GEOPHYSICAL RESEARCH LETTERS, VOL. 7, NO. 11, PAGES 945-948, NOVEMBER 1980

# STREAMING ENERGETIC ELECTRONS IN EARTH'S MAGNETOTAIL: EVIDENCE FOR SUBSTORM-ASSOCIATED MAGNETIC RECONNECTION

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Abstract. This letter reports the results of a systematic study of streaming > 200 keV electrons observed in the magnetotail with the Caltech Electron/Isotope Spectrometers aboard IMP-7 and IMP-8. A clear statistical association of streaming events with southward magnetic fields, often of steep inclination, and with substorms as evidenced by the AE index is demonstrated. These results support the interpretation that streaming energetic electrons are indicative of substorm-associated magnetic reconnection in the near-earth plasma sheet.

## Introduction

The role played by magnetic reconnection (or merging) in the substorm phenomenon has been a subject of controversy in recent years (McPherron, 1979). In a detailed examination of several individual substorms, Hones and coworkers (Hones et al., 1976; Hones, 1977) reported that several signatures of magnetic reconnection, including southward magnetic fields and streaming energetic electrons on open field lines, were observed in the magnetotail during the substorm expansion phase. However, statistical studies by Lui et al. (1976; 1977a; 1977b) concluded that in general the southward fields observed during substorms represented only a slight southward dipping of the magnetotail field and could not be interpreted as evidence for reconnection.

Although > 200 keV electrons in the plasma sheet at $X_{GSM} \sim -30\ R_E$ normally exhibit an isotropic or trapped-type angular distribution, brief intervals of intense streaming, often in association with southward fields and jetting plasma, are occasionally observed (Baker and Stone, 1976; 1977). Such streaming is indicative of an open field topology and has been interpreted as evidence for reconnection. The present report represents the first systematic study of energetic electron streaming in relationship to substorms and magnetic reconnection.

## Streaming Energetic Electrons in the Magnetotail

Figure 1 presents a streaming event observed on IMP-8 at a time when the spacecraft was located at $X_{GSM} = -37.3\ R_E$, $Y_{GSM} = 7.1\ R_E$, and $\delta Z = -4.0\ R_E$, where $\delta Z$ is displacement from the nominal neutral sheet (Fairfield, 1980). At the beginning of the time period shown, the nearly isotropic angular distributions typical of the plasma sheet were seen. These angular distributions differ markedly from the highly anisotropic one seen at the onset of the streaming event at time t = 0, where the majority of particles are concentrated within a single sector. After t = 0 the angular distribution broadened, but strong tailward streaming continued until about t = +5 minutes, when there was a sudden return to trapped-type distributions. Toward the end of the interval shown, the angular distributions are difficult to interpret due to poor statistics, but they do not exhibit the intense streaming seen at t = 0. Note that the moderate streaming at $t \approx -5$ minutes did not satisfy the stringent criterion for streaming events described below.

At the time this report was prepared, the AE index was available through the end of 1975. Accordingly, IMP-7 and IMP-8 data from launch (1972 Day 270 for IMP-7 and 1973 Day 303 for IMP-8) through 1975 were searched for occurrences of intense energetic electron streaming in the magnetotail. Solar flare periods were excluded from the analysis. Streaming events were required to satisfy the following criteria: 1) the spacecraft was located within 15 $R_E$ of the $X_{GSM}$ axis tailward of earth; 2) the > 200 keV electron intensity was $\geq 1\ (cm^2\text{-}s\text{-}sr)^{-1}$; 3) the streaming anisotropy $\xi$ was $\geq 1$; 4) the event occurred at least 2 hours after the previous event. The intensity criterion was imposed because at low intensity levels the calculated streaming anisotropy is not significant due to statistical fluctuations, but it has the additional effect of confining the analysis mostly to the plasma sheet region, as the intensity of energetic electrons in the magnetotail lobes is normally very low.

