GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 6, PAGES 664-667, JUNE 1982

PLASMA BEHAVIOR DURING ENERGETIC ELECTRON STREAMING EVENTS: FURTHER EVIDENCE FOR SUBSTORM-ASSOCIATED MAGNETIC RECONNECTION

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Abstract. A recent study showed that streaming energetic (> 200 keV) electrons in Earth's magnetotail are statistically associated with southward magnetic fields and with enhancements of the AE index. It is shown here that the streaming electrons characteristically are preceded by a ~ 15 minute period of tailward plasma flow and followed by a dropout of the plasma sheet, thus demonstrating a clear statistical association between substorms and the classical signatures of magnetic reconnection and plasmoid formation. Additionally, a brief upward surge of mean electron energy preceded plasma dropout in several of the events studied, providing direct evidence of localized, reconnection-associated heating processes.

Introduction

Magnetic reconnection at a near-Earth neutral line has been proposed as the mechanism by which energy derived from the solar wind is deposited in the auroral oval during substorms. For a spacecraft located tailward of the neutral line, the expected signatures of reconnection are (1) rapid tailward plasma flow accompanied by (2) southward magnetic fields. If reconnection leads to the formation of a plasmoid, the spacecraft may subsequently observe (3) a sudden dropout of the plasma density and (4) tailward-streaming energetic electrons as it emerges from the tailward-moving plasmoid onto open field lines. The actual occurrence of these signatures has been demonstrated for several individual substorms (Hones, 1977; 1979).

Recently, a statistical study of 19 occurrences of streaming energetic electrons revealed that these events are associated with southward magnetic fields, often of steep inclination, and with substorms (Bieber and Stone, 1980; hereafter referred to as Paper 1). The present analysis extends this study to include the behavior of the plasma during these same streaming events. (In this report, the term "streaming" refers exclusively to streaming anisotropies in the angular distribution of > 200 keV electrons. Bulk motions of the plasma will be called "flows.") This report, in conjunction with Paper 1, thus represents the first statistical analysis to embrace all four of the classical reconnection signatures mentioned above.

Plasma Behavior during Energetic Electron Streaming Events

Data from the Los Alamos plasma probe aboard IMP-8 were available for 16 of the 19 energetic electron streaming events identified in Paper 1. A superposed epoch analysis of the X_{GSE} and Y_{GSE} components of the plasma flow velocity and of the plasma density was performed, using as a fiducial mark the first observation of intense streaming of > 200 keV electrons. Analysis of the density proceeded as follows: For each event, the time interval extending from 2 hours before till 2 hours after energetic electron streaming was subdivided into 2-minute intervals, and the average density within each 2-minute interval was calculated from the high time resolution (13-second averages centered 26 seconds apart) plasma data. This yielded, for each 2-minute interval, a distribution of densities for the 16 events. The median of this distribution was then taken to represent the epoch-averaged behavior of the density. Median rather than mean values were used because the resulting epoch averages are less subject to domination by a few events.

Analysis of the plasma flow velocity was similar to that of the density, but with the added complication that the velocity is not measurable if the plasma density is too low. An individual velocity measurement was included in the 2-minute average only if its relative error was less than 100 % or if its absolute error was less than 200 km/s. As a result of this restriction, the distribution of velocities for each interval usually contained fewer than 16 events. The median value was based on this more limited distribution, provided that at least 5 events contributed to the distribution.

The superposed epoch analysis of plasma parameters appears in Figure 1. For completeness, an analysis of the AE index and of the Z_{GSM} component of the magnetic field (R. P. Lepping and N. F. Ness, private communication, 1976) also appears. These latter graphs are similar to Figure 4 of Paper 1, except that they are based on only the 16 events for which concurrent plasma data were available, and they display median rather than mean values.

