Large Alfvén wave power in the plasma sheet boundary layer during the expansion phase of substorms

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Abstract. Observations by the Polar satellite of large Poynting flux in the plasma sheet boundary layer at geocentric distances of 4 to 6 R_E and between 22 and 3 hrs magnetic local time were correlated with H-bay signatures from ground magnetometer records. We provide evidence that large Poynting fluxes occur during the substorm expansion phase. The Poynting fluxes exceeded 1 ergs/cm^{2}s (125 ergs/cm^{2}s when mapped to 100 km), were dominantly directed toward the ionosphere, and were associated with Alfvén waves. These observations demonstrate the importance of Alfvén wave power as a means of energy transport from the distant magnetotail to the ionosphere during the most dynamic phase of substorms.

Introduction

A magnetospheric substorm is a transient process that leads to a reconfiguration of the magnetotail. Beside relocation of plasma, it involves the flow of large amounts of energy in the magnetotail. Considerable amounts of this energy are eventually deposited in the ionosphere. An important topic in understanding substorm dynamics is the transport of that energy. There are several forms of energy transfer processes between the magnetosphere and the ionosphere: particle transport, static field-aligned currents (FAC) and Alfvén waves. A comparison of these forms during two Polar plasma sheet crossings at geocentric distances of 4 to 6 R_E were presented in a recent Polar study by *Wygant et al.* [2000]. It was shown that the contribution to the total energy flux at these altitudes from Alfvénic Poynting flux (1-2 ergs/cm^{2}s) was comparable to or larger than the contribution from particle energy flux and 1 to 2 orders of magnitude larger than that estimated from steady state convection electric fields and FAC. It was also shown that the large Alfvén wave power occurred on field lines that were magnetically conjugate to regions of strong energy deposition by auroral electrons in the ionosphere.

Most reported observations of Poynting flux have been made below the auroral acceleration region [e.g. *Kelley et al.*, 1991; *Louarn et al.*, 1994; *Nagatsuma et al.*, 1996; *Kletzing et al.*, 1996]. At the satellite/rocket locations, the Poynting flux reached values of several ergs/cm^{2}s. It is probable that these values are smaller than high-altitude Poynting flux (after mapping to a reference altitude) due to processes in the auroral acceleration region (such as particle acceleration and wave dispersion) which dissipate electromagnetic energy. These previous studies did not correlate their observations with substorm phases. The first observation of intense Poynting flux in association with substorm onset was by *Maynard et al.* [1996] near the inner edge of the plasma sheet.

A region of great importance to auroral substorm physics is the plasma sheet boundary layer (PSBL) [*Eastman et al.*, 1984]. It is located between the tail lobes and the central plasma sheet (CPS), connecting the auroral acceleration region with the distant tail where reconnection processes have been invoked [e.g. *Baker et al.*, 1996, and references therein]. Although it has been demonstrated that the PSBL is a key region in the creation of the aurora, its full significance is still not known. Polar's orbit allows the investigation of energy flow in the plasma sheet at geocentric distances of 4 to 6 R_E, which is intermediate between the distant magnetotail and the auroral acceleration region. In addition, the Polar spacecraft provides the first 3-D measurements of the electric field at high-altitude on plasma sheet auroral field lines.

In this paper, we provide evidence that large Poynting fluxes associated with Alfvén waves in the PSBL at high altitudes occur during times of rapid changes in the H (or X) component of ground magnetometer data. These observa-

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tions demonstrate the importance of Alfvén wave power as a means of energy transport from the magnetotail to the auroral acceleration region during the most dynamic phase of auroral substorms. It also demonstrates that the PSBL plays a very important role as a region that carries this energy flux.

Data analysis

For this study, we incorporated data from the UC Berkeley Electric Field Instrument [*Harvey et al.*, 1995], the UCLA Fluxgate Magnetometer [*Russell et al.*, 1995], and the University of Iowa Hydra Plasma Instrument [*Scudder et al.*, 1995]. We utilized all three components (6 second averaged) of the electric and magnetic field vectors. Hydra measurements of electron and ion energy flux at 13.8-second time resolution in the energy range from 12 eV to 18 keV were utilized. Ground data from different magnetometer arrays (CANOPUS, MACCS, IMAGE, 210MM [*Yumoto*, 1996]) were also used.

