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THE GEOPAUSE

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Abstract. Coupled to the Earth and protected by the geomagnetic field, terrestrial matter in the plasma state dominates a larger region of space than was suspected when the "space age" began, a region we refer to as the geosphere. Accelerated and heated by solar wind energy, this matter expands in size and increases in mass density in response to the Sun's ultraviolet spectrum, heliospheric conditions, and the occurrence of severe space storms. Such storms regularly damage spacecraft, interfere with communications, and trigger power grid interruptions or failures. They occur within the geopause region, that is, the volume defined by the limits of the instantaneous boundary between plasmas that are primarily heliospheric and geospheric. The geopause is analogous in some ways to the heliopause but also resembles the terrestrial air-sea interface. It is the boundary layer across which the supersonically expanding solar plasma delivers momentum and energy to the terrestrial plasma and gas, exciting them into motion, "evaporating" them into space, and dissipating considerable amounts of power in thermal forms, while generating energetic particles through repeated storage and explosive release of electromagnetic energy. The intensity of the solar wind and the orientation of its magnetic field jointly control the strength of the coupling between solar and terrestrial plasmas and hence the occurrence of severe storms in the geopause region.

INTRODUCTION

When the scientifically literate lay person thinks of the term "magnetosphere," the images that spring to mind are likely to be those of the dipolelike geomagnetic field in space or of the energetic van Allen radiation belts encircling the Earth within that field. Such reveries may evoke images of the aurora as well, these being the manifestations of the magnetosphere's presence that have historically been most tangible to Earth's inhabitants. These mental images have in most cases been derived from encyclopedias or other popular accounts of the aurora and radiation belts. These have lagged far behind the research frontier and still often attribute these phenomena to the penetration and trapping, respectively, of energetic solar particles in the terrestrial magnetic field. The term "magnetopause" defines the limit of the magnetosphere as the boundary between terrestrial and interplanetary magnetic fields. There has been a long debate among scientists concerning the degree to which that boundary is "open" to the entry of solar plasma or the escape of terrestrial plasma.

Often missing from such thoughts are images of the unseen and less well known component of the near-Earth space environment, the ionized conducting gas, or plasma. Plasma is the most substantial physical entity in the Earth's space environment, but its name may instead evoke images of translucent biological fluids. The geomagnetic field is sufficiently substantial to present a nearly impenetrable barrier to the solar wind that stops it about 10 R_E (Earth radii) upstream of the Earth and deflects it tens of Earth radii away from and around the Earth. However, the solar wind substantially alters the geomagnetic field, compressing and terminating it on the dayside, stretching and distending it far beyond a dipolar shape on the nightside, shearing it sharply within the equatorial flank boundary layers, and inflating the inner parts of the magnetic field, to a degree that responds to solar wind variations. The complex set of plasma regions and boundaries known as the magnetosphere is thereby formed. The morphology of this system is summarized in Figure 1, and its terminology is summarized in the glossary immediately following this introduction.

The distortions of the magnetic field produced by the solar wind imply the generation of electrical current systems at the magnetopause (boundary between terrestrial and solar magnetic field), across the equatorial region of the stretched tail of the magnetosphere, within the regions of boundary layer flow reversal (conjugate with the auroral zone), and encircling the Earth in the inner magnetosphere. Such currents are carried by charged particles drawn from the plasmas present in each of these regions. The magnetopause currents are carried largely by solar plasma. The tail

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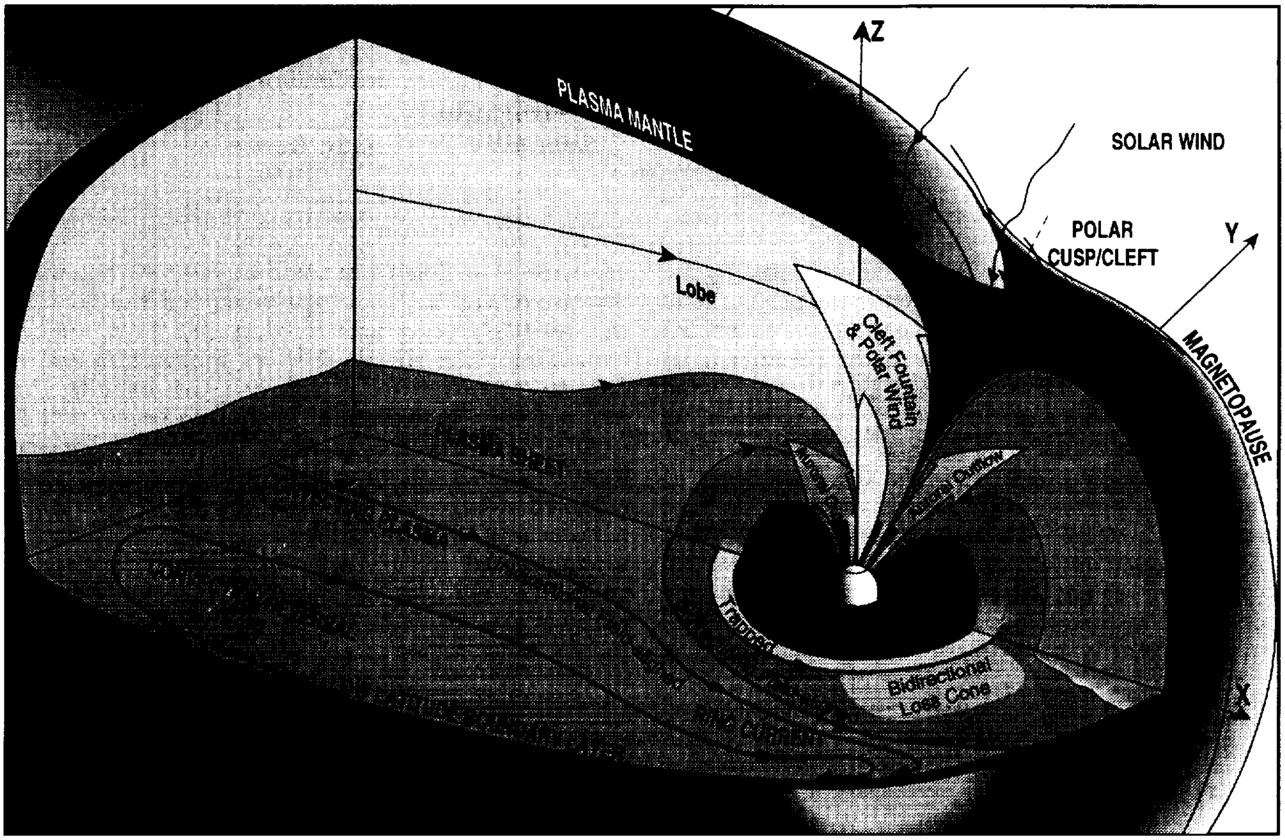

