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Particle Acceleration from Reconnection in the Geomagnetic Tail

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Particle Acceleration from Reconnection in the Geomagnetic Tail

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The acceleration of charged particles in the near geomagnetic tail, associated with a dynamic magnetic reconnection process, has been investigated by a combined effort of data analysis, using Los Alamos data from geosynchronous orbit, magnetohydrodynamic (MHD) modeling of the dynamic evolution of the magnetotail, and test particle tracing in the electric and magnetic fields obtained from the MHD simulation. The results show excellent agreement between the observations, the MHD simulations, and the test particle results, indicating flux increases corresponding to a heating of electrons and ions by a factor of ~2. In observations as well as in the test particle results, the ion heating stems mainly from an increase in energetic particle fluxes (above ~20–60 keV), whereas the ion fluxes at lower energies are not significantly affected. The simulations also identified the source regions of the accelerated ions: the dawn flank of the tail for higher energies and the more distant tail region at lower energies. This population presumably originates from the "plasma mantle," the high-latitude population entering the tail from the solar wind.

Background and Research Objectives

Plasma and field configurations in various contexts can exhibit configurational instabilities which lead to disruptions of the magnetic field and associated currents and to the conversion of magnetic energy into particle energy in the form of heating, bulk plasma flow, or the generation of subpopulations of higher energy. Prominent examples of such rapid reconfigurations and energy releases are, to our present understanding, tokamak disruptions, solar flares, and substorms in the geomagnetosphere. In each case the underlying physical mechanism that enables the disruption of the field is believed to be magnetic reconnection. This

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is a process that violates the "frozen-in" field condition of ideal magnetohydrodynamics (MHD) and leads to new connections of magnetic field lines and thereby to the reconfiguration necessary for energy release.

In the magnetospheric context, large-scale MHD simulations (e.g., Birn and Hones, 1981; Birn and Hesse, 1991) including finite resistivity have successfully modeled the dynamic changes associated with substorms, which are inferred from observations and affect primarily the long extended tail of the magnetosphere. These changes consist of the severance of a section of the tail through the reconnection process and its ejection downtail in the form of a "plasmoid" (Figure 1) and of a relaxation ("collapse") of the near tail into a more dipolar configuration, associated with a diversion of magnetotail currents along magnetic field lines to the ionosphere, across the nightside auroral region, and back into the tail (Figure 2). The MHD simulations have also provided information about the heating of the plasma associated with the reconnection process (Hesse and Birn, 1992a).

However, since the MHD equations describe only the bulk properties of the plasma, no direct information of the generation of highly energetic particles (tens or hundreds of keV as opposed to a few keV thermal energy) is provided. Bursts or "injections" of such energetic charged particles are one of the major substorm effects at geosynchronous orbits, where a large number of scientific and programmatic satellites reside. They have significant effects not only on the scientific measurements from those satellites but also on their operation and lifetime.

Ideally, one would like to describe particle acceleration in a particle code, which includes aspects of individual ions and electrons as well as the magnetic and electric fields generated by these particles. Unfortunately, the huge range of temporal and spatial scales which enter such a fully self-consistent description of the plasma and the fact that variations in two or even three space dimensions are important, prohibit, at present, self-consistent particle simulations on realistic spatial and temporal scales. Therefore, such simulations are still restricted by relatively small scales and simplified geometries, which leave out many important aspects of the dynamic magnetotail configuration.

An alternative way of investigating particle acceleration in dynamically changing magnetic and electric fields is to trace test particles in the fields obtained from a MHD simulation of tail dynamics. In this way the full particle dynamics can be included in fields that cover the actual scales of the magnetosphere. Obviously, this approach includes only the interaction of particles with large-scale waves and instabilities governed by the collective effects in the MHD equations. Our results (Birn and Hesse, 1993, 1994; Birn et al. 1996b, 1997b), however, indicate that these are indeed the dominant interactions which affect the ion acceleration at high energies, whereas interactions of particles with waves and instabilities on smaller scales seem important only for reducing local sources of free energy, such as pressure anisotropy, which can be included implicitly in the MHD code (Hesse and Birn, 1992b; Birn et al., 1995a,b).

