

Magnetic reconnection X-line retreat associated with dipolarization of the Earth's magnetosphere

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[1] Magnetic reconnection is the key process of plasma transport in the Earth's magnetotail. The 'X-line' where magnetic field lines reconnect often moves away from the Earth. However, the precise cause of the X-line motion remains unclear. Here we present data from five THEMIS probes positioned along the Sun-Earth line and show that a tailward retreat motion of the X-line (detected by the outermost probe P1) occurred when the dipolarized inner magnetosphere started to return to a more stretched, tail-like configuration (observed by the inner probes P3, P4, and P5). At an intermediate location (P2), the total pressure was increasing. These observations are consistent with the idea that the pressure increase in the inner magnetosphere eventually causes the X-line to retreat tailward. **Citation:** Oka, M., T.-D. Phan, J. P. Eastwood, V. Angelopoulos, N. A. Murphy, M. Øieroset, Y. Miyashita, M. Fujimoto, J. McFadden, and D. Larson (2011), Magnetic reconnection X-line retreat associated with dipolarization of the Earth's magnetosphere, *Geophys. Res. Lett.*, 38, L20105, doi:10.1029/2011GL049350.

1. Introduction

[2] Magnetic reconnection is the key process of plasma transport in the Earth's magnetotail. The 'X-line' where the magnetic fields reconnect produces fast plasma flows in the earthward and tailward directions with northward and southward magnetic fields, respectively [Dungey, 1961]. Therefore, its motion across a spacecraft is detected as correlated reversals of plasma flows as well as magnetic fields [Hones, 1979]. To date, many studies of magnetic reconnection have been made using the reversal signatures [e.g., Eastwood *et al.*, 2010, and references therein].

[3] It has been suggested that the location of the X-line can be 20–30 R_E downtail where R_E is the Earth's radius [e.g., Nishida and Nagayama, 1973; Nagai *et al.*, 1998] and that the near Earth X-line may 'retreat' tailward during an evolution of the Earth's magnetosphere [Russell and

McPherron, 1973]. In fact, both in situ [e.g., Hones, 1979; Eastwood *et al.*, 2010] and remote sensing [Forbes *et al.*, 1981; Nagata *et al.*, 2006] observations indicate that the X-lines move tailward rather than earthward in most cases. The X-line may retreat because one can expect a greater pressure on the earthward side of the X-line and/or because a possible external force from the interplanetary magnetic field shifts radially outward while continuing to trigger reconnection [Russell and McPherron, 1973]. Locally, X-line retreat is associated with gradients in the electric field [Murphy, 2010].

[4] A key to understanding the X-line retreat may be a 'dipolarization' of the magnetosphere and associated phenomena [Angelopoulos *et al.*, 1996]. Here, 'dipolarization' refers to the re-configuration of the magnetosphere from a stretched, tail-like configuration to a contracted, dipole-like configuration. Note also that the dipolarized region has been observed to expand outward both azimuthally [Nagai, 1982; Miyashita *et al.*, 2009] and radially [Jacquy *et al.*, 1991; Miyashita *et al.*, 2009].

[5] However, there has been no direct evidence to date that shows that an X-line moves tailward in response to the dipolarization of the inner magnetosphere. Baumjohann *et al.* [1999] suggested that magnetic reconnection cannot continue to operate once the dipolarized region reaches the X-line. Moreover, observations suggest that the X-line motion is highly variable and/or that there could be multiple X-lines during an event [Angelopoulos *et al.*, 1996; Nagata *et al.*, 2006]. Thus, the precise consequence of dipolarization for magnetic reconnection remains unknown. As such, the THEMIS mission [Angelopoulos, 2008] has been expected to provide conclusive information of X-line behaviors in the context of global evolution of the magnetosphere because it consists of five spacecraft (or probes) that are lined up at various downtail distances.

[6] It is the purpose of this paper to present a THEMIS event obtained on 7 February 2009 and to study pressure variation during X-line retreat associated with dipolarization of the magnetosphere.

2. Observation

[7] We present data from all five THEMIS probes. The magnetic field data is obtained by the Flux-gate Magnetometer (FGM, 3 s resolution) [Auster *et al.*, 2008]. The particle data is obtained by the Electrostatic Analyzer (ESA, 3 s, 10 eV - 28 keV) [McFadden *et al.*, 2008] as well as the Solid State Telescope (SST, 3 s, 28 keV - 2 MeV) [Angelopoulos, 2008]. In presenting the data, we used the Geocentric Solar Magnetospheric (GSM) coordinate system.