Figure 1. Schematic three-dimensional cutaway illustration of magnetospheric morphology [From *Giles*, 1993; *Giles et al.*, 1994]. Fine line curves indicate magnetic field lines, while bold lines indicate flow streamlines and boundaries.

currents flow in the plasma sheet, through the region of vanishing radial field component called the neutral sheet. The shear layer currents flow along magnetic field lines of the low-latitude boundary layer and plasma sheet, in plasmas that also produce auroral displays. The inner magnetospheric currents, known as the ring current, flow circumferentially around the Earth in the energetic plasma and radiation belt particles. The currents that flow into and out of the ionosphere along magnetic field lines are closed by a circuit path through the most conductive layers of that medium. All but the magnetopause currents must flow in part within the evacuated wake carved out of the solar wind by the geomagnetic field. Within that wake lie the Earth and its outgassing ionosphere, emitting a substantial flux of plasma ions and electrons generated in the upper atmosphere by solar ultraviolet radiation and auroral energy sources.

The presence of a magnetic field in a conducting fluid implies that flows act as current dynamos and therefore suffer resistive as well as frictional types of dissipation. The magnetic field, which transmits shear stress efficiently for great distances along the field lines but poorly in the direction transverse to the magnetic field, introduces anisotropy that strongly affects plasma flows. Current flows associated with magnetic field distortions, and their associated body forces ($\mathbf{J} \times \mathbf{B}$) on the plasma, provide strong coupling along field lines, organizing the plasma into "flux tubes" that behave as coherent units, in place of the fluid "parcels" of hydrodynamics. Electrodynamic coupling transmits frictional effects present in the lower reaches of the ionosphere along the entire magnetic field line. Because the middle atmosphere is largely nonconducting, this electrodynamic coupling does not extend below the ionosphere, and stress coupling to lower regions is frictional, i.e., collisional or viscous, in nature.

We know that some magnetic field lines, as shown in Figure 1, cross the magnetopause and connect the ionosphere directly with the solar wind, disrupting the topside ionosphere and allowing the two plasmas to come into contact on common flux tubes. The two plasma media also exchange momentum and energy, the antisunward flow of solar plasma being loaded by the acceleration of terrestrial plasma in the antisunward direction, as well as significant collisional friction at the earthward end of the flux tubes. As the solar plasma gains control of flux tube motion, it competes with the ionosphere to fill the flux tubes as they move into the wake of the Earth and to carry the currents that distort the tail field. Owing to the their initial distributions along the flux tubes, to the gravitational confinement of the heavy ionospheric components, and to the supersonic flow of the solar wind, the two plasmas tend to remain generally stratified along these flux tubes as they convect into the tail of the magnetosphere.

It has been postulated [*Alfvén*, 1981] that space plasmas tend to become organized into distinct cellular regions, owing in part to their tight coupling with magnetic fields. Indeed, the solar wind plasma and its magnetic field dominate interplanetary space out to an outer boundary, referred to as the heliopause, where the solar wind stagnation pressure reaches equilibrium with the interstellar plasma. Illustrating this postulate, the boundary between solar and interstellar magnetic fields (the heliomagnetopause) is thought to lie close to, but inside, the plasma boundary or heliopause, though this region has not been explored and is a subject of considerable research interest [*Suess*, 1990].

By analogy, we might anticipate a geopause in close proximity to, but inside, the (geo)magnetopause, marking the boundary between solar and terrestrial plasmas. Because the geomagnetic field, rather than the geospheric plasma, is known to support the geomagnetopause, it has long been thought that the solar wind penetrates far inside the geomagnetosphere and dominates a substantial outer region, with terrestrial plasma dominant only in the innermost dipolar field region known as the plasmasphere and having much higher plasma density and much lower plasma temperature than the solar wind [e.g., *Nishida*, 1966; *Brice*, 1967]. This inner, toroidal-shaped region often has a clear plasmapause found on average near an equatorial geocentric distance of 4–5 R_E. More recently, as will be outlined in the composition section, it has come to be appreciated that the hot plasma found outside the plasmasphere often has a heavy ion component that can only be interpreted as terrestrial and that its light ion component could also be of terrestrial origin. The region outside the plasmapause but inside the magnetopause is a highly dynamic region within which the plasmas are transported and energized to form the storm-time hot plasmas and radiation belts. The geopause position is probably highly variable but certainly lies between the plasmapause and the magnetopause, a domain referred to herein as the "geopause region." We illustrate the geopause schematically in Figure 2 with a shape and position that will be further discussed and justified in later sections.

Another useful analogy exists with the air-sea interface at the Earth's surface. The intermingling of moisture and atmospheric gases and the variable coupling of mechanical stresses across the air-sea boundary play critical roles in the development of atmospheric storms. Most of the damage associated with severe atmospheric storms results from energy dissipation in the boundary layer between the atmosphere and the liquid or solid surface of the Earth. The ocean is energized by atmospheric energy coupled across this boundary, and moisture evaporated from it into the atmosphere injects latent energy sources into the atmosphere. Analogous types of coupling, mediated by the geomagnetic field, are essential elements of the development of severe storms in geospace. As an example, regions of strong shear in the magnetospheric plasma flow, often associated with the supersonic solar wind boundary layer, generate vortices that appear over a wide range of scales. As another

