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Impulsive Ion Acceleration in Earth's Outer Magnetosphere

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Abstract

Considerable observational evidence is found that ions are accelerated to high energies in the outer magnetosphere during geomagnetic disturbances. The acceleration often appears to be quite impulsive causing temporally brief (10's of seconds), very intense bursts of ions in the distant plasma sheet as well as in the near-tail region. These ion bursts extend in energy from 10's of keV to over 1 MeV and are closely associated with substorm expansive phase onsets. Although the very energetic ions are not of dominant importance for magnetotail plasma dynamics, they serve as an important tracer population. Their absolute intensity and brief temporal appearance bespeaks a strong and rapid acceleration process in the near-tail, very probably involving large induced electric fields substantially greater than those associated with cross-tail potential drops. Subsequent to their impulsive acceleration, these ions are injected into the outer trapping regions forming ion "drift echo" events, as well as streaming tailward away from their acceleration site in the near-earth plasma sheet. Most auroral ion acceleration processes occur (or are greatly enhanced) during the time that these global magnetospheric events are occurring in the magnetotail. A qualitative model relating energetic ion populations to near-tail magnetic reconnection at substorm onset followed by global redistribution is quite successful in explaining the primary observational features. Recent measurements of the elemental composition and charge-states have proven valuable for showing the source (solar wind or ionosphere) of the original plasma population from which the ions were accelerated. New data relying on such methods hold great promise for illuminating the details of the substorm ion acceleration mechanism.

INTRODUCTION

The problem of particle acceleration in the earth's auroral zones has been attacked quite successfully over the past few years. Much of the progress in this area has been due to a strong interplay of observation and theory (e.g., Young, 1983; Klumpar et al., 1984; Chang and Coppi, 1981; Borovsky and Joyce, 1985; Ashour-Abdalla, 1985). The theoretical aspects of the auroral ion acceleration problem have been tractable since the acceleration appears to take place in a relatively localized region of space, the initial particle

distributions can be reasonably well specified, the magnetic field and electric potential structures can be assumed with some confidence, and the accelerations occur only up to modest final energies.

It is important, however, to consider that auroral acceleration processes occur, for the most part, as only one component of the overall set of events that constitute the complex conditions associated with geomagnetic activity. During high levels of geomagnetic disturbances, large fluxes of ions are accelerated out of the terrestrial ionosphere and these may have a very significant subsequent effect on outer magnetospheric processes (e.g., Young, 1985; Baker et al., 1982a). Concomitantly with the outward acceleration of ions, there is a substantial acceleration of electrons toward the earth. These accelerated electrons produce intense auroral displays and are primary carriers of global magnetospheric current systems. Together, the heating, transport, and loss of these auroral particles then constitutes one of the important energy dissipation mechanisms associated with geomagnetic activity.

When considering the larger context in which auroral ion acceleration occurs, it is useful to discuss an "elementary" episode of geomagnetic disturbance, viz., the magnetospheric substorm. In its simplest form, the substorm consists of a sequence of events such as shown in Fig. 1. In an idealized circumstance of an isolated substorm, the sequence of events will be initiated by the southward turning of the interplanetary magnetic field (IMF). This southward turning increases dayside magnetic reconnection substantially and over the course of the next hour or so large amounts of free energy (10^{21} - 10^{23} ergs) are added to the earth's magnetotail in the form of increased magnetic flux. In entering this highly energized state, the magnetosphere becomes more and more unstable to the growth of large-scale instabilities which will tend to reconfigure the magnetosphere toward a much lower energy state

(i.e., the initial ground state configuration). Present evidence (McPherron, 1979, and references therein) suggests that the massive reconfiguration and rapid energy reduction that occurs at substorm expansive phase onset is often due to the formation of a magnetic neutral line in the near-earth plasma sheet ($10 \lesssim r \lesssim 20 R_E$) in the midnight sector. Such an interpretation is represented in the cross-sectional schematic illustration of Fig. 1.

The large azimuthal scale size of the substorm neutral line (and the strong electric field thought to exist parallel to it) implies a very large region of magnetic field annihilation, plasma jetting, and (potentially) rapid energy dissipation in the tail. It is in the context of these overall processes of the global interaction of the magnetosphere with the solar wind that auroral acceleration processes largely occur (see Baker et al., 1984, and references therein). In particular, we believe that the energy to drive the auroral acceleration and dissipation comes about because of the very much more energetic processes that load energy into the magnetotail and then rapidly convert this energy in the more distant tail at substorm onset.