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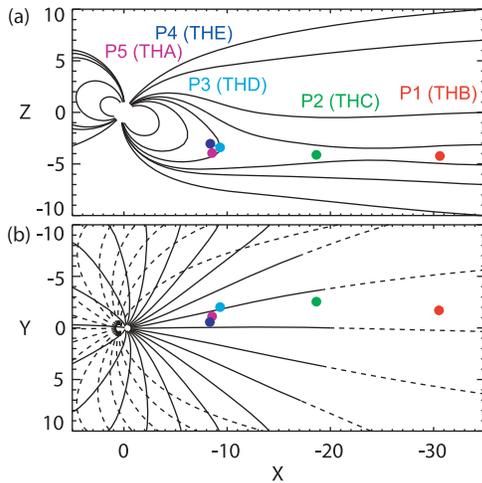


Figure 1. Locations of the THEMIS probes at 04:06 UT on 7 February 2009. Also shown is the T-96 model of the magnetic field lines [Tsyganenko, 1995].

[8] Figure 1 shows the locations of the probes at 04:06 UT on 7 February 2009. It is evident that all five probes were located in the mid-night sector but were roughly aligned in the x -direction over more than $30 R_E$, allowing us to study the large-scale evolution of the magnetotail.

[9] Figure 2 compiles various plasma parameters from all probes to show an overview of the event. First, P1 and P2 start to see tailward (negative V_x) and earthward (positive V_x) high-speed flows, respectively, at $\sim 04:00$ UT. Thus, the initial position of the X-line was in the $-19 > x > -30 R_E$ range. Then, tailward flows at P1 turned into earthward flows at around 04:18 UT as marked by the vertical line (with 1–2 min uncertainty). The magnetic field B_z also turned from negative to positive around this time. These signatures indicate that the X-line moved tailward and passed by P1 at around $\sim 04:18$ UT. After the flow reversal, P1 continued to observe bursts of earthward flows until $\sim 05:30$ UT while the fast flows at P2 persisted for only ~ 15 min even though P2 continued to reside near the neutral sheet (evidenced by $|B_x| < 5$ nT) for more than 90 min. This indicates either that the flows did not reach P2 or that the flows were deflected in the y - or z -direction and missed P2. It is clear, however, that P2 observed a gradual increase of average B_z until 05:30 UT, indicating that the plasma sheet was becoming thicker at this location.

[10] In the inner magnetosphere, probes P3, P4 and P5 observed a sudden increase of B_z at $\sim 04:06$ UT, indicating that a ‘dipolarization front’ (hereafter DF) [e.g., Nakamura et al., 2002; Runov et al., 2011] reached these locations. The DF is followed by turbulence with increasing magnetic field magnitude, indicating that the inner magnetosphere continued to become more dipole-like. Then, at $\sim 04:18$ UT (denoted by the vertical line), B_z started to gradually decrease, indicating that the inner magnetosphere began to become more tail-like. Moreover, the turbulent fluctuations of the magnetic field and the flow velocity were significantly reduced at $\sim 04:18$ UT.

[11] Here, we would like to emphasize the clear, temporal coincidence (at $\sim 04:18$ UT) between the flow reversal (observed at P1) and the beginning of the re-configuration of the inner magnetosphere (observed at P3, P4 and P5). Is

there any connection between the two features? To look for a clue, we studied the pressure variations with particular emphasis on the intermediate location P2, as will be described below.

[12] Figure 3 shows each component of the plasma and magnetic field pressures (colored curves, see caption for the definition) and their total P_{tot} (thick black curve), obtained

