Observations of kinetic ballooning/interchange instability signatures in the magnetotail

E. V. Panov,1 V. A. Sergeev,2 P. L. Pritchett,3 F. V. Coroniti,4 R. Nakamura,5 W. Baumjohann,1 V. Angelopoulos,6 H. U. Auster, and J. P. McFadden6

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1 Stimulated by a recent study of a kinetic ballooning/interchange instability by Pritchett and Coroniti [2010], we present THEMIS events that confirm the predictions of this mechanism. In these events the probes were situated in the plasma sheet at 11 Re, near the presumed location of a B minimum. Prior to substorm onset, they observed strong magnetic oscillations with periods 20–100 s and \( \delta B_x \) about 10–20 nT. Associated with these were oscillations of the electric field \( \delta E_y \sim 1 \) mV/m and the field-aligned electron velocity of several hundreds of km/s. No comparable perturbations in the ion velocity were observed. For two cases cross-correlation analyses proved duskward propagation of the elongated spatial structures with a cross-tail width of a few ion gyroradii and a propagation velocity of about the ion drift velocity. In one case THEMIS probes confirmed a sausage-like geometry of the structures.

2 Although reconnection is the major explosive energy dissipation mechanism during substorms [see, e.g., Miyashita et al., 2009], substorm onset triggering and location are still debated. It has been argued, for example, that the onset may be initiated in thin current sheets around 15–30 Re, or by a current disruption instability (CDI) between 6 and 10 Re [see, e.g., Ohtani, 2004].

3 Even though the region between 10 and 15 Re has been sparsely explored, it may be of major importance for substorm onset triggering. Saito et al. [2010] presented evidence of local magnetic field minimum formation in the equatorial region near 11 Re at the end of a substorm growth phase. A configuration with such a minimum in the equatorial plane contains a tailward gradient of \( B_z \) and may be unstable to a kinetic ballooning/interchange instability (BICI), amongst others [Pritchett and Coroniti, 2010, hereinafter PC2010]. Such an instability may generate azimuthally-localized, dipolarization-like intrusions of underpopulated plasma tubes into the inner magnetosphere and may provoke reconnection onset [Pritchett and Coroniti, 2011].

4 Ballooning/interchange processes have long been substorm onset instability candidates [Roux et al., 1991; Cheng and Lui, 1998]. As yet, however, there is no consensus about their physics, intensity, and significance for auroral breakup and reconnection onset. The clearest observational support comes from observations of azimuthally-spaced auroral forms (AAF) activated during breakup initiation. The mode numbers lie in a wide range, between 30 and 135 according to Elphinstone et al. [1995] and between 100 and 300 according to Liang et al. [2008]. Both westward and eastward propagations were reported, and azimuthal structuring was found both prior to breakup and during its initial stage [Elphinstone et al., 1995; Uritsky et al., 2009], giving the impression that different modes can contribute to this wide class of AAFs.

5 So far it has been difficult to identify ballooning perturbations using in situ observations during the turbulent dipolarization that accompanies breakup because of the complexity and mix of different perturbations during that time. Recently, Baumjohann et al. [2007] and Saito et al. [2008] reported that plasma sheet oscillations observed before breakup and dipolarization may be produced by a ballooning/interchange instability.

6 The THEMIS [Angelopoulos, 2008] probes clustered at around 10–12 Re (P3, P4, P5) make it possible for us to directly investigate cross-tail size and propagation velocity. We also have collected more evidence of the kinetic nature of ballooning/interchange perturbations and discuss their consistency with BICI signatures. To emphasize the generality of our results, we illustrate three previously published events. We use observations from the three near-Earth probes (P3, P4, P5); during 2008 P3 and P4 moved along nearly the same orbit and near their apogee at \( \sim 12 \) Re were separated by 0.8 Re mostly in Y (or by \( \sim 0.2 \) h MLT). This separation is favorable for studying cross-tail structure and wave propagation. We use observations provided by the FGM [Auster et al., 2008], ESA [McFadden et al., 2008], and EFI [Bonnell et al., 2008] instruments.

2 Signatures of Kinetic BICI From PC2010 Run

7 Figure 1 shows field and plasma parameters from the PC2010 particle-in-cell run simulating a kinetic ballooning/
interchange instability with mass ratio $m_i/m_e = 64$ in a tail-like configuration. There was used a box with $256 \times 512 \times 256$ points along the X (tailward), Y (dawnward), and Z (northward) axes. The equatorial field profile ($B_Z$) was chosen to have a minimum between $x = 32$ and 96. Correspondingly, the tailward gradient of $B_Z$ was initially set up between $x = 96$ and 224.

