Ionospheric response to oscillatory flow braking in the magnetotail

E. V. Panov,1 W. Baumjohann,1 R. Nakamura,1 O. Amm,2 M. V. Kubyshkina,3 K.-H. Glassmeier,4,5 J. M. Weygand,6 V. Angelopoulos,6 A. A. Petrukovich,7 and V. A. Sergeev7

Received 15 August 2012; revised 26 December 2012; accepted 16 February 2013; published 11 April 2013.

We study the ionospheric response to oscillatory braking of bursty bulk flow observed by THEMIS on 17 March 2008 between 10:22 and 10:36 UT. By calculating different current components generated in the plasma sheet and correlating the space and ground observations, we discriminate the ionospheric current relevant to the large-scale substorm wedge currents produced by the general reconfiguration of the magnetotail pressure gradient from the currents that appeared as a result of the flow oscillation. While the former currents are large and quasi-stable, the latter (oscillating) currents are substantially (2–3 times) weaker and flow in opposite directions during earthward and tailward flow bursts. The oscillating currents include the polarization current and the current generated by the oscillating part of the pressure gradient. The two oscillating currents appear to produce modulation of the ionospheric currents (with about 2.5 min period) that was seen as Pi2 pulsations in the ground magnetometer observations. Our estimates of the ionospheric conductance suggest that the damping of the plasma sheet flow oscillation is due to heating the ionosphere through Pedersen currents. We also found that the all-sky imager at Fort Yukon observed four auroral forms during the first two periods of the oscillatory flow braking: two auroral forms related to the earthward plasma sheet flows and the other two auroral forms related to the tailward rebounds of the earthward flow. The auroral forms evolve in accordance with the appearance and motion of the upward field-aligned current spot of the modulated part of the ionospheric field-aligned current.


1. Introduction

Bursty bulk flows (BBFs), fast plasma flows inside the plasma sheet [Hayakawa et al., 1982; Baumjohann et al., 1989, 1990; Angelopoulos et al., 1992,1994], are often

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[3] Multi-spacecraft observations have revealed that BBFs occur in very localized channels only 2–3 R_E wide [Angelopoulos et al. 1996; Sergeev et al., 1996; Nakamura et al. 2004; Snekvik et al. 2007]. At around 10 R_E, BBFs are suddenly decelerated by the dominant dipolar magnetic field, and pressure gradients pile up, leading to a substorm current wedge [Haerendel, 1992; Shiokawa et al., 1997, 1998a, 1998b; Baumjohann, 2002; Birn et al., 1999, 2004; Ohtani et al., 2009] and substorm onset. As BBFs decelerate, they can oscillate [Semenov and Lebedeva, 1991; Chen and Wolf, 1999; Panov et al. 2010b; Birn et al., 2011].

[4] Vortices are created on both sides of these channels [Keika et al., 2009; Keiling et al., 2009b; Ugai, 2009; Panov et al., 2010a, 2010b; Birn et al., 2011], possibly due to nonlinear effects of the interchange motion [Guzdar et al., 2010; Runov et al., 2012].

[5] When BBFs arrive at the inner magnetosphere, the magnetotail may dipolarize [Nakamura et al., 1994; Schödel et al., 2001a, 2001b; Baumjohann, 2002; Nakamura et al., 2010a]. The field-aligned currents that are generated in the tailward flow are then transported to the field-aligned currents that are observed at the auroral latitudes [Runov et al., 2012]. They are believed to provide the magnetic flux transport in order to overcome the “pressure balance inconsistency” [Erickson and Wolf, 1980; Pontius and Wolf, 1990; Baumjohann, 2002].

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1Space Research Institute, Austrian Academy of Sciences, Graz, Austria.
2Finnish Meteorological Institute, Helsinki, Finland.
3Institute of Physics, St. Petersburg State University, St. Petersburg, Russia.
4Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Germany.
5Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, Germany.
6Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
7Space Research Institute, Russian Academy of Sciences, Moscow, Russia.

Corresponding author: E. V. Panov, Space Research Institute, Austrian Academy of Sciences, Schmiedstrasse 6, 8042 Graz, Austria. (evgeny_panov@mail.ru)

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2169-9380/13/10.1002/jgra.50190
It has been known that BBFs may lead to onset of Pi2 pulsations [Shiokawa et al., 1998b; Kepko and Kivelson, 1999; Kepko et al., 2001; Keiling and Takahashi, 2011]. There were also numerous observations of some auroral forms at the footprints of the magnetic field lines associated with BBFs [Elphinstone et al., 1995; Henderson et al., 1998; Lyons et al., 1999, 2011; Sergeev et al., 2000, 2001, 2004; Nakamura et al., 2001a, 2001b; Amm and Kauristie, 2002; Amm et al., 2011; Borodkova et al., 2002; Zesta et al., 2002; Kepko et al., 2004, 2009; Keiling et al., 2009a, 2009b; Frey et al., 2010; Panov et al., 2010a; Lui et al., 2010; Nishimura et al., 2010, 2011; Liang et al., 2011; Tang et al., 2012]. Rae et al. [2012] have shown that the amplitude of the ionospheric pulsations and the auroral brightness correlate, suggesting that the two processes are mutually linked. Some of these auroral forms were referred to as “auroral streamers” [e.g., Elphinstone et al., 1996; Sergeev et al., 1999; Nakamura et al., 2001b], and are suggested to appear in the Type I current wedge [Boström, 1964; Untiedt and Baumjohann, 1993; Birn and Hesse, 2005], i.e., where the forces act perpendicular to the long axis of the generator plasma and drive the generator current along the axis (e.g., by inertial forces) [e.g., Paschmann et al., 2002; Haerendel, 2010].