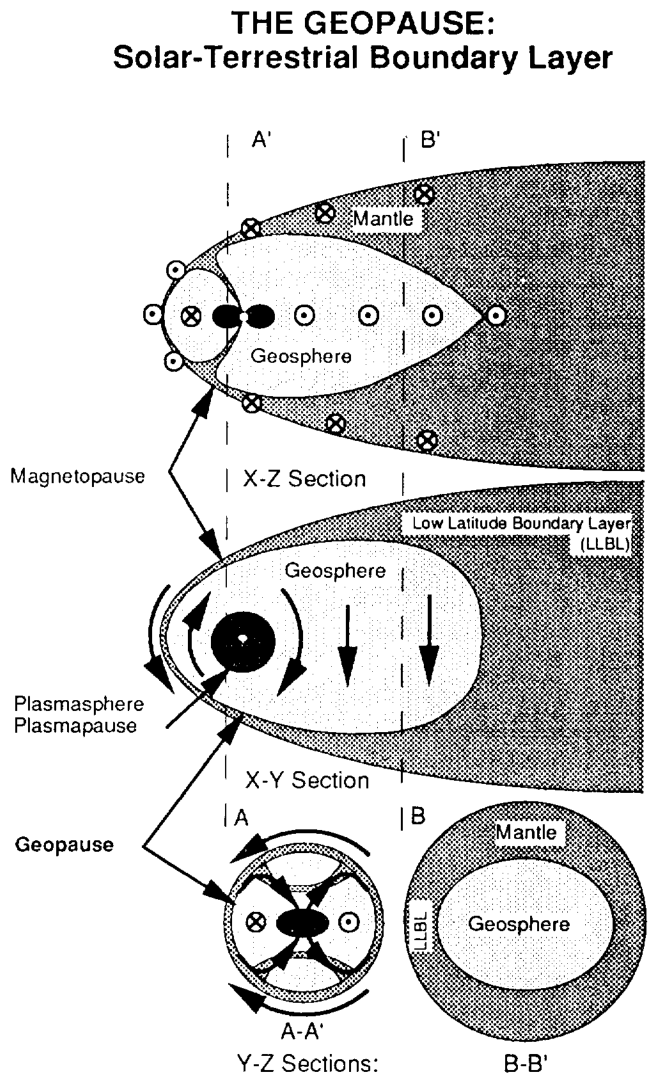

Figure 2. Schematic illustration of the geopause as the boundary between heliospheric and geospheric plasma dominance, showing its relationship to more familiar boundaries and current systems (adapted from *Moore* [1991]). The three panels correspond to views (top) X-Z, from the dusk side looking toward dawn; (center) X-Y, from over the pole looking down on the equatorial plane; and (bottom) Y-Z (two cross sections) from sunward of Earth looking radially away from the Sun. Darkness of shading is roughly indicative of plasma number density. Arrows indicate position and orientation of major current systems. Neither magnetic field nor plasma mean energy is indicated in this figure.

example, energy transported from the solar wind to the ionosphere across the boundary often leads to enhanced transport of heavy atmospheric species into the magnetosphere, where changes in mass density alter the wave propagation speeds and hence system dynamics. Like the air-sea boundary, the geopause is a boundary layer of crucial importance to the understanding of space storms and their effects.

The space storms referred to above are usually referred to as geomagnetic storms, probably because they were first detected through surface measurements of disturbances in the geomagnetic field. In the sections below, we adopt a plasma-based perspective of geospace and the energetic phenomena within it, summarizing the important sources of plasma, the global transport of plasma, the energization of plasma as it carries electric currents, and the dissipative losses of plasma and its acquired energy. We emphasize the overall balance of these processes that determines the distribution of plasma within the magnetosphere at any given time.

Auroras, geomagnetic field disturbances, and the radiation belts must ultimately be understood in terms of the behavior of the heliospheric and geospheric plasmas, under the influence of their supersonic relative motion, in the presence of their linked magnetic fields. Geomagnetic activity, as measured by ground magnetometer disturbance indices like AE (auroral latitudes), Kp (midlatitudes) and Dst (low latitudes), has long been known to be enhanced by the strong interconnection of solar and geomagnetic fields produced by a southward component of the interplanetary magnetic field (IMF). However, recent research on plasma composition has "rewritten the books," and we now know that the auroral and radiation belt plasmas are in large part of terrestrial origin, though the energy that activates the system is clearly of solar origin. Replacing the simple model of solar energetic particles penetrating the geomagnetic field, we have a much richer understanding that is magnetohydrodynamic in nature and involves the terrestrial plasma in a fundamental way. This review is an attempt to communicate this understanding to a general geophysics audience.

GLOSSARY

Cleft/Cusp: pair of regions of weak magnetic field marking the dayside boundary between the polar cap and low-latitude field lines.

Cigar-shaped: angular distribution of particle flux that is peaked along the magnetic field direction and its opposite.

Conic: angular distribution of particle flux that is peaked along an oblique cone centered on the magnetic field direction.

Dipolarization: a reduction in the degree of stretching of the magnetotail magnetic field, toward a more dipolar shape.

Footpoint: location where a magnetic field line passes through the ionosphere.

Geocorona: cold gaseous hydrogen cloud around the Earth.

GSM: geocentric solar magnetospheric coordinate system.

IMF: interplanetary magnetic field

Inverted "V": the latitude distribution of electron energy in an auroral arc, with a peak in the interior of the arc.

Lobes: regions of very low plasma density and/or energy located inside the plasma mantle and low-latitude boundary layer, bifurcated by the plasma sheet.

Low-latitude boundary layer: layer just inside the magnetopause.

Magnetic moment: the ratio of transverse (to $\mathbf{B}$) particle energy to the magnitude of $\mathbf{B}$. It is invariant for particle motion in slowly changing fields (the first adiabatic invariant).

Magnetopause: boundary between the interplanetary and geomagnetic fields.

Magnetosheath: shocked solar wind plasma flowing around the magnetopause.

Magnetotail: distended magnetic field region downstream of the Earth.

Mantle: equivalent to high-latitude boundary layer.

MLT: magnetic local time.

Neutral line: line along which the magnetic field magnitude falls to zero. Can be surrounded by "X-shaped" or "O-shaped" field lines.

Neutral sheet: surface on which the tangential component of the magnetic field falls to zero.

Pancake-shaped: angular distribution of particle flux that is strongly peaked perpendicular to the local magnetic field.

Plasma sheet: region of hot plasma surrounding the magnetotail neutral sheet.

Plasmasphere: toroidal shaped region of high-density, low-temperature, terrestrial plasma.

Plasmapause: outer boundary of the plasmasphere, often marked by a steep density drop with increasing radius.

Plasmoid: plasma parcel with self-contained magnetic field loops.

Ring current: Electrical current flowing around the Earth in the equatorial plane, due to presence of energetic plasmas.

Subsolar: region near the Earth-Sun line.

Storm (geomagnetic): development of a ring current strong enough to produce worldwide perturbation of the low-latitude surface magnetic field by ~0.3–1%.

