AIP | Physics of Plasmas

Larmor electric field observed at the Earth's magnetopause by Polar satellite

D. Koga, W. D. Gonzalez, F. S. Mozer, M. V. D. Silveira, and F. R. Cardoso

Citation: Physics of Plasmas (1994-present) **21**, 100701 (2014); doi: 10.1063/1.4897935
View online: http://dx.doi.org/10.1063/1.4897935
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/21/10?ver=pdfcov
Published by the AIP Publishing

Larmor electric field observed at the Earth's magnetopause by Polar satellite

D. Koga,[1,a)] W. D. Gonzalez,[1] F. S. Mozer,[2] M. V. D. Silveira,[1] and F. R. Cardoso[3]
[1]*National Institute for Space Research - INPE, São José dos Campos, São Paulo, Brazil*
[2]*Space Sciences Laboratory, University of California, Berkeley, California 94720, USA*
[3]*School of Engineering - EEL, University of São Paulo, Lorena, São Paulo, Brazil*

(Received 13 June 2014; accepted 29 September 2014; published online 10 October 2014)

We present, for the first time, observational evidence of a kinetic electric field near the X-line associated with asymmetric reconnection at the Earth's dayside magnetopause using Polar observations. On March 29, 2003, Polar satellite detected an asymmetric collisionless reconnection event. This event shows a unipolar Hall electric field signature and a simple deviation from the guide field during the magnetopause crossing, with the absence of an ion plasma jet outflow indicating that the magnetopause crossing was near the X-line. As expected from particle-in-cell simulations by Malakit *et al.* (Phys. Rev. Lett. **111**, 135001 (2013)), an earthward pointing normal electric field appears in the magnetospheric side of the ion diffusion region. The electric field satisfies two necessary conditions for the existence of the finite ion Larmor radius effect: (1) the ion Larmor radius (r_{g2}) is larger than the distance between the stagnation point and the edge of the ion diffusion region in the strong magnetic field side (δ_{S2}) and (2) the spatial extent of the kinetic electric field (δ_{EL}) is of the order of the ion Larmor radius. Furthermore, it is shown that the peak value of the Larmor electric field is comparable to the predicted value. The observation of the Larmor electric field can be valuable in other analyses to show that the crossing occurred near the X-line. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4897935]

Magnetic reconnection is a dynamic phenomenon which can take place in many plasma domains, such as at the solar atmosphere, solar wind, magnetosphere, and laboratory experiments.[1–4] To find reconnection events in satellite investigations, there are several signatures that one can try to follow. Hall magnetic and electric fields are important signatures in collisionless reconnection to find the ion diffusion region.[5,6] The ions are demagnetized on scale sizes of the order of the ion skin depth, while the electrons remain magnetized on such scales. Thus, these different bulk motions in the ion diffusion region cause a quadrupolar magnetic field generated from electron-carrying currents (Hall magnetic field) and a bipolar electric field pointing toward the X-line on both sides of the reconnection region (Hall electric field) during symmetric reconnection.[7–9] However, the Hall magnetic and electric fields can be modified when plasma density and magnetic field asymmetries and/or a guide-field exist. Such a modification of the Hall fields has been observed at the dayside magnetopause crossings, in laboratory experiments, and in particle-in-cell (PIC) simulations where the Hall electric and magnetic field variations become unipolar and less quadrupolar, respectively.[10–15]

Recently, using fully kinetic PIC simulation, Malakit *et al.*[16] have suggested the existence of a kinetic electric field due to finite ion Larmor radius effects slightly upstream of the ion diffusion region, which was named "Larmor electric field (LEF)" by the authors. The LEF is caused by the thin stagnation width (δ_{S2} in Figure 1) in the diffusion region during asymmetric collisionless reconnection where the stagnation point is different from the X-line location and is much closer to the stronger magnetic field side of the ion diffusion region,[17] as shown in Figure 1. Then, the LEF appears to prevent ions from crossing the stagnation point when the ion Larmor radius r_{g2} is larger than the distance between the stagnation point and the edge of the ion diffusion region in the stronger magnetic field side δ_{S2} (the first necessary condition)

$$r_{g2} > \delta_{S2}, \tag{1}$$

where the subscript 2 indicates the stronger magnetic field side (region 2). The second necessary condition for the existence of the finite ion Larmor radius effect requires that the spatial extent of the Larmor electric field δ_{EL} should be of the order of the ion Larmor radius

$$\delta_{EL} \sim r_{g2}. \tag{2}$$

The intensity of the LEF is approximately comparable to the average ion thermal energy per charge and per ion Larmor radius

$$E_L \sim k_B T_{i2}/e r_{g2}, \tag{3}$$

where k_B is the Boltzmann constant, T_{i2} is the ion temperature in the region 2, and e is the ion charge.[16] To date, it has not been reported an evidence of the ion Larmor electric field from satellite observations. Thus, in this letter, we present, for the first time, an observational evidence for the LEF associated with the Hall electric field.