For the purpose of this study the streaming anisotropy was defined as the magnitude of a vector which has components

$$\xi_X = \frac{2}{N} \sum_i N_i \langle \cos \varphi \rangle_i, \qquad (1)$$

$$\xi_Y = \frac{2}{N} \sum_i N_i \langle \sin \varphi \rangle_i, \qquad (2)$$

where $N_i$ is the number of counts in the ith sector, N is the total number summed over the 8 sectors, and $\varphi$ is azimuth angle in the ecliptic plane. Angular brackets denote an average over the angular range of the ith sector. The requirement that $\xi \geq 1$ is fairly stringent, requiring that most of the flux be concentrated within a single hemisphere. For example, for the highly collimated distribution at t = 0 in Figure 1, $\xi = 1.5$, whereas for the less anisotropic distributions near t = -5.5 and -4 minutes, $\xi = 0.9$ and 0.4. Although no constraint was explicitly imposed upon the direction of streaming, it was found that during every event that satisfied the four criteria listed above, the energetic electrons were streaming tailward.

A total of 46 energetic electron streaming events were found, of which 19 were observed on IMP-8 and 27 on IMP-7. The $X_{GSM}$ coordinate of the events ranged from $-28.6\ R_E$ to $-37.5\ R_E$. All but 7 events occurred within 5 $R_E$ of the nominal neutral sheet, and 24 of them occurred within



Paper number 80L1408.
0094-8276/80/0080L-1408$01.00

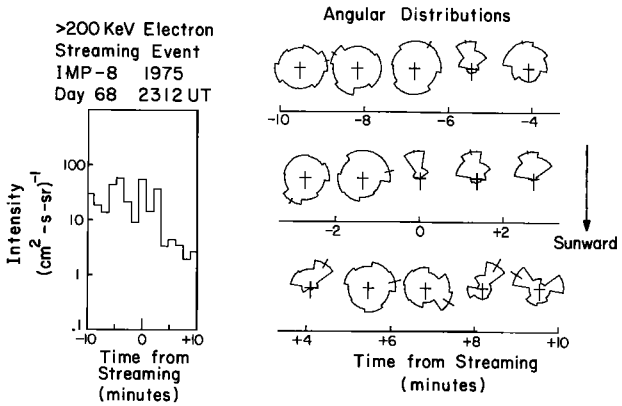


Fig. 1. Electron streaming event. Data represent 18-second averages separated by 82 seconds. Polar histograms show counts as a function of streaming direction. Statistical error bar of peak sector is indicated on each angular distribution.

the region $|Y_{GSM}| < 12\ R_E$, $|\delta Z| < 2.5\ R_E$ where Hones (1979) observed tailward plasma flow and southward fields during geomagnetically disturbed times. The total time of observation within this region was 12.7 days, which implies that streaming events with $\xi \geq 1$ occur in the central portion of the plasma sheet at a rate of about 2 per day.

## The Behavior of AE and the Magnetotail Field during Streaming Events

To determine the average behavior of AE near times of energetic electron streaming, the profiles of AE during a 4-hour interval centered on each event were averaged over the 46 events. The result of this superposed epoch analysis is presented in Figure 2. The clear peak in ⟨AE⟩ near t = 0 demonstrates that energetic electron streaming in the magnetotail occurs in association with magnetospheric substorms. The time

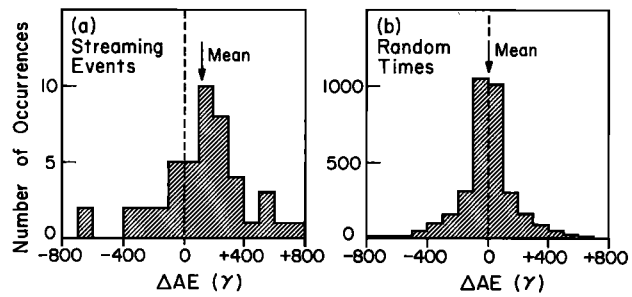


Fig. 3. Occurrence histograms of ΔAE (a) for streaming events and (b) for random times.

required for ⟨AE⟩ to depart from and return to its baseline level is consistent with the ~ 2 hour duration of a typical substorm as determined from auroral displays (Akasofu, 1964).