Thus, perhaps in contrast to most of the papers in these Proceedings, our objective is to consider the larger context of overall geomagnetic activity as it pertains to particle acceleration processes. We wish to address the "driving engine" in the outer magnetosphere which, on the more limited scale, results in the acceleration of auroral particles to energies of order 1 to 10 keV. Specifically, we will address the sporadic and impulsive acceleration of ions in the earth's outer magnetosphere to very high energies ($\lesssim 1$ MeV) during magnetospheric substorms. The observational characteristics of these populations will be reviewed, and an interpretation of such observations in the context of the model of Fig. 1 will be presented. Since a comprehensive theoretical understanding of the acceleration processes at play in the

magnetotail does not presently exist, we will conclude this paper with some recommendations for future studies.

REVIEW OF OBSERVATIONS

In this section we will recount some of the principal observational results pertaining to ion acceleration in the outer magnetosphere. In particular we will review data obtained for ion burst events ranging in altitude from the geostationary orbit ($6.6 R_E$) to the deep magnetotail.

Ion Burst Time Scales

Spacecraft data in the earth's magnetotail ($10 \sim 30 R_E$) show that, in an average sense, substorm expansive phase onsets regularly produce hot, jetting plasmas in the plasma sheet (e.g., Bieber et al., 1982, and references therein). At the same time there frequently are also substantial increases in the fluxes of energetic particles in the plasma sheet (Scholer et al., 1985).

A particularly striking class of ion acceleration event is shown in Fig. 2 (Krimigis and Sarris, 1979; Sarris et al., 1976). The uppermost part of the diagram shows the occurrence of impulsive burst ion events in three energy ranges between 0.29 MeV and 1.85 MeV. As shown in the lower portion of Fig. 2, these ion bursts exhibit a strong ($10^4:1$) tailward streaming characteristic, directed along the local magnetic field line. These particular events were detected by IMP-7 instruments in the duskside magnetotail at a geocentric radial distance of $\sim 35 R_E$. Note that these ion bursts last only for a few 10^{-5} s of seconds.

Simultaneous plasma data from the same spacecraft have been examined for many such events (Belian et al., 1981) and an example is shown in the middle panel of Fig. 3. The upper insets repeat the data for two of the impulsive

burst events of Fig. 2. Two episodes of extreme plasma sheet thinning are indicated (Fig. 3) by the complete dropout of plasma sheet density on 26 March 1973 at ~1900 UT and again at ~1942 UT. The impulsive bursts of high energy ions were observed right at the time of the plasma dropouts, i.e., right at the edge of the thinning plasma sheet. In this instance, and in most other impulsive burst cases, the high energy ions occur right at the onset of the substorm expansive phase. This general feature is illustrated in the bottom panel of Fig. 3 which shows a magnetogram from the ground station at Kiruna, Sweden, which was near local midnight at the time of the magnetotail events. The ion bursts occurred near the beginning of an intense negative bay which is one of the classic signature of a substorm expansive phase onset.

Much nearer the earth, geostationary orbit spacecraft have shown that hot plasma and energetic particle populations become significantly more intense at substorm expansive phase onset. It has been supposed that such plasma increases at $6.6 R_E$ are due to the "injection" of particles into an azimuthally limited region of space near (and beyond) the geostationary orbit (McIlwain, 1974).

At high energies ($E \geq 200$ keV) geostationary orbit data show the common occurrence of ion "drift echo" events (Belian et al., 1978). An example of such an event is shown in Fig. 4 (Belian et al., 1981). In this figure we have plotted the proton differential flux versus universal time for a two-hour period of 14 April 1977. These data, from the geostationary orbit spacecraft 1976-059, correspond to two proton (ion) energy channels, viz, 0.4-0.5 MeV and 0.5-0.6 MeV. Spacecraft local time (LT) is shown at the top of the figure. The "drift echo" character, and hence the name of this phenomenon, comes from the periodic series of alternating peaks and valleys in the flux profile. Analysis on this and many similar events shows that a drift echo event

corresponds to the injection of a single discrete bunch of energetic ions in the outer magnetosphere. These ions drift azimuthally around the earth many times (often 5 or more) maintaining a reasonable coherence. The recurrence periods of the "echoes" of the original ion burst depend on the gradient and curvature azimuthal drift times for each particle in the earth's confining magnetic field.