All of the signatures of magnetic reconnection and plasmoid formation mentioned in the introduction are evident in Figure 1. Moreover, they occur in the expected sequence and are clearly associated with substorms, as evidenced by the substorm-like enhancement of the AE index. The top two panels show that both the X and Y components of the median flow velocity remain fairly small — generally below 200 km/s — for most of

Paper number 2L0672.
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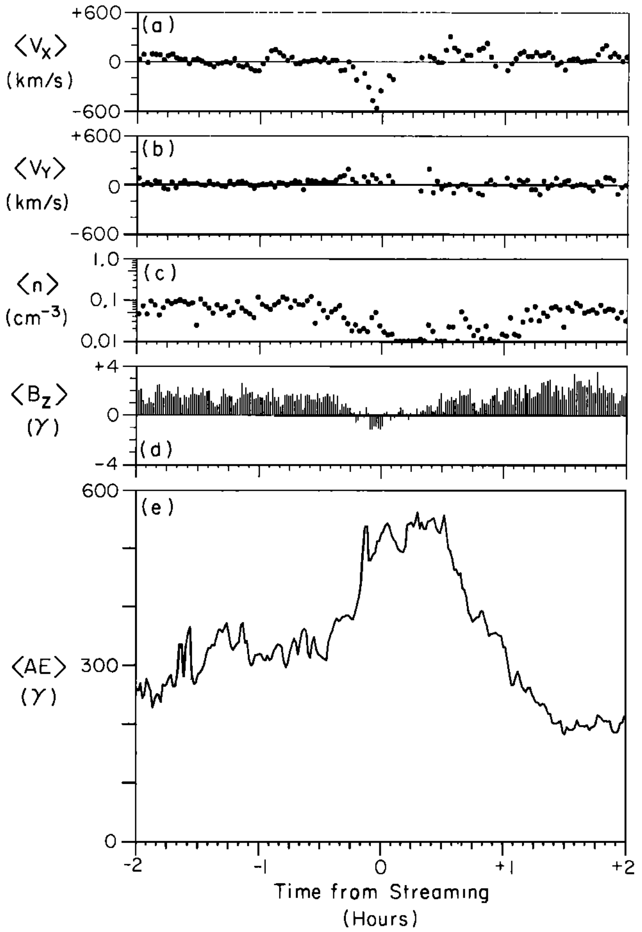

Fig. 1. Superposed epoch analysis of (a) X_{GSE}-component of plasma flow velocity; (b) Y_{GSE}-component of plasma flow velocity; (c) plasma density (plasma parameters are 2-minute averages for protons of energy 84 eV to 15 keV); (d) Z_{GSM}-component of magnetic field (1-minute averages); (e) AE index (1-minute averages). Plotted values are the median over 16 events. Zero epoch time is determined by the first observation of intense tailward streaming of > 200 keV electrons.

the 2 hours before the streaming event. However, about 15 minutes before the streaming event, and coincident with the sharply rising portion of ⟨AE⟩, $\langle V_X \rangle$ begins to decrease to large negative values, reaching a minimum of $\langle V_X \rangle$ = −570 km/s about 3 minutes before the streaming event. (The fairly smooth decrease to this minimum should not be interpreted as indicating a gradual onset of strong tailward flow in individual events. Rather, the onset is frequently rather abrupt, but occurs at somewhat different times in different events, resulting in a gradual decrease in the median value.) The Y component of the velocity remains small during this period of tailward flow. Shortly after the streaming event, the flow velocity becomes unmeasurable due to the low plasma density. When the velocity again becomes measurable at about +20 minutes, it has returned to small values and remains small thereafter, although there is some evidence for earthward flow, as might be expected if the neutral line had moved tailward of the satellite (see, e.g., Hones, 1977).

Figure 1c shows that the median plasma density fluctuates between about 0.05 and 0.1 cm^{-3} for most of the 2 hour interval before the streaming event. This median value is somewhat lower than typical plasma sheet densities of a few tenths per cm^{-3} because the spacecraft was periodically in the magnetotail lobe for some events, and these lobe observations tended to decrease the overall median value.

