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EVIDENCE FOR PARTICLE ACCELERATION DURING MAGNETOSPHERIC SUBSTORMS

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ABSTRACT

Magnetospheric substorms represent the episodic dissipation of energy stored in the geomagnetic tail that was previously extracted from the solar wind. This energy release produces activity throughout the entire magnetosphere-ionosphere system, and it results in a wide variety of phenomena such as auroral intensifications and the generation of new current systems. All of these phenomena involve the acceleration of particles, sometimes up to several MeV. In this paper we present a brief overview of substorm phenomenology. We then review some of the evidence for particle acceleration in Earth's magnetosphere during substorms. Such in situ observations in this most accessible of all cosmic plasma domains may hold important clues to understanding acceleration processes in more distant astrophysical systems.

Subject headings: acceleration of particles — Earth — solar wind

1. INTRODUCTION

The Sun produces a continuous outflow of plasma known as the solar wind. When this plasma strikes Earth's magnetic field, a comet-shaped cavity called the magnetosphere is formed in the solar wind, the boundary of that cavity being where the internal (mostly magnetic field) and external (mostly plasma) pressures balance. The Earth's magnetosphere, schematically depicted in Figure 1, has a magnetotail that extends several hundred Earth radii antisunward. The magnetotail plays an essential role in magnetospheric dynamics since it serves as a reservoir for energy extracted from the solar wind. That energy is stored in the form of magnetic flux, and it is periodically dissipated through a process known as a magnetospheric substorm (e.g., Baker et al. 1981). The energy released during substorms powers auroral displays and accelerates particles throughout the magnetotail.

Auroral variations have been known since ancient times, but it is only relatively recently that they have been systematically observed and studied. E. C. Herrick (1838; cited by Siscoe 1980) noted "*seasons of greatest brilliance* or *fits of maximum intensity,* at intervals of about four hours . . [and that] . . this is a common feature of Auroral exhibitions of unusual brillance" (italics in the original). The magnetic signature of such events were first studied by Birkeland (1913), who classified what he thought were five types of "polar elementary storms." Sidney Chapman felt that the events discussed by Birkeland were a phase of the larger and longer lived geomagnetic storms. Hence he named them substorms (Chapman & Bartels 1940). The modern concept of substorm as a repeating global chain of events independent of magnetic storms was introduced by Akasofu (1964) almost three decades ago based on all-sky camera observations of the aurora. Since that time considerable progress in understanding the nature of substorms has occurred.

Prior to the onset of a substorm there is a period known as the growth phase during which dayside reconnection results in a transfer of flux to the magnetotail (e.g., McPherron 1979). At the onset of what is known as the substorm expansion phase, a preexisting discrete auroral arc (typically the one that is closest to the equator) suddenly brightens, generally near the midnight meridian. The western edge of the arc forms a convoluted structure called a westward-traveling surge that generally moves westward, while to the east a bulge of bright auroral emissions forms and expands poleward. After about an hour the auroral expansion slows, then stops, and the auroral oval returns to its preactivity configuration during what is known as the recovery phase. This sequence is illustrated in Figure 2.

It soon became clear that the substorm was related to dynamic changes in the magnetosphere as well. During the growth phase the plasma sheet thins in the north-south direction as flux is added to the magnetotail and the current systems intensify. At substorm expansion phase onset, a portion of the current that flows across the center of the magnetotail in the near-Earth ($<10\ R_E$) region is apparently diverted along magnetic field lines into the ionosphere. There the current flows westward until it meets the westward traveling surge, where it returns to the magnetotail as a field-aligned current (McPherron et al. 1973). The resulting current system, illustrated in Figure 3, is called the substorm current wedge. Within the sector subtended by the current wedge, the plasma sheet rapidly expands and the magnetic field reconfigures to a more dipolar orientation ("dipolarization"). Spacecraft within the expanding plasma sheet register an increase in the flux of energetic particles (McPherron et al. 1973; Sauvaud & Winkler 1980; Baker 1984; Lopez et al. 1989). In the more distant magnetotail, bursts of energetic particles extending up to several MeV occur (e.g., Krimigis & Sarris 1979), tail magnetic flux is dissipated (e.g., Baker et al. 1981), and reconnection produces a magnetic structure disconnected from Earth,

