Multi-point in-situ and ground-based observations
during auroral intensifications


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Abstract. Analysis of in-situ and ground-based observations is performed to establish the precise timing of observed signatures during two successive auroral activations. The first, minor, activation was interpreted as a pseudo-breakup, while the second, major one, was classified as a substorm. Timing of observations aboard four of the THEMIS probes situated in the plasma sheet in the tail-aligned conjunction indicates initial activity at $X_{GSM} \approx -$
Magnetic field variations, tailward fast flows, and signatures in particles behavior observed by two THEMIS probes in the mid-tail plasma sheet suggest magnetic reconnection as the source of the first activation. The substorm onset, detected 6 min after the pseudo-breakup, was found to be associated with the rapid decrease of the magnetic field strength, dipolarization, and increase of plasma density and pressure, i.e., signatures of the cross-tail current reduction (disruption), observed in the near-Earth plasma sheet at $X_{GSM} > 10R_E$. Thus, in this case, reconnection in the mid tail preceded the near-Earth current reduction. A scenario based on a model of the near-Earth breakup triggered by the fast Earthward flow, generated by preceding reconnection, is proposed.
1. Introduction

Although it is generally accepted that active auroral phenomena, such as substorms [Akasofu, 1964] and pseudo-breakups [see, e.g., Aikio et al., 1999], are counterparts of dissipative processes in the magnetotail plasma sheet, the concrete causal relationship is still unclear.

It is established that the magnetospheric substorm involves processes on different temporal and spatial scales: magnetotail stretching with a time scale of tens of minutes during a growth phase [e.g., Voronkov et al., 2003; Petrukovich et al., 2007], a rapid dissipation process with a time scale of 1 - 3 min [e.g., Sergeev et al., 1996b], a breakup, and tens of minutes-long processes during a recovery phase [e.g., Voronkov et al., 2003]. Substorm manifestations in the ionosphere include an intensification and an equatorward motion of an auroral arc during the growth phase, an explosive-like brightening of the arc, and a rapid development of vortex structures with poleward expansion of those structures during the breakup. Substorm onset is commonly identified by ground magnetic signatures of the currents associated with auroral arc intensification, including irregular variations in the 40 - 150 s range, called Pi2 pulsations [see, e.g., Kepko et al., 2004, and references therein]. The term “pseudo-breakup” is used to describe an auroral disturbance that does not exhibit significant poleward expansion and generally ceases in 5 - 10 minutes [Voronkov et al., 2003]. Pseudo-breakups are associated with the same type of Pi2 pulsations as substorm breakups [Aikio et al., 1999].

Substorm phases may also be identified by magnetic field variations at geosynchronous orbit. The magnetic field on the night side becomes more tail-like during the growth phase,
which results in an increase of the Earthward magnetic field component at geosynchronous orbit. The breakup (onset of the expansion phase) corresponds to a reconfiguration of the magnetic field to a more dipolar-like configuration (dipolarization) [e.g., Nagai, 1982]. It was also found that the dipolarization occurs first in a longitudinally localized sector, expanding westward and eastward. Thus the growth-phase signatures may co-exist with the dipolarization just after onset [Nagai, 1991].

Substorm breakup is associated with a sudden decrease in the tail current intensity and the formation of field-aligned currents (FACs) flowing downward on the dawnside and upward on the duskside of a substorm meridian and forming the substorm current wedge [McPherron et al., 1973; Nagai, 1987]. In-situ observations have shown that the cross-tail current reduction (often referred to as Current Disruption, CD) usually starts in the near-Earth magnetotail at $|X| < 15R_E$ [e.g., Ohtani et al., 1988; Jacquey et al., 1993]. Based on such observations, the CD model of the magnetospheric substorm was proposed [Lui, 1996]. According to this model, a substorm is triggered locally in the inner magnetotail, presumably by an instability that involves a cross-tail wave vector component [Lui, 1991]. Potential candidates are cross-field current-driven instabilities [e.g., Lui, 1991] or interchange/ballooning modes [Roux et al., 1991; Pu et al., 1997; Bhattacharjee et al., 1998; Cheng and Lui, 1998].

On the other hand, statistical studies of high-speed bursty bulk flows [Baumjohann et al., 1990; Angelopoulos et al., 1992] in the magnetotail plasma sheet (PS) and their relation to auroral phenomena suggest that magnetospheric substorms are initiated by magnetic reconnection in the mid-magnetotail at $X \approx 20R_E$ [e.g., Baumjohann et al., 1990; Nagai et al., 1998; Nakamura et al., 2001a; Nagai et al., 2005]. A set of observations
supports the scenario of transient instability of a thin current sheet, forming at the end of the growth phase in the magnetotail plasma sheet, resulting in a spatially localized high-speed plasma flow with a temporal scale of 1 - 3 min [Sergeev et al., 1996b]. The Earthward high-speed bursty bulk flow (BBF), originating in the mid-tail plasma sheet, may cause the cross-tail current reduction (disruption) in the near-Earth magnetotail, due to the pileup of the northward magnetic field during BBF’s breaking in the transition region between tail-like and dipolar magnetic fields [Hesse and Birn, 1991; Haerendel, 1992; Shiokawa et al., 1998]. More recently, it was shown by modeling that an Earthward BBF may trigger nonlinear ballooning instability at the inner edge of the plasma sheet [Voronkov, 2005]. The model predicts a jump-like increase of the plasma pressure, collapse-like dynamics of the magnetic field (a rapid reduction of the cross-tail current) in tens of seconds, with subsequent tailward expansion of the unstable region.

