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P K. Toivanen

D N. Baker

W K. Peterson

A Viljanen

Niescja E. Turner
Trinity University

See next page for additional authors

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Authors
P K. Toivanen, D N. Baker, W K. Peterson, A Viljanen, Niescja E. Turner, X Li, and C A. Kletzing

A SUBSTORM ONSET OBSERVED BY THE POLAR SPACECRAFT IN CONJUNCTION WITH THE IMAGE CHAIN

P. K. Toivanen[1], D. N. Baker[1], W. K. Peterson[2], A. Viljanen[3], N. E. Turner[1], X. Li[1], and C. A. Kletzing[4]

[1]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA
[2]Lockheed Martin Space Science Laboratory, Palo Alto, California, USA
[3]Finnish Meteorological Institute, Helsinki, Finland
[4]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA

ABSTRACT

We present observations of the Polar spacecraft of magnetospheric substorm signatures in the plasma sheet midway along auroral field lines between the ionosphere and the equatorial plasma sheet. An isolated substorm on October 17, 1997, is studied in detail. The onset time at 2040:42 UT was defined to be almost simultaneous (within 20 sec) on the ground and at Polar altitude ($\sim 4R_E$). At Polar, the onset was manifested as strong magnetic field variations and plasma flow bursts with amplitudes exceeding 20 nT and 100 km/s, respectively. Bursts of parallel Poynting flux of $\sim$ 0.5 ergs/cm^2 were related to these variations, and they were predominantly directed toward the ionosphere. In addition, a sequence of weak magnetic field variations and flow bursts were observed at Polar $\sim$ 10 min before the onset. Associated with this, a weak westward electrojet was observed on the ground. We discuss the importance of these observations in the physics of substorm onset.

Key words: Substorm onset; timing; signatures.

1. INTRODUCTION

One of the remaining open questions in substorm physics is the transport of energy and information from the magnetotail to the ionosphere at substorm onset. A considerable amount of the energy released during substorms is deposited into the ionosphere in forms of Joule heating and auroral precipitation. The precipitation is associated with particle energization in the auroral acceleration region (Carlson et al., 1998). The ionospheric closure currents of the substorm current wedge account for a major portion of the Joule dissipation. Details of the propagation of the information along the auroral field lines are important when reconciling the substorm signatures and their timing on the ground and in the equatorial plasma sheet. To date, it has not been possible to reconcile the time of the substorm onset on the ground and in the equatorial plasma sheet (Liou et al., 1999). Thus the cause-and-effect relationship among onset signatures is unclear and this greatly complicates the validation of substorm onset models.

The characteristics of the Polar orbit provide a new approach for studies in magnetospheric substorms: Polar crosses the plasma sheet midway along field lines between the ionosphere and the equatorial plasma sheet; and the timescale of the crossing is of the same order as a characteristic substorm timescale ($\sim$ 2 hrs). Thus during a substorm, the plasma sheet footpoint of Polar traces a prolonged path in the central plasma sheet. This gives a view of the plasma sheet dynamics quite different from that of relatively fixed near-equatorial spacecraft. Furthermore, the crossing takes place above the auroral acceleration region, which complements observations on auroral processes obtained by low-altitude spacecraft such as Freja or FAST. In this paper, we study an isolated substorm event on October 17, 1997, to demonstrate that the Polar observations provide new insights to the physics of substorm onset and observational constraints for substorm onset models.

2. OBSERVATIONS

The event on October 17, 1997 was an isolated substorm. The AE index showed that the substorm onset took place $\sim$ 2041 UT after a quiet period of over two hours. During that time, Polar was located in the midnight sector, and the ionospheric footpoints of Polar lay $\sim$ 15 degrees east of the IMAGE chain (Toivanen et al., 2000a). The timing of the main onset in this event was studied in detail by Toivanen et al. (2000a). Their study showed that the onset of the negative bay (2040:42 UT) was almost simultaneous ($\pm$ 10 sec) with the start of the electron precip-

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itation on the ground and an electron flux increase and a sudden magnetic field variation at Polar. Such accurate timing coincidence is consistent with the Alfvén transit time, ~ 10 sec between Polar and the ionosphere.