The most notable feature of Figure 1c is the period of very low densities which occurs just after the streaming event. During the interval from 0 to +2 minutes, densities characteristic of the magnetotail lobe — specifically, $n < 0.025$ cm^{-3} — were observed in 11 of the 16 events. By contrast, during the pre-substorm interval from −120 to −30 minutes, only 34 % of the individual 2-minute averages were below this threshold. The predominance of lobe-like densities just after streaming onset is consistent with the interpretation that the streaming energetic electrons in most cases mark the exit of the spacecraft from a tailward-moving plasmoid, where the magnetic field lines close in a loop structure, onto the open field lines of the magnetotail lobe. After the period of very low densities, the median density exhibits rather large fluctuations for a time, and does not return to a state resembling its pre-substorm behavior until about +75 minutes, about the same time that ⟨AE⟩ returns to its pre-increase level.

To determine the statistical significance of the strong tailward flow signature evident in Figure 1, Figure 2 compares the general distribution of individual 2-minute averages of V_X for

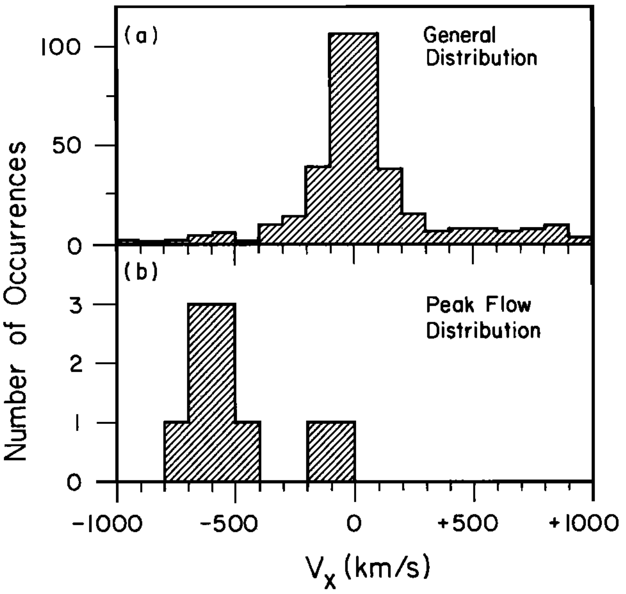

Fig. 2. (a) Distribution of 2-minute averages of V_X for the period −120 to −30 minutes. Of 720 possible samples, 392 appear in the histogram, 5 had V_X > +1000 km/s, and 323 were unmeasurable. (b) Distribution of 2-minute averages of V_X at the time of peak tailward flow (−4 to −2 minutes). Of 16 possible samples, 10 appear in the histogram, and 6 were unmeasurable.

the period from -120 to -30 minutes with the distribution obtained from -4 to -2 minutes, when $\langle V_X \rangle$ reached its minimum value. At this time, V_X was measurable for 10 of the 16 events, and for 8 of these 10, tailward flow in excess of 400 km/s was observed. This predominance of strong tailward flow is far greater than would be expected on the basis of the general distribution, where only 4.3 % of measurable velocities are < -400 km/s.

Figure 2 shows that the velocities at the time of peak flow lie mostly between -400 and -800 km/s. This may be explained by reconnection theory, which predicts that the plasma ejected from the neutral line flows at the Alfvén velocity (Vasyliunas, 1975). For typical plasma sheet parameters of B ~ 10 γ and n ~ 0.2 cm^{-3}, the Alfvén velocity is about 500 km/s.

Heating of Plasma Sheet Electrons

Evidence for localized energization of plasma sheet electrons was observed in 5 of the events included in this analysis. These events, one example of which appears in Figure 3, consistently displayed the following behavior:

(1) The energized electrons appear in a pulse that typically lasts ~ 2 minutes. During this pulse, the mean electron energy increases by a factor of 2 to 5, peaking in the range 1 to 4 keV. Examination of the actual electron distribution function reveals that, although nonthermal features are sometimes present, the energization primarily represents a heating process.