On March 29, 2003, an asymmetric collisionless reconnection event was encountered by Polar satellite at the Earth's dayside magnetopause, where the radial distance was $9.05R_E$, the magnetic local time was 10:57, and the magnetic

a)Electronic mail: dkaqua@kyudai.jp.

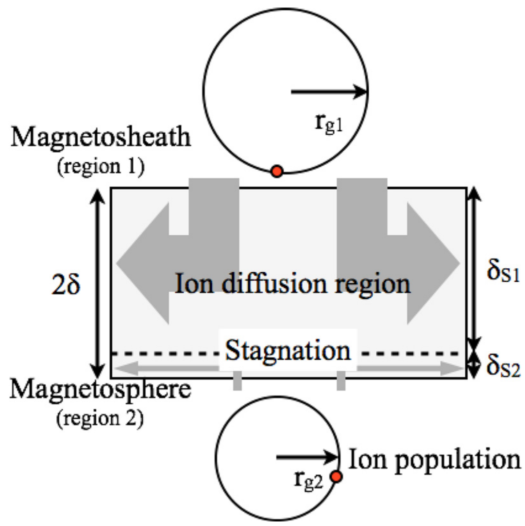

FIG. 1. Schematic of the ion flow in the ion diffusion region during asymmetric reconnection at the magnetopause. The circles denote the ion Larmor motions with the Larmor radius r_g where the subscripts 1 and 2 correspond to the magnetosheath and the magnetosphere, respectively. (Modified from Figure 1 of Malakit *et al.*[16]).

latitude was 2.36°. Figure 2 shows the magnetic and electric fields and plasma measurements for the interval 10:48:00–10:48:50 UT. In order to discuss reconnection signatures at the magnetopause, we need to determine an appropriate boundary coordinate system. The minimum variance analysis of the magnetic field (MVAB) is the most popular way to determine the normal direction to a boundary such as the magnetopause.[18] The direction of the maximum varying magnetic field component is well-defined using the MVAB method. On the other hand, the maximum variance analysis of the electric field (MVAE) can determine the direction of the maximum varying electric field component, which corresponds to the normal component of the electric field *Ex* at the reconnection site. Joint variance analysis (JVA) makes the best use of both methods so that the X (normal) direction is given by the MVAE and the coordinate system is rotated around this X axis until the Z direction is closest to the Z axis obtained from the MVAB.[19] The unit vectors obtained from the JVA method are $\hat{x} = (0.8311, -0.5029, 0.2374)$, $\hat{y} = (0.5498, 0.6787, -0.4869)$, and $\hat{z} = (0.0837, 0.5352, 0.8406)$ in the Geocentric Solar Ecliptic (GSE) coordinate system and the JVA coordinate basis is used for Figure 2. The magnetic and electric fields and plasma measurements were obtained from the Magnetic Field Experiment (MFE) instrument,[20] the Electric Field Instrument (EFI) instrument,[21] and the HYDRA instrument,[22] with a time resolution of 0.12 s, 0.05 s, and 13.8 s, respectively. For the present study, we used "dot0" versions