The data for this study were obtained as the Polar satellite crossed the lobe-PSBL interface at geocentric distances of 4 to 6 R_E. Electric and magnetic field measurements were used to calculate the associated Poynting flux. In addition, for each crossing we identified a ground station that was in the general proximity of Polar's magnetic footpoint. The ground data were used to establish a relationship between the high-altitude Poynting flux observations and substorm phases. Only the unfiltered H or X component - depending on which magnetometer chain was used - is presented, because it is this component which responds most strongly to the substorm auroral electrojet. This component is routinely used as an indicator of substorm onset/intensification.

Figure 1 presents one lobe-PSBL crossing (5/23/1996) by Polar in more detail to illustrate the analysis technique. The top panel shows the E_z component of the electric field which points northward (approximately along GSE z) and is approximately perpendicular to the nominal plasma sheet boundary. The second panel shows the eastward perturbation of the magnetic field. This component lies approximately in the plane of the nominal plasma sheet boundary. Note that both the electric and magnetic field data were detrended in order to show the smaller scale perturbations. The detrending was done by subtracting a 3-min running average from the original data. The third panel shows the field-aligned Poynting flux calculated from the three components of the perturbation electric field and the three components of the perturbation magnetic field. The calculated Poynting flux vector was then projected onto the average magnetic field direction, calculated from the measured magnetic field vector averaged over 3 minutes. The last two panels show the energy spectra of ions and electrons.

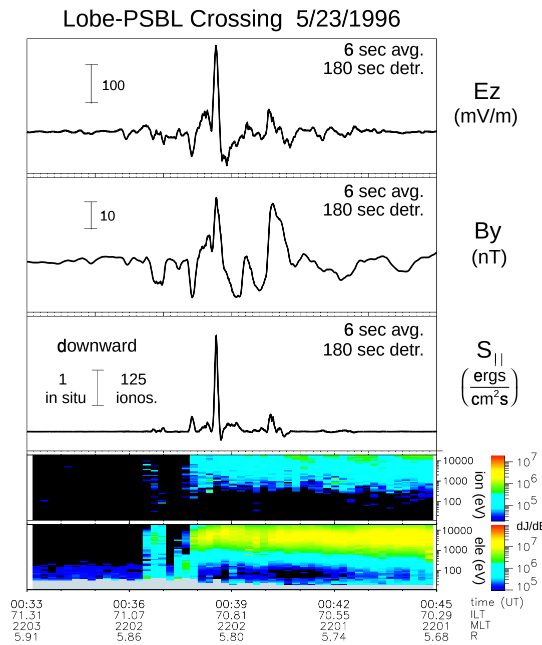

Figure 1. Measurements from the Polar satellite on 5/23/1996 during a lobe-PSBL crossing. The panels show, from top to bottom, the electric field component approximately normal to the plane of the plasma sheet boundary, the east-west component of the magnetic field (model subtracted), the Poynting flux component along the magnetic field, and energy-time spectrograms of ions and electrons.

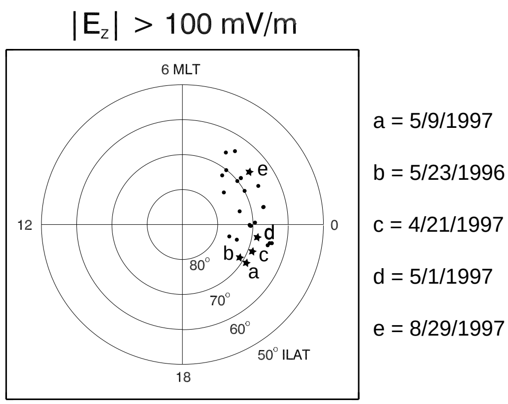

Figure 2. Distribution of electric field events as a function of invariant latitude (ILAT) and magnetic local time (MLT) for values of the electric field larger than 100 mV/m (modified from K1). The spacecraft locations for the five events presented in this study are indicated by stars.

Polar entered the PSBL, identified from Hydra particle data (sharp flux increase of ions and electrons) from the lobe at ∼00:37 UT at a geocentric distance of ∼5.84 R_E. Immediately adjacent to the lobe-PSBL interface, Polar encountered large electric and magnetic field fluctuations with peak values of 220 mV/m and 20 nT, respectively. The electric and magnetic fields were very similar in waveform. The ratio of the peak electric and magnetic field signals is 11,000 km/s. This is comparable to the local Alfvén speed of 14,000 km/s determined from in situ plasma parameters, suggesting that these fields were the perturbation fields of Alfvén waves. Strong Poynting flux (exceeding amplitudes of 2 ergs/cm^{2}s), directed towards the Earth was associated with these Alfvén waves (third panel). The scale in this panel shows both the in situ value of Poynting flux and its value mapped to 100 km altitude. The Poynting flux was largest near the lobe-PSBL interface. Preliminary results of a study (in process), investigating the phasing of the electric and magnetic wave fields, indicate the presence of frequency components which have reflected off at altitudes below the satellite, but as shown in the third panel, the earthward propagating components by far dominate over the reflected ones.