It is crucial therefore to pinpoint the time and the spatial location of the very first signatures of the activity. For the analysis, the following three requirements are essential:

1) multi-point observations in the magnetotail, to prob the mid-tail and the near-Earth plasma sheet simultaneously; 2) simultaneous ground-based observations with high time resolution; and 3) precise mapping between the magnetotail and the ionosphere. The last is indeed critical and difficult to do since the statistical models of the magnetospheric magnetic field [e.g., Tsyganenko, 1995] may not provide a precise solution during active periods. Event-oriented models [cf., Kubyshkina et al., 1999, 2002] may give more adequate mapping. Also, the flow bursts in the plasma sheet are found to be localized in the north-south within <1 R_E and cross-tail directions within 1 - 3 R_E [Nakamura et al., 2004b].
Thus a tail-aligned spacecraft constellation is needed to record the timing and location of the initial activity.

The timing of signatures during auroral activations is the primary goal of the THEMIS mission [Angelopoulos, 2008; Sibeck and Angelopoulos, 2008]. THEMIS employs five identical satellites (hereafter termed “probes”) on orbits enabling recurrent probe alignments parallel to the Sun-Earth line (probes within $Y_{GSM} \pm 2 R_E$ from each other), referred as the major conjunctions. The probes thus monitor tail phenomena simultaneously from $\sim 10$ to $\sim 30 R_E$ downtail, while mapping magnetically to a network of ground-based observatories (GBOs) recording substorm onsets.

In the present study, we analyze the in-situ measurements along with the images obtained by the THEMIS GBOs during a set of auroral intensifications between 0130 and 0205 UT on March 1, 2008. The main aim of this study is to establish the exact timing of the signatures, observed in the mid-tail ($-17 > X > -23 R_E$), the near-Earth ($X \sim 10 R_E$) plasma sheet, and at geostationary orbit and associate them with distinct auroral intensifications (a pseudo-breakup and a substorm) detected by GBOs.

2. Instrumentation

Each THEMIS probe carries identical scientific equipment [Angelopoulos, 2008]. Data from the following instruments aboard the THEMIS probes are used in this study: 1) the Flux Gate Magnetometer [FGM, Auster et al., 2008], providing DC magnetic field measurements with a temporal resolution of 1 vector per spin ($\sim 3$ s, spin-fit data set) and 4 vectors per spin (fast survey mode). The fast survey mode was maintained during the entire event. 2) The Electrostatic Analyzer [ESA, McFadden et al., 2008], providing ion and electron distribution functions in the energy range from 5 eV up to 25 keV with a
time resolution of 1 distribution function per spin in the fast survey mode. 3) The Solid State Telescope [SST, Larson et al., 2008], detecting high-energy (25 keV - 1 MeV) ion and electron fluxes with a time-resolution of 1 distribution function per spin in the fast survey mode. The set of THEMIS Ground-based Observatories provides complimentary data including images from the all-sky cameras (ASI) with a time resolution of 1 image per 3 s and magnetometers that record the 3-axis variations of the magnetic field at a 2 Hz frequency [GBO, Mende et al., 2008].

Additionally, the magnetic field data from the two NOAA Geostationary Operational Environmental Satellite (GOES 10 and GOES 12) [Singer et al., 1996] were used in this study. The time resolution of the GOES magnetometers is 1 vector per 0.5 s.

3. Event overview

The auroral activity was registered by the THEMIS all-sky camera array starting at 0148:42 UT. Figure 1 shows mosaic images from the all-sky cameras in Eastern Canada, with foot points of four THEMIS probes (P1 - P4) and two geosynchronous satellites (GOES-10 and GOES-12) determined using T96 model [Tsyganenko, 1995]. The UT of the aurora onset registrations are listed in Table 1. The first, minor, intensification was detected at the easternmost station (GBAY). The aurora expanded westward to TPAS. No poleward expansion was detected, which allows us to classify this intensification as a pseudo-breakup. The next, major, intensification onset was detected first at 0152:27 at SNKQ. The auroral activity expanded azimuthally and poleward and may, therefore, be classified as a substorm.

The keogram from the all-sky camera located at Thykkvibaer, South Iceland, shows continuing equatorward motion of the aurora until 0156 UT (growth phase) with a local
intensification at 0149 UT (not shown; E. Woodfield, private communication). Thus de-
spite a lack of data eastward of GBAY, the minor intensification onset at 0148:42 seems
to be the very initial activation.

Figure 2 shows the history of the integrated brightness (image totals) of all-sky images at
a set of stations located from east (GBAY) to west (GILL). The first minor intensification
is pronounced at the GBAY record (bottom panel). The integrated brightness jumped at
0148:42 UT then decreased, but did not drop down to the pre-intensification level.

Figure 3 shows the solar wind velocity (GSM coordinate system), dynamic pressure, and
IMF GSM components from the WIND spacecraft ($X=198.6$, $Y=-37.2$, and $Z=-41.4\, R_E$),
along with original and band-passed filtered (40 - 150 s) magnetograms from the set of
geomagnetic stations between 280 and 300° geographic longitudes. The vertical dashed
lines indicate times of the two auroral onsets: the minor one, detected at 0148:42 UT at
GBAY, and the major, observed at around 0155:00.

The solar wind velocity was high ($V_x \approx -750$ km/s) and with large variations of $V_y$ and
$V_z$ (up to 150 km/s). However, since the solar wind density was on average $2.51/cm^3$,
the dynamic pressure was modest, varying between 2 and 3 nPa. At the first onset, $V_y$
changed from 0 to $\sim 60$ km/s, and $V_z$ reversed from $\sim 20$ to $\sim 20$ km/s. At the second
onset, $V_y$ reversed from $\sim 60$ to $-25$ km/s, and $V_z$ from $-20$ to 50 km/s. The IMF $B_z$ was
southward ($-6$ nT) during both the minor and the major disturbance onsets. The IMF $B_y$
reversed from dawnward (negative) to duskward (positive) at around the first onset and
from duskward to dawnward at around the second one.

Ground-based magnetometers in GBAY, DRBY (54.5 mlat, 6.4 mlon), and, LOYS (50.6,
357.2) detected positive $B_y$ variations and distinct onsets of $B_x$ pulsations in the PI2 range.
between 0148:40 and 0149:00 UT. CHBG, situated westward, detected $B_y$ variations at ~0151 and the distinct Pi2-pulsations onset at 0156:30 UT. No distinct magnetic field variations were detected by KUUJ until 0155:30 UT. A negative $B_x$ bay at the second onset was registered.