To characterize the degree of variation between individual events, and also to determine whether the average profile might be dominated by a few events, Figure 3a presents an occurrence histogram of ΔAE for the 46 events, where ΔAE is the value of AE (5-minute average) at t = +30 minutes minus the value of AE at t = -30 minutes. For comparison, Figure 3b presents ΔAE calculated for 3379 random one-hour intervals. For 72% of streaming events, AE was larger 30 minutes after the event than 30 minutes before. The probability that this predominance of positive ΔAE would be obtained by chance is less than 0.5%. The value of ΔAE for the average profile in Figure 2 is simply the mean (123 γ) of the histogram in Figure 3a and is consistent with the modal value. This demonstrates that the profile appearing in Figure 2 is a representative average.

For the 19 streaming events observed on IMP-8, simultaneously acquired 15-second averages of the magnetotail magnetic field were available (R. P. Lepping and N. F. Ness, private communication). Figure 4 presents superposed epochs of the GSM Z-component ($B_z$) of the magnetotail field during a 4-hour interval centered on the stream-

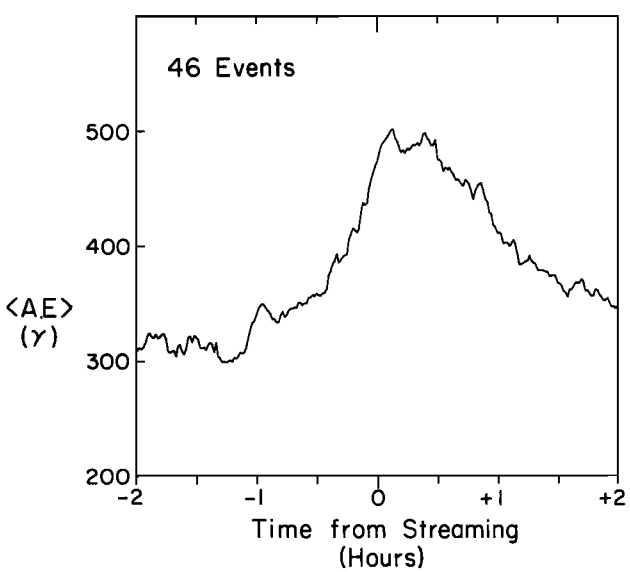


Fig. 2. Superposed epoch analysis of AE. Temporal resolution is 1 minute.

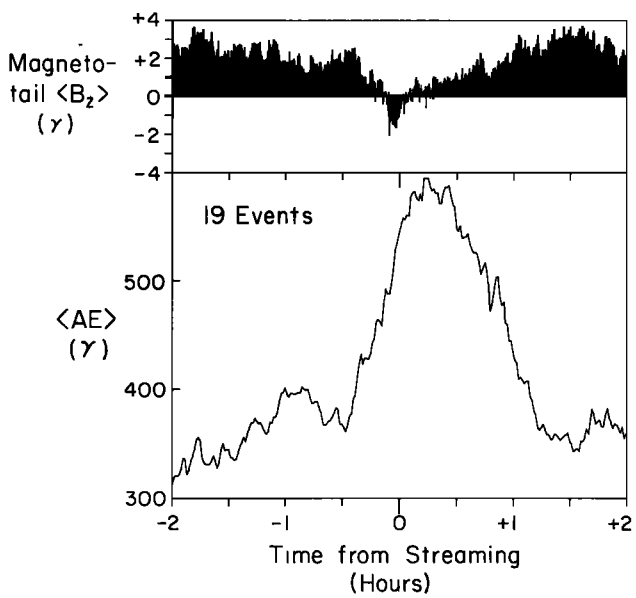


Fig. 4. Superposed epoch analysis of magnetotail $B_z$ (GSM) and AE.