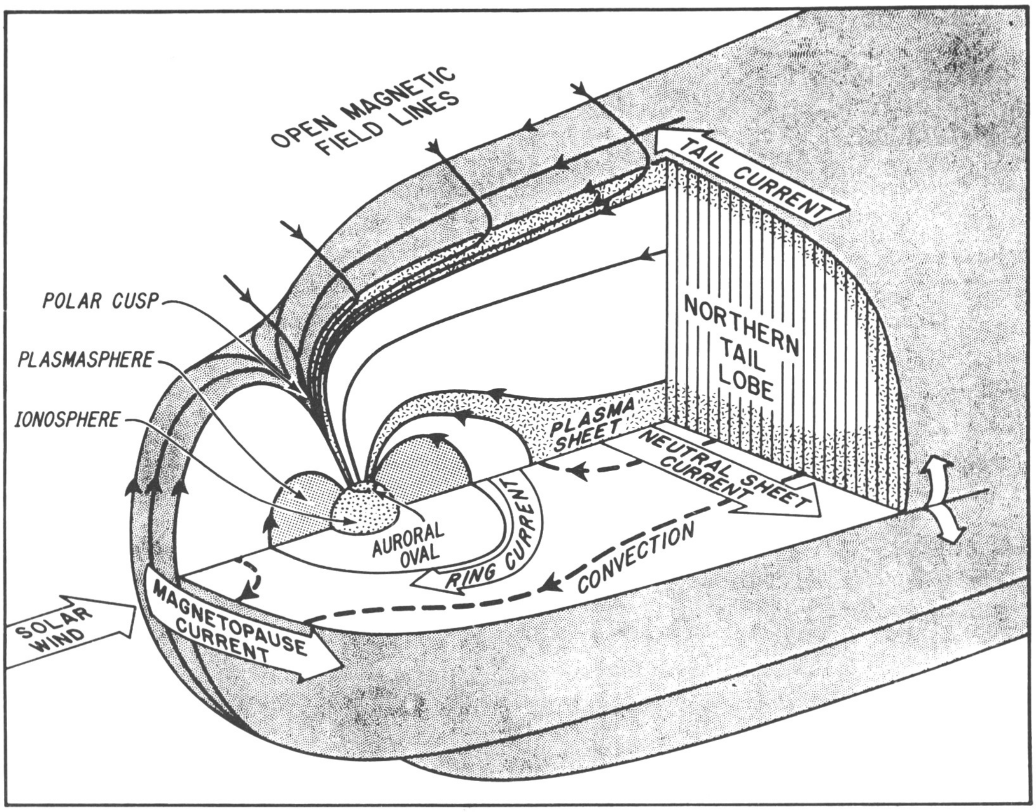

FIG. 1.—Schematic of Earth's magnetosphere showing different plasma regimes and current system

known as a plasmoid, which is ejected down the tail (e.g., Baker et al. 1987).

A variety of models have been proposed to organize substorm observations (e.g., Lopez 1992 and references therein), though we do not review them here. The most common and well-accepted model for substorms is the near-Earth neutral line (NL) model (e.g., Hones 1979). In that model the substorm expansion phase is driven by the formation of a new, near-Earth reconnection region. In one form of the NL model, the expansion phase begins when the neutral line forms on closed field lines in the central plasma sheet (McPherron et al. 1973; Hones 1984). In another form, the expansion phase begins when reconnection, which began in the growth phase, explosively intensifies when it reaches the lobe, where the Alfvén speed is much higher (e.g., Baker & McPherron 1990). Flows from the reconnection region, and the reconnection region itself, divert the cross-tail current into the ionosphere (e.g., Hesse & Birn 1991), forming the current wedge. Reconnection continues until the excess flux in the magnetotail is dissipated and a region of closed field lines disconnected from Earth (the substorm plasmoid) is ejected down the tail. The NL model places the region of substorm initiation in the near-Earth magnetotail and suggests that this region should show evidence for the formation of substorm-associated X-lines.

A variation of the NL model that has recently gained considerable acceptance is the current disruption (CD) model (Akasofu 1972; Lopez et al. 1990a; Lui 1991). In that model the onset of the expansion phase corresponds to the onset of an instability in the near-Earth (7–10 R_E) cross-tail current sheet. The exact nature of this instability is not yet understood, although there are candidates (Lui et al. 1990; Roux et al. 1992). The instability produces a local disruption of the current sheet, which in turn produces a localized dipolarization and particle energization. The disruption then spreads down the tail, either by growing in radial extent or through the formation of new disruption regions (Lopez et al. 1990a, b). Depending on the conditions in the magnetotail, a reconnection region may form either as an immediate consequence of the change in the current distribution closer to Earth or because of a coalescence of the disruption region(s). Once formed, the reconnection region drives phenomena as envisaged in the NL model. Thus the CD model is a close cousin of the NL model.

In both models particles are accelerated by inductive electric fields produced by current disruption and reconnection in the magnetotail. The currents that are diverted into the ionosphere are presumed to produce field-aligned potential drops that accelerate auroral particles, especially the electrons that produce the bright arcs, westward-traveling surges, and other visible auroral forms. In fact all substorms models explictly incorporate particle acceleration as a fundamental aspect. Why is this so? It is not for any a priori reason; rather, it is because overwhelming evidence has shown that particle acceleration occurs during substorms throughout the magnetospheric system. In the following sections we review some of that evidence. We will begin at auroral altitudes and discuss where and how auroral particles are believed to be accelerated. Moving outward, we will examine evidence gathered by near-geostationary spacecraft in the near-Earth magnetotail that points to local accelera-

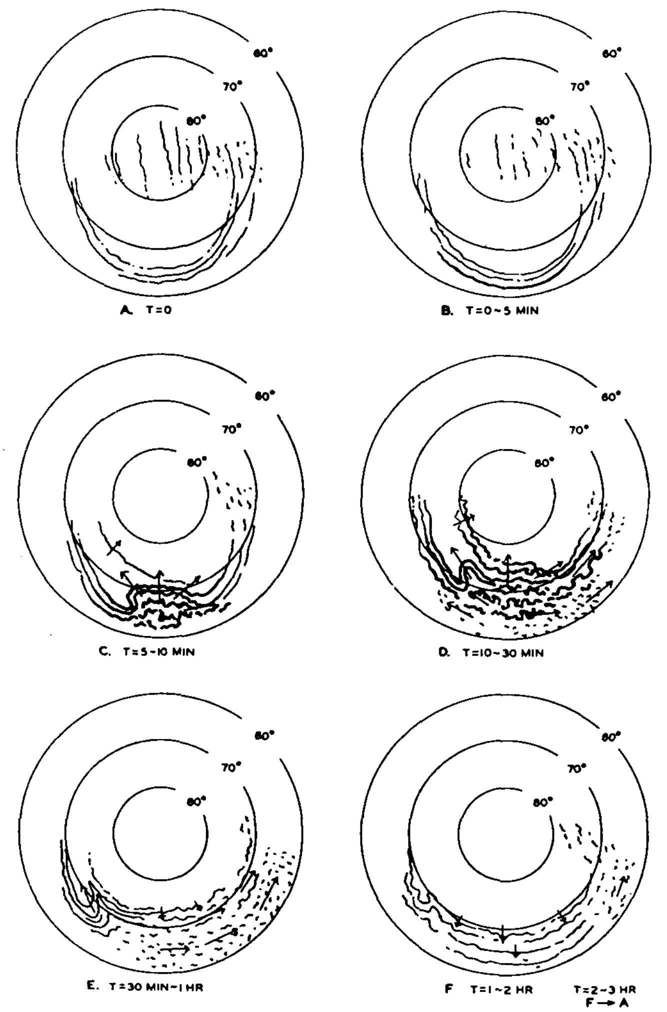

FIG. 2.—The development of a magnetospheric substorm (from Akasofu 1964).

tion of particles up to many hundreds of keV. Finally, we discuss the more distant magnetotail, where some of the most energetic particles (up to several MeV) are produced. We then conclude with a discussion of some possible implications for astrophysical plasmas.