Substorm: a single convulsive episode of plasma energization and transport from the tail toward the

Earth. Recurrence at a rate that exceeds losses implies a full-fledged space storm.

Superthermal: having speed higher than the thermal speed.

COMPOSITION

The discoveries of the Earth's energetic radiation belts and storm time plasmas, both of which occupy the inner, dipolar regions, played an important role in the development of thinking concerning the origins of energetic plasmas within the magnetosphere. The discovery that another very hot plasma, the plasma sheet, exists in the equatorial plane of the geomagnetic tail also contributed. The simple fact that particles gain energies of several keV to several MeV, which previously had been encountered in nature only as a result of atomic or nuclear forces, gave rise to wonder at the acceleration mechanisms that must operate to generate them. Minimizing the demands on such remarkable processes, it was tacitly assumed that the seed populations were provided by the more energetic solar wind ions rather than by the local ionosphere. These solar plasmas were assumed to find open field lines along which to cross the magnetopause in the boundary layers of the magnetosphere and in the cusp regions where solar plasma enters deeply into the magnetosphere along field lines facing into the solar wind at the boundary layers (known as the mantle at high latitudes and as the low-latitude boundary layer elsewhere). Early on in magnetospheric physics, ions came to be referred to as protons, and no strong motivation was recognized to design instruments capable of species identification during the first decade of study by space instrumentation.

If some terrestrial ions were to become part of the hot plasma in the magnetosphere, theoretical work of the 1960s suggested that they would be primarily protons with some He^+, since these were the only terrestrial species light enough to escape from Earth's gravitation at the temperatures then known to prevail in the ionosphere. Serious consideration of the possible ionospheric origin of the radiation belt and auroral precipitating ions was given by *Axford* [1970], in part based upon arguments concerning helium isotope accretion and loss rates. With H^+ as the primary component of both solar wind and expected ionospheric outflows, termed "polar wind" by Axford, helium charge state or isotopic composition appeared to be the best discriminator of solar and terrestrial sources, but these were difficult measurements at that time.

In what was without doubt regarded as a high-risk undertaking, efforts were made to develop mass-per-charge-discriminating energetic plasma instruments, bearing their first published fruit in the pioneering work of *Shelley et al.* [1972]. This study demonstrated that magnetospheric hot plasma contains a significant component of O^+, mainly in connection with strong geomagnetic activity. This result spawned numerous similar efforts that both confirmed the result and provided much more information concerning the nature and extent of ionospheric plasma participation in magnetospheric dynamics. Numerous papers hailed the new observations as evidence that the old assumptions had been wrong and that the ionosphere was a significant and perhaps dominant contributor to magnetospheric plasmas.

A controversy arose between those who defended the assumptions on which a large literature was based and the new challengers of those assumptions. One of the more careful efforts to assess the overall impact of the ionosphere on the hot plasma population within the magnetotail was that of *Hill* [1974]. He considered the overall particle content of the magnetotail and the rate of loss from it due primarily to precipitation into the atmosphere. He compared this loss rate with the total ion outflow then thought to result from the light ion polar wind, which had not been widely observed at that time. The conclusion to which this comparison led him was that the upper limit of known ionospheric outflows was barely sufficient to provide the lower limit on the number of plasma ions and electrons known to be needed, whereas the solar wind flux incident on the magnetopause exceeded the losses by 3 orders of magnitude. The natural conclusion was that the bulk of the hot plasma was most likely provided by entry of the magnetosheath plasma into the magnetosphere through the cusp, mantle, or low-latitude boundary layer. Even with the contemporary observations of *Shelley et al.* [1972], Hill did not think it necessary to consider the O^+ content of the hot plasma, at least for purposes of discussing average conditions, since the O^+ was not yet widely observed and appeared to be associated mainly with space storm periods.

During the 1970s a related controversy was raging in the magnetospheric physics community over whether auroral particle acceleration was effected by significant electric potential drops oriented parallel to the local magnetic field above auroral displays, i.e., parallel to the direction of magnetic-field-aligned currents. A crucial observation was that of field-aligned beams of ionospheric ions traveling upward with energies of hundreds of eV to several keV above auroral forms, where electrons could reasonably be assumed to be precipitating into the atmosphere with similar energies [*Shelley et al.*, 1976].

This observation was convincing and reproducible enough to lend credibility in many minds both to the hypothesis of parallel electric fields and to the idea that low-energy ionospheric plasma could contribute to the energetic plasmas of the magnetosphere. A mechanism had been found that could accelerate ionospheric ions to solar wind energies, and it was conveniently found at the footpoints of plasma sheet field lines, where it could feed such ions into the plasma sheet for further processing, circulation, or precipitation.

The question of the source of the plasma sheet ions has been pursued by *Sharp et al.* [1982] using the International Sun-Earth Explorer (ISEE, in eccentric orbit to 20-R_E apogee) Ion Composition Experiment data. They used a bookkeeping approach in which the composition of the solar wind and ionospheric sources were specified, and they derived the ratio in which those two sources must be mixed in order to reproduce the observed plasma composition in the geotail between 10 and 20 R_E. The He^{++} was assumed to be specific to the solar wind source and played a crucial role in the accounting, as did the O^+/H^+ ratio. For an ionospheric source composition fixed at 0.50 O^+, the result was an inference that the plasma sheet was strongly dominated by solar wind in quiet times and comparably supplied by both sources in active times. If the ionospheric source was assumed to be reduced in O^+ content during quiet times, as was suggested by *Moore* [1980], the result was comparable source contributions during quiet times, with ionospheric dominance in active times.

A similar data set that was obtained closer to the Earth, in geosynchronous orbit [*Young et al.*, 1982] extended over several years and permitted a study of solar cycle effects. This study clearly indicated increasing O^+ content with increasing solar activity. Another important result of this study was that the long-term average He^{++} (M/q (mass/charge) = 2) content was found to be only 0.8%. This represents a significant deficit relative to the average solar wind alpha abundance of 4%. This finding indicates that the ionosphere contributes 80% of the sampled plasma (100 eV to 16 keV), if all the He^{++} has its origin in the solar wind and if H^+ and He^{++} have equal access to geosynchronous orbit. However, charge exchange with geocoronal hydrogen can provide an internal loss of He^{++}, while auroral processes can provide an internal source, complicating this matter.