The results shown in Figure 1 are the time averaged quantities over three electron cyclotron periods in order to remove the high-frequency noise in the simulation. They correspond to simulation time $\Omega t = 37.5$ when the instability is still in the linear stage. Figure 1a shows the (x, z)-cut of the electric field Y-component at $y = 464$. The white lines are magnetic field lines. As mentioned in PC2010, this electric field structure makes clear that the electron flow in the simulation is almost entirely field aligned, demonstrating that the BICI mode is a non-local mode in which significant kinetic ion and electron effects (bounce and drift resonant interactions) are present which are not included in an MHD treatment.

Figure 1b shows an (y, z)-cut of perturbations produced by BICI in the $B_X$ magnetic field component at $x = 130$ (slightly tailward of $B_Z$ minimum, as marked by the star showing the location of a virtual spacecraft at $x = 130$, $z = -50$ in Figure 1a). The perturbations are absent across the neutral sheet, so the mode at this cross-section is mostly confined to the off-equatorial part of the plasma sheet. The peaks above and below the neutral sheet either both increase or both decrease the field, revealing a sausage-like finger structure produced by the kinetic BICI. The perturbations produced by the BICI in $B_X$ and the other fields drift duskward at about one tenth of the ion thermal speed. Due to this drift the Y-profile of perturbations in Figure 1 is nearly equivalent to a temporal plot of parameters that would be observed by a magnetospheric spacecraft.

Figures 4c–4f show Y-cuts of the basic parameters, suggesting duskward propagation of the entire pattern (as observed in simulations); these plots can be directly compared with temporal variations observed in the magnetotail. Note that since at $z = 0$ the density is constant on the scale of the BICI wavelength and is also much larger than at $z = -50$, we do not show it in this figure. The oscillations in the magnetic field components $\delta B_X$ and $\delta B_Z$ are in phase; those in the electric field $E_Y$-component are phase shifted by $\pi/2$. The $E_Y$ oscillations are, however, in phase with the $X$-component of the electron velocity (Figure 1g), which is the largest of the three $U_e$ components and not accompanied by comparable ion velocity variation. Strong $\delta B_X$ (compressional) and $\delta N_e$, together with phase-shifted $\delta E_Y$ and $\delta U_{eX}$, reveal distinctive BICI signatures in the cross-section near the $B_Z$ minimum, and the structure of BICI fingers cross-tail-drifting in the westward direction. Note that similar signatures were seen during the non-linear stage of the instability development also (see Pritchett and Coroniti [2010] for details).

3. THEMIS Observations of Oscillations Resembling Kinetic BICI Signatures

Figure 2 shows THEMIS probe (P3, P4, and P5) observations on 11 February 2008 between 4:24 and 4:30 UT. The probes were clustered at radial distances between 9.8 and 10.8 RE downtail. As shown by Sergeev et al. [2012], auroral intensification onset at 04:27:08 UT was accompanied by azimuthal striations and was followed by explosive auroral brightening $\sim$10 seconds later, at 04:27:18 UT. At 04:27:30 UT P4 started to observe a fast flow burst and dipolarization. The time delay between observations at P4 and P5 suggests that the associated dipolarization propagated earthward. The probes were located within 1 hour MLT eastward of the auroral breakup arc.

This substorm onset followed 2 min-long strong field and plasma oscillations (period about 20 seconds) observed by P3 and P4 after 04:25:30 UT. Figure 2b shows that the oscillations’ amplitudes in the $X_{GSM}$ magnetic field component reached 20 nT at P4. P4 was located between P3, which was in the plasma sheet boundary layer, and P5, which was
in the central plasma sheet. It is interesting that the oscillations at P5 (i.e., in the neutral sheet) did not exceed 2 nT. This suggests that the current sheet oscillations could be sausage-like (i.e., balloons) rather than flap-like structures (i.e., kinks). The oscillations in the perpendicular $Y_{\text{GSM}}$ (not shown) and $Z_{\text{GSM}}$ magnetic field components are one order of magnitude smaller than in the field-aligned $X_{\text{GSM}}$ magnetic field component. The $B_X$-oscillations were accompanied by phase-shifted electric field oscillations with the major $E_Y$-component (Figure 2d), such that $E_Y \sim -\partial B_x/\partial t$ (not shown here).