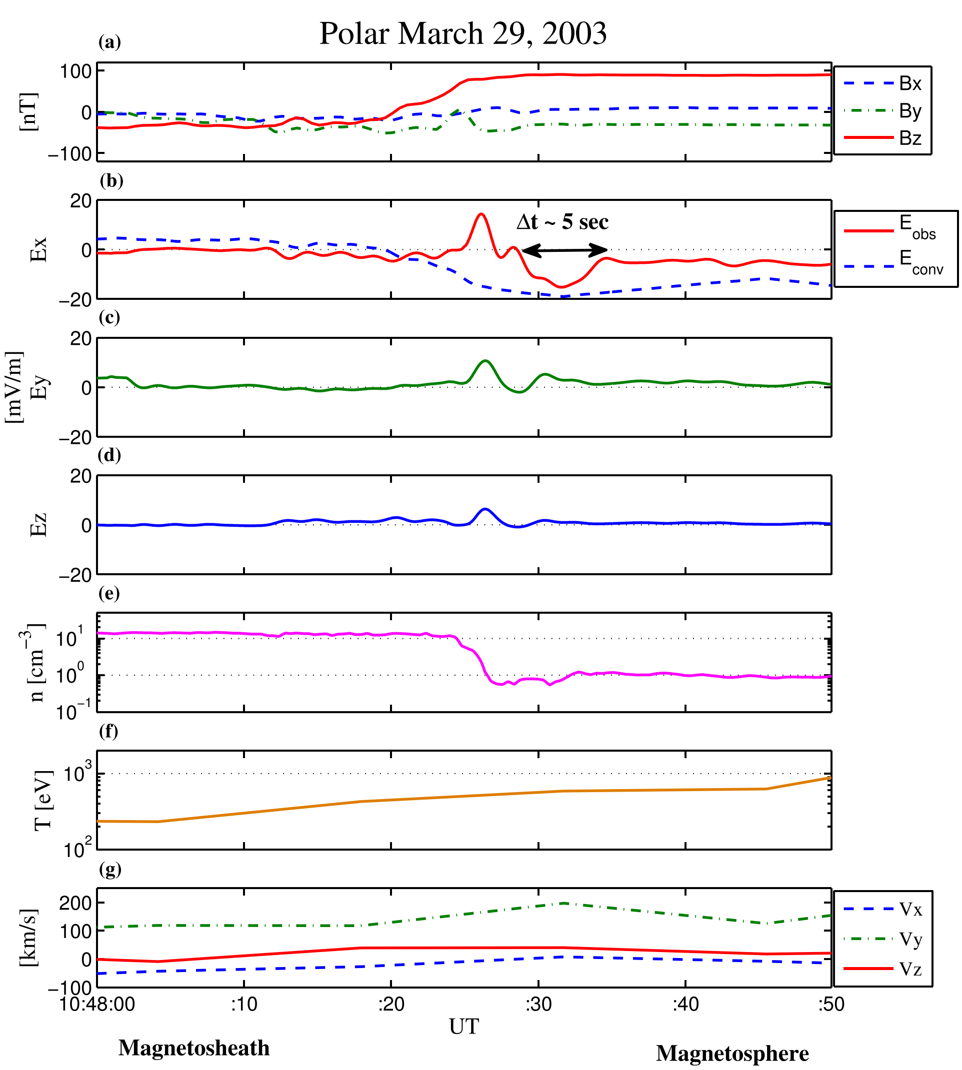

FIG. 2. Polar measurements of the asymmetric collisionless reconnection event on March 29, 2003. From the top to the bottom, three components of the magnetic field, three components of the electric field, the ion density, temperature, and three components of the ion bulk velocity are shown. The dashed line in the panel (b) is the normal component of the ion convection electric field.

of the 3D electric field data where the spin axis-electric field is estimated to be zero, using the assumption $\mathbf{E}\cdot\mathbf{B}=0$.[23] It is reasonable to use this version of data set since the dominant component of the Hall electric field is perpendicular to the reconnecting magnetic field and the Bz component is much larger than the others. Here, both magnetic and electric fields have been low-pass filtered at 0.5 Hz to eliminate the large-amplitude and high-frequency electrostatic fluctuations so that the low-frequency electric field variations are clearly shown. The ion bulk velocity and the electric field were transformed into a frame moving in the X direction and fixed to the magnetopause by requiring that the tangential component of the electric field be continuous in the magnetopause frame. Here, the computed magnetopause speed is about 25 km/s.

During the magnetopause crossing of Polar, the north-south magnetic field component Bz changed from -31.47 nT to 88.68 nT, as shown in Figure 2(a) (solid line). Then, the observed changes in the ion density and temperature also showed the magnetopause crossing, as shown in Figures 2(e) and 2(f). Thus, this event clearly shows magnetic field and plasma density asymmetries. The east-west component By (dashed-dotted line) in Figure 2(a) did not show any clear bipolar variation related with the Hall effect but showed a simple deviation from the guide-field $By\sim-30$ nT to zero for the interval 10:48:20–10:48:30 UT. Such a variation has been demonstrated in observations and PIC simulations of asymmetric reconnection.[11] Furthermore, the value of the normal magnetic field Bx (dashed line) during the crossing is about -10 nT. This negative Bx indicates that Polar traversed northward of the X-line.