At the left-hand side of Fig. 4 we show the H-component magnetogram from Leirvogur for the period in question on 14 April. The sharp drop in the magnetogram at ~2235 UT indicates a strong substorm expansive phase. This time agrees to within a few minutes with the occurrence time for the drift echo event at $6.6 R_E$. Hence, we have concluded that drift echo events are very much a substorm expansive phase phenomenon. Furthermore, as with impulsive bursts in the tail, the initial drift-echo burst is a temporally limited feature lasting several 10^{-2} s of seconds to a few minutes.

The similar energy, timing, duration, and energy spectra of impulsive burst ions in the deep tail and drift echo bursts at $6.6 R_E$ led Baker et al. (1979) to suggest a common origin for the two classes of event. A model (to be discussed below) was advanced to explain this common source.

Particle Anisotropies and Ion Source Locations

As shown in Fig. 2 above, measurements at $\sim 30 R_E$ often show that impulsive burst ions are strongly streaming tailward. This free-streaming propagation along field lines has been taken as very convincing evidence of a source of energetic ions earthward of $30 R_E$ on field lines adjacent to the edge of the plasma sheet. A very consistent and plausible source for these particles would be the near-earth substorm neutral line (Sarris and Axford, 1979; Baker et al., 1979).

On the other hand, the data from geostationary orbit show rather conclusively that injected energetic ion populations come from outside of $6.6 R_E$ (i.e., from locations at greater radial distances). The method employed to assess this issue is the flux gradient measurement. Because of their large gyroradii, ≥ 100 keV ions can provide good information about the strength and direction of gradients as may exist in injected clouds of hot plasma at $6.6 R_E$ at substorm onset.

The east-west gradient parameter is computed as

$$A_{EW} = (E - W)/(E + W)$$

where E is the flux measured in the sector wherein the sensor looks eastward and W is the ion flux with the sensor looking westward. Given the fact that the magnetic guiding center field is generally northward at geostationary orbit, $A_{EW} > 0$ implies a higher flux (or particle density) inside the spacecraft orbit, while $A_{EW} < 0$ implies a higher flux outside the spacecraft orbit.

Baker et al. (1982b) used this technique to illustrate the general tendency of energetic ion injection pulses to arrive from outside of $6.6 R_E$. These results are shown here in Fig. 5. The solid line (with scale on the left) shows the >145 keV proton flux measured by S/C 1977-007 on 29 July 1977. The dashed line (scale on right) shows the computed value of A_{EW} . At the leading temporal edges of the ion injections at 1200 UT and 1205 UT the value of A_{EW} became strongly negative. This is a common characteristic for ion injection events and shows that injected ion bunches reach $6.6 R_E$ from a source region at substantially higher altitude than the geostationary orbit.

Substorm Recovery Events

Impulsive, temporally-limited injection events at substorm onset constitute essentially the only distinctive sort of ion flux increase at geostationary orbit. Of course, injection events do not always extend to very high energies and only under certain conditions are drift echo events seen (see Baker et al., 1979). Nonetheless, substorm expansive phase injection events seem to be the primary means of populating the outer magnetosphere ion trapping region.

On the other hand, thermal and suprathermal protons seem to be present virtually all the time in the plasma sheet (Scholer et al., 1985). It is found that the very energetic protons are greatly enhanced in intensity during geomagnetic activity and, as discussed above, impulsive bursts are closely associated with substorm expansive phase onset. However, the vast majority of ion "events" in the deeper magnetotail are not of the impulsive burst variety.

The majority of discrete high-energy ion events in the tail tend to be seen at substorm recovery and, roughly speaking, exhibit a rapid rise-slow decay time profile. An example of such an event is shown in Fig. 6 (Ipavich and Scholer, 1983). This figure shows proton fluxes from ~30 keV to over 300 keV in energy. It is generally found that the suprathermal protons (30 ~ 100 keV) closely follow the behavior of the thermal plasma sheet ions (Ipavich and Scholer, 1983; Scholer et al., 1985). Thus, as shown by the data of Fig. 6, the plasma sheet recovered (expanded over the ISEE S/C) at ~0320 UT on 26 March 1978 and remained present for the next several hours. Although the 30-36 keV protons diminished in absolute intensity very gradually over the period from 0330 to 0600 UT (probably due to a gradual plasma sheet cooling), there was no significant evidence in these ISEE-1 data of major changes in the plasma sheet bulk plasma after the initial recovery at 0320 UT. We note that

ground magnetic records (e.g., at Great Whale River) showed a clear substorm recovery beginning at ~0300 UT.