Note that while in some of these works space-born observations of the auroral forms were used (e.g., UVI images from Polar spacecraft) with resolution up to about 100 km, in the other works, there were ground-based all-sky imager (ASI) observations used with the field of view closer than about few hundred km from the location of the imager.

In this report, we employ THEMIS [Angelopoulos, 2008] probes (P1–P5) observations on 17 March 2008 between 10:22 and 10:36 UT to improve the understanding of the relation between the oscillatory flow braking, the ionospheric Pi2 pulsations and the appearance of the auroral forms in terms of the ionosphere-magnetosphere current loop. We use magnetotail observations provided by the magnetometer FGM [Auster et al., 2008], the particle detector ESA [McFadden et al., 2008], and ground-based observations provided by the THEMIS All-Sky Imager (ASI) and magnetometer (MAG) CANMOS, CARISMA, DTU, GIMA, MACCS, STEP, THEMIS, and USGS arrays over Greenland and North America [see Mende et al., 2008; Mann et al., 2008; Weygand et al., 2011, for details].

2. Observations

Figures 1a and 1b show the results obtained in [Panov et al. 2010b], where the oscillatory BBF braking was investigated, on 17 March 2008 just after 10:22 UT. The five THEMIS spacecraft observed the plasma sheet at XGSM between 9 and 13 R_E, and at YGSM between 2 and 5 R_E (cf. Figure 3 in [Panov et al. 2010b] for details). Figure 1a shows the radial pressure gradient (∂P/∂R) based on differences in the sum of the plasma and the magnetic pressure between P3 and P2. For the sake of better visibility, the higher-frequency fluctuations in ∂P/∂R were suppressed by averaging its value over a 45 s-long window, sliding with 3 s steps (one spacecraft spin). One can see that ∂P/∂R increased (decreased) nearly simultaneously with earthward (tailward) flows detected by P2 (see Figure 1b for radial ion velocity VR at P2) whose azimuthal location presumably was at the center of the BBF funnel and the radial location was near the equilibrium position of the bubble.

Figure 1c shows the time derivative of VR at P2, ∂VR/∂t. The oscillations in ∂VR/∂t are expected to produce polarization current Jp/∂R. Additionally, the oscillations in the radial pressure gradient are expected to generate corresponding pressure gradient current Jp/∂R [see, e.g., Haerendel et al., 1992; Paschmann et al., 2002; Haerendel, 2010]. These currents are generated perpendicular to the equatorial plasma sheet field Bz and flow azimuthally either duskward or downward depending on the sign of ∂VR/∂t and ∂(∂P/∂R) ≈ (see, e.g., Hasegawa and Sato, 1980; Keiling et al., 2009b; Lui et al., 2010) (not shown here). It appeared that these parallel currents would anti-correlate with the polarization current (as was suggested by Lui et al. [1999]).

To understand the general plasma sheet properties and to also link the plasma sheet observation of the BBF flow bursts to the ground-based ionospheric observations, we employed an adapted Tsyganenko model [Kubyshkina et al., 2009]; more exactly, the AM-03 version of the model, in which we used the total pressure measurements by P2 (at about 11 R_E downtail) as an estimate for the lobe magnetic field. Estimating the lobe magnetic field allows reconstruction of a thin current sheet [see Kubyshkina et al., 2011, for details]. Magnetic field measurements from the THEMIS probes were taken as input spacecraft data also. We applied the AM-03 model at 1 min cadence. A comparison of THEMIS magnetic field observations and the AM03 model results showed a good correlation.

Figure 1e shows the plasma sheet current density predicted by the AM-03 model at the neutral sheet at x = −8 R_E. One can see that during the oscillatory flow braking, the neutral sheet current density decreased from 2.5 to about 1.9 nA/m^2. One can also notice that this decrease was oscillatory rather than monotonic, similarly to the behavior of ∂P/∂R in Figure 1a.

Figure 1f shows the magnetic latitude of the footprint of the magnetic field line that was near P2. The footprint was found just near the coast northward of Fort Yukon (67.5°N MLat and 97.2°W MLon). One can see oscillations also in the magnetic latitude of the footprint. The amplitude of the oscillation was about 0.5°. One can also notice that the average footprint’s magnetic latitude drifted northward by about 15° within 10 min.
The all-sky imager at Fort Yukon observed enhanced total luminosity during the oscillatory flow braking shown in Figure 1g around 10:24:50 UT, 10:26:00 UT, 10:27:10 UT, and 10:28:50 UT (denoted by numbers 1–4). To calculate the total luminosity, we projected the camera observations at 110 km height with the field of view limited to about 500 km from the camera, and the corresponding elevation angle of about 12°. We note that because of cloudy weather at the other ASI sites, we are unable to identify if the onset arc appeared somewhere else.