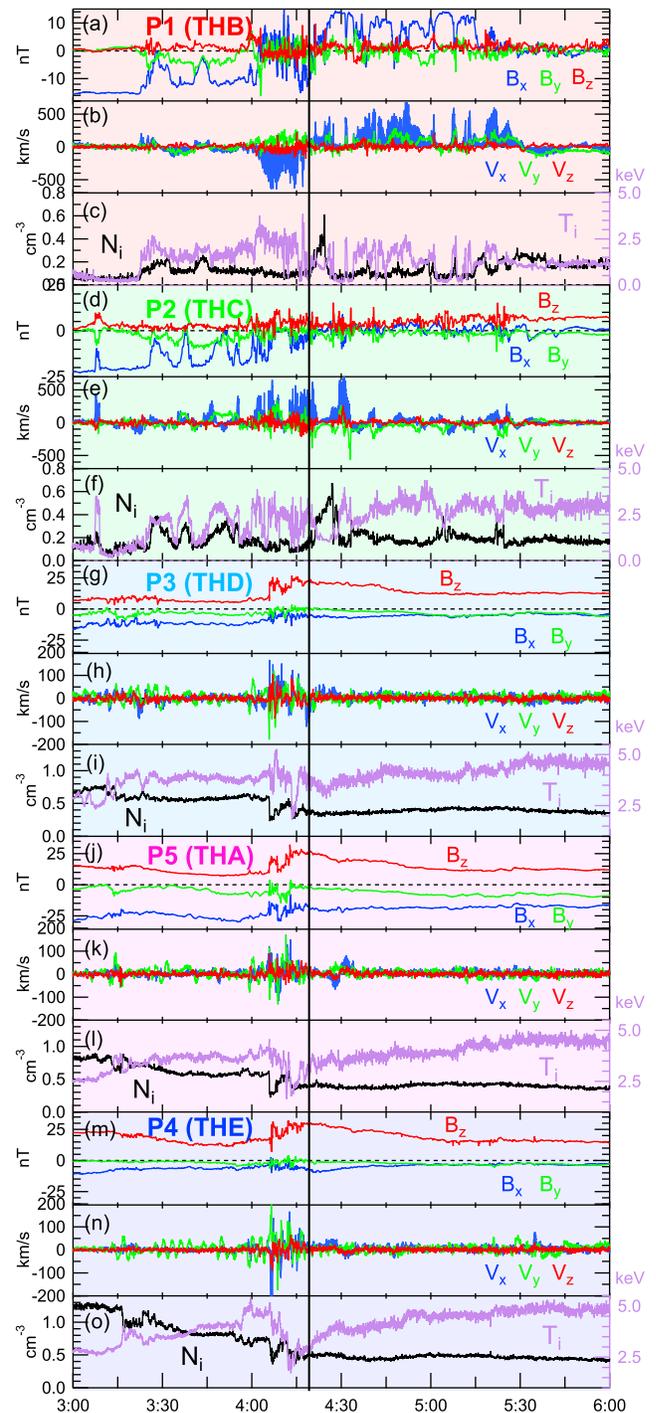


Figure 2. An overview of the X-line retreat event on 7 February 2009. The magnetic fields, the flow speeds and the higher moments (ion density and ion temperature) are shown for the five probes in order of decreasing distance to the Earth.

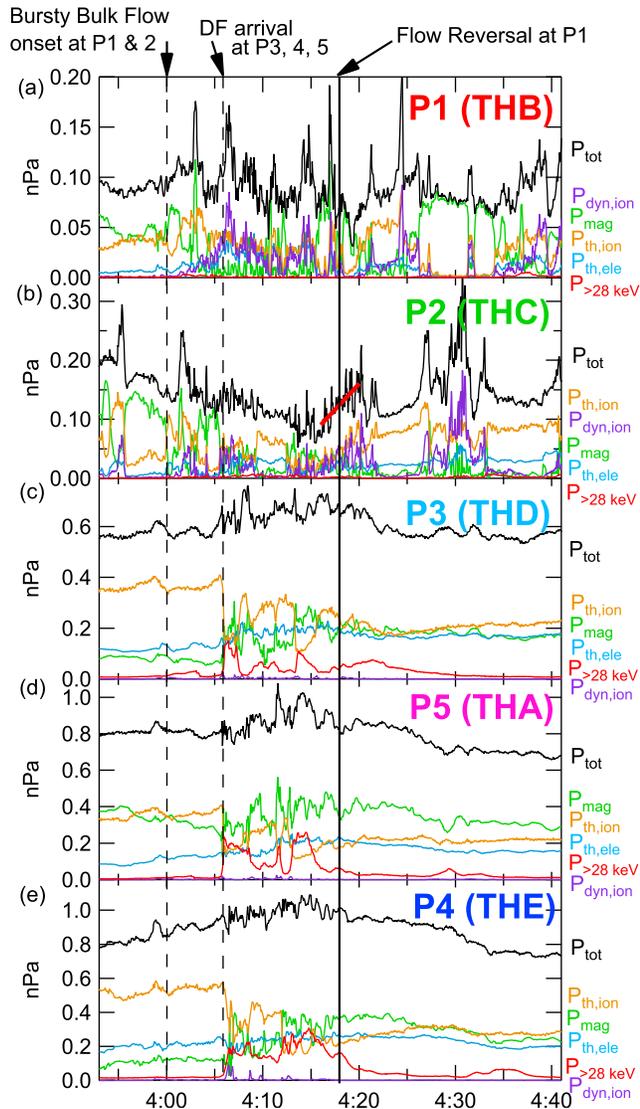


Figure 3. Pressure variations during the X-line retreat event on 7 February 2009. In each panel are the dynamic pressure of ions $P_{\text{dyn,ion}} = N_i m_i V_i^2$, the magnetic pressure $P_{\text{mag}} = B^2/2\mu_0$, the ion thermal pressure $P_{\text{th,ion}} = N_i T_i$, the electron thermal pressure $P_{\text{th,ele}} = N_e T_e$, and the energetic ion pressure $P_{>28\text{keV}}$ and their total P_{tot} . Note $P_{>28\text{keV}}$ covers the SST ion energy range of >28 keV. Here, the energetic electron data are not used because its contribution to the pressure was negligible.