The normal component of the electric field Ex is shown in Figure 2(b). Here, there is no clear negative peak of Ex expected from symmetric collisionless reconnection in the magnetosheath side of the crossing. One can also see that the positive peak of Ex appears after the magnetopause crossing and reaches $\sim$14.3 mV/m. This kind of unipolar electric field variation has been observed at the magnetopause.[6] This electric field is associated with the Hall effect in the ion diffusion region and shows a unipolar variation because Bz/n, the ratio between the north-south magnetic field component and the ion plasma density, is sufficiently large in the magnetospheric side of the crossing. The east-west Ey and the north-south Ez electric field components during the magnetopause crossing show small positive variations in Figures 2(c) and 2(d). This is consistent with the previous PIC simulation results in Figures 6(e) and 6(f) of Pritchett and Mozer[24] when a spacecraft traversed northward of an X-line and observed Ey and Ez variations associated with ion convection. We would like to emphasize that the existence of a Hall electric field, i.e., positive peak of Ex in the magnetospheric side, is a strong evidence of reconnection. The By component also shows another evidence of an asymmetric reconnection, which is associated with the Hall effect in the ion diffusion region.[11] Furthermore, there is a non-zero Bx (normal component) amplitude. Thus, these results show that this is an asymmetric reconnection event.

After observing the Hall electric field, we find a negative peak of the Ex field in Figure 2(b). There are no other similar variations over the entire interval. The existence of the negative value of the Ex field implies that some physical processes which differ from the Hall effect might be happening just upstream of the ion diffusion region. Malakit *et al.*[16] have suggested that a kinetic electric field associated with the finite ion Larmor radius effect would be observed at the dayside magnetopause. Their PIC simulations have shown that an earthward pointing electric field is expected to exist just upstream of the ion diffusion region, in other words, at the Hall electric field site.

In order to verify that Polar observed the Larmor electric field, the related parameters from Malakit *et al.*[16] are calculated. First of all, we need to find the distance between the stagnation point and the edge of the ion diffusion region in the magnetospheric side of the magnetopause (δ_{S2}). To evaluate this distance, the half width of the ion diffusion region for the asymmetric Hall reconnection from Cassak and Shay[25] δ is used in CGS units

$$\delta \sim \frac{B_1+B_2}{2\sqrt{B_1B_2}}\left[\frac{m_i^2c^2}{4\pi e^2}\frac{B_1+B_2}{m_i(n_1B_2+n_2B_1)}\right]^{1/2}, \quad (4)$$

where c is the speed of light, m_i is the ion mass, and the subscripts 1 and 2 correspond to the magnetosheath and the magnetosphere, respectively. Using $2\delta=\delta_{S1}+\delta_{S2}$, the expected size of δ_{S2} becomes

$$\delta_{S2} \sim \left[\frac{n_2B_1}{n_1B_2+n_2B_1}\right]2\delta, \quad (5)$$

where δ_{S1} is determined as $\delta_{S1}\sim\delta_{S2}/(n_2B_1/n_1B_2)$.[17] The magnetosheath and magnetospheric magnetic fields, B_{sh} and B_{sp}, are here calculated as $\sqrt{By^2+Bz^2}$. Then, the reconnecting magnetic fields are defined as $B_1=B_{sh}\sin(\alpha-\theta)$ and $B_2=B_{sp}\sin\theta$, respectively, where α is the shear angle between B_{sh} and B_{sp} and θ is the angle between B_{sp} and the modeled X-line.[26] The angles α and θ are 123.02° and 55.07°, respectively. For the present event, the magnetic field intensities, ion densities, and ion temperatures (averaged parameters) are $B_1=36.78$ nT, $n_1=13.82\,\mathrm{cm}^{-3}$, and $T_1=289$ eV in the magnetosheath side and $B_2=77.18$ nT, $n_2=0.97\,\mathrm{cm}^{-3}$, and $T_2=675$ eV in the magnetospheric side. Using these observational values, the half width of the ion diffusion region is $\delta=78.34$ km (Eq. (4)) and $\delta_{S2}=5.08$ km (Eq. (5)), the ion Larmor radius $r_{g2}=34.40$ km, and the expected Larmor electric field intensity is $|E_L|=19.62$ mV/m (Eq. (3)). Thus, the first necessary condition for the existence of the Larmor electric field, $r_{g2}>\delta_{S2}$, was satisfied for this event.