ing event together with the AE profile averaged over only these 19 events. Figure 4 shows that although the average magnetotail field in the plasma sheet region is predominantly northward, the streaming onset occurs near the end of a ~ 10-minute period of southward field. The association of energetic electron streaming with southward fields supports the interpretation that the spacecraft is located on an open field line as the result of the prior formation of an X-type neutral line earthward of the spacecraft.

The average profile of $B_z$ appearing in Figure 4 is a representative average in the sense that it is not dominated by a few events. This is demonstrated in Figure 5, which presents occurrence histograms of 5-minute averages of $B_z$ calculated at 4 different times during each event. The histograms of the 5-minute averages at 1 hour before and at 1 hour after streaming, shown in Figures 5a and 5d, exhibit a clear predominance of northward fields. Only ~ 20% of the individual events had negative 5-minute averages at these times. In sharp contrast is the distribution for the 5-minute interval before streaming, shown in Figure 5b, for which ~ 80% of the 5-minute averages were negative. The distribution for the 5-minute interval after streaming, shown in Figure 5c, exhibits a greater frequency of southward fields than was seen during intervals (a) and (d), but it is not so strongly shifted toward negative values as the distribution for interval (b).

An additional important factor is whether the field is inclined only slightly southward, as the results of Lui et al. (1976; 1977a; 1977b) would suggest, or whether it is more steeply inclined, as would be characteristic of reconnection. Examination of individual streaming events reveals that the field frequently becomes steeply inclined southward near the time of streaming, but the interval of steep inclination is usually so brief that it is revealed only in high time resolution (~ 15 seconds) data. Figure 6 presents occurrence histograms of the elevation $\theta$ of the most steeply southward inclined magnetic field vector (15-second average) observed during the same 5-minute intervals utilized in Figure 5. This figure shows that steeply inclined southward vectors are frequently seen during the 5-minute interval before streaming, but that they

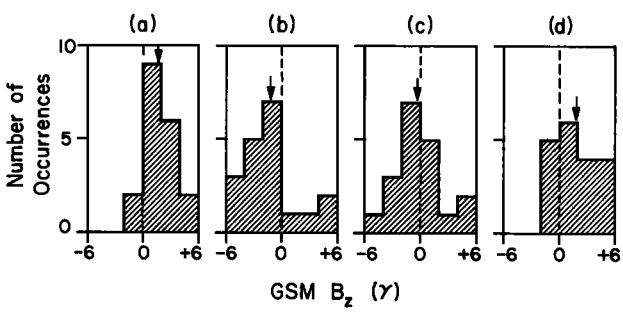


Fig. 5. Occurrence histograms of 5-minute averages of $B_z$ over intervals (a) from -60 to -55 minutes, (b) from -5 to 0 minutes, (c) from 0 to +5 minutes, (d) from +55 to +60 minutes. Zero time is onset of intense energetic electron streaming. Arrows above histograms indicate mean values.

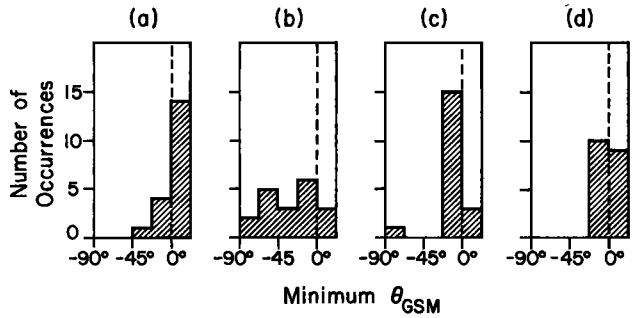


Fig. 6. Occurrence histograms of the greatest southward field inclination $\theta_{GSM}$ (15-second average) observed during the intervals utilized in Figure 5. Events with no observations of southward field appear in the rightmost bin.

are a relatively rare occurrence at other times. For each of intervals (a), (c), and (d) there was at most one event with an observation of $\theta < -22.5°$, but during interval (b), 10 of the 19 events had at least one vector with $\theta < -22.5°$.