The higher energy protons showed a substantially different behavior than the lower energy plasma. Note in Fig. 6 that after the initial rapid rise in the >100 keV fluxes (lower three panels), all of these higher energy flux profiles exhibited a nearly monotonic decrease in intensity. Ipavich and Scholer (1983) showed that the decay time scale for the high energy ions is energy-dependent (as in Fig. 6) with the decay constant being shortest for the highest energies.

Thus, many (if not most) high-energy ion burst events in the magnetotail are due to entry of the observing satellite into the plasma sheet during substorm recovery periods. Baker et al. (1979) found that ~75% of the periods in which there were energetic proton events were characterized first by a plasma sheet thinning (substorm onset) followed by a plasma sheet expansion (substorm recovery). As the expanding plasma sheet envelopes the observing satellite, a rapid rise in energetic proton intensity is then observed. As pointed out by Scholer (1984), multiple burst ion events are often due to repeated entries and exits of the spacecraft into and out of the confined ion population in the plasma sheet. Certainly - under such circumstances - one need not and should not invoke a separate acceleration episode for each "burst" during the substorm recovery epoch. Nonetheless, any successful model of magnetotail dynamics must explain the presence in the plasma sheet of a greatly enhanced population of energetic particles during substorms.

INTERPRETATION

Acceleration at Substorm Onset

As we have shown above, the observational evidence suggests quite strongly that acceleration of energetic particles during the substorm expansive phase is an intimate and integral part of the global substorm process. At least the highest energy and most intense ion fluxes tend to be closely associated with the substorm onset, and such strong bursts of particles appear to originate in the near-earth plasma sheet region.

A successful substorm model must, of course, account for several distinct magnetospheric phenomena:

- Intensified polar ionospheric current systems;
- Global magnetospheric field reconfigurations;
- Strong plasma jetting in the near-earth plasma sheet;
- Large plasma injections into the vicinity of geostationary orbit; and,
- Overall typical energy dissipation rates of 10^{18} - 10^{19} ergs/sec for periods of 30-60 min during the initial phases of substorm activity.

The model described in the Introduction and shown in Fig. 1 can account for many of these features primarily through the extraction and conversion of energy which was originally contained in the solar wind flow impinging on the earth. Many of the rapid dissipations and/or reconfigurations which are observed during substorms come about in the model of Fig. 1 due to the abrupt formation of the near-earth neutral line.

For the purposes of intense energetic particle acceleration, a substorm model must be extended to include several features which have been outlined in this paper:

- Intense, brief bursts of $0.1 \leq E_p \leq 1.0$ MeV ions streaming tailward along boundary field lines in the plasma sheet at substorm onset;
- Injection of temporally and spatially limited bunches of ions in a similar energy range into the vicinity of geostationary orbit, again at substorm onset.

Realistically, a substorm model should account for these acceleration features in a fairly natural way rather than positing ad hoc acceleration sites throughout the magnetosphere independent of the dominant dynamical processes mentioned in the previous paragraph.

Baker et al. (1979) suggested a model which accounted in a reasonable way for most of the observations both in the plasma sheet and at geostationary orbit. An illustration of the substorm-onset features of this model is shown in Fig. 7. Both the observation of tailward-streaming impulsive bursts in the plasma sheet and drift echo events at geostationary orbit suggests a brief, intense acceleration process right at substorm onset. As illustrated by Fig. 7, we associate both of these particle populations with the near-earth substorm neutral line (see Fig. 1) which is also responsible for plasma sheet jetting, magnetic field reconfiguration, etc.

Farthward of the acceleration region the high-energy particles are introduced onto closed field lines. The observation of drift echo events (i.e., brief, narrow bursts of several hundred keV protons) implies that these particles are produced primarily in a brief period at the onset of the substorm. These substorms producing such high energy particles typically occur during quite disturbed geomagnetic conditions. Thus the suggestion would be, as shown in Fig. 7, that under such circumstances, large induced electric fields would exist in the vicinity of the neutral line acceleration region. Total, integrated electric potentials along the electric field must be of order

1 MV, or more, in many such cases. The largest values of $\partial B/\partial t$ must be quite transient since the drift echo events are typically quite short (≤ 1 min) in temporal extent.