2. AURORAL ACCELERATION OBSERVATIONS

The original definition of the onset of the expansion phase of a substorm was based upon auroral observations (Akasofu 1964), and that definition still holds today. The sudden brightening of a discrete auroral arc suggests the sudden release of energy and acceleration of particles. However, auroral arcs bright enough to be visible exist independently of substorm phenomena. As we shall see, and as the reader might suspect, auroral acceleration during substorms is apparently a more intense and widespread version of the acceleration processes that produce quiet arcs. We will now briefly review evidence for the acceleration of auroral particles in auroral arcs with special regard to substorm-related aurorae, although we will not discuss other auroral acceleration processes resulting from wave-particle interactions that are thought to produce more transient features such as electron bursts (e.g., Burch 1991).

Sounding rockets carried the first scientific instruments into auroral arcs and determined that the visible emissions were caused by the influx of 5–10 keV electrons (McIlwain 1960). Subsequent investigations found that most of the incoming energy was in the form of a "near-monoenergetic beam" superposed on a broader Maxwellian spectrum (Evans 1968; Westerlund 1968). Low-altitude satellite observations of substorm auroral forms such as westward traveling surges have shown that these are also produced by precipitating electrons with the same general spectral features as in quiet arcs, although the energy of the monoenergetic peak in the spectrum tends to be greater than for quiet arcs (e.g., Meng et al. 1978; Chiu et al. 1983). Evans (1974) provided a model in which a field-aligned potential drop accelerates electrons, and Figure 4 presents an example of model results compared with observations. In addition, the upward-accelerated ion beams observed in conjunction with downward-accelerated electrons could also be explained by such field-aligned potentials (e.g., Mozer et al. 1980). Thus this model has come to be generally accepted as the basic acceleration mechanism for auroral particles (e.g., Burch 1991).

Given that substorm aurorae and auroral arcs are created by an influx of keV electrons accelerated by field-aligned potential drops, where are these electrons accelerated? Reiff et al. (1988) used simultaneous measurements from a low-altitude satellite and one at high-altitude to confirm the potential drop model and to determine the location of the acceleration region. This configuration is schematically illustrated in Figure 5. Three methods of determining the field-aligned potential drop were employed. The first was to determine the energy of the accelerated precipitating electrons and assume that this was the magnitude of the potential drop. The second was to determine the energy of the upgoing ion beam. The third was to determine the widening of the electron loss cone at high altitudes when the satellite crossed the arc and to assume that this widening was due to the addition of a field-aligned velocity component due to acceleration. All three methods gave consistent results for the magnitude of the potential drop. Moreover, the observations demonstrated that the higher satellite (at 3

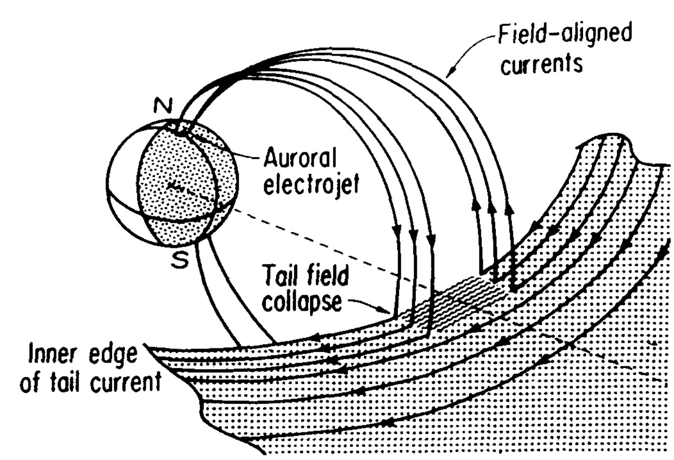

FIG. 3.—The substorm current wedge (from McPherron et al. 1973)

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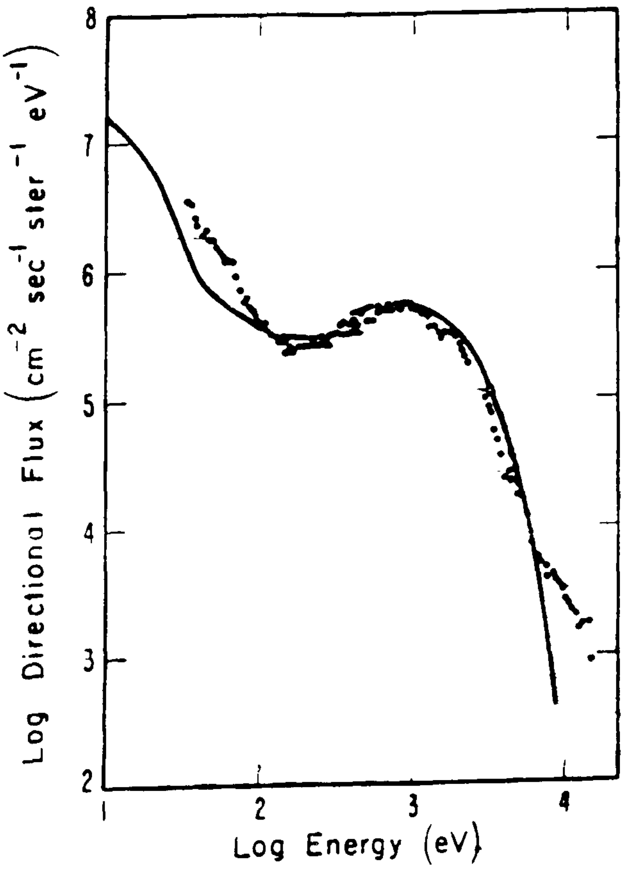

FIG. 4.—Model electron spectrum (*solid line*) assuming a 400 V field-aligned potential and an initial 800 eV Maxwellian distribution compared to observations (*dots*) (from Evans 1974).