Figure 1h shows the B_H magnetic field component measured during the BBF oscillatory braking at Fort Yukon. One can notice in these data similar characteristics previously found for V_R and ∂P/∂R. First, the ground oscillations had a similar period. Second, the oscillation amplitudes decreased with time. Also, there was a gradual decrease in

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**Figure 1.** (a) Radial pressure gradient ∂P/∂R between P3 and P2. (b) Radial velocity component at P2 with positive values in the Earth’s direction V_R. (c) Time derivative of the radial velocity component ∂V_R/∂t at P2. (d) Perpendicular plasma sheet current densities of the currents generated by oscillations in ∂P/∂R (j_t/pm), by ∂V_R/∂t (j_av), and their sum (j_t/pm + j_av). (e) Cross-tail current density at the neutral sheet at X_GSM=−8 R_E, and (f) magnetic latitude of the footprint of the magnetic field line at P2, as predicted by the AM-03 model. (g) Total luminosity at Fort Yukon in arbitrary units. (h) B_H magnetic field component from ground magnetometer at Fort Yukon. (i) Integral upward and downward SECS scaling factors, J.
Figure 2. (a) Cross-correlation coefficient between $V_R$ (shown in Figure 1b) and the oscillations in $J_{up}$ and $J_{down}$ (shown in Figure 1i) with periods between 20 and 200 s; (b) $V_R$, $J_{up}$, and $J_{down}$ (shifted by –35 s); (c) $V_R$ and the oscillations in $J_{up}$ and $J_{down}$ (shifted by –35 s); (d) Cross-correlation coefficient between $j_r(\rho P) + j_{\partial V/\partial t}$ shown in Figure 1d and the oscillations in $J$; (e) $j_r(\rho P) + j_{\partial V/\partial t}$ multiplied by an area of about $9 R_E^2$ and the oscillations in $J_{up}$ and $J_{down}$ shifted by ~50 s.

We further used the magnetometer arrays in order to obtain an estimate for the ionospheric currents using the 2D Spherical Elementary Current Systems (SECSs) method \cite{Amm, 1997, 1998; Amm and Viljanen, 1999; Weygand et al., 2011; Vanhamäki and Amm, 2011]. In this method, the divergence-free elementary current system is expanded at each pole of the grid shown in Figure 2 of \cite{Weygand et al., 2011}. This way, horizontal ionospheric equivalent currents (EICs) during the BBF oscillatory braking were derived. Using EICs, we also were able to calculate the vertical components of the curl of EICs integrated over each grid point area. We will call the vertical components "SECS scaling factors" because it is the amplitude of each elementary system that is scaled (measured in [A]). The SECS scaling factors are proportional to the field-aligned currents (FACs) if the gradient of the ionospheric conductance is parallel to the electric field direction \cite{Amm and Kauristie, 2002]. In this case, the factor of proportionality between FACs and the SECS scaling factors would be the Hall-to-Pedersen conductance ratio.

Figure 1i shows the total amount of upward (red, from here onward $J_{up}$) and downward (blue, from here onward $J_{down}$) SECS scaling factors observed around Fort Yukon (geomagnetic longitudes between 75 and 120°W and geomagnetic latitudes between 60 and 80°N). One can see that the upward and downward FACs may be after the initial rise period represented as a sum of two components: a slowly decaying part and an oscillating part.
Figure 3. (top) Total luminosity from Figure 1g shifted by ~50 s. (bottom) $j_{Vr} + j_{VA}$, from Figure 2e. Red (blue) rectangles show time intervals with positive (negative) values of $j_{Vr} + j_{VA}$.

$J = B_0 \exp(-t_0^2) + B_1 \exp(\omega t - t_1)$, where $t_0$, $t_1$, $B_0$, and $B_1$ are some constants, and $\omega$ is equal to $2\pi$ divided by the period of the oscillations (about 2.5 min).

[20] Figure 2a shows the cross-correlation coefficient between $V_R$ and the oscillations in $J_{up}$ and $J_{down}$ ($\delta J_{up}$ and $\delta J_{down}$) with periods between 20 and 200 s. Figure 2b shows $V_R$ (from Figure 1b), $J_{up}$, and $J_{down}$ in the same plot (where $J_{up}$ and $J_{down}$ are shifted by ~35 s). One can see now that the time scale is the same time near 10:23 UT. Also, Figure 2c shows $V_R$, and shifted by ~35 s $\delta J_{up}$ and $\delta J_{down}$. One can see that $\delta J_{up}$ and $\delta J_{down}$ rather closely repeat the shape of the $V_R$ curve. Figure 2d shows cross-correlation coefficient between $j_{VA} + j_{Vr}$ from Figure 1d, and $\delta J_{up}/\delta J_{down}$. The largest cross-correlation coefficient is at about 50 s time shift, because there is a phase shift of about $\pi/4$ between $V_R$ and $\delta J_{up}/\delta J_{down}$. Note that $j_{VA} + j_{Vr}$ was multiplied by an area of about $9$ $R^2$ in order to match the observed oscillations in the SECS scaling factors.