In the next section, this and four other large Poynting flux events are compared to ground magnetic field observations.

Conjugate Study

A survey of two years of Polar electric field data by *Keiling et al.* [2000], hereafter K1, yielded 24 very large amplitude electric field events (larger than 100 mV/m). These fields were perpendicular to the ambient magnetic field and also approximately perpendicular to the plasma sheet boundary. The majority of events (∼85%) occurred inside the PSBL. Figure 2 shows the distribution of these events in ILAT and MLT. In a temporal comparison of 14 events to magnetograms of magnetically conjugate ground stations, it was found that the events occurred in close temporal proximity to substorm onset. In the study presented herein, Poynting fluxes were calculated for five of these events (indicated in Figure 2 by stars). These events were selected because they show well-correlated electric and magnetic perturbation fields (c.f. Figure 1). The perturbation fields were obtained by subtracting either a 1-min or 3-min running average (depending on the scale size of large-scale background fields) from the original data. The ratios, ranging between 8,000 and 11,000 km/s, and the phasing for the five events were consistent with Alfvén waves, so that a calculation of the Alfvénic contribution to the Poynting flux was unambiguous. This conclusion is based on the detailed analysis of two events (5/1/97, 5/9/97) by *Wygant et al.* [2000] and results presented here. An analysis of the other events from K1 will be presented in a later paper. Preliminary results also show large parallel, downward Poynting flux in conjunction with the substorm expansion phase for the majority of events. A separation of the Alfvénic contribution, however, requires additional investigations, because the waveforms of the electric and magnetic field signals seem to be related in a more complicated way.

The five events presented in this study occurred during a variety of geomagnetic conditions: strong substorms (≥500 nT), weak substorms (≤150 nT), isolated substorms, and multiple intensifications. Figure 3 shows the Poynting flux (red line) along the ambient average magnetic field direction at Polar's location overlaid on ground magnetometer data (black line) from magnetically conjugate ground stations to show the temporal relationship between the two quantities. Each panel in Figure 3 shows a different substorm. The substorm onsets/intensifications are identifiable in the magnetograms by strong negative excursions of the H (or X) component. The magnetogram at Gillam (first panel) shows a negative 300-nT magnetic bay between 5.3 and 6.1 UT. The expansion phase lasted until 5.7 UT, and was associated with a strong Pi 2 pulsation train. During the expansion phase, Polar measured strong Poynting flux pulses directed downward towards the ionosphere, which coincided with Polar entering the PSBL from the lobe (not shown). At the times of large Poynting flux occurrence, Polar's magnetic footpoint was west and north of Gillam by 0.5 hrs MLT and 5° ILAT, respectively.

The events shown in the remaining four panels of Figure 3 show similar good correlations between strong Poynting flux at Polar's location and the expansion/intensification phase