In our study we investigated particle acceleration from magnetic reconnection in the magnetotail more deeply. This involved primarily a more systematic study of test particle orbits in the dynamic magnetic and electric fields. However, we also included an extensive data study to identify plasma properties that accompany the increases in energetic charged particle fluxes ("injections"). Recent observations indicated a potentially crucial role of thin current sheets, forming during the early phase of a substorm, in the subsequent breakup. We therefore updated the initial state as well as the large-scale MHD simulation, which forms the basis of the particle study to include the formation and breakup of such a thin current sheet. The prime objectives of our research were (1) an identification of typical acceleration mechanisms at different energies, (2) the identification of source regions of accelerated particles at different energies, (3) an investigation of temporal and spatial properties of energetic particle fluxes.

Importance to LANL's Science and Technology Base and National R&D Needs

The proposed research is of relevance not only for the understanding of energetic particle bursts affecting satellites in the Earth's magnetosphere but also for the deeper understanding of the underlying acceleration process of magnetic reconnection which operates in a variety of space, astrophysical, and laboratory contexts.

Scientific Approach and Accomplishments

Our approach consisted of several steps. The first step was to simulate the dynamic changes in the earth's magnetotail in a large-scale magnetohydrodynamic (MHD) simulation, using our three-dimensional nonlinear MHD code, and to store the resulting magnetic and electric fields. Recent observations have demonstrated that an important element in the dynamic energy release from the earth's magnetotail is the formation of a thin current sheet in the near tail region of the magnetosphere, where the field makes a transition from the dipole to the stretched tail (e.g., Schindler and Birn, 1993; Sanny et al. 1994). This thin current sheet with strongly enhanced electric currents is important not only for the structure of the fields in which the particles become accelerated but also for the onset of the instability which initiates the dynamic evolution, and hence for the buildup of strong induced electric fields which are crucial for the gain of large amounts of energy.

In response to these results, a new equilibrium model was developed that includes the inner tail region with the transition to a more dipole like field (Hesse et al., 1994; Birn and Hesse, 1996). This equilibrium was subsequently subjected to an imposed external electric field, which led to the expected formation of the thin current sheet in the early phase of the

MHD simulation. The subsequent breakup was initiated by imposing finite resistivity, which is the assumed consequence of a microscopic wave-particle interaction (Birn and Hesse, 1996; Birn et al., 1994, 1996a). Previous runs (e.g., Birn and Hesse, 1991) had shown that the tail instability leads to magnetic reconnection in the near tail and the formation and ejection of a plasmoid, illustrated in Figure 1. The new run, however, was more realistic as it led to a much faster evolution and generated a stronger, more localized electric field in the inner tail as a consequence of a collapse of this region.

In a parallel effort, the observed properties of dispersionless charged particle injections were investigated systematically, using a full year of data from the Los Alamos magnetospheric plasma analyzer (MPA), covering energies up to ~40 keV, and the synchronous-orbit particle analyzer (SOPA), covering energies above ~50 keV (Birn et al., 1996c, 1997a). This study revealed the existence of five classes of dispersionless injection events, well ordered by their average local times: ion injections without accompanying electron injection at ~21 LT, ion injections followed a few minutes later by an electron injection centered at ~22 LT, simultaneous ion and electron injections close to midnight, electron injections that are followed by an ion injection at ~1 LT, and finally pure electron injections at ~2 LT. This result can be understood from a modification of the well-known picture of an "injection boundary," limiting the region of enhanced particle fluxes. We postulated an east-west displacement of the boundaries for ions and electrons in combination with an (observed) earthward motion of this boundary. This is illustrated in Figure 3.

The energetic particle flux increases were found to be accompanied by characteristic changes of the thermal populations. The thermal electrons show a significant increase in temperature (from ~1 keV to ~2 keV) and pressure at substorm onset, while the density and the thermal ion signatures (below ~30 keV) are typically weak. However, energetic ions (above ~30 keV) contribute significantly to the total ion pressure and temperature, leading to a rise in the total temperature from ~10 keV to ~16 keV. Preexisting perpendicular anisotropies in the thermal electrons and ions are reduced during the substorm growth phase but become enhanced again after onset, sometimes after a brief period of parallel anisotropy. Figure 4 demonstrates the characteristic changes of (top) ion fluxes as functions of time and (bottom) of the ion distribution functions.

