wind drivers drive stronger auroral region activity [Tsurutani and Gonzalez, 1987; Huttunen et al., 2002; Pulkkinen et al., 2006b]. Our results indicate that high level of fluctuations is typically associated with a rather strong driver and higher than average solar wind pressure. However, if the driver intensities are the same, the fluctuations could not be shown to have any effect on either the ionospheric activity or the geostationary field configuration.

[50] Furthermore, e.g., Lopez et al. [2004] assert that the solar wind Mach number affects the solar wind-magnetosphere coupling efficiency. The compression ratio of the magnetic field across the bow shock is about 4 for Mach numbers above \( \sim 8 \); for \( M_a = 4 \) the compression ratio is down to about 3. This would indicate that the magnetosphere is actually interacting with a weaker IMF than one would assume based on assumptions derived from more typical solar wind conditions. In our data set, if the driver intensities (\( E_y = -VB_z \)) are chosen to be comparable, the Mach number in the solar wind played no role in determining the level of ionospheric activity or
inner magnetosphere field configuration. Virtually the only difference between the low and high Mach number data sets was that the low Mach number events tended to have slightly more asymmetric ring current with slightly lower SYM-H disturbance and slightly larger ASY-H.

[51] Our study finds that the coupling efficiency is a strong function of the driving electric field and also depends on the solar wind dynamic pressure. When the driving is moderate, proportionally more energy gets both into the ionosphere and in the ring current (as measured by SYM-H and ASY-H), and the geostationary field is proportionally more stretched, than when the driving is stronger ($E_y$ is larger). The large pressure events show similarly weaker coupling with the magnetosphere, although the coupling efficiency of the geostationary orbit field inclination showed no dependence on the dynamic pressure. As these factors couple both with the solar wind Mach number and the level of fluctuations, we suggest that the correlations derived earlier arise from the different levels of driving. The lower SYM-H response during high driving may be explained by the strong cross-tail current reaching to the inner magnetosphere, which tends to leave more particles on open drift paths and therefore allow less symmetric ring current development. However, as the ring current is typically already enhanced during such periods, the less efficient field stretching may be accounted for by the balancing effect of the ring current inside geostationary orbit, which would tend to make the field increasingly dipolar. It is probably then the joint effect of these changes in the tail configuration that leads to lesser amount field-aligned current within the substorm current wedge during the activation expansion.

[52] Comparing the power input into the ionosphere estimated using $\epsilon$ and dissipation using the Ahn et al. [1983] formula for estimating the Joule heating based on the electrojet indices ($JH = 3 \cdot 10^8$ AL, where $JH$ is in gigawatts and AL given in nT) gives that about 25% of the energy input is dissipated in the ionosphere during storm time activations. Tanskanen et al. [2002] show that the average for isolated substorms is around 30%, which is consistent with the results discussed above that during moderate driving relatively larger amount of energy is dissipated in the ionosphere. Similar behavior is obtained for the sawtooth events; the auroral electrojet intensity is smaller than one would expect based on correlation analysis of the driver intensity and AL index during isolated substorms.

[53] Earlier analyses of the solar wind dependence of the ionospheric potential have shown (1) that there is a background potential that is independent of the level of IMF driving [Reiff et al., 1981] and (2) that while for small levels of driving the potential is linearly dependent on the driving $E_R$, the potential saturates for higher values of the solar wind electric field [Siscoe et al., 2002]. Furthermore, Russell et al. [2000] showed that the ionospheric Joule heating grows linearly for small electric field values, while the rate of increase becomes smaller for larger values of the driving $E_y$. These results are consistent with those found in this paper, although a simple function describing the saturation or coupling efficiency could not be derived based on our results.

[54] It is clear from our results that a significant number of the storm time activations, and a lesser but nonzero number of the sawtooth oscillations, are triggered by solar wind pressure pulses and/or IMF northward turnings. Triggering is more likely to occur if the solar wind pressure, density, and velocity are higher but did not show any dependence on magnitude of the IMF. This would indicate that it is easier to launch an instability by an external trigger when the magnetosphere is in a more compressed state, which tends to intensify the cross-tail current and bring it closer to the Earth. The stronger cross-tail current also means that the delicate balance between the negative $B_Z$ produced by the tail current and the positive $B_Z$ produced by the dipole (and the ring current) may be more easily disturbed to create islands of negative $B_Z$ [Erickson and Wolf, 1980; Tsyganenko, 1989] and hence allow reconnection to proceed. As these events do not show clear dipolarizations in the inner magnetosphere, it seems that the triggering causes the activity onset further out in the magnetotail, maybe in the typical $B_Z$-minimum region around $10–12 R_E$ [Tsyganenko, 1989]. For the sawtooth events it is interesting to note that the pressure and $B_Z$ change occur about 30 min before the zero epoch time. This is true for many of the individual events, and we have checked that these consistent differences cannot be accounted for by errors in the solar wind transit times. However, the physics related to the delay between the trigger and the onset remains open.