by the five probes. Figure 3b indicates that P_{tot} at P2 was already decreasing, well before dipolarization started at 04:06 UT, and it reached its minimum (~ 0.06 nPa or nearly 30% of the pre-dipolarization level of 0.2 nPa) at 04:16 UT. Then, it rapidly recovered up to ~ 0.15 nPa within a few minutes during which the flow reversal was detected at P1. The superposed red line is a linear fit to the data between 04:16 UT and 04:20 UT and the rate of increase was ~ 0.3 pPa/s. At the inner probes P3, P4 and P5 (Figures 3c–3e), P_{tot} was more than 0.5 nPa before 04:00 UT and showed slight enhancement during dipolarization (between 04:06 UT and 04:18 UT). P_{tot} then decreased gradually afterward and

reached the pre-dipolarization level by 04:40 UT. At the outer probe P1 (Figure 3a), P_{tot} did not show any systematic increase or decrease (~ 0.1 nPa on average) despite the short time scale spikes.

[13] To further discuss the meaning of the observed pressure variations, Figure 4 takes the data from four different times in Figure 3 and re-organizes them as function of radial distance $r = \sqrt{x^2 + y^2}$. It is evident that P_{tot} decreases considerably with an increasing distance from the Earth. We fit the data set using a double-exponential form. Here, we did not use P5 data for the fitting because it stayed away from the magnetic equatorial plane as evidenced by the large $|B_x|$ (Figure 2j).

[14] Figure 4 then allows us to discuss the pressure gradient. Well before dipolarization (03:57 UT, blue solid curve), the pressure gradient was ~ 0.04 nPa/ R_E between the inner probes and P2. During dipolarization, however, P_{tot} increased at the inner probes, but decreased at P2 (see also Figure 3) so that, just before the flow reversal (04:16 UT, red solid curve), the pressure gradient had increased more than 60% between the inner probes and P2 (~ 0.07 pPa/ R_E) while it became almost flat between P1 and P2. Then, after a short period of time during which the X-line passed over P1 (04:20 UT, red dashed curve), the pressure profile recovered to levels similar to the initial profile, although P_{tot} remained high at the inner probes. The profile persisted until well after the dipolarization had occurred (04:40 UT, blue dashed curve).

[15] Note again that the X-line was located between P1 and P2 before the flow reversal. Because we observed a sudden increase of the pressure gradient between P1 and P2, we consider that the resultant force exerted by the large-

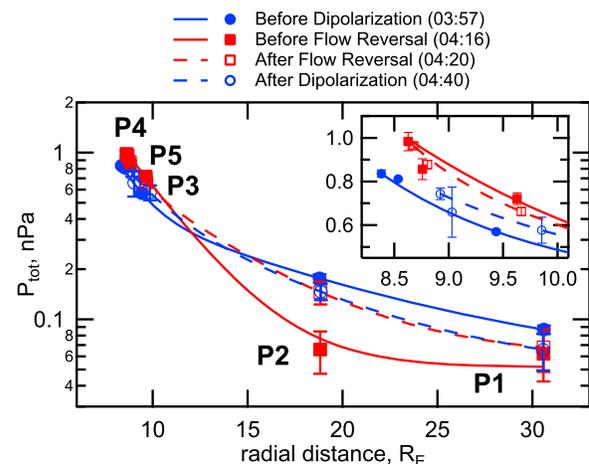


Figure 4. Large scale pressure variation during the X-line retreat event of 7 February 2009. The total pressure P_{tot} is plotted as function of $r = \sqrt{x^2 + y^2}$, obtained at four different times. The inset is a blow-up around the inner probes. The error bars are the standard deviation within ± 1.5 minute of each time. The curves represent the best fit model expressed as $P(r) = C + A_1 \exp[-(r - r_0)/\tau_1] + A_2 \exp[-(r - r_0)/\tau_2]$ where $(C, A_1, \tau_1, A_2, \tau_2, \chi^2/d.o.f) = (0.05, 0.46, 1.40, 0.36, 10.4, 7 \times 10^{-4}/3)$ at 03:57, $(0.05, 0.53, 2.82, 0.53, 2.81, 0.79/3)$ at 04:16, $(0.06, 0.35, 0.48, 0.79, 4.62, 1.1 \times 10^{-3}/3)$ at 04:20 and $(0.05, 0.41, 1.86, 0.44, 7.06, 3.8 \times 10^{-3}/3)$ at 04:40. Note $r_0 = 8.3 R_E$ is a constant and is not a fit parameter.

scale pressure gradient might have caused the X-line to retreat tailward.