R_E) was located above the acceleration region, whereas the lower satellite (<1 R_E) was located below the acceleration region.

To summarize our main points:

1. Auroral arcs, including substorm auroral forms, are produced by precipitating 1–10 keV electrons.

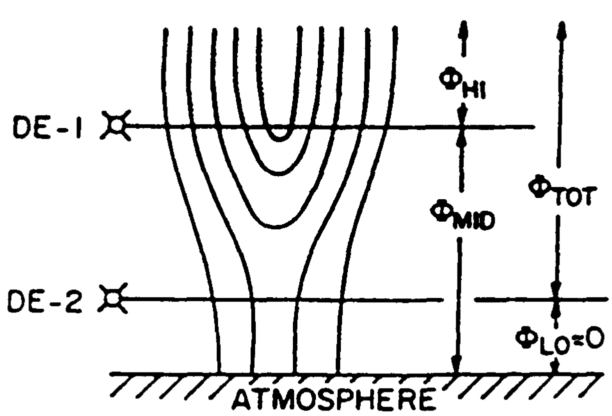

FIG. 5.—Two-satellite configuration relative to auroral potential structure (from Reiff et al. 1988).

2. These electrons are accelerated by field-aligned potential structures that also accelerate upgoing ion beams.
3. The acceleration region is located between about 1 R_E and 3 R_E in altitude.

3. NEAR-EARTH MAGNETOTAIL ACCELERATION OBSERVATIONS

The nightside auroral oval is magnetically connected to the magnetotail, and power dissipation in the aurora is an indicator of magnetotail activity. But where in the magnetotail? At the onset of the substorm expansion phase it is typically the most equatorward discrete arc that first brightens, and this arc is statistically located at about 67° magnetic latitude (Craven & Frank 1987). There are many reasons to believe that such latitudes at the equatorward boundary of the discrete aurora, and hence the substorm initiation region, map relatively close to Earth (e.g., Feldstein & Galperin 1985). Recent work using empirical magnetic field models to map these auroral arcs indicates that they are connected to the relatively near-Earth (<10 R_E) magnetotail (Elphinstone et al. 1991; Murphree et al. 1991; Pullkinen et al. 1991), and there has even been an in situ observation of an active region in the magnetotail current sheet at 8.5 R_E that was directly linked to a westward-traveling surge (Lopez et al. 1990a). The evidence is fairly conclusive: active aurorae during substorms are initially driven by processes that occur in the near-Earth magnetotail, and it is evidence for particle acceleration in that region that we now investigate.

It has been long known that variations in the flux of energetic particle occur in the near-Earth magnetotail during substorms (see Baker 1984 and references therein). An example, taken from Walker et al. (1976), is presented in Figure 6. The energetic particle flux is seen to vary by as much as two orders of magnitude. The growth phase reduction in the particle flux and the sudden increase in the flux at substorm onset is clear for each event. Attending the flux variations are significant variations in the magnitude and direction of the magnetic field. Prior to the onset, during the growth phase, the cross-tail current in the near-Earth region intensifies. This causes the magnetic field to assume a more stretched, or "tail-like," configuration. At the onset of the expansion phase, a portion of this enhanced current is diverted into the ionosphere through the substorm current wedge, and the magnetic field recovers to a more dipolar configuration (e.g., McPherron et al. 1973).

Much of the observed variation in the energetic particles is due to the changes in magnetic configuration that occur during a substorm. During the growth phase the near-Earth plasma sheet narrows in the north-south direction as the magnetic field become more tail-like. Spacecraft find themselves on higher latitude field lines that have less plasma content, and instruments detect a steady reduction in the flux of particles. At the onset of the expansion phase, the near-Earth plasma sheet rapidly expands as the field becomes more dipolar and satellites record a sudden increase in particle flux that is generally termed an injection. This scenario is schematically illustrated in Figure 7.

How can one determine if the observed flux increases at substorm onset truly represent an injection of a freshly accelerated populations and not just changes due to a reconfiguration