Tailward of the acceleration region, the high-energy ions are introduced onto essentially open magnetotail field lines. The high-energy impulsive burst ions stream tailward from the neutral line region at the edge of the thinning plasma sheet as shown in Fig. 7. These bursts are of very short duration and, in fact, show "inverse" velocity dispersion (low energy particles appear before high energy particles). This dispersion effect (Sarris and Axford, 1979) represents a time-of-flight effect of different energy particles moving along field lines away from the fixed neutral line source region. This source is only active for a brief, limited time (Baker et al. 1979). As the plasma sheet thins more and more during substorm onset, the loci of higher and higher energy particles sweep over an observing spacecraft near the edge of the plasma sheet.

As noted, the tailward flowing impulsive burst protons escape essentially along open field lines down the tail, while drift echo protons subsequently drift in trapped orbits about the earth and disperse continually. As shown by the dotted line in the lower panel of Fig. 7, the magnetic field has changed from a highly taillike configuration (on the nightside) to a more dipole-like configuration during the substorm injection process. Given that the ions were accelerated deep in the tail, it may well be that the ion bursts maintain their coherent initial structure in drift echo events because of such a rapid field reconfiguration in the equatorial region. We would expect, as shown by the diagram in Fig. 7, that the earthward-injected energetic ions would travel along the original taillike field lines and would go deep toward the low-altitude foot of the field lines. Such nearly field-aligned particles spend much of their total bounce time near the mirror points. By the time the ions

have mirrored and returned to the equatorial region, the field line could have collapsed substantially toward the earth. Hence, the ion bunch will have been brought effectively much closer to the earth but will not have undergone the strongly dispersive gradient and curvature drift that would be expected if the particles were brought closer to the earth as a bunch of largely equatorial ($\alpha \approx 90^\circ$) particles.

This hypothesized effect for ions might also explain the relative absence of electron drift echo effects. Because of their much shorter bounce times at a given energy compared to protons ($\tau_p \sim 40 \tau_e$), and because of their strong tendency to scatter in whistler-mode wave turbulence during the injection process, electrons will sense the equatorial collapse of the field line much more than the ions. Thus the electrons, even if they were bunched initially like the ions, will tend to be broadly dispersed by drift effects during the injection process.

A final outstanding issue about the high-energy acceleration process is why the energization seems so temporally limited at the highest energies. Certainly at lower energies ($E < 100\text{-}200$ keV) Baker et al. (1979) noted that a more "normal" type plasma heating and particle acceleration apparently continued as long as the neutral line remained in position in the near plasma sheet and as long as the substorm expansive phase was in progress.

Our present belief remains that the highest energy particle acceleration corresponds to an "explosive" phase of reconnection early in the substorm sequence. The rate of magnetic reconnection (e.g., Axford, 1984) is determined essentially by the Alfvén speed ($V_A = \frac{B}{\sqrt{4\pi\rho}}$) in the inflow region of the substorm neutral line. As long as plasma sheet field lines are being reconnected, then B is characteristic of the plasma sheet (5-10 nT) and the mass density ($\rho = nm_p$) is determined by the plasma sheet number densities

($n \sim 1 \text{ cm}^{-3}$). As soon as reconnection has progressed to the stage shown in Fig. 7 where lobe-like field lines are reconnecting, then B at the inflow region would be much higher (20-40 nT) and plasma densities would be greatly diminished ($n \lesssim 10^{-2} \text{ cm}^{-3}$). Thus, we concur with the speculation of Axford (1984) that the high-energy substorm bursts probably correspond to the situation when the reconnection rate suddenly jumps from a rate determined by $V_A \sim 100 \text{ km/s}$ (deep in the plasma sheet) to a rate determined by $V_A \sim 1000\text{-}2000 \text{ km/s}$ at the plasma sheet-lobe interface. During this brief, transient transition interval, very large acceleration apparently takes place.