Next, we verified the second necessary condition, i.e., $\delta_{EL}\sim r_{g2}$, where δ_{EL} is the spatial extent of the ion Larmor electric field. The time interval for the negative value of the LEF is approximately 5 s, shown in Figure 2(b). The computed magnetopause speed is about 25 km/s. Then, the observed spatial size of the LEF is about 125 km and this value is in good agreement with the predicted value ($\sim$35 km) although there is a difference of factor $\sim$3. Thus, the second condition was also appropriately satisfied for the present event. Furthermore, the peak intensity of the LEF is 15.25 mV/m, which is in good agreement with the predicted value (~20 mV/m). The PIC simulation results from Malakit *et al.*[16] imply that there is also a difference of a factor of ~1/3 for the intensity and ~3 for the spatial extent from the predicted value (Figure 3 of Malakit *et al.*[16]). Their simulations have shown that the Larmor electric field is roughly equilibrated with the ion convection term in Ohm's law since this electric field appears upstream of the ion diffusion region where the plasma is frozen-in. The LEF intensity calculated from the present event is approximately comparable to the convection electric field as shown in Figure 2(b) ($|E_c| \sim 19\,\mathrm{mV/m}$). Thus, the calculated values from the observation are consistent with PIC simulation results. To understand the physical reason of the factor difference, more statistical analysis and PIC simulations are needed as a future work.

Finally, the northward ion plasma jet expected from magnetic reconnection, Vz, was not detected in this event (solid line in Figure 2(g)). If the spacecraft was close enough to the X-line to see the Larmor electric field, it is not expected that it should see an outflow jet since this jet is formed further away from the X-line. However, the Larmor electric field could be observed near and far from the X-line. From the Malakit *et al.* PIC simulations, the spatial extent of the LEF in the Z (north-south) direction is about 40 c/ω_{pi} (for the present event ~2800 km, c/ω_{pi} ~70 km), where ω_{pi} is the ion plasma frequency. Thus, the Larmor electric field is predicted as an indicator of being near the X-line but it has never been observed until now.

In summary, we presented, for the first time, observational evidence of a Larmor electric field associated with asymmetric reconnection at the Earth's dayside magnetopause using Polar observations. On March 29, 2003, Polar satellite detected an asymmetric collisionless reconnection event. This event showed a unipolar Hall electric field signature and a simple deviation from the guide field during the magnetopause crossing, with the absence of an ion plasma jet. An earthward pointing normal electric field appeared in the magnetospheric side of the ion diffusion region, in agreement with the PIC simulation results from Malakit *et al.*[16] This electric field satisfied two necessary conditions for the existence of the finite ion Larmor radius effect: $r_{g2} > \delta_{S2}$ and $\delta_{EL} \sim r_{g2}$. Furthermore, it was shown that the peak value of the Larmor electric field was comparable to the predicted value. The present results showed that the Polar crossing was close to and northward the X-line and observed the Hall and Larmor electric field. The upcoming Magnetospheric Multi-Scale (MMS) mission is expected to have better chances to encounter the LEF and to allow the investigation of this phenomenon.

This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) Grant Nos. 300406/2011-8 and 301911/2013-4 and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). We thank Professor C. T. Russell and Professor J. Scudder for the use of MFE and HYDRA data.