[21] Figure 4 is an attempt to explain the substorm wedge current dynamics by discriminating the ionospheric current relevant to the large-scale substorm wedge currents produced by the general reconfiguration of the magnetotail pressure gradient from the currents that appeared as a result of the flow oscillation. Figure 4a shows the integral downward SECS scaling factors $J_{down}$ from Figure 1b (blue curve), and $j_{VA} + j_{Vr}$ from Figure 1d that was multiplied by an area S (magenta curve). The scaling area S was estimated to be about $4.5$ $R^2$ using the similar scaling area $S_{EM}$ estimated in Figure 2e and taking into account that the amplitude of the oscillations in the integral SECS scaling factors decreased about two times after applying a filtering algorithm.

[22] From the difference between the blue and magenta curves that is shown by orange curve in Figure 4a, one can see that $j_{VA} + j_{Vr}$ current may explain only a small oscillating part of the integral SECS scaling factors. The rest of the integral SECS scaling factors (orange curve in Figure 4a) is apparently generated during the pressure and magnetic flux pileup process in the near-Earth plasma sheet. This (major) current depends on the difference between the initial and the final equilibrium values of the cross-tail current density, as indicated to the right from Figure 1e. We will denote this current $J_{VP}$ because it, probably, mainly depends on the pressure gradients along x, y, and z, with the predicted largest $\partial P/\partial x$-component [Birn et al., 1999].

[23] One can notice two phases of development of $J_{VP}$. During the first phase, i.e., between the magnetotail reconnection onset and the reconnected flux arrival to the near-Earth region (between 10:23:20 and 10:25:40 UT), $J_{VP}$ rapidly increased because the pressure gradients and the magnetic flux piled up. The second phase is, on the contrary, characterized by a $J_{VP}$ slowly decreasing with time. This phase was observed after 10:25:40 UT, i.e., during the tailward movement of the dipolarization, and in accordance with MHD simulations by Birn et al. [2011].

[24] In order to highlight the gross behavior of development of the $J_{down}$ curve, in Figure 4b, we followed the reverse approach, where we reconstruct the shape of the ground-measured integral SECS scaling factors $J_{down}$. Based on the orange curve shown in Figure 4a, for this purpose, we assumed that the $J_{VP}(t)$ behaved as $J_{VP}(t) = (t - t_0)^{\mu} \exp(-\ln(t - t_0) - \mu^2)$, where $t_0$ is about 10:23:20 UT, $t$ is time and $\mu$ is a constant. Note that magenta curve in Figure 4b is the same as in Figure 4a. We then summed up $J_{VP}(t)$ and $S \times (j_{VA} + j_{Vr})$. The result is shown by the blue curve in Figure 4b. One can now see more clearly which peaks and dips in $J_{down}$ from Figure 4a may be explained by the oscillations in $j_{VA} + j_{Vr}$. This way, we concluded that the oscillations in the integral SECS scaling factors originated from the oscillation in the polarization current $j_{VA}$ and from the oscillations in the current $j_{Vr}$ that was generated by the oscillating part of the radial pressure gradient.

[25] Figure 5 shows snapshots of the EICs (arrows) and the SECS scaling factors (color: upward in reddish, and downward in blueish) that were calculated using the
Figure 4. (a) Integral downward SECS scaling factors $J_{\text{down}}$ from Figure 1i (blue); $j\nabla (\delta P) + j\partial V/\partial t$ from Figure 1d multiplied by an area $S = 4.5 R_E^2$ (magenta); Difference of the blue and magenta curves (orange). (b) $-(t-t_0)^{-1}\exp(-(\ln(t-t_0)-\mu)^2)$, where $t_0$ is about 10:23:20 UT, $t$ is time and $\mu$ is a constant (orange); magenta curve is the same as in Figure 4(a); Sum of the black and the magenta curves (blue). See text for details.

ground-based magnetometer arrays. The snapshot times are chosen ~50s after the peak velocity during first two earthward flows and their tailward rebounds, i.e., at the times of the peak luminosity, as indicated by the numbered red arrows in Figure 1g. The footprints of the five THEMIS spacecraft are overplotted as crosses, at the locations that were predicted by the AM-03 model (red for P1, green for P2, blue for P3, cyan for P4, and magenta for P5). One can see that in all four snapshots, there exists a westward electrojet (indicated by magenta arrows). This electrojet can also be seen as a gradual decrease in the $B_H$-component from Fort Yukon magnetometer shown in Figure 1h. Around the westward electrojet, a dipolar current system can be seen, consisting of a bluish spot corresponding to downward currents and a reddish spot corresponding to upward currents. Related to both the earthward flows (left-hand side snapshots number 1, and 3 in Figure 5) and to their tailward rebounds (right-hand side snapshots number 2, and 4 in Figure 5) the upward and downward current region was observed at almost the same location, i.e., the overall pattern of the currents appeared to be rather stable through the whole oscillation interval. An exception is a clockwise
Figure 5. Snapshots of EICs (arrows) and the SECS scaling factors (color: upward in reddish, and downward in blueish) that were calculated using the ground-based magnetometer arrays. The snapshot times are chosen ~50 s after the peak velocity during two earthward flows and two tailward rebounds of the flows, at the times of the peak luminosity, as indicated by the red numbered arrows in Figure 1g. The footprints of the five THEMIS spacecraft denoted by overplotted crosses, as predicted by the AM-03 model (red for P1, green for P2, blue for P3, cyan for P4, and magenta for P5).

rotation of the dipolar system by about 50° between 10:25:50 UT and 10:27:20 UT, i.e., between snapshots 2 and 3.