The concept of a geopause, separating solar- and ionospheric-dominated plasmas, was implicit in the work of *Sharp et al.* [1985], who used the method of *Sharp et al.* [1982] in a more extensive study of composition in the inner magnetosphere. They found that ionospheric dominance is characteristic of the inner plasma sheet, with the mean apparent composition evolving smoothly from solar-dominated to ionospheric-dominated with decreasing radius. The region dominated by the ionosphere increases in greatly in volume with geomagnetic activity, extending well beyond geosynchronous orbit during the active periods studied.

Observations of ionospheric outflows in the early 1980s greatly expanded our knowledge of this source of plasma for the magnetosphere. Superthermal fluxes were monitored over unprecedented durations by the Dynamics Explorer spacecraft (DE 1, in eccentric polar orbit to 4.5 R_E apogee; and DE 2, in nearly circular polar orbit to 1000-km altitude), leading to the statistical studies of ion outflow, which revealed, among other things, a strong increase of O^+ outflow with magnetic activity and with solar cycle, and a dominance of the total ion flux at the lowest energies sampled: 10–100 eV [*Yau et al.*, 1985] (see also *Ghielmetti et al.* [1987]).

Observations of low-energy ion outflows (down to spacecraft potential) from the retarding ion mass spectrometer (RIMS) instrument on DE 1 revealed a fundamentally new view of the topside ionosphere, including the predicted supersonic polar wind; upwelling ion flows from the cleft region; a "geomagnetic mass spectrometer" or "cleft ion fountain," resulting from velocity filtering of the antisunward flow over the polar cap; outflows of N^+ and molecules N_2^+, NO^+, and O_2^+; acceleration profiles of the polar wind at lower altitudes, "X" events in low-energy ions coincident with "inverted V" events in the auroral zone, toroidal ion velocity distributions in which the entire core of the distribution is transversely accelerated, and equatorial transverse heating in the outer plasmasphere. These features of ionospheric plasma transport have been reviewed by *Chappell* [1988], *Yau and Lockwood* [1988], and *Moore et al.* [1989].

On the basis of the increasingly evident importance of the ionosphere as a plasma source, *Chappell et al.* [1987] reassessed the adequacy of the ionospheric outflows to populate the magnetosphere with its observed plasmas. Citing observations of molecular ions accelerated to energies of hundreds of keV [*Klecker et al.*, 1986] as evidence that energy is no obstacle to the participation of ionospheric plasmas in the magnetosphere, they identified a number of uncertainties in previous assessments of ionospheric plasma content in the magnetosphere. First, they raised the issue of whether magnetospheric composition is being measured in a way which includes the low-energy core of the plasma distribution in a given volume of space, noting that many composition results in the literature are based on measurements above an energy threshold that varies widely, depending on the instrumentation involved. Second, they noted that, even when instrument thresholds are not a factor, there is considerable difficulty in observing the core plasma in regions of low plasma density due to positive spacecraft floating potentials in sunlight. Third, they noted that the largest uncertainties are associated with the identity of the protons of the magnetosphere, which can only be inferred by study of the relative abundance of other species.

The O^+/H^+ ratio, as used by *Sharp et al.* [1982, 1985], was questioned on the grounds that both theory and observation indicate a highly variable composition in ionospheric outflows [e.g., *Barakat et al.*, 1987; *Cannata and Gombosi*, 1989; *Yau et al.*, 1985] (see discussion below). Low-energy flows of ionospheric ions in the magnetosphere are significantly affected by velocity dispersion, which leads to wide spatial separations of different ion species, producing local compositions that are not representative. Finally, the source uniqueness of He^{++} was questioned in light of the observation of low-energy ions with $M/q = 2$ even in the relatively cold outer plasmasphere [*Young et al.*, 1977, 1982; *Comfort et al.*, 1988]. If He^{++} is not source specific, this could reduce the apparent solar wind plasma content in many studies.

Using flux and mean energy information on all of the known ionospheric outflow regions and simple convection concepts, *Chappell et al.* [1987] calculated estimated densities for various magnetospheric regions based on source flux, residence time, and volume. They found that in all cases the ionospheric source strength was adequate to account for the observed density levels, and that in the active plasma sheet, a surplus of density was produced. *Chappell et al.* [1987] concluded that the new ionospheric outflow observations lend renewed credibility to the hypothesis that magnetospheric plasmas are predominantly of ionospheric origin, as first proposed by *Axford* [1970]. They conceded that Active Magnetospheric Particle Tracer Explorers (AMPTE) observations of higher charge states of oxygen (*Kremser et al.* [1985] and, more recently, *Kremser et al.* [1987a, b]; see below) were clearly indicative of a solar wind source but noted the trivial contributions of such ions to the plasma.

The development of new types of ion composition instrumentation has made it possible to perform charge state analysis in addition to M/q analysis of energetic ions. Reporting on such measurements made aboard the AMPTE Charge Composition Explorer (CCE) spacecraft, *Kremser et al.* [1987a, b] showed that all charge states of oxygen up to +6 are found in the magnetosphere. Characteristic spatial distributions of these oxygen ions were interpreted in terms of a terrestrial source for the lower charge states, a solar wind origin for the higher charge states, and mixed contributions to the intermediate states, with considerable charge exchange evolution occurring in both directions to produce O^{3+}.

A broader overview of the AMPTE composition results has been provided by *Gloeckler and Hamilton* [1987]. Their main conclusions relevant to plasma origins (with observational bases in parentheses) are as follows: (1) There is little or no mass-dependent bias in the processes governing entry, transport, and acceleration of solar wind ions. (Magnetosheath and magnetospheric ratios are similar for ions clearly of solar origin, e.g., O^{5+}, O^{6+}.) (2) Ions of solar and ionospheric origin have much different acceleration and/or transport histories. (Ions clearly of solar origin have positive radial gradients of abundance during storm times, whereas ions clearly of ionospheric origin, e.g., O^+, tend toward negative radial gradient of abundance.) (3) The storm plasmas and near-Earth plasma sheet are substantially (40–80%) of ionospheric origin in the energy range 5–315 keV (from comparison of H^+ to CNO ions in the magnetosheath and in the magnetosphere).

Further studies of the GEOS 2 data set have been reported by *Stokholm et al.* [1989], which fill out the time period for study of solar cycle effects initially reported by *Young et al.* [1982]. It was found that the O^+ partial density in the 100 eV to 16 keV range varies by a factor of 14 over the solar cycle, that 27-day solar-driven periodicities appear in the composition data, and that solar cycle variations in H^+ density are statistically significant but small (30%) and in the opposite direction from the O^+ trend.