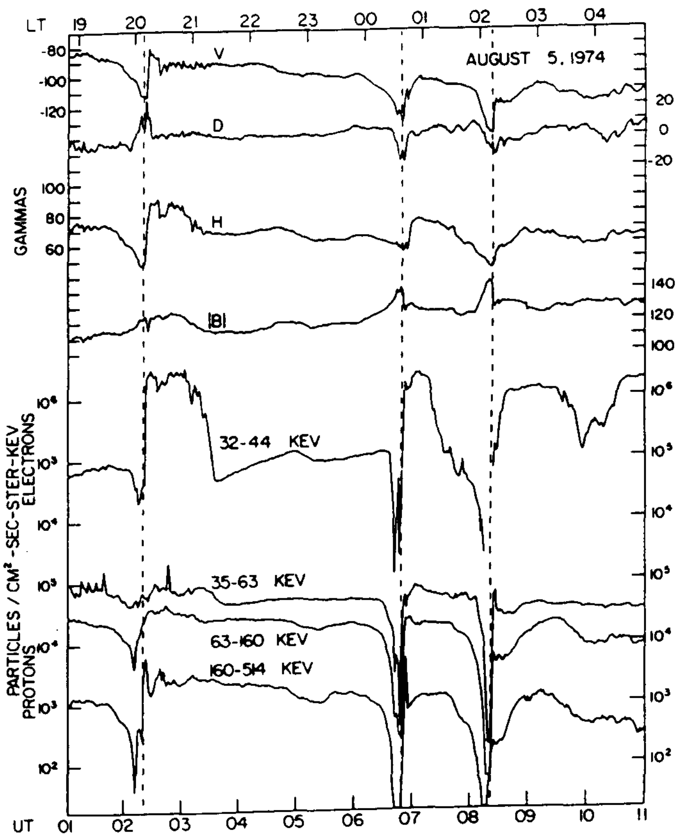

FIG. 6.—Geosynchronous magnetic field and energetic particle variations during substorms. The magnetic field is in *VDH* coordinates (*V* is radially outward, *D* is positive eastward, and *H* is positive northward along Earth's dipole axis), and the substorm on sets are marked with the vertical dashed lines (from Walker et al. 1976).

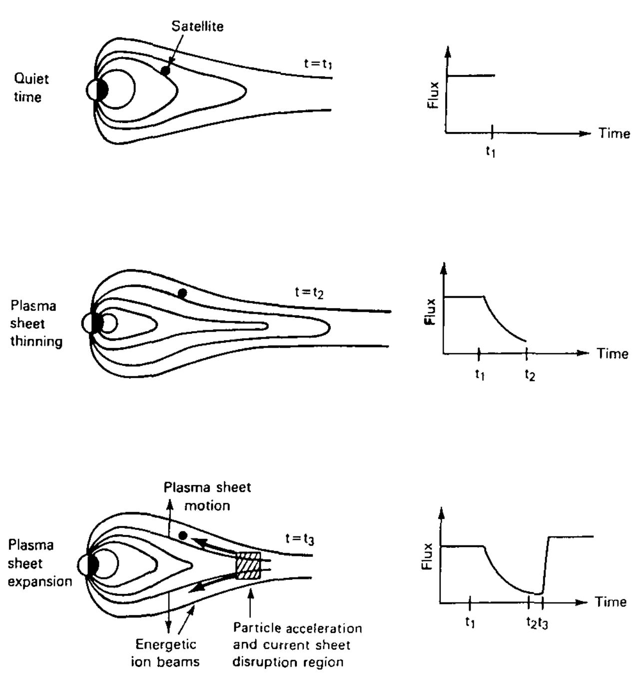

FIG. 7.—A schematic illustration of energetic particle flux variations in response to magnetic field configuration changes during substorms.

of the magnetic field? One indication can be seen in Figure 6. After the onset of a substorm we find the flux levels tend to be higher than they were prior to the growth phase even though the field configuration is almost the same as before the growth phase. This suggests that there has been a net increase in energetic particles. Furthermore, the events show no net increase in magnetic field intensity, so some nonadiabatic process must be at work. Other evidence comes from studies of energetic particles using the Los Alamos geosynchronous ($R = 6.6\ R_E$) spacecraft. Multisatellite observations have shown that particles injected at one location drift to other locations—just what one would expect for a freshly accelerated population—and sometimes a bunch of particles will continually reappear at a spacecraft in what is known as a "drift echo" (e.g., Baker 1984). An example of this phenomenon is given in Figure 8.

Near-Earth energetic particle injections are often observed to be essentially dispersionless, that is the flux increase appears over a wide range of energies essentially simultaneously (Sauvaud & Winckler 1980; Baker 1984; Lopez et al. 1989). This suggests that during such events the acceleration region was located fairly close to the satellite; otherwise, energy dependent drifts would introduce temporal dispersion. And even energy-dispersed injections have been traced back to their dispersionless point of origin using empirical magnetospheric models (e.g., Reeves et al. 1991). In fact, it has been long postulated that at the onset of a substorm there is a region in the near-Earth magnetotail roughly centered on magnetic midnight with a relatively sharp Earthward boundary above which plasma is suddenly accelerated, and that the accelerated plasma subsequently drifts through the magnetosphere (Mauk & McIlwain 1974). This phenomenological "injection boundary" model has been able to explain a large number of particle observations throughout the inner magnetosphere, and it has been incorporated into the CD model for substorms (Lopez et al. 1990b).

Another important piece of evidence is alluded to in the bottom panel of Figure 7. At the leading edge of the injection as the satellite enter the expanding plasma sheet, Earthward-directed ion beams are observed (Lopez et al. 1989). These

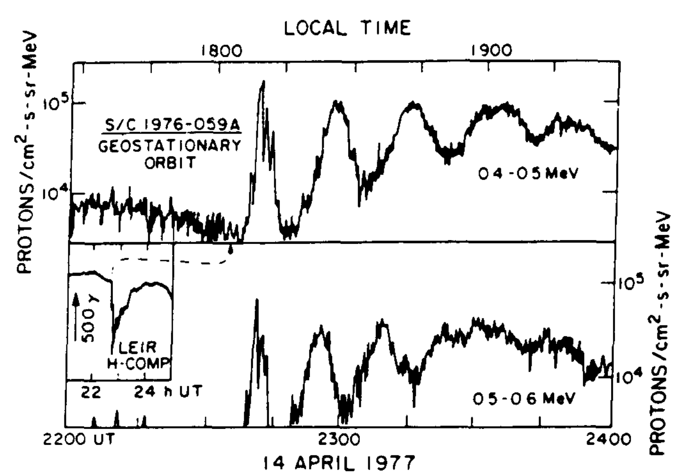

FIG. 8.—Geosynchronous energetic particle data displaying the "drift echo" phenomenon. Injected particles drift around Earth on closed drift paths and continually reappear at the satellite.