The next step was the development of a particle code that traces particles in the MHD fields, suitably interpolated in space and time. This code is based on the explicit integration of the equation of motion of individual particles. As we are interested in acceleration processes which may violate the conservation of adiabatic invariants of the particle motion, the full particle trajectories were integrated. Although the tracing of a limited number of ions had already provided some information on characteristic properties (Birn and Hesse, 1993, 1994), a larger number was necessary to derive systematically the distributions at selected times and locations for a comparison with the observations. This is important in particular in view of the chaotic aspects of the particle orbits, which imply that particles with close locations and speeds at a given time may come from or end at quite different locations and energies. At several selected locations in the simulation region the velocity magnitude and direction was varied and particles were traced backwards in time until a well defined initial state or the boundary of the system was reached. This procedure allowed us to identify the sources of the accelerated particles. Using Liouville's theorem, which states the conservation of phase space density for the evolution of a collisionless plasma, enabled us further to construct the distribution functions at given locations and times from the given initial and boundary conditions (Birn et al., 1996b, 1997b).

The energetic particle flux changes obtained from the test particle orbits agree well with the observations that demonstrate rapid ion flux increases at energies above ~20 keV but little change at lower energies. This is illustrated by Figure 5, showing (top) proton fluxes as functions of time and (bottom) the associated changes in the distribution function as obtained from the test particle simulation. The "injection region" inferred from the test particles not only has a sharp earthward boundary (the usual injection boundary) but also a sharp but ragged tailward boundary well earthward of the neutral line. The earthward portion of enhanced ion flux can be traced to the enhanced cross-tail electric field associated with the collapse and dipolarization of the inner tail, whereas the tailward edge is closely associated with the near-Earth x-type neutral line at the reconnection site. Due to the rapid earthward motion of accelerated ions away from the neutral line, however, this boundary is displaced earthward to where the energetic ions become more adiabatic in the stronger dipolar field. Lower-energy ions are not affected by cross-tail acceleration in the strong electric fields because their earthward **E×B** drift dominates the cross-tail drift, except very close to the neutral line.

In a further attempt to bridge the gap between large-scale simulations and microscopic particle processes, a recently developed algorithm for the coupling of parallel and perpendicular ion pressure components, based on the effects of ion cyclotron instability, was incorporated into the MHD code. Simulations with this new code showed the important role of isotropizing mechanisms in destabilizing the magnetotail (Birn et al., 1995a,b).

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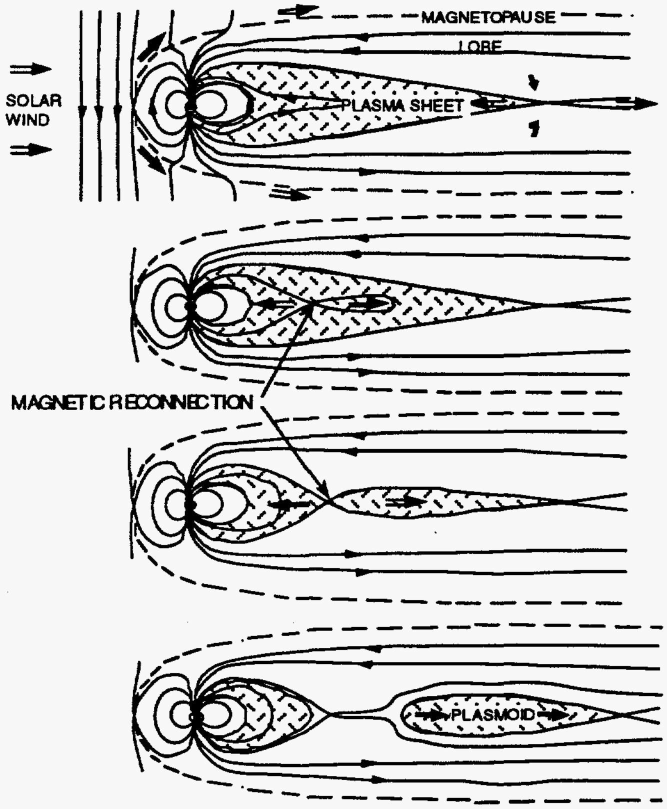

Fig. 1. Characteristic changes of the magnetosphere during a magnetospheric substorm.