Particle Redistribution at Substorm Recovery

In essence the Baker et al. (1979) model assumes that as a result of the expansive phase acceleration and injection processes there exists a high density of quasi-trapped energetic particles in the outer radiation zones at the beginning of the substorm recovery. As the plasma sheet expands (thickens) during the substorm recovery phase, the plasma sheet eventually envelopes a relatively low-latitude observing spacecraft in the magnetotail. Then, as the plasma sheet increases in size, the model suggests that energetic ions from the outer magnetosphere ($6 \lesssim r \lesssim 10 R_E$) rapidly leak and/or diffuse outward to fill the newly expanded plasma sheet volume. Thus, rather than invoking a new, impulsive acceleration at substorm recovery, the model suggests that the plasma sheet is largely filled by redistributed particles which were produced at substorm onset. Balian et al. (1981) found that the thin, residual plasma sheet may be filled with particles continually leaking out of the trapping regions throughout the expansive phase.

Baker et al. (1979) and Belian et al. (1981) examined many substorm-recovery events and found substantial support for the above picture. They concluded that the energy spectra at $6.6 R_E$ and in the recovering plasma sheet were very similar and absolute intensities at $6.6 R_E$ were high enough to be consistent with the leakage hypothesis. Furthermore, this model also accounted quite well for the dawn-to-dusk anisotropy (Sarris et al. 1976) often seen in the recovering plasma sheet energetic ions. This anisotropy is consistent with a strong gradient of particle density equatorward and earthward of the magnetotail spacecraft. Of course, the model also explains the rapid rise-slow decay flux time profile seen during substorm recoveries (see Fig. 6); Baker et al. (1979) did some detailed modeling of this particular feature.

Scholer et al. (1985) suggested a specific extension of the above model primarily to account for the presence of energetic (≤ 150 keV) ion beams at the edge of the expanding plasma sheet. This amalgamated model is shown here as Fig. 8. Scholer et al. pointed out that the tailward retreating neutral line (during substorm recovery) could be the source of the field-aligned beams which are injected toward the earth. But, as in the original Baker et al. model, the very high energy ions leak out of the outer radiation zones onto the newly reconnected (closed) field lines. As shown by the shading in Fig. 8, the very high energy particles are found on field lines nearer the center of the plasma sheet. The figure shows that as the neutral line moves tailward it creates more and more newly reconnected field lines and these tend to contain the lower energy, isotropized ions produced recently by the retreating neutral line.

Scholer et al. (1985) pointed out several concerns about the original Baker et al. model. These primarily hinge on the issues of the character of the spectrum (power law or exponential) of the recovering plasma sheet particles and whether the total population of quasi-trapped ions could supply

the recovering plasma sheet. As noted above, Baker et al. (1979) did some modeling of the required trapped ion source strength and particle redistribution mechanism, but a complete numerical model was not employed. Thus, there remain several areas where more complete modeling is necessary and important.

CONCLUSIONS AND FUTURE STUDIES

We conclude from ongoing studies of energetic particles in the earth's outer magnetosphere that highly impulsive ion acceleration often occurs during substorms. As we have emphasized throughout this paper, this acceleration appears to be intimately related to the primary dynamical processes in the earth's magnetotail which cause global substorm effects. Although energetic ion acceleration in the magnetotail is not of dominant importance (either in energetics or dynamics), it is extremely important as a prototype of cosmic acceleration mechanisms. We conclude from the observations that:

- Acceleration occurs in a relatively localized region in the near-earth plasma sheet.
- The mechanism operates on a short (or even explosive) timescale of 1 to a few minutes.
- The process accelerates some particles to very high energies (≥ 1 MeV), i.e., well-above ordinary cross-tail potentials.

In the foregoing parts of this paper we have described a model which provides a qualitative description of the acceleration, injection, and redistribution of energetic ions during substorms.

Despite the general understanding that presently exists concerning energetic ion acceleration, and despite the two decades of observational work in this area, we still have much work to do. From an observational

perspective, the present-day situation permits relatively large constellations of observing spacecraft at geostationary orbit and throughout the near-earth plasma sheet. These chance configurations of spacecraft should be exploited to pin down source locations and particle transport details. Furthermore, the modern instrumentation provides very substantial improvement in the available energy spectral resolution and in the 3-dimensional angular distribution measurement capabilities.

The role of energetic heavy ions in the magnetosphere has recently come under heightened consideration (e.g., Williams and Sugiura, 1985, and references therein). The advent of sensor systems capable of mass and charge identification are beginning to reveal the complex competition between the ionospheric and solar wind plasmas in controlling magnetospheric dynamics. With regard to the problem of high-energy ion acceleration, Blake et al. (1983) were able to use the earth's magnetic field as a large ion charge-state analyzer. By combining high-energy ion drift echo detection with the mass resolution capability of the SCATHA spacecraft, Blake et al. could identify the ultimate plasma source of a substorm-accelerated ion burst. They determined that in this case the very energetic ions produced at substorm onset were of solar wind, not ionospheric, origin. The new observational capabilities now available (as with the AMPTE spacecraft) hold the potential of answering most questions about the details of ion acceleration if the data sets can be fully exploited.