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beams are presumably generated in an acceleration region located at the equatorial crossing point of the field lines, at the center of the current sheet that is being disrupted. Several cases have been reported in which the *Charge Composition Explorer* satellite (*CCE*) was located within the disruption region. Figure 9 presents magnetic field data from *CCE* for such an event. The satellite was located in the midnight sector and at a radial distance of 8.2 R_E. Prior to the onset the magnetic field was considerably weaker than the dipole value, indicating the presence of a strong westward current primarily tailward of *CCE*, and the small value of the radial component indicates that the satellite was near the midplane of the current sheet. The onset of the event occurred at 2209 UT. The event had a very turbulent magnetic field signature, which has been termed current sheet disruption, and there was even a southward excursion of the field. Such southward excursions are quite typical for events observed close to the neutral sheet (Lopez et al. 1989). After the event the H component was much larger than before the onset, and the field had assumed a more "dipolar" character.

Associated with the magnetic perturbations during current sheet disruption there are bursts of energetic particles with extending into the hundreds of keV, and sometimes up to around one MeV. Such bursts were observed during the event presented in Figure 2, with ions appearing first Earthward, then

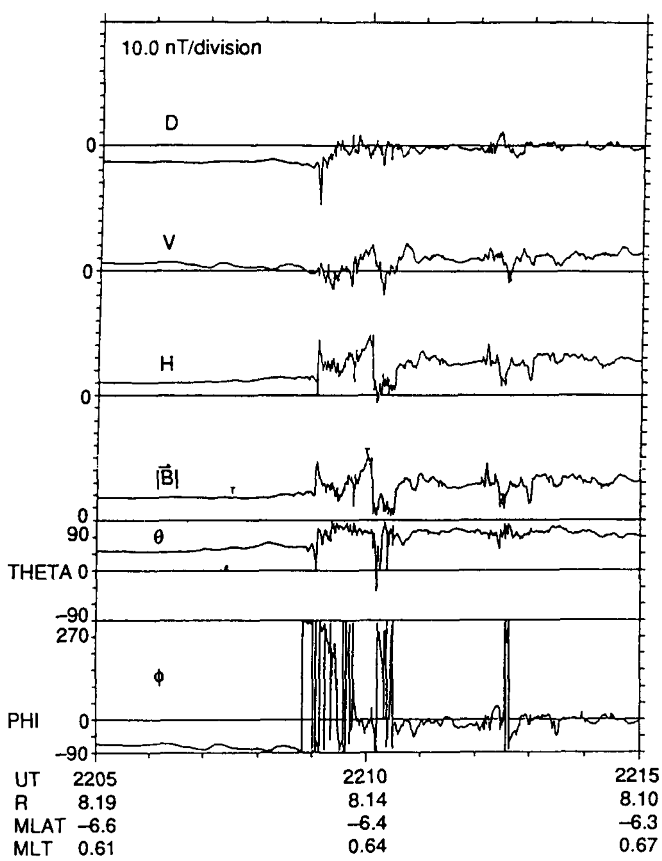

FIG. 9.—Magnetic field data from the *Charge Composition Explorer* showing in situ observations of the disruption of the near-Earth cross-tail current sheet. The data are in VDH coordinates (see Fig. 6) with a time resolution of 0.125 s.

tailward of the satellite (data not shown). This localization of energetic particles strongly suggests that the satellite was close to one or more acceleration regions, and studies of several events reveal that the current disruption regions are initially only about 1–2 R_E across (Lopez 1992). Given the very high level of magnetic variations during these events (often greater than 100 nT s^{-1}), it is likely that large inductive electric fields are present. Energetic particles would be able to move across the magnetically turbulent regions and so be energized. Estimates based on magnetic field data suggest that particles could be energized up to several hundred keV, as is observed (Lopez et al. 1989).

Given that current disruptions involve a localized energization of plasma and occasional reversals of the north-south component of the magnetic field, is it possible that such disruptions are the signature of the near-Earth neutral line? The first published case study of a disruption did argue in favor of this interpretation (Takahashi et al. 1987), but subsequent studies cast doubt on such an identification and instead argued that the CD model was a more valid interpretation (e.g., Lopez et al. 1989, 1990a). Moreover, statistical studies of substorm-associated fast plasma flows have shown that inside of 20 R_E such flows are almost always directed earthward, suggesting that the neutral line is generally tailward of 20 R_E (e.g., Baumjohann et al. 1989). Therefore the current sheet disruptions observed by *CCE* do not appear to be the signature of the neutral line expected in the NL model. Rather, proponents of the NL model have argued that the phenomena observed in the near-Earth region are produced by the NL further down the tail (Baker & McPherron 1990; Hesse & Birn 1991). Regardless of which interpretation is correct, it is clear that these events are an important source of energetic particles during substorms and their study has been a significant element in the reevaluation of the importance of the near-Earth magnetotail for overall substorm dynamics (e.g., Baker & Pulkkinen 1991).

To summarize:

1. There is abundant evidence that the flux increases observed in the near-Earth magnetotail during substorms represent locally accelerated populations.
2. Particles are regularly energized to hundreds of keV by inductive electric fields in turbulent current sheet disruption regions.

4. DISTANT MAGNETOTAIL ACCELERATION OBSERVATIONS

Energetic particle bursts have been observed well beyond the near-Earth magnetotail. Of particular note are observations made by the *IMP* series of spacecraft, which sampled the more distant (30–40 R_E) magnetotail (Sarris et al. 1976; Krimigis & Sarris 1979; Sarafopoulos & Sarris 1988). These particle bursts often have maximum energies of a couple of MeV, in spite of the fact that the potential drop across the magnetotail is on the order of 100 keV. Thus the generation of such particles must be related to processes such as those thought to operate during a substorm. The bursts are generally substorm-associated, and it has been suggested that they are related to the generation of reconnection regions in the tail (Hones 1984), or acceleration of particles through inductive electric fields (Krimigis & Sarris 1979). Calculations based on this idea have shown that acceleration up to MeV energies is possible (Galeev 1979; Zelenyi et al. 1984; Taktakishvili & Zelenyi 1990; Zelenyi et al. 1990).