[26] However, as shown in Figure 1h, the ground magnetic field revealed ~2.5 min-period oscillations (or Pi2 pulsations). Figure 6 shows the snapshots of these oscillations obtained by filtering the magnetic field measurements from the ground-based magnetometer arrays with periods between 20 and 200 s. The snapshot times are chosen during maximum amplitude of the horizontal \( (B_Y, B_D) \) magnetic field component. The footprints of the five THEMIS spacecraft are overplotted as in Figure 5. Magnetic midnight is shown by solid green line in the first snapshot of Figure 6. One can see that while during the earthward plasma sheet flow bursts, the ground magnetic fields deflected largely southward (snapshots 1, and 3 in Figure 6), during the tailward rebounds they deflected largely northward (snapshots 2, and 4 in Figure 6). This result is in agreement with the spacecraft footprint oscillation in the north-south direction shown in Figure 1f.

[27] Figure 7 shows the snapshots of the oscillations in the ionospheric equivalent current (arrows) and in the SECS scaling factors (color: upward in reddish, and downward in blueish) with periods between 20 and 200 s. The snapshot times are chosen as in Figure 5, i.e., ~50s after the peak velocity during first two earthward flows and their tailward rebounds, i.e., at the times of the peak luminosity, as indicated by the numbered red arrows in Figure 1g. The footprints of five THEMIS spacecraft are overplotted as in Figure 5. One can see that in all four snapshots, there exists a dipolar current system, consisting of a bluish spot corresponding to downward currents and a reddish spot corresponding to upward currents. While during the first earthward flow (snapshot 1 in Figure 7), the upward current region was observed at the southern side of the dipolar system, during the first tailward rebound (snapshots 2 in Figure 7) the upward current region was observed at the northern side of the dipolar system. Thus the oscillating part of the SECS scaling factors changed polarity with the flow changing direction from tailward to earthward. A similar change of polarity was observed between the second earthward flow burst (snapshot 3 in Figure 7) and the second tailward rebound (snapshot 4 in Figure 7). We note that there is a difference in the location of the bluish and reddish spots between snapshot pairs 1-2 and 3-4, i.e., between 10:25:50 UT and 10:27:20 UT. This difference is due to the clockwise rotation by about 50° of the double-vortex current system that was shown in Figure 5 (the rotation occurred exactly between 10:25:50 UT and 10:27:20 UT). While the polarity change is obviously related to the plasma sheet...
flow oscillation, the rotation, on the other hand, might be related to the polarization electric field effect described by Amm et al. [2011]. With an additional polarization electric field, we expect a north-south geometry of the SECS scaling factors, and not the (usual) east-west one.

Figure 8 shows the snapshots of the four auroral forms when they exhibited the highest brightness ~50 s after the corresponding positive and negative perpendicular oscillatory plasma sheet current (as we showed in Figure 3) that are, in turn, related to the two earthward flow bursts (around 10:24:50 UT and 10:27:10 UT) and to their two tailward rebounds (around 10:26:00 UT and 10:28:50 UT). One can notice that the forms appeared to track the path of the reddish spots in the oscillations of the SECS scaling factors (see Figure 7). This is less obvious to notice in panels 4 of Figures 7 and 8. However, we note that only the most southward (dim) part of the auroral form appeared just before 10:28:50 UT, while its northern (brightest) part pre-existing for some time, and the upward spot in panel 4 of Figure 7 moved southward as the auroral form developed north-to-south (not shown here).

One can also find three peculiarities in the ASI observations. First, one can see that the two auroral forms related to the two earthward flow bursts (panels 1 and 3 in Figure 8) were located about 1° westward and southward with respect to the auroral forms related to the two tailward rebounds (panels 2 and 4 in Figure 8). Such difference in the auroral forms location during the earthward and the tailward flows would be in agreement with the hypothesis that while the auroral forms during the earthward flow bursts were generated duskward from the flows, the auroral forms during the tailward rebounds were generated dawnward from the flows. This observation is in agreement with the location of the upward currents shown in snapshots 1–4 in Figure 7.

Second, the auroral forms that are related to the first earthward flow burst and to the first tailward rebound were located more southward than the two auroral forms related to the second earthward flow burst and the second tailward rebound. This observation would, in turn, be in agreement with the results given in Figure 1f, where we showed that the footprint of the magnetic field line at P2 moved between 10:22 UT and 10:32 UT about 1° northward.