To achieve true understanding, theoretical and numerical modeling efforts must be greatly increased. Given the rapidly increasing capabilities of present-day computers and the improving sophistication of numerical techniques, much more complete models of tail acceleration should be possible. Our present thinking is that a self-consistent, 3-D MHD model of the earth's magnetotail

To achieve true understanding, theoretical and numerical modeling efforts must be greatly increased. Given the rapidly increasing capabilities of present-day computers and the improving sophistication of numerical techniques, much more complete models of tail acceleration should be possible. Our present thinking is that a self-consistent, 3-D MHD model of the earth's magnetotail could be employed with the added feature of test particles to simulate the energetic ion population (J. Birn, private communication, 1984). Such modeling, using the detailed comparison of such results with new observations, holds genuine promise for revealing in a very precise way the workings of the powerful accelerator in the earth's magnetotail.

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Figure Captions

- Fig. 1. A noon-midnight cross-sectional view of the earth's magnetosphere showing the possible sequence of events involved in a magnetospheric substorm. Enhanced dayside reconnection between the earth's field and the interplanetary magnetic field leads to "open" field lines which are dragged into the tail lobe on the earth's nightside. After a period (30 ~ 60 min) of such loading of magnetic flux into the tail lobes, a substorm neutral line forms in the near-earth plasma sheet causing large magnetospheric reconfiguration and earthward injection of hot plasma particles.
- Fig. 2. IMP-7 energetic particle data for 26 and 27 March 1973. The top panel shows three proton energy channels and one electron channel at a basic time resolution of 10.24 sec. The middle and bottom panels show angular distributions of the impulsive ion bursts (see upper panel) in successive 10.24 sec time intervals. Large ($\sim 10^4:1$) tailward streaming anisotropies of the 0.29 MeV ions are seen (from Krimigis and Sarris, 1979).
- Fig. 3. (Top) Representative example of energetic ion impulsive bursts as recorded by the IMP 7 satellite (see Fig. 2). IMP 7 was in the plasma sheet near the dusk magnetopause at the time of these observations. The measured IMP 7 electron plasma density is shown in the middle panel while the nature of the concurrent auroral geomagnetic activity is shown by the Kiruna magnetogram in the lower panel (from Belian et al., 1981).
- Fig. 4. An example of an energetic proton drift echo event as recorded by spacecraft 1976-059 at synchronous orbit. The upper panel shows 0.4-0.5 MeV proton fluxes while the lower panel shows 0.5-0.6 MeV fluxes. The inset at the left shows the auroral zone magnetogram from Lairvogur (from Belian et al., 1981).
- Fig. 5. A comparison of the >145 keV proton flux (solid line) and the associated east-west gradient anisotropy (dotted line) for a period on 29 July 1977. Strong gradient anisotropies occur (at ~ 1200 UT and ~ 1205 UT) as newly energized particles are injected near synchronous orbit (from Baker et al., 1982b).
- Fig. 6. Energetic ion count rate profiles in four different energy ranges as measured by ISEE-1 on 26 March 1978. An abrupt increase in all energy channels was seen at ~ 0320 UT when ISEE rapidly entered the plasma sheet (from Ipavich and Scholer, 1983).
- Fig. 7. Two cross-sectional views of the magnetosphere showing the substorm neutral line, its associated electric field pattern, and the jetting of hot plasma from the neutral line. Magnetic field lines are shown in the x-z plane in the lower panel with energetic ions streaming along field lines away from the neutral line both earthward and tailward. These features, associated with substorm onset, are taken as the primary type of impulsive ion acceleration in the model of Baker et al. (1979).

Fig. 8. A schematic illustration of the proposed sequence of events in the earth's magnetotail during a substorm recovery (Scholer et al., 1985). The model combines the tailward retreat of the substorm neutral line with the leakage of particles on closed field lines as originally proposed in the model of Baker et al. (1979).

Fig. 1

IMP-7 PROTONS
(SARRIS ET AL., 1976)

Fig. 4

Fig 5

Fig. 6

FIG 7

Fig. 8