One of the most important features of these bursts is that they often exhibit inverse velocity dispersion (IVD), with the lower energy particles arriving before the higher energy ones (e.g., Sarafopoulos & Sarris 1988). The IVD generally occurs on a 10–20 s timescale, although the total burst timescale can range from about 10 s to several minutes (e.g., Krimigis & Sarris 1979). Figure 10 presents energetic particle data for three such bursts. Those data show that the energy of the burst extends up to about 2 MeV and that both the onset of the burst as well as the time when the flux peaked was earlier for lower energies. This phenomenon has been interpreted as resulting from the finite time needed to accelerate particles, since to gain the maximum energy a particle must move across the entire acceleration region. If an observer is close enough to the acceleration region, the first particles observed will be lower energy ones that are first produced and escape the acceleration region (Taktakishvili & Zelenyi 1990). This mechanism has been able to explain the IVD observed during plasma sheet expansion, when other mechanisms for producing IVD would not be applicable (Sarafopoulos & Sarris 1988). Therefore the observation of IVD is fairly conclusive evidence of proximity to a spatially localized region where particles are accelerated by inductive electric fields.

Observations in the distant magnetotail have also provided evidence for the source of the energy that drives the substorm process (e.g., Baker et al. 1981). Figure 11 presents geosynchronous energetic particle data in the bottom four panels, while the upper panel shows the magnetic field magnitude at *IMP 8,* located at 35 R_E. Prior to the substorm, during the growth phase, the tail field magnitude increased. Shortly after the expansion phase began (marked by the dashed line) *IMP 8* recorded a decrease in the tail magnetic field. Such observations are evidence for storage and then dissipation of magnetic energy. The reconnection region that is responsible for the dissipation of lobe magnetic flux produces a topological change in the magnetic field. A portion of the plasma sheet is severed to form the closed magnetic structure called a plasmoid (e.g., Hones 1979; Baker et al. 1987). Given that the reconnection region that creates a plasmoid has a much greater extent in the dawn-dusk direction than the approximately 1–2 R_E–sized near-Earth current disruption region, the maximum energy that such regions can produce is greater, which appears to be consistent with observations. There may also be particle acceleration within plasmoids since simulations of turbulent magnetic field reconnection indicate that O-lines at the center of plasmoids can be efficient acceleration regions (Matthaeus et al. 1984).

To summarize:

1. During substorms, particles in the mid- to distant magnetotail are accelerated up to several MeV.
2. Magnetic field energy dissipated in large-scale reconnection regions that produce topological changes in the magnetotail is the energy source for this acceleration.

5. CONCLUSION

Magnetospheric substorms are a means by which the magnetosphere rids itself of excess internal energy following periods of enhanced energy input from the solar wind. As a consequence of that energy release, particles are accelerated at a

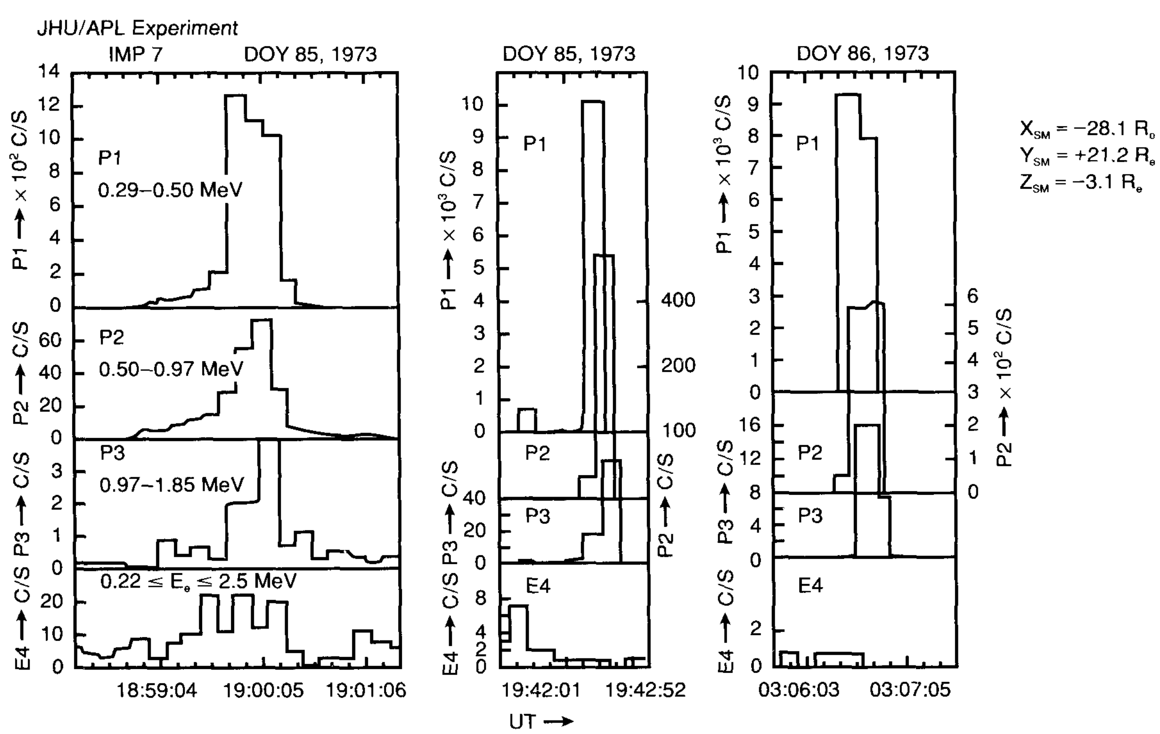

FIG. 10.—Energetic particle data from the *IMP 8* satellite for three substorm-associated particle bursts. All three events show inverse velocity dispersion, with both the onset of the burst and the peak in the flux occurring earlier for lower energies.