Figure 4 shows positions of the five THEMIS probes (P1/THB, red; P2/THC, green; P3/THD, cyan; P4/THE, blue, and P5/THA, magenta) and GOES 10 (asterisk) and GOES 12 (plus) satellites. The THEMIS probes were in the pre-planned major conjunction: P1 - P4 were at $5.9 < Y_{GSM} < 6.7 R_E$ and $X = -22.7, -17.4, -9.29, and -7.97 R_E$, respectively. Mapping the spacecraft to the ionosphere using the T96 model [Tsyganenko, 1995] and verified with the event-oriented model [Kubyshkina et al., 1999], shows P1 and P2 foot points slightly eastward of GBAY, while P3, P4 and GOES-10 mapped closer to KUUJ (Figure 1). GOES-12 mapped more westward near SNKQ. It should be noted that due to the significant $Z$-component of the solar wind bulk velocity, the mapping may be imprecise.

Figure 5 presents the spin-averaged magnetic field from the FGM and the thermal ion velocity from ESA instruments, observed by THEMIS P1 - P4, along with the magnetic field, observed by GOES 10 and GOES 12 satellites during 0100 - 0210 UT. The PEN coordinate system (with P-component directed poleward, E-component directed Earthward, and N-component directed eastward) is used for the GOES measurements. The vertical bars indicate the two auroral onsets: at 0148:42 UT (GBAY) and 0155:21 UT (KUUJ).

Before the first onset (0100 - 0148 UT), the two outermost probes (P1 and P2) were in the plasma sheet experiencing slow variations of $B_x$ in the range of -15 - 15 nT with neutral sheet crossings. These long period variations correlate with variations of the IMF.
$V_z$ (see Figure 3) and, most likely, were solar-wind induced. The two innermost probes, initially staying at a $B_x$ level of 20 nT, exhibited a gradual increase of $B_x$ up to 40 nT starting at 0110 UT. The increase of $B_x$ was accompanied by a decrease of $B_y$ from -10 nT at P3 and -17 nT at P4 down to -30 nT at P3 and -40 nT at P4. This extra-flaring (up to $\sim 45^\circ$) indicates an unusual state of the magnetosphere during our interval of interest.

The geosynchronous satellites GOES-10 and GOES-12 detected a gradual increase of the radial magnetic field component ($B_e$) starting at 0115 UT. The plasma sheet state at P1 and P2 locations ($X=-22.7$ and $-17.4 R_E$, respectively) changed abruptly at around 0149:00 UT, when first P2 (at 0148:40 UT) then P1 (0149:30 UT) detected an arrival of fast ($V_x \approx -500$ km/s) tailward-duskward bulk flow accompanied by a sharp variation of $B_y$ (negative at P2 and positive-then-negative at P1) with an amplitude of 15 nT and a bipolar north-then-south variation of $B_z$. The tailward flow was detected within $\sim 2.5$ min by both probes. The two near-Earth THEMIS probes (P3 and P4) detected only minor (of $\sim 5$ nT amplitude) variations of $Y$ and $Z$ magnetic field components starting at about 0148:30 UT (see Fig. 12). $B_x$ as well as the total field increased continuously, indicating a build-up of the total current in the plasma sheet.

At 0154:40 UT, P2 detected a large negative variation of $B_y$, with an amplitude of 20 nT, a positive variation of $B_z$ with an amplitude of 5 nT, and the onset of tailward-dawnward bulk flow. P1 detected an intensification of the tailward flow at 0154:40 UT and significant $B_y$ and $B_z$ (both negative) variations at 0155:10 and 0155:25 UT, respectively.

The situation in the near-Earth plasma sheet also changed dramatically: at about 0154:50, P4 (the most Earthward probe) detected an intensification of the ion flow and a rapid decrease of $B_x$ and $|B_y|$, accompanied by an increase of $B_z$ modulated by $\sim 5$ nT-amplitude...
variations. Similar signatures were detected by P3 starting at 0155:30 UT. GOES-10 and GOES-12 started to detect a dipolarization (increase of $B_p$) with a decrease of $B_e$ and variations in $B_n$ at about 0155:00 UT, i.e., roughly simultaneously with the magnetic field variations detected by P4.

4. Detailed Data Analysis

4.1. Dynamics at $-23 < X < -17 R_E$

Figures 6 and 7 present summary plots of FGM, SST, and ESA instruments measurements between 0140 and 0205 UT. In the angular spectrograms $\Phi$ is the detector looking azimuth in the probe spin plane. For P1 and P2 $\Phi=0$ corresponds to the anti-Sunward, $90^{\circ}$ - to duskward, $180^{\circ}$ - to the Sunward, and $270^{\circ}$ - to the dawnward looking directions. Before the first auroral onset at 0148:42 UT, marked by a vertical dashed bar, both P1 ($X=-22.7 R_E$) and P2 ($X=-17.4 R_E$) observed a quiet but rather hot plasma sheet with a particle number density of $0.1 \text{ cm}^{-3}$, and a plasma pressure (including thermal and super-thermal ion and electron components) of $0.15 \text{nPa}$. Both P2, situated in the nearest vicinity of the neutral sheet ($|B_x|<10\text{nT}$) and P1, remaining at $B_x$ of $-15\text{nT}$, detected a significant duskward flux ($270^{\circ}$, SST-ion angular spectrograms) of high-energy ions, increasing at about 0145:00 UT. The enhancement of the duskward high-energy ion flux indicates current sheet thinning: the sheet thickness becomes comparable with the $\sim 30\text{ keV}$ ion gyroradius ($\sim 2500\text{ km}$ at $B=10\text{nT}$) and the ions start meandering [Speiser, 1965]. The duskward-drifting ions co-existed with a counter-streaming Earthward ($0^{\circ}$) and tailward ($180^{\circ}$) high-energy ion population. The thermal ions were rather isotropic, although a somewhat larger flux density is visible over $180^{\circ}$ in ESA-ion angular spectro-
grams. Prior to the onset, P2, situated near the neutral sheet, detected $B_y = -3.54 \pm 1.04 \text{nT}$, and $B_z = 2.08 \pm 0.31 \text{nT}$.