Figure 2 shows the magnetic variations of the geographic north-south component (X; positive toward north) at the IMAGE stations (for station locations, see Viljanen and Häkkinen (1997)). The vertical dashed line at 2040:42 UT indicates the onset of a negative bay as observed in Sørøya (SOR). This timing is consistent with the onset of the electron precipitation as defined from the all-sky camera located in Muonio (MUO) (Toivanen et al., 2000a). The location of the westward auroral electrojet was given by Toivanen et al. (2000b): shortly after the onset, the location was uncertain because of the strong variations in magnetograms; after 2050 UT the electrojet was located near SOR; and the center of the substorm current wedge was located east of the IMAGE chain. Sequences of Pi2 pulsations occurred during the studied interval as shown by thick solid lines in Figure 1. The onset of Pi2 pulsations took place at ~ 2041 UT. A sequence of weak Pi2 pulsations occurred also before the onset starting ~ 2031 UT. This was related to a weak westward electrojet located between Masi (MAS) and MUO that is ~ 2° south of the main electrojet.

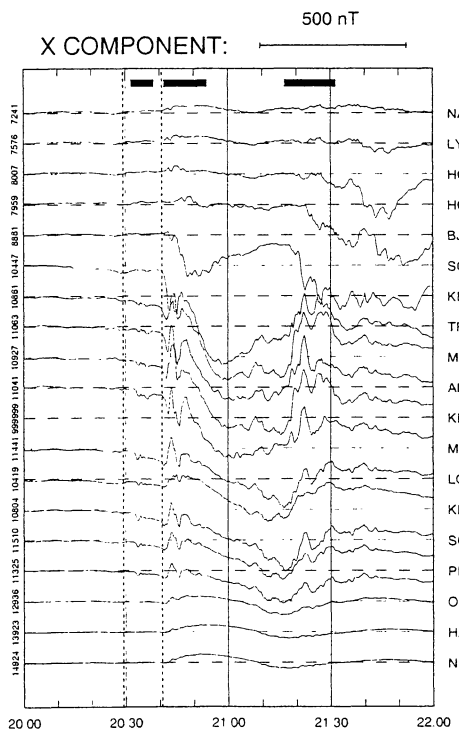

Figure 1. The geographic north-south (positive toward north) component of the magnetic field variations and Pi2 pulsations (thick solid lines).

Figures 1a-1c show energy spectrograms deduced from CEPPAD/IPS (17–235 keV protons), CEPPAD/IES (18–200 keV electrons) (Blake et al., 1995), and HYDRA (0.01–20 keV electrons) Scudder et al. (1995) instruments on Polar. They indicate that Polar was in the plasma sheet prior to and after the onset: the outer radiation belt was seen as high fluxes in CEPPAD/IES before ~ 2029 UT; the plasma sheet was observed by HYDRA between ~ 2025 UT and ~ 2112 UT; the tail lobe appeared as low fluxes in HYDRA after ~ 2112 UT. At the onset, an abrupt enhancement in electron fluxes (Figure 1c). In CEPPAD/IES, a sudden flux enhancement occurred ~ 2 min later. CEPPAD/IPS measured a more gradual flux increase embedded in the proton background of the plasma sheet.