variety of locations throughout the magnetosphere. In this paper we have presented a very brief overview of observational evidence for such particle acceleration. It seems likely that similar processes may occur in astrophysical plasmas. However, unlike astrophysical settings, Earth's magnetosphere is accessible to space probes. Recent observations from the Swedish low-altitude Viking satellite indicate that the auroral acceleration region may be composed of numerous small-scale double layers created by density variations (Block & Fälthammar 1991). Observations from higher altitude satellites have demonstrated the great complexity of magnetotail acceleration processes, and such idealized notions as simple two-dimensional X-type reconnection have been superseded by much more sophisticated three-dimensional simulations (e.g., Hesse & Birn 1991). Other recent results, especially from near-Earth spacecraft, have emphasized the importance of acceleration by inductive electric fields during turbulent disruptions of thin current sheets (e.g., Lopez et al. 1989).

In spite of these advances, much remains unknown. However, upcoming or very recently launched missions may shed important new light on many critical issues. The *FAST* small-class *Explorer*, illustrated in Figure 12, will make detailed, high-time resolution measurements in the auroral acceleration region. Such observations will help us to understand the nature of the accelerator and how the field-aligned electric field couples to the higher altitude transverse electric fields that function as the "batteries" of the aurora. This, in turn, will allow us to better predict under what astrophysical conditions a similar process may operate and the maximum energies one could expect from such acceleration. The *Geotail* satellite, launched in 1992 July, will provide significant new data on the mid and distant magnetotail. Perhaps the missions that hold the most promise are Cluster, a European mission slated for launch in 1995, and Grand Tour Cluster, a proposed NASA mission. Each of these will involve four identical spacecraft flying in a tetrahedral formation. This will allow a true calculation of the curl of the electric and magnetic fields for the first time. One such detailed observation of a near-Earth current sheet disruption would represent a tremendous advance in our understanding of the stability and disruption of thin sheets of electrical current, and the consequent particle acceleration, a process that must be ubiquitous to space plasmas. Thus the knowledge gained by studying acceleration processes during magnetospheric substorms may provide us with critical clues to understanding acceleration processes in more distant astrophysical settings.

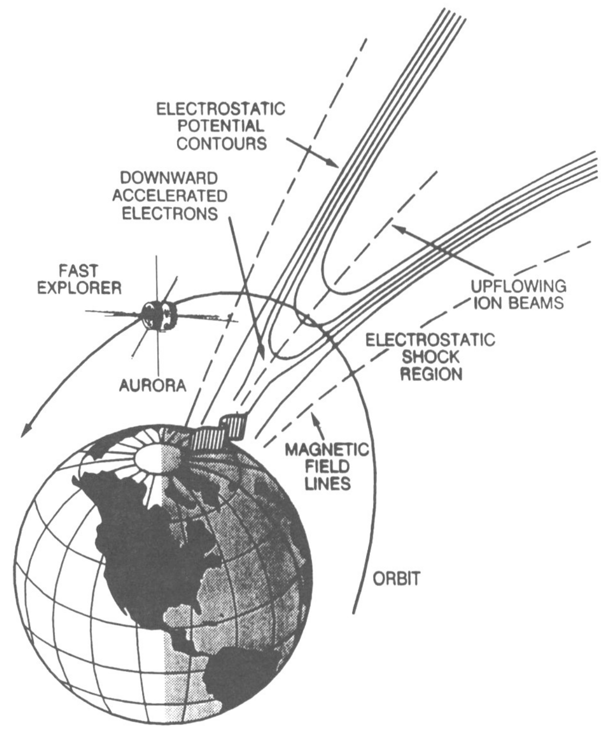

FIG. 12.—Schematic depiction of auroral acceleration region and the path of the *FAST* satellite.

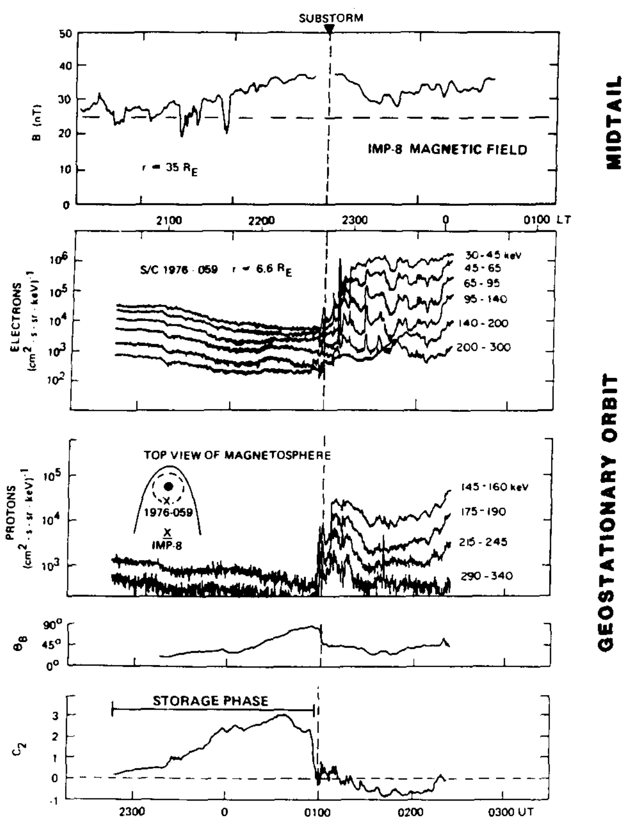

FIG. 11.—Electron anisotropy (C_2), magnetic field inclination (θ_B), energetic proton, and electron data from the geosynchronous satellite *1979-059*, and magnetic field magnitude at $R = 35\ R_E$ measured by *IMP 8*.

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