At around the first onset, P2 started to detect ion and electron energization with the enhanced flux of super-thermal and thermal tailward streaming ions. At the same time, some increase of $B_x$ (of $\sim 10 \text{nT}$ amplitude), the negative $B_y$ (of $20 \text{nT}$ amplitude) and the bi-polar north-south $B_z$ (of $\sim 10 \text{nT}$ amplitude) variations were detected by P2/FGM. The particle density decreased down to $0.05 \text{cm}^{-3}$, the bulk flow velocity reached -500 km/s, the plasma pressure first increased then decreased, while the magnetic pressure increased, and total pressure ($P_t = P_i + P_e + B^2/2\mu_0$), calculated from both ESA and SST inputs, also first increased then decreased. The pressure variations indicate plasma and magnetic field compression on the front of the tailward flow burst. The dawnward $B_y$, along with the positive $B_x$, the southward $B_z$, and the tailward bulk flow may be interpreted as a signature of the quadrupolar magnetic field due to the Hall effect [e.g., Runov et al., 2003], suggesting the reconnection-related origin of the tailward fast flow. The flow burst continued for about 2 min, which is a typical time scale for elementary dissipative processes in the plasma sheet [Sergeev et al., 1996b; Runov et al., 2008]. The observed bulk velocity of 500 km/s is about 70% of the Alfven speed, calculated for $B=10 \text{nT}$ (the average magnetic field strength at the first tailward flow onset) and the density of $0.1 \text{cm}^{-3}$.

The same sequence of signatures was observed by P1 about 40 s later than by P2, but the $B_y$ variation is bipolar (first positive then negative) with an amplitude of 15 nT. This variation of $B_y$ may hardly be explained by the Hall effect. Likely, the spacecraft crossed a part of a complex 3-D current system with a local vertical current filament, transported by the tailward plasma flow.
Figure 8 shows the Φ-spectrograms of SST and ESA ion fluxes along with normalized fluxes in several energy channels during 0148:00 - 0149:30 UT at P2 and during 0149:00 - 0150:00 at P1 plotted versus UT. Signatures observed by both probes are similar, including a pronounced high-energy (>30 keV, SST) flux anisotropy with an enhanced flux in the duskward (270°) direction, gradually turning to the tailward (180°) direction, accompanied by the spectral density increase at around 0148:40 UT (i.e., at the onset marked with the vertical dashed bar) at P2 and at 0149:20 UT at P1. The thermal ion flux in the tailward (180°) direction increased at about 0148:45 UT at P2 and at 0149:30 UT at P1. The Inverse Velocity Dispersion (IVD) [Sarafopoulos and Sarris, 1988] of the high-energy ions was observed by both probes: the flux of ∼60 keV ions exhibited the increase earlier than the fluxes of 90, 130, and 200 keV ions. An onset of the 60 keV ions flux increase was observed at P2 at about 0148:25 UT, i.e., 15 - 20 s prior to the auroral onset. P1 observed the increase of the 60 keV ions flux at about 0149:10 UT.

A similar IVD was detected by P1 during the second tailward flow burst between 0154:00 and 0155:30 UT (not shown). The ∼60 keV ion flux began increasing at 0154:45 UT. However, no pronounced velocity dispersion (either direct or inverse) was detected at P2, which rapidly crossed the current sheet during the second tailward flow interval.

The thermal ion flux at Φ ≈180° (tailward bulk flow) increased between 0148:45 and 0148:50 at P2 and between 0149:25 and 0149:30 at P1 without any visible dispersion. This lag time suggests tailward propagation velocity of 800 km/s, which is 40% faster than the observed tailward bulk velocity.

Figure 9 presents pitch-angle distributions (PAD) of SST and ESA electrons, obtained by P2 between 0147:00 and 0150:00 UT and P1 between 0148:00 and 0151:00 UT. P2
detected a pancake-like PAD of high-energy electrons until 0147:20 UT, staying at the
eutral sheet. Between 0147:20 and 0148:25 UT the bi-directional (0 and 180°) SST-
electrons PAD was observed. At 0148:25 UT (about 20 s prior to the first auroral onset),
an enhancement of the 0° and 180° super-thermal electron flux was detected. The PAD
changed again to the pancake-like with a transient enhancement of duskward-directed
(270°) flux between 0148:25 and 0148:40 UT. After 0149:10 UT, the high-energy elec-
tron flux was mainly anti-parallel to the magnetic field. Thermal electrons with energies
between 0.5 and 21 keV exhibited a drop in the flux between 0147:20 and 0148:40 UT.
The flux increased up to a maximum at about 0149:00 UT, remaining isotropic. After
0149:10 UT, P2 detected the bi-directional thermal-energy electron flux with a somewhat
larger density in the anti-parallel direction. The low-energy (0.1 - 0.5 keV) electron flux
was detected to be bi-directional (0 and 180°) between 0147:10 and 0148:20 UT, during
a local maximum of the magnetic field. Between 0148:20 and 0148:40 UT, P2, staying
at \( B_x = 3 \text{nT} \), detected a mainly anti-parallel low-energy electron flux. The flux decreased
between 0148:40 and 0149:00 UT, coinciding with a minimum (maximum value) of the
negative \( B_y \) variation. A local increase of first a parallel, then a bi-directional low-energy
electron flux, was detected between 0149:00 and 0149:15 UT.