Third, one can notice that while the auroral forms in snapshots 1 and 2 in Figure 8 developed more horizontally, the other two auroral forms developed more in the north-south direction. This is in agreement with rotation of the
Figure 7. Snapshots of the oscillating parts (with periods between 20 and 200 s) of the EICs (arrows) and SECS scaling factors (color: reddish for upward and bluish for downward). The snapshot times are chosen ~50s after the peak velocity during two earthward flows and two tailward rebounds of the flows, at the times of the peak luminosity, as indicated by the red numbered arrows in Figure 1g. The footprints of five THEMIS spacecraft are overplotted as crosses (red for P1, green for P2, blue for P3, cyan for P4, and magenta for P5).

1 @ 102430 UT
2 @ 102550 UT
3 @ 102720 UT
4 @ 102850 UT

Figure 9 shows the evolution of the auroral form from panel 1 in Figure 8. The form emerged at about 10:23:25 UT and started as an east-west oriented auroral form (more southeast-northwest in geographic coordinates) till about 10:23:55 UT. Then, i.e., after the BBF stoppage process began just before 10:24:00 UT, the auroral form started to evolve into a counter-clockwise spiral. At some point (after about 10:24:10 UT), it reshaped into a fork-like auroral form, and then fainted (around 10:25:00 UT). Hence, it is interesting to note that the changes in the auroral form’s shape from a simple east-west aligned auroral form into a spiraling and then into a fork-shaped auroral form happened during the process of the flow deceleration (see Figure 1c and 4). Note, that a similar (although less clear), but clockwise spiraling auroral form was observed during the stoppage of the first tailward rebound (between 10:25:40 and 10:26:50 UT, see one snapshot of this auroral form that was shot at 10:25:48 UT in Figure 8; all snapshots can be found in the video in the supporting information).

Figure 10 shows the (top) oscillating part of the SECS scaling factors and (bottom) six ASI snapshots for similar times to demonstrate the relation between the auroral forms and the development the oscillating part of the SECS scaling factors using the auroral form observations at Fort Yukon between 10:26:30 UT and 10:27:20 UT (auroral form from panel 3 in Figure 8). The auroral form appeared shortly before 10:26:30 UT. By 10:27:30 UT it moved in the north-west direction by about 3°. One can also notice that while the southward part of the auroral form moved westward by about 2°, the northward part of the auroral
form moved eastward by about 4°, i.e., the auroral form rotated clockwise by about \(\pi/6\) rad. The top part in Figure 10 shows similar northward motion of the reddish spot that indicates the location of the upward currents. We therefore conclude that the auroral forms trace the region of upward currents that were generated by the alternating currents in the plasma sheet. Note, that a similar evolution was found for the fourth auroral form in Figure 8, albeit with an opposite movement direction (equatorward rather than poleward; not shown here).

3. Discussion

[34] In this paper, we investigated ground-based magnetometer and all-sky imager observations during the oscillatory BBF braking on 17 March 2008 between 10:22 and 10:36 UT. Using the ground-based magnetometer observations, we calculated the (horizontal) equivalent ionospheric currents (EICS) and the (vertical) SECS scaling factors. We used the SECS scaling factors as a proxy to the vertical ionospheric (field-aligned) currents. With the help of the AM-03 model [Kubyshkina et al., 2009, 2011], we linked the plasma sheet observations to the ionospheric observations.

[35] By cross-correlating the current generated by the flow oscillations in the plasma sheet with the ionospheric vertical current oscillations, we found that the ionospheric currents can be explained as a superposition of currents generated by (1) the general magnetotail pressure gradient reconfiguration during the initial magnetic and pressure flux pileup and a consequent tailward dipolarization, and also by (2) the plasma sheet oscillatory flow braking. The oscillation currents include the polarization current \(J_{V/\partial t}\) and the current generated by the oscillating part of the radial pressure gradient \(J_{V(\delta P)}\).

[36] The two alternate currents \(J_{V/\partial t}\) and \(J_{V(\delta P)}\) appeared to be comparable between each other, but had \(\pi/2\) phase shift. They were responsible for the \(~2.5\) min-period modulation of the total ionospheric current that was seen as Pi2 pulsations in the ground measurements of the magnetic field.

[37] We found that the ionospheric vertical current oscillations lagged behind the current generated by the flow oscillations. See video file in the supporting information for all snapshots.
oscillations in the plasma sheet by about 50 s. This lag is on the order of the estimated Alfvénic transit time (∼55±10 s, as predicted by the AM-03 model) and is close to $\pi/3$ radians in phase lag, i.e., within the limits predicted by MHD modeling results given in Figure 25 of Wolf et al. [2012]. This lag is largely dependent on the iono-

Figure 9. Sequential ASI snapshots of the auroral form observed at Fort Yukon between 10:23:30 UT and 10:24:30 UT. The footprints of five THEMIS spacecraft are overplotted as crosses (red for P1, green for P2, white for P3, cyan for P4, and magenta for P5).