Storm time plasma observations have been reported from an instrument aboard the Viking spacecraft [*Stüdemann et al.*, 1987]. These observations demonstrated asymmetries of the storm plasmas that could not be simply accounted for in terms of charge exchange losses and suggested differential losses due to pitch angle scattering processes.

Extensive study of the ISEE Plasma Composition Experiment data set covering the range from 100 eV to 16 keV in the 10- to 20-R_E region of the plasma sheet has been undertaken by *Lennartsson* [1987], who noted marked mass dependencies in the behavior of ion densities and mean energies. The O^+ ions increase dramatically in density with increases of the auroral activity index *AE* (defined in terms of auroral zone ground magnetometer disturbances), while the mean energy of the O^+ is relatively unrelated to this parameter. In contrast, the H^+ and He^{++} ions tend to decrease slightly in density with auroral activity, while their mean energies rise dramatically. He^+ ions tend to be relatively unrelated to auroral activity in either density or mean energy. The interpretation given is that the H^+ and He^{++} are of solar wind origin and that the rate of capture from the solar wind seems therefore to be relatively independent of IMF orientation (known to be well correlated with *AE*), while the energization of these ions is strongly controlled by auroral activity.

Lennartsson [1988] further examined the question of plasma sheet H^+ and He^{++} density on IMF orientation, finding that both ions are in fact slightly more abundant for northward IMF conditions and that the plasma sheet (10–23 R_E) proton density tracks reasonably well the solar wind proton density. Arguing again for solar wind origin of these ions, Lennartsson reiterates the conclusion that solar wind ion entry must then be relatively independent of IMF orientation (and therefore of degree of interconnection with the geomagnetic field).

Training his attention on the solar activity influences on plasma sheet composition by density, *Lennartsson* [1989] found that O^+ and He^+ increased strongly with the $F10.7$ solar index, while decreasing slightly in energy. He^{++} is found to increase with solar activity as well, but in keeping with an increase in the solar wind He^{++} content. H^+ was found to be the generally dominant species in the plasma sheet. Both terrestrial and solar wind contributions to the H^+ were inferred, with the former dominating closer to the Earth and the latter dominating in the more distant plasma sheet. The presence of a terrestrial component was inferred solely on the basis of negative radial gradient in the H^+ density, the opposite of the trend for He^{++}. It should be noted that this behavior is highly consistent with the conclusions of *Sharp et al.* [1985] and with the inferences based on higher energy data of *Gloeckler and Hamilton* [1987].

Further evidence of ionospheric contribution to storm plasmas was found by *Hamilton et al.* [1988], who suggest that heavy ionospheric ions generally dominate the hot plasmas near the maximum of great space storms. *Kistler et al.* [1989] found that the storm time composition data can, at least in some cases, be well modeled using a simple convection field and charge exchange losses based on the observed distributions.

The low-energy plasma of the plasmasphere and plasmapause region has long been accepted to be of ionospheric origin. Recent results relating to the composition of the low-energy plasma in the magnetosphere include the observation of heavy ion enhancements in the outer plasmasphere region [*Roberts et al.*, 1987], a statistical study of the equatorially trapped warm ion populations [*Olsen et al.*, 1987], modeling of the minor ion populations [*Chandler et al.*, 1987], studies of the angular distributions of warm plasmapause populations [*Sagawa et al.*, 1987; *Giles et al.*, 1988], and surveys of the thermal ion composition in the plasmasphere [*Gallagher et al.*, 1988; *Newberry et al.*, 1989; *Farrugia et al.*, 1989]. *Comfort et al.* [1988] show that $M/q = 2$ ions are present in the ionospheric low-energy plasma at an abundance of approximately 0.2%. If such ions are He^{++} rather than D^+, this would imply a small source of ionospheric alpha particles that would, if so accounted for, marginally reduce the inferred solar wind contributions derived by Sharp, Lennartsson, and others.

The study of plasma composition in the magnetosphere over the past 20 years has rendered obsolete our space age textbook and encyclopedia accounts of the Earth's space environment. Auroras and energetic plasmas that damage spacecraft are not produced by incident solar particles, but rather by solar wind energy that has energized and accelerated our own outer atmosphere. This simple statement summarizes the situation well but fails to convey the complexity that has been introduced into space physics by this research. To understand and predict the storm behavior of our space environment, we will have to comprehend the intricacies of a global-scale electrical dynamo that converts mechanical energy into plasma heating and locally accelerated energetic particles. The sections that follow outline recent research on the sources, transport, energization, and losses that affect this system.

SOURCES

The principal plasma sources within the heliosphere and geosphere are the solar and terrestrial atmospheres, both of which are ionized largely by superthermal fluxes of radiation emitted by processes deeper within the Sun. Other sources of less significance in the Earth's vicinity include the atmospheres of other planets, notably Venus because it is upstream of Earth in the solar wind, outgassing from comets; the moon; debris from human activities in space; and the permeating interstellar gas. In addition, it has recently been suggested that the Sun may be a source of atoms at Earth [*Gruntman*, 1994; E. Hildner, private communication] as well as a source of plasma. Any gas can of course become ionized or alter the composition of the plasma by charge exchange.

None of the minor sources seem able to compete with the transport of plasma from the higher-density atmospheric regions. When a significant artificial source of plasma was deliberately introduced in the solar wind as part of the Active Magnetospheric Particle Tracer Experiment [*Krimigis et al.*, 1986], it was detectable only in close proximity to the release and could not be found inside the magnetosphere.

In the Earth's vicinity, then, the only significant "source" of plasma is therefore the Earth's atmosphere and ionosphere. Similar to the Sun, significant volumetric production rates are limited to an atmospheric layer that is thin in comparison with the scales of the heliosphere and geosphere. Thus we must regard geospace as being filled with plasma by transport from the two source regions, the solar and terrestrial atmospheres.

This section entitled "sources" will thus deal mainly with plasma transport in the regions where the plasma source is well defined, that is, in the solar wind and in the ionosphere. A subsequent section will deal with transport in the geopause region, that is, in the region where plasma is of mixed or ambiguous origin.