Similar signatures were observed by P1 starting at 0149:00 UT. It is interesting to note
an increase of bi-directional high-energy electron flux, coinciding with the positive \( B_y \)
variation. Another interesting feature is the observation of an enhanced flux of parallel
thermal energy electrons coinciding with an increase of mainly anti-parallel flux of the low-
energy electrons between 0149:10 and 0149:45 UT. Since the probe was in the southern
part of the sheet detecting the tailward bulk flow, these observations may be interpreted
as signatures of low-energy electron inflow and thermal-energy electron outflow, expected
from the Hall reconnection model [e.g., Hoshino et al., 2001].

Thus summarizing the observations at \(-23 < X < -17 R_E\), the activity in the mid-tail
plasma sheet started at around 0148:25 UT, when the increase of high-energy particle
(both electrons and ions) fluxes was detected by P2 at \(X = -17.4 R_E\). Observed IVD of
the high-energy ion flux indicates that the probe was close to the acceleration region (see
subsection 5.1 in Discussion).

### 4.2. Dynamics at \(-10 < X < -8 R_E\)

Figures 10 and 11 present observations in the near-Earth plasma sheet at P3 (\(X = -9.3 R_E\)) and P4 (\(X = -8.0 R_E\)) between 0140:00 and 0205:00 UT. Note that for P3 and P4
\(\Phi = 0\) corresponds to the anti-Sunward and 90 - to the dawnward looking directions. Both
probes observed a continuous increase of \(B_x\) until a rapid decrease at 0154:30 UT (P4)
and 0155:30 UT (P3), i.e., around the second (major) auroral onset. \(B_y\) and \(B_z\) at both
probes experienced minor variations starting at 0148:30 UT. \(B_y\) at both probes rapidly
decreased along with \(B_x\) at around 0155 UT, when \(B_z\) began fluctuating and,
on average, increased. The dipolarization and drops of \(B_x\) and \(B_y\) were accompanied by
rapid ion and electron energization, a step-like increase of the plasma density, and a burst
of ion bulk velocity mainly dawnward and southward at P3 and dawnward and tailward
at P4. The corresponding anisotropy of the ion thermal flux is clearly seen in ESA ion
energy-phi spectrograms. These observations may be interpreted as signatures of current
disruption, observed in the near-Earth plasma sheet. It seems to be associated with
the second (major) auroral onset, which happened about 6 min after the first auroral
activation and first dynamic signatures, observed at \(X = -17 R_E\). Since the drop of the
magnetic field and the plasma pressure jump were detected first by P4, then by P3, this front propagated tailward (see Figure 4) at a velocity of 150 km/s.

Notable features, common for P3 and P4 observations between the two onsets, should be highlighted. 1) the plasma and total pressure were gradually decreasing starting at the first onset, while the magnetic pressure was gradually increasing. 2) the plasma density decreased starting at about 0152 UT until the step-like increase. This density decrease is also seen in ion and electron spectrograms. The density decrease was preceded by a local increase of the super-thermal ion flux, visible in SST Φ-spectrograms, with a spectral maximum gradually shifting from 0 (360° to 180°, the latter corresponds at P3 and P4 to Earthward flowing ions). It is also worth noting a tailward (0°) ion beam detected by SST aboard P4 at 0153:00 UT, corresponding to local variations of the magnetic field, plasma and total pressures.

Figure 12 presents magnetic field measurements at P3 and P4 in the field-aligned frame along with magnetic field variations measured by two geosynchronous satellites GOES-10 and GOES-12 in the PEN coordinate system. The two dashed bars mark the first and second onsets. The main magnetic field ($B_{facz}$) at P3 and P4 grew continuously until the second (major) onset, while the behavior of $B_{facx}$, directed vertically, and $B_{facy}$, directed duskward along $Y_{GSM}$, changed at around the first onset. Namely, $B_{facy}$ at both probes experienced a positive (i.e., duskward) variation with an amplitude of about 7 nT between the two onsets. This variation may be interpreted as a signature of a field-aligned current (FAC) sheet underneath the probes. The sign of variation suggests the anti-parallel direction of the current, i.e., outward FAC. $B_{facx}$ started wiggling without a
pronounced growth at the first onset, and exhibited a large positive variation up to 20 nT (dipolarization) starting at the second onset.

GOES-10, mapped to the ionosphere close to P3 and P4 (Figure 1), started detecting a large-amplitude (up to 27 nT), two-peak variation of the eastward component \( B_n \) of the magnetic field at about 0148:45 UT (first onset). Again, interpreting the eastward \( B_n \) variation as a signature of outward FAC, flowing above the satellite, the pair of P3/P4 and GOES-10 were bracketing the FAC in the north-south direction. The earthward component, continuously increasing prior to the first onset, also exhibited significant variations, first a transient decrease, coinciding with the first maximum of \( B_n \), then an increase, followed by a decrease, coinciding with the second maximum of \( B_n \). No significant variations of the polar \( B_p \) were detected until the dipolarization at the second (major) onset.

GOES-12, mapped about 10° westward of GOES-10, detected a rather minor variation of \( B_n \) about 20 s after the first onset. A drop of \( B_e \) and strong dipolarization, accompanied by large-amplitude variations of \( B_n \) were detected by GOES-10 and GOES-12 roughly simultaneously at the second onset.

4.3. Timing of observed signatures

Table 2 summarizes timing of the observed signatures. The very first indication of an activity was observed by P2 (event #1 in Table 2), located at \( X=-17.4 \) R\(_E\) at 0148:25 UT, i.e., 17 s prior to the minor auroral intensification detected by the all-sky camera at GBAY (event #4). Spacecraft, located in the near-Earth plasma sheet, detected signatures of an upward FAC (event #3) a couple of seconds prior to the minor auroral intensification.

The second, major, intensification, observed at KUUJ (event #17) was associated with the dipolarization and the current reduction, observed at geostationary orbit (events #10,
(events #11, 14, 17). The tailward flow, accompanied by significant magnetic field variations, was observed by P2 at $X=-17.4$ (event #12) and by P1 at $-22.7 R_E$ (event #15) roughly simultaneously with the dipolarization at $X=-8 R_E$, suggesting independent processes acting in the near-Earth and mid-tail plasma sheet.