(2) Concurrently with the pulse of heated electrons, the plasma density decreases by a factor of 2 or more, but remains above the level characteristic of the magnetotail lobes.

(3) The heated electrons are observed in conjunction with southward magnetic fields, which most often are strongest ($\theta_{GSM} < -50^\circ$; $B_Z \sim -5$ to -15 γ) near the beginning of the pulse.

(4) An interval of strong tailward plasma flow ($V_X \sim -500$ to -1000 km/s for both ions and electrons) precedes the pulse.

(5) Streaming > 200 keV electrons are observed within 3 minutes following the peak of the pulse.

(6) The heated electrons are located near the tail neutral sheet, as indicated by reversals in the sign of B_X. All 5 events occurred within 5 R_E of the center of the aberrated magnetotail.

The cross-tail component of the convection electric field present during heated-electron events can be inferred from the formula $E_Y = V_X B_Z - V_Z B_X$. The Z component of the flow velocity is not measured by the Los Alamos plasma instrument, but the quantity $V_Z B_X$ can probably be neglected in comparison with $V_X B_Z$, at least during intervals of steep southward magnetic fields (i.e., when B_X is small). Taking $B_Z \sim -7$ γ and $V_X \sim -700$ km/s as typical values near the beginning of the pulse, the inferred cross-tail electric field is thus ~ 5 mV/m or 30 kV/R_E. This may be the induction electric field predicted by tearing-mode reconnection theories (Schindler, 1974; Galeev et al., 1978), since the expected cross-tail electric field is only ~ 0.3 mV/m, based upon observed polar cap potential drops. The presence of large induction electric fields during substorms was also suggested by Baker et al. (1979) to explain their high-energy proton observations.

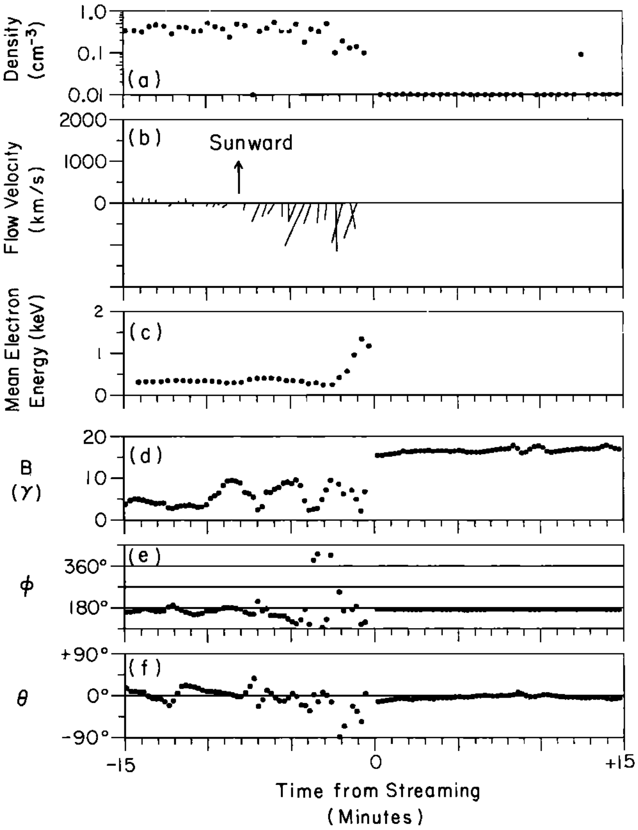

Fig. 3. An event during which a pulse of heated plasma electrons was observed. Shown are: (a) density of protons (energy range 84 eV to 15 keV); (b) flow velocity of protons; (c) mean energy of electrons; (d) magnetic field magnitude B; (e) magnetic field azimuth φ (GSM); (f) magnetic field elevation θ (GSM). Tailward streaming of > 200 keV electrons was first observed at t = 0, which corresponds to 1537:05 UT on day 318 (November 14) of 1973. The spacecraft was located at $X_{GSM} = -32$ R_E, $Y_{GSM} = +3$ R_E about 0.5 R_E south of the nominal (Fairfield, 1980) neutral sheet. A well-defined substorm onset appears in the Cape Chelyuskin magnetogram at ~ 1530 UT (t ≈ -7 minutes).