Solar Wind

The shocked solar wind, sometimes referred to as the magnetosheath, stagnates in the subsolar region of the magnetopause and then accelerates rapidly as it moves tangentially along the magnetopause. As it does so, it creates a boundary layer of decelerated solar plasma that is referred to simply as the low-latitude boundary layer along the equatorial flanks and as the mantle at high latitudes over the polar regions. In addition, it penetrates deeply into the cusp regions of each hemisphere, as is illustrated in Figure 2.

The entry of solar wind particles into the magnetosphere across the magnetopause was considered by *Lee and Akasofu* [1989]. On the basis of simple estimates of the amount of interconnected magnetic flux, they estimated that the rate at which solar wind plasma penetrates the magnetosphere varies between zero and 7×10^{28} ions s^{-1}, which exceeds the upper limits of ionospheric escape rate by 2 to 3 orders of magnitude for average conditions. However, the authors note that most of these particles pass through the mantle and exit the magnetosphere at the antisolar end without becoming trapped. This observation is generally in agreement with points made by *Axford* [1970] and *Hill* [1974], who noted that the solar wind flux incident on the magnetosphere is enormously large. On the other hand, *Lee and Akasofu* [1989] made no apparent effort to assess the fraction of particles entering through the magnetopause that would contribute to the inner magnetospheric plasma on closed field lines. They were content to note that the ionosphere is inadequate to compete with the solar wind flux in the outer magnetosphere, conceding that the ionosphere has the capability to be an important plasma source for $X_{GSM} \geq -30$ R_E (the Geocentric Solar Magnetospheric, or GSM, coordinate system has its X axis pointing toward the Sun from the Earth, so that $X_{GSM} = -30\ R_E$ is in the tail of the magnetosphere).

As was noted by *Axford* [1970], plasma that does enter on open field lines near the cusp penetrates to low altitudes along cusp or cleft field lines owing to its large magnetic-field-aligned ram pressure at its point of incidence upon the cusp. However, Axford found it difficult to see how solar plasma could find its way through the lobes to the inner magnetosphere from points downstream of the cusps, since it accelerates rapidly to a supersonic antisunward flow in the mantle and high-latitude boundary layer, and exceedingly few particles would have velocities such that they would return toward the Earth from such positions.

One case of "ion polar rain," that is, what would be expected if solar wind plasma were able to backstream from the mantle through the lobes to the polar cap, has been reported by *Newell and Meng* [1988]. They note that only one previous report of such a phenomenon has been made and that the flux for that event was only 10% of that in the event they reported. Unfortunately, they did not report on interplanetary conditions that might determine if this rare event was made possible by unusually low Mach number magnetosheath flow or an unusual magnetic topology. Thus while electron polar rain is a well-known and persistent phenomenon [*Baker et al.*, 1987; *Gussenhoven and Mullen*, 1989], ion polar rain is exceedingly rare and/or of very low flux, perhaps consistent with entry of only the "low energy tail" of the mantle flow. This general comparison of observation likelihood is consistent with the much higher thermal speed of the electron gas, particularly its superthermal component, which permits significant fluxes of electrons to find their way through the lobes to the polar cap ionosphere and no doubt into the near-Earth plasma sheet as well.

The same interconnection of solar and geomagnetic fields that enhances the transmission of momentum and energy into the magnetospheric plasma quite likely improves the admission of solar plasma into the polar cusps of the magnetosphere. Thus it seems quite likely that the solar contribution is at its largest in absolute terms during magnetically active times. Yet the plasma during such times is found to be ionospherically dominated, albeit by heavy ions, suggesting that the enhancement of ionospheric outflow and energization is a larger effect than the enhanced entry of solar plasma.

Solar wind protons that gain access to the subsolar low-latitude boundary layer have nonadiabatic interactions with the cusp magnetic and electric fields [*Delcourt et al.*, 1992]. That is, the rapid variation of the fields, as seen in the particle frame, cause the particles to gain or lose energy. Because adiabatic energy changes scale directly with the magnetic field magnitude, the proper measure of nonadiabatic energization is the ratio of particle transverse (to the magnetic field) energy to magnetic field magnitude, or magnetic moment. Particles can either lose magnetic moment and penetrate to ionospheric heights or gain magnetic moment and be mirrored at high altitude, depending on their gyro phase. The number of particles that penetrate to the cusp ionosphere, out of a random sample of gyro phases, is much larger when this effect is taken into account. This should have a marked impact on the absolute fluxes of ions reaching low altitudes in the cusp for a given solar wind flux.

The entry of solar wind-magnetosheath plasma into the cusp has modeled [*Onsager et al.*, 1993] using an approach somewhat similar to that of Delcourt et al. but in an adiabatic approximation. Excellent qualitative agreement and good quantitative agreement with observations were obtained. Comparison with the observations from *Newell et al.* [1991] shows that the cusp and mantle footprint is defined by the energy dispersion of the entering solar plasma. *Mukai et al.* [1991] have also reported initial results from the EXOS-D (Akebono) plasma experiment, on the entry of magnetosheath plasma into the cusp region.

The cusp protons that gain magnetic moment were found by *Delcourt et al.* [1992] to become trapped in the field minimum of the cusp entry region and are then carried more deeply into the lobes by convection. The deepest penetration limit is set by the last field line to have a field intensity minimum along its length. These authors plotted the shape of this boundary and referred to it as the "entry boundary," citing it as the location of the inner edge of the mantle. The entry boundary is perhaps most easily visualized in the noon-midnight meridian but is a magnetic-field-aligned surface, located inside the lobe magnetopause, with a shape that is dependent in detail on the high-latitude magnetic field distribution. Moreover, the entry boundary is energy dispersive, and particles can convect inside it to a degree that increases with decreasing particle energy. Thus the magnetosphere tends to select the slowest solar wind particles for internal consumption.

The entry of solar wind protons and alpha particles into the magnetosphere was considered by *Lennartsson* [1992]. He has proposed an entry route proceeding from the low-latitude boundary layer flanks, along the plasma sheet boundary layer, toward the tail center, and thence into the plasma sheet, bypassing to a large extent the cusp and lobe route. As will be shown below, empirical models of the plasma flow field in the magnetosphere provide quantitative support of this proposal.

Loss of solar particles that cross the magnetopause by escape down lobe field lines is an increasingly recurrent theme that seems to have culminated in the identification of the "entry boundary" concept of *Delcourt et al.* [1992]. Such a boundary is likely to be a good approximation to the geopause concept in the region poleward and antisunward of the magnetospheric cusps or clefts.