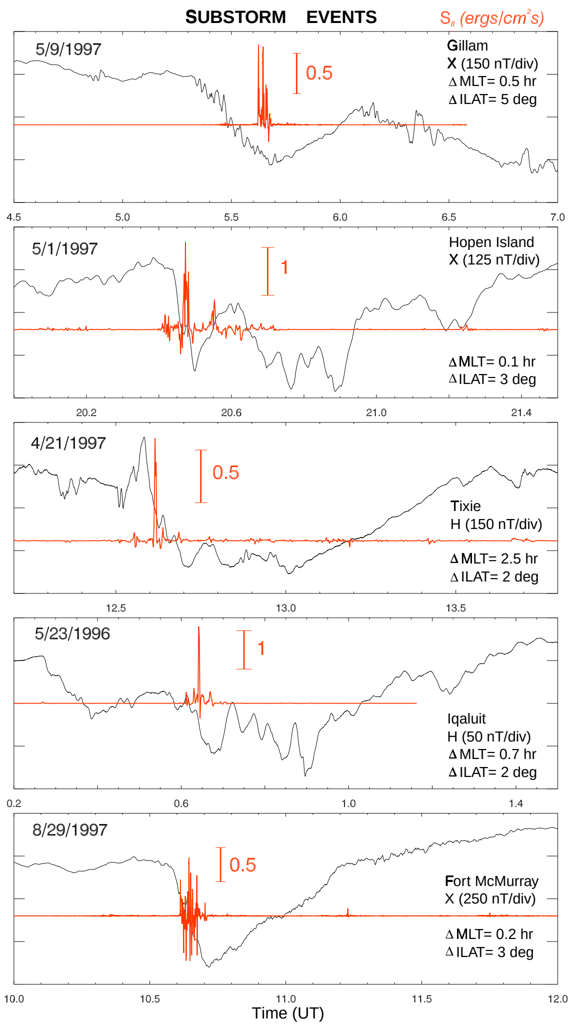

Figure 3. Temporal comparison of in-situ field-aligned Poynting flux (red line) measured by Polar and ground signatures of H-bays (black lines). The Poynting flux component shown is parallel to the average background magnetic field. The Poynting flux scale shows in situ values. Positive values indicate directions downward, towards the ionosphere. The relative separation between Polar's footpoint and the ground stations is given as ΔMLT and ΔILAT.

determined from ground magnetograms. The relative separations between Polar's magnetic footpoint and the ground stations is given as ΔMLT and ΔILAT. Polar's locations for the five events ranged between 4.6 and 5.8 R_E, and 22 and 3 hrs MLT. At the times of largest Poynting flux occurrence, the satellite was in the PSBL at or very near its poleward edge. The fact that we present only strong Poynting flux events, that occurred inside the PSBL, should not be taken to imply that strong Poynting fluxes do not occur deeper inside the plasma sheet. Indeed, K1 reported large perpendicular electric field events, that occurred in the CPS. A study of the nature of these fields inside the CPS in comparison to observations in the PSBL is in process. The peak Alfvén wave power for all five events ranged between 0.8 and 2.5 ergs/cm^{2}s. In four events, the net Poynting flux was dominantly directed towards the northern hemisphere ionosphere. One event showed large incident and reflected Alfvén wave power with similar amplitudes. The important result to observe here is that the largest Poynting fluxes occurred during times of rapid change in the H (or X) component. This time corresponds to the most dynamic phase of substorms. The reason why Polar observed intense Poynting flux only for several minutes while the expansion phase lasted for up to 20 minutes, is most likely a spatial effect. A simple explanation would be that the Poynting flux is confined to a thin layer, which is only crossed by the satellite for a period of several minutes in the spacecraft frame due to the relative velocities between Polar (moving at 1-2 km/s) and the plasma sheet, which can expand at much larger velocities than the spacecraft velocities. This can also explain why Polar does not encounter large Poynting flux during every substorm expansion phase.

Conclusions

In order to understand substorm dynamics, it is necessary to understand the flow of energy in the magnetotail. We have provided evidence for 5 substorms that large Alfvén wave power in the PSBL at geocentric distances of 4 to 6 R_E was directly linked to the expansion phase. We presented in-situ Poynting flux and ground magnetic field data for these five events. Although there is uncertainty in obtaining the exact time of substorm onset using a single ground station, this is not critical for our results, which depend only on substorm phases. In 4 out of 5 events, the by far dominant flow direction was into the ionosphere. One event showed both strong incident and reflected power. The Poynting flux for all events was dominantly associated with north-south polarized electric fields when mapped to the ionosphere. The only other intense Alfvénic Poynting flux observations in the magnetotail associated with substorm onset were described by *Maynard et al.* [1996], who examined events near the inner edge of the plasma sheet which had large downward Poynting flux into the ionosphere due to dusk-dawn electric fields. They argued that this Poynting flux was part of establishing the field-aligned current of the substorm current wedge.

The peak Alfvén wave power for the events presented here ranged between 0.8 and 2.5 ergs/cm^{2}s, corresponding to Poynting fluxes of 100 and 315 ergs/cm^{2}s when mapped to 100 km altitude. This Poynting flux exceeds the energy flux necessary to power very intense auroras [*Wygant et al.*, 2000]. Since Polar makes only single point measurements, we cannot infer the total energy flow associated with these events. Nevertheless, these observations are suggestive that Alfvén waves play an important role during the energy release of stored magnetic field energy in the magnetotail at times of substorm expansion. Theoretical models of substorms will have to show these waves or they are missing a key piece of the physics. Furthermore, it is shown that the PSBL can be carrier of the electromagnetic energy flux associated with Alfvén waves.

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