5. Discussion

Before the discussion, it is important to remember that the main aim of this work is to establish the precise timing of the observed signatures, and locate the first indication of the activity in the magnetotail. All the observations suggest a possible scenario of the activity development, which is described at the end of the Discussion.

5.1. When and where did the activity start?

The analysis of in-situ measurements reveals that the first indication of the activity in the plasma sheet was detected by P2 at $X=-17.4 R_E$ about 20 s prior to the minor auroral intensification and the onset of Pi2 pulsations, detected on the ground. It should be noted, however, that according to the T96 model, P2 mapped eastward of GBAY, where the first auroral brightening was detected (Figure 1). Application of the event-oriented magnetic field model [Kubyshkina et al., 1999] does not change the longitudes of the spacecraft foot points, but shifts their latitudes $\approx 2$ degrees equatorward. Thus the 20 s delay should be treated with the caution: it is a time delay between the energetic particles' burst arrival in the field of view of the detector aboard P2 and the aurora appearance in the field of view of the GBAY all-sky camera. The activity in the plasma sheet might start earlier than its signatures were detected by the spacecraft.
Activated prior to the first minor onset, the plasma sheet at $X = -17 - 23 \, R_E$ remained in an active state (see Figures 6 and 7). Thus the time of the first activity indication, detected by P2, gives a rough estimate of when the plasma sheet became activated and may be adopted as the time-zero of the entire event, including both onsets.

The first indications of the activity observed by P2 (see Table 2, #1, 2) were the enhancement of the bi-directional (0 and 180° PA) flux of the energetic ($E > 30$ keV) electrons and the appearance of a tailward-directed super-thermal ion flux. The inverse velocity dispersion (IVD) was observed during the tailward burst of high-energy ions: the enhancement of the 60 keV ion flux was detected about 20 s earlier than that of the 200 keV ions. The IVD of high-energy ion bursts is a frequently observed phenomenon in the distant magnetotail [e.g., Sarris et al., 1996]. Also, observations of the energetic ion IVD in the near-Earth plasma sheet were reported [Lui et al., 1988]. Two alternative explanations of the IVD were suggested: 1) a spatial model [Sarafopoulos and Sarris, 1988], implying that the spacecraft cross the plasma sheet toward the plasma sheet boundary layer (PSBL) in the vicinity of X-line (low energy ions are carried deeper inside the PS, while higher-energy ones remain on the outer lines on the PSBL); 2) a temporal model [e.g., Taktakishvili et al., 1993], suggesting particle acceleration by an inductive electric field in the course of magnetic reconnection (tearing mode instability). It was shown that particles of higher energy are “born” in a later stage of the instability development than smaller-energy ones [Taktakishvili et al., 1993]. Since in our case the ion IVD was observed deep inside the plasma sheet (see Figures 7 and 8), the temporal explanation seems more suitable. The model gives us the possibility to make a quantitative estimation of the distance between the acceleration region (AR) and the spacecraft location. Let us assume
that all ions are protons and the length of the AR is of \(10^1/\omega_{pi}=7210\) km \((n_i=0.1\ \text{cm}^{-3})\) [e.g., Pritchett, 2001]. Setting an instability growth time equal to the time between the onset of the flux increase and the flux maximum \((\approx30\ \text{s}, \text{see Figure 8})\), \(B_0=40\ \text{nT},\ \ \ b_{0z}=B_z(t_s)/B_0=0.25\), where \(t_s\) is an instance of the maximum flux, and using equation (14) of Taktakishvili et al. [1993], we obtain the estimation of the critical distance from the source, within which the IVD may persist, \(S_c=5\ R_E\). Comparing the lag time between the flux maxima of 60 and 200 keV ions \((\approx20\ \text{s})\) with the model calculations [Fig. 3 in Taktakishvili et al., 1993], the distance between the AR and the probe is estimated to be about \(1 - 3\ R_E\). Thus the activity started at \(X \approx-15\ R_E\). Observed signatures of the Hall-related magnetic field and the electron inflow, mentioned above, suggest collisionless magnetic reconnection as a driver of the activity. Since no Earthward flow was observed, reconnection, if any, was strongly transient: no quasi-steady tailward retreating X-line was formed.

5.2. What happened in the near-Earth plasma sheet?

The observations at the two near-Earth THEMIS probes (P3 and P4) and at the geosynchronous satellites show a continuous increase of the magnetic field until the onset of major activation (substorm). Both THEMIS probes were above the neutral sheet, at the \(B_x\)-level of \(40\ \text{nT}\). This may explain why no distinct signatures of an earthward outflow, expected from reconnection, were observed by P3/P4: the earthward flow might be collimated in a narrow flow channel in the vicinity of the neutral sheet. Alternatively, the earthward outflow might be broken at larger geocentric distances.

Transient FAC signatures with a pattern similar to a localized current wedge, i.e., FAC out of (into) the ionosphere at the dusk (dawn), can be observed at the leading edge of
the fast flowing plasma [e.g., Sergeev et al., 1996a]. Shear in the magnetic fields and flows between the leading edge region and the main body of the fast flow produces an FAC.

Simultaneous in-situ and ground-based observations support this current wedge pattern associated with bursty flows [Kauristie et al., 2000; Grocott et al., 2004]. The FAC region on the duskside of a bursty bulk flow, where the current is flowing out of the ionosphere, has been identified consistently with the electron precipitation region in auroral images [Nakamura et al., 2001b; Sergeev, 2004]. In our case, the outward FAC was detected by P3, P4, and GOES-10 between the first intensification and the substorm onset (Figure 12, Table 2, #3). Since the FAC started to be observed about 6 min before the increase of $B_z$ (dipolarization) and decrease of $B_x$, it can not be attributed to the current wedge [McPherron et al., 1973; Hesse and Birn, 1991]. P3, P4 and GOES-10 were located in the duskward sector and mapped westward of the initial auroral intensification. These FAC signatures may be hypothetically interpreted as a remote sensing of the Earthward fast flow resulting from reconnection [Nakamura et al., 2001b, 2004a]. (Note that this interpretation does not imply that the Earthward fast flow reached $X \approx -8 R_E$, where the FAC was detected; see Fig. 7 in [Nakamura et al., 2001b].)