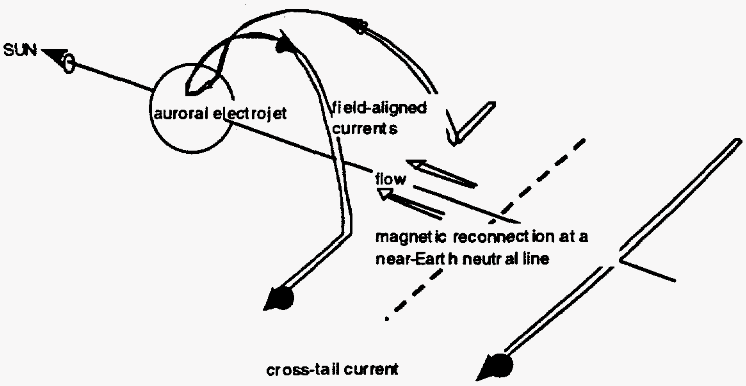

Fig. 2. Current diversion in the substorm current wedge.

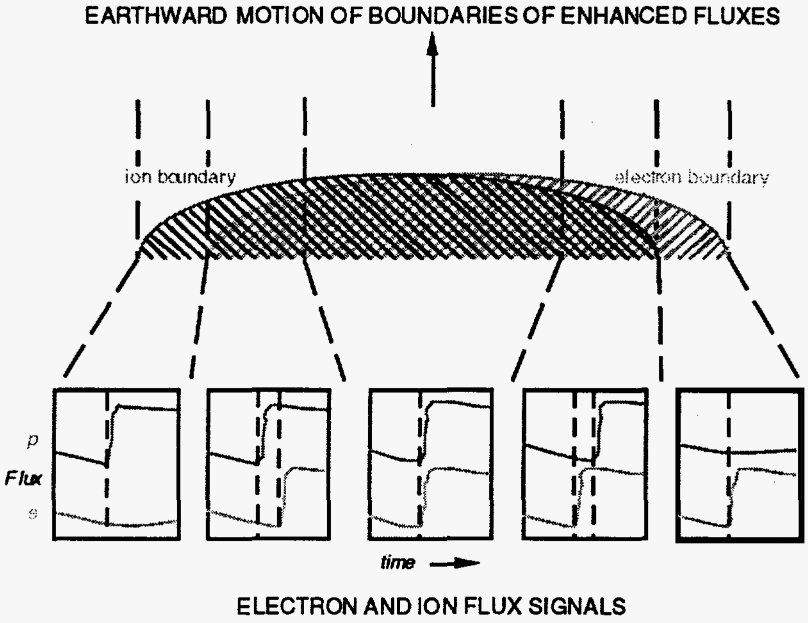

Fig. 3. Postulated east-west displacement of ion and electron boundaries in the equatorial plane with earthward motion.