## Discussion

According to the phenomenological substorm model described by Hones (1977), when the field lines that bound the outer edge of the plasma sheet reconnect, the portion of the plasma sheet tailward of the neutral line (the plasmoid) becomes decoupled from earth and is ejected down the magnetotail, and it is at this point that streaming of energetic electrons is observed. The data presented here tend to support this scenario. Figure 4 shows that most of the interval of southward field precedes the streaming event, and Figure 6 shows that steeply inclined southward fields are most frequently seen just before the observation of intense streaming. This may indicate that prior to the onset of intense streaming, the spacecraft is located in the earthward part of a magnetic island or plasmoid, where field lines have a southward component but are closed about an O-type neutral line, resulting in trapped-type angular distributions (see Figure 1).

The superposed epochs of AE presented here show that ⟨AE⟩ begins to rise rapidly ~ 25 minutes before zero epoch time. A similar behavior is evident in superposed epochs of AE presented by Caan et al. (1978), who used mid-latitude magnetograms to determine zero epoch time, and by Swanson (1978; see also Sauvaud and Winckler, 1980), who used energetic electron injection at synchronous orbit to determine zero epoch time. If the onset of the rapid rise in ⟨AE⟩ corresponds to the beginning of reconnection in the plasma sheet, and if the streaming electrons are seen shortly after the field lines that bound the plasma sheet reconnect, then it is possible to estimate the merging rate (Vasyliunas, 1975) from the data presented here. Assuming a plasma sheet half-thickness of 3 $R_E$, the merging rate is $V \sim 3\ R_E/25$ minutes $\approx 13$ km/s. The electric field required to drive the plasma at this rate in a 10 γ (X-component) magnetic field is $E_Y = 1.3 \times 10^{-4}$ V/m, which corresponds to a potential drop of about 33 kV over a distance of

40 $R_E$. Thus it appears that the normal cross-tail electric field is sufficient to drive merging at the rate required to explain the observations presented here.

An alternative explanation for the 25 minute delay between the time ⟨AE⟩ begins to rise and the time the streaming electrons are observed might be found in models of plasma sheet reconnection that invoke the tearing mode instability. Galeev et al. (1978) suggest that the development of this instability can be divided into a linear growth phase (Schindler, 1974) lasting some tens of minutes and a nonlinear, explosive growth phase which lasts only a few minutes and during which large inductive electric fields are generated. Thus the period preceding the streaming event during which ⟨AE⟩ is rising may reflect the linear growth of the tearing mode instability, and the observation of streaming electrons may indicate its explosive culmination.

## Conclusions

1) Streaming energetic electrons in the plasma sheet region are usually observed in conjunction with southward magnetic fields that are often steeply inclined.
2) The source of the streaming electrons is earthward of $X_{GSM} \sim -30\ R_E$, as evidenced by the fact that intense streaming was directed tailward in every instance.
3) The concurrent behavior of the AE index indicates that streaming events usually occur during magnetospheric substorms.

These results support the interpretation that streaming energetic electrons in the magnetotail are a result of substorm-associated magnetic reconnection in the near-earth plasma sheet.

Acknowledgments. We thank R. P. Lepping and N. F. Ness for providing us with IMP-8 magnetometer data, and D. N. Baker and E. W. Hones, Jr. for useful discussions. This work was supported in part by the National Aeronautics and Space Administration under contracts NAS5-11066 and NAS5-25789 and grant NGR 05-002-160.

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(Received August 29, 1980;
accepted October 2, 1980.)