Figure 10. (top) Oscillating part of the EICs (arrows) and SECS scaling factors (color) and (bottom) Fort Yukon ASI snapshots for six sequential times between 10:26:30 UT and 10:27:20 UT.
spheric conductance, which may be different at different MLTs [e.g., Wolf, 1970], and should be studied further on a statistical basis.

[38] We propose to use the cross-correlation of the flow (or pressure gradient) oscillations in the plasma sheet and the SECS scaling factors in future ionosphere-magnetosphere-conjugate studies as a more reliable method of obtaining the time delay between the space and ground observations of substorm onset.

[39] The AM-03 model shows that during the oscillatory BBF braking, the footprints of the magnetic field lines at the locations of five THEMIS spacecraft oscillated also. Note that in addition to the oscillatory motion of the ionospheric footprints, we also found a gradual northward progression of the footprints (by about 1° during about 10 min). This happened during the dipolarization, which is first observed in the near-Earth plasma sheet and then moves tailward [Nakamura et al., 1994; Baumjohann et al., 1999; Birn et al., 2011], and is therefore consistent with a retreat of the activity downtail.

[40] There has been a standing question to what extent the ionospheric conductance is provided by Pedersen and Hall currents [e.g., Untiedt et al., 1978; Untiedt and Baumjohann, 1993]. Different calculations suggest that there should probably be a combination of the two [e.g., Lysak, 1990; Yang et al., 2012, and references therein]. Our observations can contribute to this area. It is the Pedersen conductance that is related to wave damping. Thus, following Glassmeier et al. [1984], we estimated the Pedersen conductance based on the observed damping factor. Since both the magnetospheric and the conjugate ionospheric oscillations had similar periods T and damping factors γ, one can conclude that the ionospheric conductance was the major source of oscillations' damping. Assuming that γ ≈ (10ΣpL)⁻¹, where L is the McIlwain shell parameter, γ is in s⁻¹, and Σp is Pedersen conductivity in S, and also assuming that T ≈ L²/2 [Newton et al., 1978], we estimated that the height-integrated ionospheric Pedersen conductance Σp was between 4.5 and 6.5S. This value range appears to be reasonable and support the assumption that the BBF oscillations are damped due to ionospheric Joule heating through Pedersen currents.

[41] It may also be that the nature of the ionospheric conductance depends on the mechanism of the current wedge formation. It has been widely known that the current wedge is expected to be formed through magnetotail pressure gradients [e.g., Shiokawa et al., 1998a, 1998b; Birn et al., 1999; Xing et al., 2011; Mende et al., 2012] and by polarization currents [Paschmann et al., 2002; Birn et al., 2004; Birn and Hesse, 2005; Birn et al., 2011; Haerendel, 2011]. Another source of the wedge currents may also come from field line twisting [e.g., Sato and Iijima, 1979; Hasegawa and Sato, 1980; Lui, 1996; Birn et al., 2004; Birn and Hesse, 2005; Keiling et al., 2009b; Lui et al., 2010; Birn et al., 2011; Haerendel, 2011; Ge et al., 2011]. However, we found that the parallel current generated by changes in vorticity (not shown here) would provide a part of the current wedge that anti-correlates with the polarization current (as was suggested by Lui et al. [1999]). However, since we were able to explain the ionospheric current oscillations with the pressure gradient and polarization currents alone, we assumed that the current from the vorticity changes was negligible.

[42] Figure 11 shows a sketch illustrating the relation between different current components shown in Figures 1 and 4. The instantaneous superposition of perpendicular current systems that are generated as a consequence of the oscillatory flow braking (green and black) and as a consequence of the general reconfiguration of the magnetotail pressure gradient (orange), and then diverted into parallel current, forms substorm current wedge (blue J_down and red J_up). J_down and J_up are also connected to each other through the ionospheric Hall and Pedersen currents.

[43] Although we do not specify here the generation mechanism of J⊥—the current generated by the general magnetotail pressure gradient reconfiguration during the initial magnetic and pressure flux pileup and a consequent tailward dipolarization—it is worth noting that Birn et al. [1999], using MHD simulation, suggested that the largest part of this current would be produced by ∂P/∂z.

[44] One should note that the observations of ionospheric double-vortex current systems from ground-based magnetic field measurements have long been widely known [among the earliest are works by Pashin et al., 1982; Baumjohann and Glassmeier, 1984; Behrens and Glassmeier, 1986;
Glassmeier et al., 1988]. These authors showed ionospheric equivalent current systems associated with Pi2 pulsations and found that the vorticity changed sign with the period of the Pi2, i.e., what one would expect for a transient set up of the substorm current system. In the present work, we are able to demonstrate the magnetospheric driver mechanism of those ionospheric/ground observations.

It is interesting to note that the Pi2 pulsations started to also be observed by the ground magnetometers located farther away from the shown double-vortex current system. However, the amplitudes of such Pi2 pulsations are tens of times smaller. We also admit that the generation mechanism of the Pi2 pulsations that are observed farther away from the double-vortex current system may be different.