[1] Y. Su, A. M. Veronig, G. D. Holman, B. R. Dennis, T. Wang, M. Temmer, and W. Gan, Nat. Phys. **9**, 489 (2013).
[2] J. T. Gosling, Space Sci. Rev. **172**, 187 (2012).
[3] G. Paschmann, M. Øieroset, and T. Phan, Space Sci. Rev. **178**, 385 (2013).
[4] M. Yamada, R. Kulsrud, and H. Ji, Rev. Mod. Phys. **82**, 603 (2010).
[5] F. S. Mozer, S. D. Bale, and T. D. Phan, Phys. Rev. Lett. **89**, 015002 (2002).
[6] F. S. Mozer, V. Angelopoulos, J. Bonnell, K. H. Glassmeier, and J. P. McFadden, Geophys. Res. Lett. **35**, L17S04, doi:10.1029/2007GL033033 (2008).
[7] T. Terasawa, Geophys. Res. Lett. **10**, 475, doi:10.1029/GL010i006p00475 (1983).
[8] M. Fujimoto, M. S. Nakamura, I. Shinohara, T. Nagai, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun, Geophys. Res. Lett. **24**, 2893, doi:10.1029/97GL02821 (1997).
[9] Q. Lu, C. Huang, J. Xie, R. Wang, M. Wu, A. Vaivads, and S. Wang, J. Geophys. Res. **115**, A11208, doi:10.1029/2010JA015713 (2010).
[10] H. Karimabadi, D. Krauss-Varban, N. Omidi, and H. X. Vu, J. Geophys. Res. **104**, 12313, doi:10.1029/1999JA900089 (1999).
[11] F. S. Mozer, P. L. Pritchett, J. Bonnell, D. Sundkvist, and M. T. Chang, J. Geophys. Res. **113**, A00C03, doi:10.1029/2008JA013535 (2008).
[12] P. L. Pritchett, J. Geophys. Res. **113**, A06210, doi:10.1029/2007JA012930 (2008).
[13] K. G. Tanaka, A. Retinò, Y. Asano, M. Fujimoto, I. Shinohara, A. Vaivads, Y. Khotyaintsev, M. André, M. B. Bavassano-Cattaneo, S. C. Buchert, and C. J. Owen, Ann. Geophys. **26**, 2471 (2008).
[14] J. P. Eastwood, M. A. Shay, T. D. Phan, and M. Øieroset, Phys. Rev. Lett. **104**, 205001 (2010).
[15] T. D. Tharp, M. Yamada, H. Ji, E. Lawrence, S. Dorfman, C. E. Myers, and J. Yoo, Phys. Rev. Lett. **109**, 165002 (2012).
[16] K. Malakit, M. A. Shay, P. A. Cassak, and D. Ruffolo, Phys. Rev. Lett. **111**, 135001 (2013).
[17] P. A. Cassak and M. A. Shay, Phys. Plasmas **14**, 102114 (2007).
[18] B. U. Ö. Sonnerup and M. Scheible, *Analysis Methods for Multi-Spacecraft Data* (ISSI Scientific Report SR-001, 1998), edited by G. Paschmann and P. W. Daly, Chap. 8, pp. 185–220.
[19] F. S. Mozer and A. Retinò, J. Geophys. Res. **112**, A10206, doi:10.1029/2007JA012406 (2007).
[20] C. T. Russell, R. C. Snare, J. D. Means, D. Pierce, D. Dearborn, M. Larson, G. Barr, and G. Le, Space Sci. Rev. **71**, 563 (1995).
[21] P. Harvey, F. S. Mozer, D. Pankow, J. Wygant, N. C. Maynard, H. Singer, W. Sullivan, P. B. Anderson, R. Pfaff, T. Aggson, A. Pedersen, C.-G. Fälthammar, and P. Tanskannen, Space Sci. Rev. **71**, 583 (1995).
[22] J. Scudder, F. Hunsacker, G. Miller, J. Lobell, T. Zawistowski, K. Ogilvie, J. Keller, D. Chornay, F. Herrero, R. Fitzenreiter, D. Fairfield, J. Needell, D. Bodet, J. Googins, C. Kletzing, R. Torbert, J. Vandiver, R. Bentley, W. Fillius, C. McIlvain, E. Whipple, and A. Korth, Space Sci. Rev. **71**, 459 (1995).
[23] J. W. Bonnell, F. S. Mozer, G. T. Delory, A. J. Hull, R. E. Ergun, C. M. Cully, V. Angelopoulos, and P. R. Harvey, Space Sci. Rev. **141**, 303 (2008).
[24] P. L. Pritchett and F. S. Mozer, J. Geophys. Res. **114**, A11210, doi:10.1029/2009JA014343 (2009).
[25] P. A. Cassak and M. A. Shay, Phys. Plasmas **16**, 055704 (2009).
[26] W. D. Gonzalez and F. S. Mozer, J. Geophys. Res. **79**, 4186, doi:10.1029/JA079i028p04186 (1974).