Signatures observed by P3 and P4 at around the second (major) onset, including first a plasma density and pressure decrease, then a rapid jump-like increase, dipolarization and reduction of the magnetic field simultaneously with bursty ion and electron energization, may be interpreted in terms of the cross-tail current reduction or disruption (CD) [Jacquey et al., 1991, 1993; Ohtani et al., 1992]. Note that the term “CD” is used to describe the observed complex of signatures without a reference to any particular CD model. The aforementioned density decrease may indicate thinning of the current/plasma sheet prior
to the CD. The dipolarization first was detected by GOES-12, mapped onto the field of view of SNKQ (Figure 1), where the substorm onset was observed, then, roughly simultaneously, by GOES-10 and P4 and, finally after about 40 s, by P3. Therefore, the dipolarization expanded azimuthally and tailward. The plasma pressure jump was observed first by P4, then by P3. Thus the pressure front propagates tailward at a velocity of 150 km/s, which is consistent with the previous CD observations [Jacquey et al., 1993] but larger than the reported velocity of tailward retreat of a dipolarization [Baumjohann et al., 1999]. The tailward flow, detected by P1 and P2 roughly simultaneously with the CD, was generated by the local source, presumably reconnection acting independently from the CD.

5.3. A scenario

According to the integrated brightness from ground-based images (Figure 2) the first intensification may be interpreted as a precursor of the second, major, intensification (substorm). The precursor onset was most likely caused by magnetic reconnection on closed field lines, creating tailward (detected by P2 and P1) and Earthward (missed) outflows. The FAC, detected by P3, P4, and GOES-10 may hypothetically indicate the presence of the Earthward outflow from the reconnection site. The earthward flow, broken between \( X = -15 \) and \(-10 \, R_E \), may lead the magnetic field pile-up and trigger an instability in the near-Earth plasma sheet [Haerendel, 1992; Shiokawa et al., 1998]. If the plasma/current sheet was thinning prior to the CD (the density decrease) then an instability, triggered by the Earthward flow, seems more adequate than the pile-up effect only. The jump-like increase of the plasma pressure indicates a non-linear evolution that predicted by the coupling model of a near-earth breakup based on the nonlinear ballooning instability.
triggered by an Earthward fast flow [Voronkov, 2005]. More comprehensive data analysis
and modeling, exceeding the scope of the present work, are needed to define the exact
mechanism of the instability causing the major auroral intensification.

6. Conclusions

We have analyzed simultaneous spacecraft and ground-based observations during two
successive auroral intensifications: minor (pseudo-breakup) and major (substorm) de-
tected in 6 min. The data from the tail-aligned THEMIS constellation and the geosyn-
chronous satellites were used. The main results of the data analysis are the following:

1. The observed pseudo-breakup was caused by a dynamic process generating the in-
ductive electric field at $X \approx -15 R_E$. The first signature of the activity in the magnetotail
plasma sheet was observed at $X = -17.4 R_E$ about 20 s prior to the auroral intensification.
The character of the observed tailward bursty bulk flows, associated magnetic field vari-
ations, and the particle behavior suggest transient magnetic reconnection as the source.
The activity in the mid-tail plasma sheet started earlier than that in the near-Earth
plasma sheet.

2. The substorm onset detected 6 min following the pseudo-breakup was associated
with the rapid reduction of the cross-tail current, the magnetic field dipolarization, and
the jump-like increase of the plasma pressure, observed in the near-Earth plasma sheet at
$-9.4 \geq X \geq -6.6 R_E$.

3. Signatures of the field-aligned current were observed in the near-Earth magnetotail
between the pseudo-breakup and substorm. These signatures are hypothetically inter-
preted as a remote sensing of the transient Earthward flow, resulting from reconnection.
This interpretation suggests that the instability in the mid-tail plasma sheet (reconnection) triggers the subsequent cross-tail current reduction (disruption), observed in the near-Earth plasma sheet.

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References


Jacquey, C., J.-A. Sauvaud, and J. Dandouras (1991), Location and propagation of the magnetotail current disruption during substorm expansion: analysis and simulation of


Figure 1. THEMIS all-sky camera observations at 0148:50 UT (minor intensification) and at 0154:30 UT (major intensification) on March 1, 2008. Foot points of THEMIS probes, GOES-10 and GOES-12 are shown by circles, asterisk, and plus, respectively.
Table 1. Geomagnetic coordinates and timing of minor (4th column) and major (5th column) onsets observations

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Minor Onset</th>
<th>Major Onset</th>
</tr>
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<tbody>
<tr>
<td>GBAY</td>
<td>60.73</td>
<td>23.08</td>
<td>01:48:42</td>
<td>01:55:36</td>
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<tr>
<td>KUUJ</td>
<td>66.89</td>
<td>13.23</td>
<td>01:48:51</td>
<td>01:55:21</td>
</tr>
<tr>
<td>CHBG</td>
<td>59.57</td>
<td>3.62</td>
<td>01:49:39</td>
<td>01:56:33</td>
</tr>
<tr>
<td>SNKQ</td>
<td>66.45</td>
<td>356.99</td>
<td>01:50:54</td>
<td>01:52:27</td>
</tr>
<tr>
<td>GILL</td>
<td>66.18</td>
<td>332.78</td>
<td>01:51:18</td>
<td>01:54:21</td>
</tr>
<tr>
<td>TPAS</td>
<td>63.27</td>
<td>323.80</td>
<td>01:51:21</td>
<td>01:54:30</td>
</tr>
</tbody>
</table>