[55] In addition to the subset of storm time activations showing a stretched field in the evening sector, another subset shows strong field stretching in the morning sector. Analysis of the solar wind parameters did not yield any hint regarding what would control the location of the strongest currents in the inner magnetosphere. Especially, there is no $B_Z$ dependence on the peak current location. However, this subset of events tends to occur during the peak of the SYM-H activity and during strong storms indicating that they are associated with highly disturbed conditions. Similarly, the AL activity is stronger and longer-lasting than during the other storm time activations. While it is easier to understand how an evening sector peak is created by drifting (partial) ring current ions, it is less evident what would create a strong current in the morning sector. However, such peaks have been observed by the IMAGE satellite [Brandt et al., 2002]. Note that at geostationary orbit, one would expect to be tailward of the peak of the symmetric ring current, and hence the effect of a strong symmetric ring current torus would be to produce a positive $B_Z$ and increase of the field inclination. Thus such field stretching is not produced by the typically observed torus-like symmetric ring current. Strong stretching in the morning sector can be accounted for by a strong inward intrusion of the cross-tail current with particle orbits skewed to the dawn sector by an unusual electric field convection pattern [Brandt et al., 2002].

[56] The SYM-H index is relatively unchanged for most of the storm time activations, although the morning-sector stretching events and the sawtooth events do show a small positive deflection in the SYM-H index following the zero epoch time. It is interesting to note that the SYM-H effect arises in these two data sets but not in the one showing evening-sector stretching, which otherwise showed characteristics similar to the sawtooth oscillations. One would
assume that the positive deflection is mainly associated with reduction in the cross-tail current at onset but can also be affected by the field-aligned current patterns associated with the substorm current wedge. However, Ohtani et al. [2001] note that the start of the Dst recovery is associated with tail current weakening at a substorm onset, while the ring current peak occurs slightly later. This might indicate that during the more intense storms during which the morning-sector stretching events occurred, one is more likely to observe the positive deflection caused by the tail current change. Furthermore, as the SYM-H is the average of the disturbances around the Earth rather than a true symmetric part, events where stretching and dipolarization cover a broad range of local times is more likely to produce a stronger signal also in the SYM-H index.

Another difference between the storm time activations and the sawtooth oscillations is that while the former show a clear increase of the ASY-H index, there is no signal in the ASY-H index in the latter data set. The increase in ASY-H is usually attributed to the growth of a partial ring current in the evening sector but will of course follow from any asymmetry in the current configuration. The global nature of the sawtooth events and the rapid expansion of the injection thus may mask the ASY-H signal in the sawtooth event statistics.

In conclusion, the presence of the storm affects the nature of the solar wind-magnetosphere coupling. While the overall level of activity is higher than during nonstorm substorms, a relatively smaller portion of the incoming energy is coupled to the ionosphere and to the inner magnetosphere. It also seems that activation triggering is much more likely to occur under generally highly fluctuating IMF driver, whether that is due to the availability of triggers or the more unstable state of the magnetosphere under such driving remains an open issue.

9. Conclusions

A superposed epoch analysis is used to show that:
1. About half of storm time activations show substorm-like behavior; the other half shows complex dynamics that may involve fluctuations at geosynchronous orbit or occur further out in the magnetotail.
2. Sawtooth oscillations have inner magnetosphere and auroral characteristics that are quite similar to those found during a subset of other storm time activations. Hence sawtooth events do not represent a specific type of magnetospheric activity.
3. The 2–3 hour recurrence time of both storm time activations and sawtooth events remains an open issue. It is clearly not associated with the driver properties and could only be linked to the combined growth and recovery times of substorm-like activity.
4. About 30% of storm time activations and about 20% of the sawtooth oscillations have associated IMF and/or solar wind changes that can act as triggers. Triggering is more likely to occur during high solar wind pressure and fluctuating IMF. As these are not typical conditions during the sawtooth events, this may explain the lower occurrence rate of triggered events in that data set.
5. The energy coupling between the ionosphere and the solar wind is not dependent on the either the solar wind Mach number or the level of IMF fluctuations but is a function of the driving solar wind electric field. The energy dissipation in the ionosphere is about 25% of $E$ during periods of high $E_B$ while it is about 30% during nonstorm substorms and storms when $E_B$ is below 4 mV/m. Similarly, the increasing solar wind pressure decreases the coupling efficiency.

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**References**


Pulkkinen, T. I., D. N. Baker, P. K. Toivanen, R. J. Pellinen, R. H. W. Friedman, J. C. Samson, F. Creutzberg, T. J. Hughes, D. R. McDiarmid, M. G. Henderson, G. D. Reeves, and M. F. Thomsen, Los Alamos National Laboratory, 871 Taos Road, Los Alamos, NM 87545, USA (mthomsen@lanl.gov; reeves@lanl.gov; mthomsen@lanl.gov).