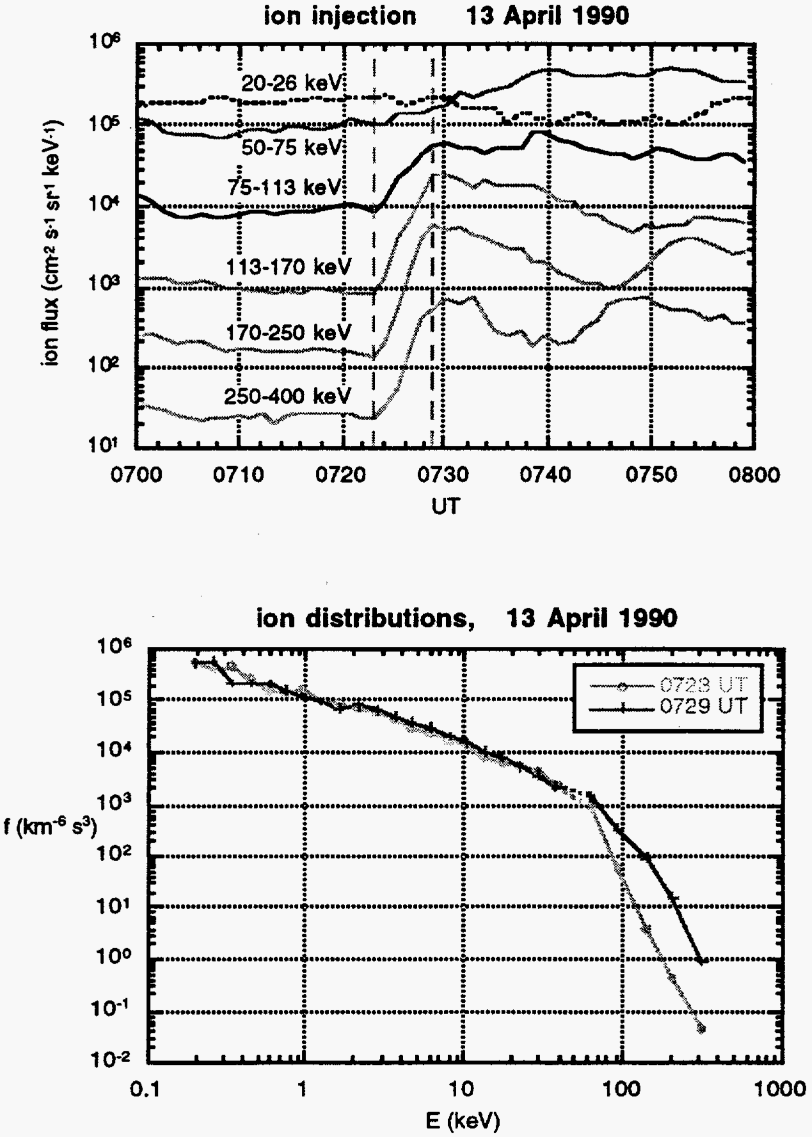

Fig. 4. Characteristic changes of (top) ion fluxes and (bottom) ion distribution functions during an injection observed by Los Alamos instruments on a geosynchronous satellite.

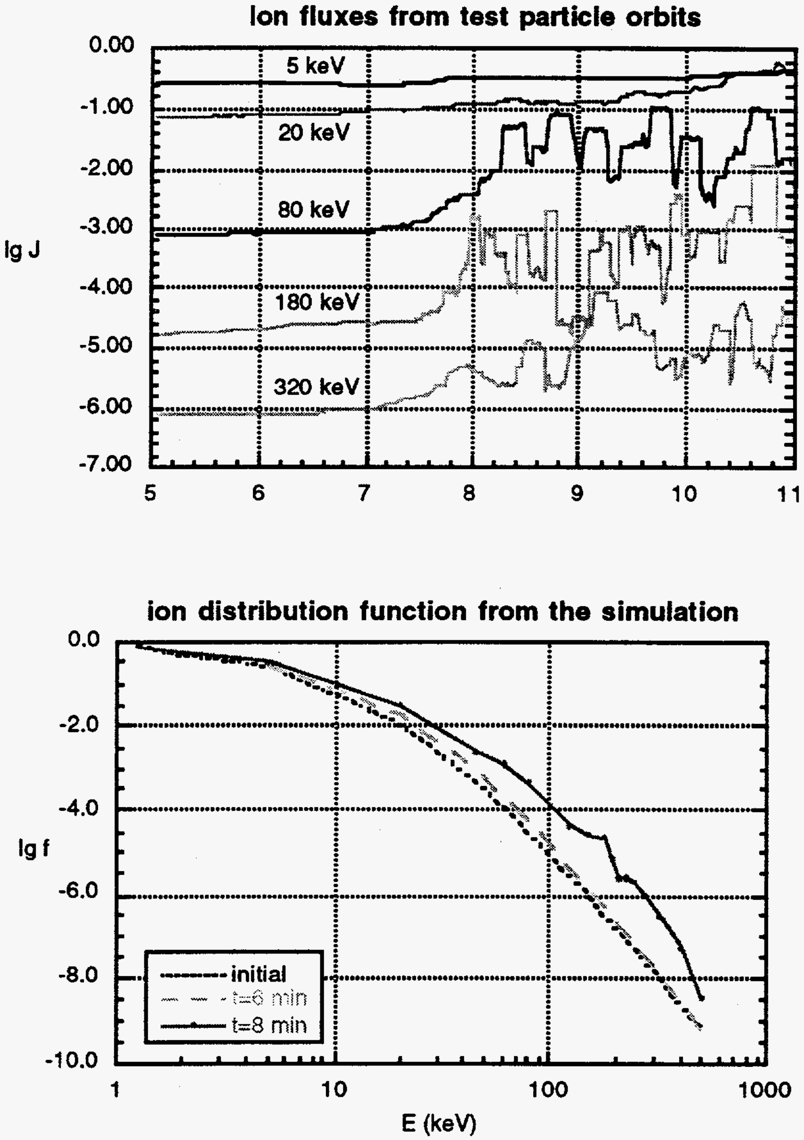

Fig. 5. Energetic particle flux changes obtained from test particle orbits shown as (top) proton fluxes and (bottom) changes in distribution functions.