[13] The intense $B_X$ and $E_Y$ oscillations are typical of the kinetic BICI suggested in PC2010. Another signature of this instability is the oscillating $X_{\text{GSM}}$ electron velocity component unaccompanied by corresponding ion velocity oscillations (see Figure 2e). The electron velocity oscillations were in phase with the oscillations in $E_Y$. It is important to note that the electron velocity oscillations along the X-axis are entirely field aligned (dashed and solid blue curves in Figure 2e repeat each other between 4:26 and 4:27 UT). The oscillations’ amplitude in $V_Y$ was much smaller than in $V_X$. The peak magnitude of $V_Z$ appeared to be comparable to that of $V_X$. The electron velocity peaked at about 300 to 600 km/s, i.e., at up to 50% of the thermal ion velocity $V_{Ti}$ ($V_{Ti} \approx 1200$ km/s for $T_i \approx 8$ keV). The corresponding field-aligned current densities could reach $40–50$ nA/m$^2$. The strong peaks in electron $V_X$ with amplitudes comparable to $V_{Ti}$ are another essential signature of kinetic BICI (PC2010). A striking feature is that the ion velocity oscillations were one order of magnitude weaker than observed during the flow burst, which can be seen later at 4:28 UT. During the flow burst, ion and electron flows were associated with an intense flux transport and were equally fast. Good correlation between the $Z_{\text{GSM}}$-components of the $E \times B$-drift velocity and the ion velocity during the oscillations (magenta and green curves in Figure 2g) confirms good ion-moment quality.

[14] Figure 3 presents a much longer oscillation event on 28 February 2008 between 7:12 and 7:38 UT (the oscillations started at about 7:00 UT, not shown here). The
observations at P4 (red line) were shifted in time by 50 seconds to highlight the similarity of curves at P3 and P4. Figures 3a and 3b show anti-correlated oscillations of the electron density and the $X_{GSM}$ magnetic field component with a period of $\frac{100}{24}$ seconds observed by P3 and P4. Figures 3c–3e show nearly the same BlCl signatures as the observations in Figure 2: smaller-amplitude oscillations in $B_Z$ and large oscillations in $E_Y$ (Figures 3c and 3d). Figure 3e also shows similar oscillations in the $X_{GSM}$-component of the electron velocity, without comparable ion velocity oscillations (for better visibility we do not show the ion velocity). The electron velocity components have been time averaged over 5 probe spins (15 seconds) to remove high-frequency thermal noise.

[15] In this event, a substorm onset was identified at about 07:34 UT as onset of Pi2 waves and current wedge formation on the ground, together with strong oscillations at GOES-11 (at $\sim 22.5$ h MLT).

[16] There are several notable new features. First, the spiky appearance of the oscillations in the $X_{GSM}$-component of the electron velocity and the $Y_{GSM}$-component of the electric field is correlated with the asymmetric (sawtooth) shape of the magnetic field oscillations (steeper rises and sloping drops in $B_X$). This correlation also highlights the synchronization between the negative $E_Y$ peaks and the positive $V_X$ peaks.

[17] Second, the long duration of the oscillations and different locations of P3 and P4 with respect to the neutral sheet allowed us to see that spiky $E_Y$, $V_X$ and density oscillations were substantially weaker both near the neutral sheet (large density $\sim 0.6$ cm$^{-3}$ and small $|B_X|$ amplitude) and in the lobes (density was below 0.4 cm$^{-3}$ and $|B_X|$ exceeded 30 nT). We indicated the region of largest oscillation amplitudes between the plasma sheet center and its outer edge with a green rectangle in Figures 3a and 3b.

[18] Third, in this event P3 and P4 were separated by 5950 km mostly along the $Y_{GSM}$-axis. Long-lasting oscillations allowed us to compute the cross-correlation of the signals from P3 and P4, which gave a distinct peak at 50 seconds and indicated duskward propagation at a velocity of about 120 km/s. The characteristic cross-tail scale for the half-period of $T = 50$ seconds is then 6000 km.

[19] Using the AM-03 model [Kubyshkina et al., 2011] it was shown that the oscillations on 11 February 2008...
and on 28 February 2008 were observed in the stretched parts of the magnetotail, which were nearly horizontally oriented in the GSM coordinates [Sergeev et al., 2012; E. V. Panov et al., Kinetic ballooning/interchange instability in a bent plasma sheet, submitted to Journal of Geophysical Research, 2012].