3. Discussion

[16] Let us further discuss the force balance in the radial direction r in the magnetic equatorial plane. The momentum equation of the magnetohydro-dynamics (MHD) reads

$$\frac{\partial(\rho V_r)}{\partial t} = -\frac{\partial P_{\text{tot}}}{\partial r} + \frac{[(\mathbf{B} \cdot \nabla)\mathbf{B}]_r}{4\pi} \quad (1)$$

where ρ is the mass density, V_r is the radial component of the flow velocity, $P_{\text{tot}} = \rho V_r^2 + P_{\text{th}} + B^2/2\mu_0$ is the total pressure. In a stationary condition, the pressure gradient force is balanced by the earthward tension force. The general feature of P_{tot} decreasing considerably with an increasing distance from the Earth implies that the tension force becomes larger closer to the Earth [e.g., Kistler *et al.*, 1992]. In our case of a tailward retreating X-line, we should consider a non-stationary condition and so we assume that the force exerted by the large scale pressure gradient was larger than the tension force of the globally varying magnetic field.

[17] Then, how large was the force imbalance and how fast can it make the X-line move? Unfortunately, we cannot directly measure the tension force as well as the retreat speed V_{XL} because only one probe detected the flow reversal. We can only estimate an upper limit. If we assume constant density and uniform pressure gradient in the mid-tail region, the X-line acceleration should not exceed

$$\frac{V_{\text{XL}}}{\Delta t} \sim \frac{\partial V_r}{\partial t} < \frac{1}{\rho} \left| \frac{\partial P_{\text{tot}}}{\partial r} \right| \sim 5.7 [\text{km/s}^2]. \quad (2)$$

Here, we used the pressure gradient of ~ 6.0 pPa/ R_E obtained between P1 and P2 at 04:18 UT. For the number density, we used 0.1 cm^{-3} measured both at P1 and P2 at 04:18 UT. Note also that P_{tot} started to increase at P2 at $\sim 04:16$ UT, which may be regarded a possible start time of the retreat motion. If so, the above acceleration gives an upper-limit of $V_{\text{XL}} < 680$ km/s within the two minutes. In fact, previous studies obtained smaller V_{XL} . While an early study gave a rough estimate of $V_{\text{XL}} \sim 1 R_E/\text{min}$ [Russell and McPherron, 1973], a recent multi-spacecraft observation [Imada *et al.*, 2007] as well as global MHD simulations [Kuznetsova *et al.*, 2007] obtained a similar value $V_{\text{XL}} \sim 100$ km/s.

[18] We now discuss the timing of the observed features. A striking feature in our event is the temporal coincidence (at $\sim 04:18$ UT) between the flow reversal at P1 and the beginning of the re-configuration from a contracted, dipole-like magnetosphere to a stretched, tail-like magnetosphere at the inner probes. The flow reversal also coincided with a significant reduction of the turbulent fluctuations in the inner magnetosphere. Such fluctuations have often been discussed in the context of ‘flow braking’ [Shiokawa *et al.*, 1997] or ‘current disruption’ (equivalently ‘substorm current wedge’) [Lui, 1996]. We suggest that this region has possibly shifted outward at the time of the re-configuration due to the persistent earthward flow observed at P1 and P2 (Figures 3 and 4).

[19] The temporal coincidence (within the uncertainty of 1–2 min) is not surprising because the sound speed C_s was quite fast. At P2 and P4, the ion temperature was larger than

2.5 keV so that $C_s > 640$ km/s. Therefore, a pressure pulse could have propagated the magnetotail within a few minutes, or even less if we considered the fast magneto-sonic speed.

[20] A very similar temporal coincidence between a flow reversal and a beginning of re-configuration of the magnetosphere as well as a reduction of turbulent fluctuation can be found in another THEMIS event of 26 August 2008 [see Angelopoulos *et al.*, 2008, Figure 3]. However, we note that there was another event on the same day, and the flow reversal occurred much earlier than the dipolarization of the inner magnetosphere [see Pu *et al.*, 2010, Figure 3], which does not seem to fit the scenario that a large-scale pressure gradient causes X-line to retreat. Thus, it would be important to examine a larger number of events in order to verify the generality of the scenario proposed in this paper.

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