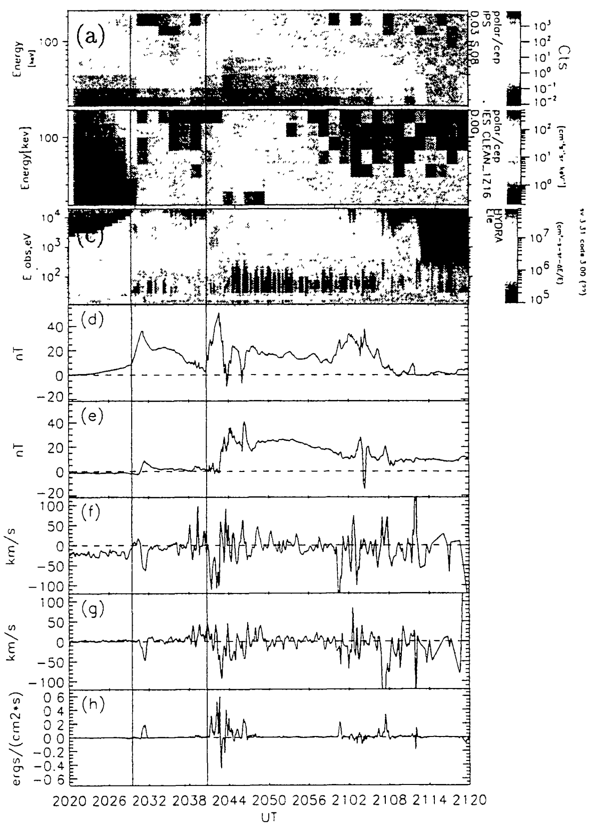

Figure 2. Polar observations for Event A: (a) CEPPAD/IPS proton energy spectrogram; (b) CEPPAD/IES electron spectrogram; (c) HYDRA electron spectrogram; (d) magnetic field Y_{GSM} component; (e) magnetic field Z_{GSM} component; (f) perpendicular proton flow velocity Y_{GSM} component; (g) perpendicular proton flow velocity Z_{GSM} component; (h) parallel Poynting flux (positive toward the ionosphere).

Magnetic field measurements by MFE (Russell et al., 1995) are presented as $\delta B_{Y_{GSM}}$ (Figure 2d) and $\delta B_{Z_{GSM}}$ (Figure 2e) after the removal of the magnetic field model (T89+IGRF) values from the actual measurements. At the onset, the ambient magnetic field was essentially in the X_{GSM} direction, and Y_{GSM} and Z_{GSM} represent the coordinates perpendicular to the ambient field. At the onset, $\delta B_{Y_{GSM}}$

indicated a sudden deviation ($\sim$ 40 nT) of the magnetic field from the model field. The deviation of the Z_{GSM} component occurred $\sim$ 2 min later.

The perpendicular proton flows in Y_{GSM} (Figure 2f) and Z_{GSM} (Figure 2g) were obtained from moments of the three dimensional ion distributions of the TIMAS instrument (Shelley et al., 1995). They are consistent with the electric field measured by the electric field instrument (EFI) (Harvey et al., 1995). At the onset, the Y_{GSM} component of the perpendicular flow was reversed $\sim$ 3 min after the first appearance of flow bursts at $\sim$ 2038 UT (Figures 2f and 2g). Note also the flow bursts at $\sim$ 2030 UT (dashed vertical line at 2029:30 UT) and the associated signatures in the magnetic field and particle data. These signatures are similar to the signatures at the main onset with exceptions that they were smaller in magnitude and less bursty than at the main onset.

Figure 2h shows the parallel Poynting flux as deduced from the TIMAS (Figure 2a–c) instrument. The Poynting flux is related to the flow bursts and magnetic field fluctuations observed shortly before and after the onset. The vector velocities determined from TIMAS velocity moment calculations are interpreted as the local plasma flow velocities in order to infer the 3-d electric field perpendicular to the measured magnetic field. The parallel Poynting flux with peak values reaching $\sim$ 0.6 ergs/(cm^{2}s) locally was initiated at substorm onset.

3. INTERPRETATION

In this section, we discuss a possible interpretation of this event. We assume that the signatures at $\sim$ 2030 UT and $\sim$ 2041 UT are causally connected. Peterson et al. (2000) discussed this event in terms of pseudobreakups. Figure 3 illustrates a possible interpretation of this event. The signatures at $\sim$ 2030 UT both on the ground and at Polar were related to onset of reconnection of closed field lines (Figure 3b). Reconnection proceeded to field lines connecting to higher magnetic latitudes and in about $\sim$ 10 min it reached the open-closed boundary (Figure 3c). This caused the expansion onset at $\sim$ 2041 UT.