Figure 2. Integrated brightness of all-sky camera images at several stations from East (bottom) to West (top).
Figure 3. From top to bottom: GSM components of the solar wind bulk velocity, solar wind dynamic pressure, \( X \) (blue), \( Y \) (green), and \( Z \) (red) GSM components of the magnetic field from the WIND spacecraft (time shifted using the solar wind velocity and the distance between WIND \( X=198.6 \) RE and \( X=0 \)); Magnetograms (components and band-pass filtered X-component) from GBAY, DRBY, LOYS, KUUJ, and CHBG stations. Here and in the other figures dashed vertical bars mark the time of the two auroral onsets (events \#4 and \#16, see Table 2).
Figure 4. THEMIS and GOES 10 and 12 spacecraft positions (GSM) at 0150 UT on March 1, 2008
Figure 5. Spin-averaged (3s) magnetic field and ion velocity (GSM) observed by THEMIS P1 - P4, and the magnetic field (PEN) observed by GOES 10 and GOES 12 satellites during 0100 - 0210 UT on March 1, 2008. Note that the $B_n$ component is eastward in the PEN coordinate system.
Figure 6. Summary of P1 (THEMIS B) observations between 0140 - 0205 UT. From top to bottom: GSM components of the magnetic field; Omnidirectional ion ET spectrogram from SST (30 - 500 keV); Omnidirectional ion ET spectrogram from ESA (0.1 - 30 keV); Φ-angular ion spectrogram from SST (Φ is the azimuth of the detector looking direction in the probe spin plane, see text for the details); Φ-angular ion spectrogram from ESA; Ion number density, ion bulk velocity, and ion scalar pressure (all three quantity are calculated from ESA and SST distributions); Omnidirectional electron ET spectrogram from SST (30 - 500 keV); Omnidirectional electron ET spectrogram from ESA (0.05 - 30 keV). Vertical bars indicate the two auroral onsets (events #4 and #16, see Table 2).
Figure 7. Summary of P2 (THEMIS C) observations between 0140 - 0205 UT. The same format as in Figure 6.
Time-angular spectrograms of super-thermal (SST, 30< \( W < \) 500 keV) and thermal (ESA, 1< \( W < \) 21 keV) ions and normalized fluxes within 160° < \( \Phi < \) 214° (tailward-streaming) at specified energies at THEMIS P2 (a) and P1 (b). The dashed vertical bar in panel a) marks the first auroral onset (event #4, see Table 2).
Figure 9. Magnetic field components (upper panel) and electron pitch-angle distributions at energies $E > 30$ keV (SST), $0.5 < E < 21$ keV and $E < 0.5$ keV (ESA), collected around the first onset marked by the dashed vertical bar (event #4, see Table 2) at P2 (LHS column) and P1 (RHS column).
Figure 10. Summary of P3 (THEMIS D) observations between 0140 - 0205 UT. The same format as in Figure 6
Figure 11. Summary of P4 (THEMIS E) observations between 0140 - 0205 UT. The same format as in Figure 6
Figure 12. The magnetic field at P3 (red) and P4 (blue) in the field-aligned coordinate system; magnetic field variations observed by GOES 10 and GOES 12, PEN coordinate system: $B_p$ is directed poleward, $B_e$ - Earthward, and $B_n$ - eastward.
Table 2. Timing of the signatures, observed by the four THEMIS probes (P1, P2, P3, and P4), GOES 10 (G10) and GOES 12 (G12) satellites, and by ground based observatories (GBO)

<table>
<thead>
<tr>
<th>#</th>
<th>UT</th>
<th>SC/GBO</th>
<th>signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0148:25</td>
<td>P2</td>
<td>high-energy electron flux increase</td>
</tr>
<tr>
<td>2</td>
<td>0148:25</td>
<td>P2</td>
<td>$\sim$65 keV ion flux increase</td>
</tr>
<tr>
<td>3</td>
<td>0148:40</td>
<td>P3, P4, G10</td>
<td>$dB_y$ (FAC)</td>
</tr>
<tr>
<td>4</td>
<td>0148:42</td>
<td>GBAY</td>
<td>minor auroral onset (precursor)</td>
</tr>
<tr>
<td>5</td>
<td>0148:45</td>
<td>GBAY</td>
<td>Pi2 onset</td>
</tr>
<tr>
<td>6</td>
<td>0148:45</td>
<td>P2</td>
<td>$dBy$ and $dBz$</td>
</tr>
<tr>
<td>7</td>
<td>0148:50</td>
<td>P2</td>
<td>Tailward flow</td>
</tr>
<tr>
<td>8</td>
<td>0149:30</td>
<td>P1</td>
<td>Tailward flow, $dB_y$, and $dB_z$</td>
</tr>
<tr>
<td>9</td>
<td>0152:21</td>
<td>SNKQ</td>
<td>Auroral onset</td>
</tr>
<tr>
<td>10</td>
<td>0153:30</td>
<td>G12</td>
<td>Dipolarization</td>
</tr>
<tr>
<td>11</td>
<td>0154:20</td>
<td>G10, P4</td>
<td>Dipolarization</td>
</tr>
<tr>
<td>12</td>
<td>0154:30</td>
<td>P1</td>
<td>Tailward flow</td>
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<tr>
<td>13</td>
<td>0154:30</td>
<td>P2</td>
<td>$dB_y$, $dB_z$</td>
</tr>
<tr>
<td>14</td>
<td>0154:40</td>
<td>P4</td>
<td>Drop of $B_t$, $dV_y$, and $dV_z$</td>
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<tr>
<td>15</td>
<td>0155:00</td>
<td>P2</td>
<td>Tailward flow</td>
</tr>
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<td>16</td>
<td>0155:21</td>
<td>KUUJ</td>
<td>Auroral onset</td>
</tr>
<tr>
<td>17</td>
<td>0155:50</td>
<td>P3</td>
<td>Dipolarization, drop of $B_t$, $dV_y$ and $dV_z$</td>
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</tbody>
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