It is possible that heated plasma sheet electrons are a common feature of reconnection events, but were observed in only ~ 30 % of events studied here due to their spatial localization and the short duration of the pulse. These events may thus provide important information on the details of magnetic reconnection in Earth's magnetotail. Heating of electrons has been observed in laboratory reconnection experiments (Gekelman and Stenzel, 1981). Also, energization of plasma inside a magnetic island (plasmoid) has been noted in numerical simulations of the tearing mode instability (Terasawa, 1981), but this energization was accompanied by an increase in plasma density, not a decrease as observed in the magnetotail. A detailed understanding of the heated-electron events must await further investigation.

Summary

Tailward-streaming energetic electrons in Earth's magnetotail have proved to be an excellent marker of substorm-associated magnetic reconnection events. A superposed epoch analysis of 16 streaming events reveals that the characteristic behavior of the AE index and of plasmas, magnetic fields, and energetic particles in the magnetotail may be divided into three phases, where time is measured from the onset of intense streaming of energetic electrons:

(1) A disturbance of the plasma sheet is first apparent at -15 minutes. Tailward plasma flows are observed, and $\langle B_Z \rangle$ begins to decrease. Concurrently, ⟨AE⟩ begins to rise sharply. The strongest tailward plasma flow occurs at about -3 minutes, with $\langle V_X \rangle = -570$ km/s. The magnetic field is substantially southward from -6 to +1 minutes, and steep southward inclinations are frequently observed in high time resolution data, as shown in Paper 1. Throughout this phase, the energetic electrons, if present, exhibit isotropic or trapped angular distributions, indicating that the spacecraft is located on closed magnetic field lines.

(2) At zero epoch time, onset of intense tailward streaming of > 200 keV electrons indicates that the spacecraft has moved onto open magnetic field lines. Following this, the median plasma density falls to very low levels, suggesting that the spacecraft has exited the plasma sheet in the majority of events. During the next 75 minutes, the median density fluctuates somewhat, but remains generally below its pre-substorm level.

(3) By ~ +75 minutes, ⟨AE⟩ has returned to its pre-increase level. The epoch-averaged behavior of the plasma and the magnetic field resembles the behavior observed during the pre-substorm interval from -120 to -15 minutes.

This study has thus demonstrated a statistical relationship between substorms as evidenced by the AE index and the 4 classical signatures of magnetic reconnection and plasmoid formation in the magnetotail — specifically, tailward plasma flow, southward magnetic fields, plasma dropout, and streaming energetic electrons. The results are in general agreement with the phenomenological substorm model described by Russell and McPherron (1973) and Hones (1977). According to this model, the first phase mentioned above is initiated by the formation of a neutral line in the near-Earth plasma sheet, the second phase indicates the tailward ejection of a plasmoid, and the third phase indicates the recovery of the plasma sheet to its pre-substorm state.

In addition to the statistical results listed above, several events were identified in which a brief pulse of heated plasma electrons appeared shortly before plasma sheet dropout. The heated electrons were always observed near the neutral sheet in association with very strong tailward plasma flows and steep southward magnetic fields. These events provide direct evidence of reconnection-associated heating processes in the near-Earth plasma sheet.

Acknowledgements. We thank R. P. Lepping and N. F. Ness for providing 15-second averages of IMP-8 magnetometer data. 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 April 5, 1982;
accepted April 20, 1982.)