Figure 4 shows THEMIS observations on 5 March 2008. Similar oscillations were found after 5:50 UT and before the auroral breakup at 06:04 UT. This event was reported by Uritsky et al. [2009], who focused on conjugate ground all-sky camera observations of azimuthally-drifting auroral waves. They noticed a time shift between the oscillations at P3 and P4 and interpreted the oscillations as flapping (kink) waves propagating duskward at a velocity between 90 and 100 km/s. The character of these oscillations is similar to those in the events previously mentioned. The observations at P4 (red line) were shifted in time by 45 seconds to highlight the similarity of curves at P3 and P4. This assured us that the oscillations were a relatively long-lived spatial pattern drifting duskward. A 45 seconds time delay over cross-tail separation of 5500 km suggests a 120 km/s propagation speed (similar to that from the observations on 28 February 2008). The characteristic cross-tail scale for the $T = 38$ seconds half-period would then be 4500 km. The 5 March 2008 observations are also morphologically similar to those on 28 February 2008: in both events, THEMIS probes observed sawtooth-shaped $B_X$ oscillations and spiky $E_Y$ and $V_X$ patterns as well as confinement of the oscillations to a region between the neutral sheet and the boundary layer.

4. Discussion and Conclusions

[21] In this paper we show THEMIS observations of field and plasma oscillations at 11 $R_E$ prior to breakup. Detailed comparison of these observations with the PIC simulation run from PC2010 suggests that the oscillations grew during development of a kinetic ballooning/interchange instability. In particular, we find agreement regarding the strong dominance of the electron $V_X$ oscillations over the ion velocity oscillations; the general sausage character of the mode perturbations; and the frequency, wavelength, and duskward velocity drift of the oscillations. The oscillations drifted duskward at about 120 km/s, and their wavelengths were about nine to twelve thousand km, comparable to a gyroradius of 10 keV ion in $B \sim 2$ nT.

[22] Although we are unaware of any theoretical study which could suggest that similar signatures may appear during the development of another than the BICI instability, it is important to keep this possibility open.

[23] There are also several disagreements between the simulations and THEMIS observations. Whereas in
THEMIS observations $\delta B_x$ was observed to be very strong between the neutral sheet and the lobes (up to 50% of the lobe field), it did not exceed 5% of the lobe field in the PC2010 run. The amplitude of $\delta B_x$ may, however, depend on other parameters, such as the plasma beta and ion-to-electron mass ratio; this should be further investigated. Note that in the PC2010 run, a large value for the initial $B_z$ field was chosen because of numerical constraints.

[24] BICI growth is expected in the region of the tailward gradient of $B_z$ (PC2010). Such reversed $\partial B_z/\partial X$ can appear, e.g., tailward of a magnetic field minimum B at the outer edge of dipole-like magnetic field region [Saito et al., 2010]. Identification of such plasma sheet configurations with sparse spacecraft coverage is a challenge. Nevertheless, the $Z_{GSRa}$-component of the magnetic field was rather small, less than 1–2 nT at about 11 $R_E$ downtail. This is consistent with a larger magnetic field farther downtail (with a local minimum B at around 11 $R_E$) required to explain the large auroral oval width, $>50^\circ$ of the magnetic latitude. Although not a rigorous proof, this argument suggests that the assumption of a local magnetic field minimum is reasonable and would allow link observations with PC2010 simulation results.

[25] An important conclusion from our results is that the observed entirely field-aligned electron $V_x$ oscillations and decoupling of the electron and ion flows clearly demonstrate that the BICI mode contains features that cannot be explained by a fluid treatment and suggest that electron kinetics should not be neglected in future theoretical studies of ballooning/interchange instability in the Earth’s plasma sheet.

[26] Also, Pritchett and Coroniti [2011] have shown that under some circumstances the kinetic ballooning/interchange instability can provoke reconnection onset. As was demonstrated by Uritsky et al. [2009], Sergeev et al. [2012] and Panov et al. (submitted manuscript, 2012) in all the THEMIS events considered above, oscillations ended with a substorm onset. Although reconnection was observed in all three events, in the 28 February 2008 event the oscillations persisted over tens of ion gyroposters without a substorm onset, suggesting that the BICI does not always immediately lead to magnetotail reconnection. Therefore more realistic simulation runs of BICI should be compared with additional in situ observations of BICI to study the operational region, the growth conditions, different phases and non-linear effects of instability development, and how instability relates to substorm onset.

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