We note that there are a number of BBF-associated models that suggest the mechanism of Pi2 generation [see a review paper by Keiling and Takahashi, 2011]. For the investigated THEMIS observations, we, however, confirm that Pi2 pulsations at the double-vortex system can be understood as a periodic modulation of the field-aligned currents, as was suggested in [Pashin et al., 1982; Glassmeier et al., 1988]. We further find that the periodic modulation of the field-aligned currents is caused by a heavily damped oscillatory braking of the plasma sheet flows.

We also find that the auroral forms were detected related to the two earthward plasma sheet flows and also to their tailward rebounds. The auroral forms appeared to follow the location of the upward current spot of the oscillating part of the total ionospheric current. Note however, that the radius of the vortices in the plasma sheet on the two sides of the oscillating flow was estimated to be about 5 R$_E$ [Panov et al. 2010b]. This scale would be ten times larger than the auroral form thickness when mapped down to the ionosphere. Also, we found that the distance between the auroral form locations during the earthward and tailward flow bursts corresponded well to the expected BBF azimuthal size of 2–3 R$_E$, when mapped into the plasma sheet. These two facts suggest that only a small part of the vortex adjacent to the two sides of the flow burst might be involved in the process of electron precipitation.

Another open question would be the change in the shape of auroral forms that at times are observed as a rather straight auroral form, and at times auroral forms have a tendency to turn into spiral- or curl-like forms. The presented observations suggest that such a spiraling (here we discuss the auroral forms in Snapshots 1 and 2 in Figure 8) seem to happen during deceleration of the first earthward flow burst and of its tailward rebound. This suggestion would be in agreement with the theoretical idea that the spiral generator may be an increase of the driving forces [see, e.g., Section 3.5 Auroral Spirals/Westward Traveling Surge in Haerendel, 2011]. To answer this question, a more detailed ionosphere/plasma sheet conjunction study is needed, in which also the perpendicular-to-parallel diversion of the generator current would be comprehensively investigated.

Interestingly, the magnetic flux tube oscillatory braking process has been systematically detected in the solar coronae. For example, Nakariakov et al. [1999] reported on TRACE observations of a damped coronal loop oscillation. Therefore, the analysis of the ionospheric behavior during the oscillatory BBF braking suggests that the solar corona may also be heated by Joule dissipation during the damped coronal loop oscillations.

4. Conclusions

We found that during the oscillatory braking of the bursty bulk flow observed by THEMIS on 17 March 2008 just after 10:22 UT:

1. The major wedge current was generated by the general reconfiguration of the pressure gradient in the magnetotail; it appeared immediately with the pressure and magnetic flux pileup, was quasi-stationary and disappeared slowly during the tailward dipolarization. The second important contribution to the wedge current appeared to be provided by the polarization current $J_{\Lambda/\vartheta}$ and by the current generated by the oscillating part of the radial pressure gradient $J_{\nabla^2 \varphi}$, $J_{\Lambda/\vartheta}$ and $J_{\nabla^2 \varphi}$ were comparable though substantially weaker (about 3 times less) than the radial pressure gradient current, and also were alternating: they switched direction during earthward and tailward flow bursts. In addition, there was a $\pi/2$ rad phase shift between $J_{\Lambda/\vartheta}$ and $J_{\nabla^2 \varphi}$.

2. While the major current was perhaps responsible for large-scale ground magnetic field changes, the superposition of the two alternate currents ($J_{\Lambda/\vartheta} + J_{\nabla^2 \varphi}$) appeared to be responsible for the $\approx 2.5$ min-period modulation of the total ionospheric current that was seen as Pi2 pulsations in the ground measurements of the magnetic field.

3. The ionospheric current oscillation lagged behind the magnetospheric oscillations in ($J_{\Lambda/\vartheta} + J_{\nabla^2 \varphi}$) by $\approx 50$ seconds which is nearly equal to the Alfvénic transit time of about 55±10s, as was estimated by the AM-03 model. This result corresponds to about 3/4 radians phase shift, i.e., also in agreement with the MHD modeling results given in Figure 25 of Wolf et al. [2012].

4. Estimates of Pedersen conductance suggest that the damping of the plasma sheet flow oscillation may be provided by Joule heating in the ionosphere through Pedersen current.

5. During the tailward retreat of the dipolarization, there was identified a gradual northward progression of the ionospheric current system that is consistent with the northward motion of the spacecraft footprints predicted by the AM-03 model (by about 1° in 10 min).

6. Auroral forms were shown to be related to the two earthward plasma sheet flows and also to their tailward rebounds. The auroral forms appeared to follow the location of the upward current spot in the oscillating part of the total ionospheric current.

7. The distance between the auroral form locations during the earthward and tailward flow bursts corresponded well to the presumed BBF azimuthal size, when mapped into the plasma sheet.

Acknowledgments. We acknowledge NASA contract NAS5-02099 for use of data from the THEMIS Mission, and specifically, for the use of FGM data supported through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302. For the GBO/ASIs, we acknowledge S. Mende and E. Donovan, NASA contract NAS5-02099 and the CSA for logistical support in fielding and data retrieval from the GBO stations. The authors gratefully acknowledge CANMOS, CARISMA, DTU, GIMA, MACCS,