On the ground, $\sim$ 10 min prior to the main negative bay, a gradual decrease of the X component and a sequence of Pi2 pulsations were observed. This indicates a weak enhancement of the westward electrojet (Figure 1) that is quite typical during the late growth phase (McPherron, 1970). The decrease began at $\sim$ 2031 UT coinciding with a dynamical signature in the Polar data shown in Figure 2. Due to the prevailing observational geometry, the deviation of $B_{Y_{GSM}}$ from the model field value (Figure 2d) can be interpreted as a weak field-aligned current signature related to the weak electrojet seen on the ground. After this signature Polar encountered a quiescent region of plasma sheet. The transient nature of this signature can be a spatial effect, Polar moving relative to the field lines connected to the

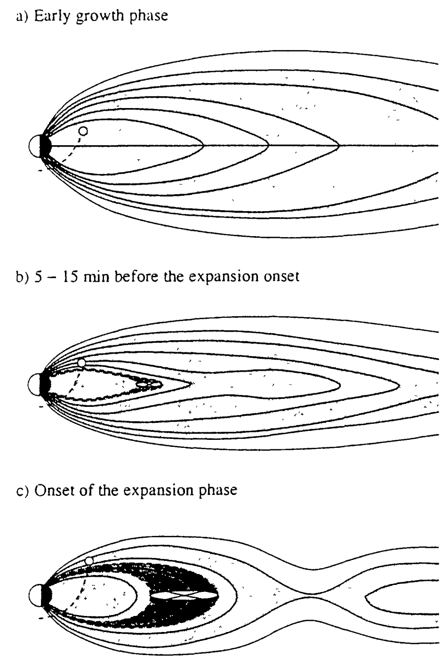

Figure 3. A schematic presentation of the development of the magnetospheric magnetic field configuration toward the substorm onset. The light gray shading corresponds to the plasma sheet. (a) The magnetospheric field configuration during the early growth phase. (b) Reconnection of the closed field lines 5 – 15 min prior to the substorm expansion onset and associated current perturbation earthward of the reconnection side (dark shading). (c) Reconnection of open magnetic field lines at the substorm expansion onset and associated current perturbation (current wedge; dark shading) earthward of the reconnection side. The white dot indicates the location of Polar with respect to the field configuration.

active region of the plasma sheet. However, if the continuous enhancement of the westward electrojet is attributed to this signature, it is likely that the physical process initiated at $\sim$ 2030 UT persisted in the plasma sheet.

The observed magnetic and electric field fluctuations and the associated parallel Poynting flux presented here are similar to the results by Wygant et al. (2000) and Toivanen et al. (2000b)(see Event B). Thus they most probably are signatures of the same physical process taking place in the equatorial plasma sheet. Wygant et al. (2000) showed strong parallel Poynting fluxes near the plasma sheet boundary during the expansion phase. They studied in detail two substorm expansion phase intervals during which the Polar spacecraft crossed this boundary and mapped to a region of strong precipitation in the auroral bulge as observed by the Polar UVI imager. Toivanen et al. (2000b) showed that such Poynting fluxes appeared at a previously quiet plasma sheet boundary at the time of the plasma sheet expansion associated with the auroral bulge expanding to the local time sector of Polar. This strongly suggests that these field variations and the associated Poynting flux are signatures of reconnection of open field lines. Before the reconnection of open field lines, the closed field lines have to be reconnected first Coroniti (1985). In the studied event, the dynamical signature $\sim$ 10 min before the onset may be a signature of the onset of reconnection of the closed field lines.

4. CONCLUSION

We present Polar and IMAGE data of an isolated substorm event on October 17, 1997. In this event, Polar was able to observe the plasma sheet dynamics as a function of magnetic latitude. At $\sim$ 2030 UT, Polar observed weak flow bursts and magnetic field variations associated with a weak westward electrojet. At expansion onset ($\sim$ 2041 UT) the magnetic field and flow signatures were more drastic and the auroral electrojet was located $\sim 2°$ higher in magnetic latitude than at $\sim$ 2030 UT. We interpreted this event in terms of the present form of the Near-Earth Neutral Line model (NENL) (Baker et al., 1996): at $\sim$ 2030 UT, the reconnection on closed field lines began; and at $\sim$ 2041 UT, the reconnection of open field lines started.

Our interpretation of this event and the association of the magnetic field and plasma flow variations with the reconnection are based on only a few events. Thus more events similar to the studied event have to be analyzed in order to to affirm or refute the interpretation given in this paper. However, we have demonstrated in this paper that the Polar spacecraft provides valuable observations in the plasma sheet midway between the ionosphere and the equatorial plasma sheet. These observations give constraints to the substorm onset process in the equatorial plasma sheet. Any suggested plasma process responsible for the substorm onset has to produce signatures described in this paper while reaching the ionosphere. This is a crucial test for global substorm onset models.

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