Ionosphere

A three-dimensional summary of ionospheric flows at DE 2 heights near and below 1000-km altitude was assembled by *Heelis et al.* [1992], adding to their previous modeling of ionospheric convection by documenting thoroughly a persistent pattern of vertical ionospheric flows. In the dayside region, where sunward flows turn into the polar cap region through the "throat" or cusp region, there appears an organized upflow. Within the polar cap, in contrast, there appears a persistent downflow region. Integration of the plasma fluxes over both regions indicates that the upflow exceeds the downflow by an amount smaller than either upflow or downflow, but significant and comparable to the total outflow flux to high altitudes.

The statistical properties of the polar ion outflows in the altitude range from 1000 to 4000 km have been surveyed by *Chandler et al.* [1991], with the finding that subsonic outflows are quite common in that altitude range despite theoretical expectations and numerous observed cases of supersonic flow. Chandler finds further that the outflow velocity of the H^+ polar wind, as observed by DE 1 below 4000-km altitude, is modulated by a factor in excess of 4 as the IMF varies from northward to southward, with the largest outflow velocities found during northward IMF. No aeronomical linkage with IMF is known. One possible interpretation of this observation, derived from simple concepts of pressure boundary conditions on polar wind flow, seems to be that enhanced solar plasma entry into the polar lobe region sets up a back pressure that causes the polar wind to shift toward lower-speed subsonic flows. This interpretation seems to be at odds, however, with some theoretical work on the role of superthermal electrons in polar wind acceleration [*Barakat and Schunk*, 1984]. On the other hand, more recent theoretical work [*Wilson et al.*, 1990; *Singh and Torr*, 1990] appears to confirm the simple argument that high finite plasma pressure in the polar caps or lobes will tend to suppress polar wind flow. If correct, such an interpretation argues for a positive activity dependence of H^+ content in the magnetosphere if solar wind is the dominant proton source, or a negative activity dependence of H^+ (as observed) if the polar wind is dominant.

The basic phenomenon of increasing O^+ in the ionospheric outflows (and in the magnetospheric hot plasma) as solar activity increases has been addressed by at least two theoretical papers that examine the ionospheric effects of well-known solar EUV-driven changes in the neutral atmosphere. Following the suggestion of *Moore* [1980, 1984], *Barakat et al.* [1987] used an isothermal, collisional, chemically reacting, subsonic description of the topside ionosphere below a 600- to 1500-km upper boundary, embedded in an empirical model of the neutral thermosphere. It was found that limiting fluxes existed for both O^+ and H^+ species but that the limits were interdependent. It was further found that the limiting flux of O^+ increased with solar EUV owing to the enhanced neutral temperature and resultant changes in density profiles. It was argued that the H^+ flow would approach its limiting value everywhere outside the plasmapause, while the O^+ flux would vary strongly with the amount of plasma heating present in the topside, from essentially zero to its limiting value. Thus the heating rate due to magnetospheric energy dissipation would exert primary control over the O^+ flux, but solar activity would set a firm and highly variable limit on the maximum flux that could be obtained and on the flux that would be obtained at a given level of heating or demand for plasma.

A more comprehensive ionospheric model that is time-dependent, provides for supersonic flow, and extends to 8000 km altitude has been brought to bear on this problem by *Cannata and Gombosi* [1989]. Driving their model with a specified downward electron heat flux of presumed magnetospheric origin, they found that O^+ flux varied by a full order of magnitude as the solar EUV flux was varied from solar minimum to solar maximum values. The H^+ flux showed almost no discernible variation over the same range of solar conditions. This behavior seems consistent with the *Barakat et al.* [1987] results when the imposition of a specified magnetospheric electron heat flux is regarded as the imposition of a fixed demand for ion outflow. Thus the observed variation of O^+ in the ion outflow (and lack of H^+ variation) with solar activity can apparently be fairly well understood, strictly in terms of ionospheric source variability. In addition, the strong dependence of O^+ outflow on the dissipation of energy in the topside ionosphere seems to have a strong basis in these models.

A quantitative assessment of total ion outflow from the upwelling ion region identified statistically by *Lockwood et al.* [1985] and analyzed quantitatively on a single case study basis by *Moore et al.* [1986] was reported by *Pollock et al.* [1990]. This region of ion outflow also shows up prominently in the statistical survey of *Yau et al.* [1985]. Individual event fluxes are typically dominated by O^+, and the O^+ fluxes observed range up to and beyond the limiting fluxes derived from steady state models. *Pollock et al.* [1990] cite an extreme case of 10^{10} O^+ cm^{-2} s^{-1}, adjusted to 1000-km altitude. By folding together the event distributions of ion velocity, density, and flux with the spatial occurrence distribution of upwelling events, *Pollock et al.* [1990] developed an integral assessment of the ion flux from this important outflow region for the period studied in 1981–1982. The result was that this localized region emits 2.6×10^{25} ions s^{-1}, equaling in O^+ the polar cap H^+ escape flux and the upper limit for total ionospheric escape flux estimated by *Hill* [1974].

Many other recent observational studies have focused on the low-altitude heating of and outflow from the ionosphere [*Peterson et al.*, 1988, 1989; *Lundin et al.*, 1987; *Jones et al.*, 1988; *André et al.*, 1987, 1988; *Collin et al.*, 1987, 1988; *Lockwood et al.*, 1987; *Tsunoda et al.*, 1989; *Wahlund and Opgenoorth*, 1989]. These studies highlight the importance of ionospheric dissipation mechanisms in controlling the heavy ion contribution of the ionosphere to the magnetosphere. Many such mechanisms have been proposed to account for the large escape fluxes of O^+ that are observed and for the unique angular distribution signature known as ion "conics" (peak ion flux in the direction $\leq 90°$ from the direction upward along the local magnetic field). Work continues in this area on heating by ion cyclotron resonance [*Crew et al.*, 1990; *Ball*, 1989; *Ashour-Abdalla et al.*, 1987, 1988; *Ganguli and Palmadesso*, 1988; *Satayanarayana et al.*, 1989; *Winglee et al.*, 1987, 1988, 1989]. Attention has been brought to the strong velocity shear observed in regions of auroral heating [*Basu and Coppi*, 1988, 1989]. A new mechanism that has been proposed for ion heating is based on the existence of sharp discontinuities in the otherwise steady convection electric field, which would "pump" the ion's transverse energies [*Lundin and Hultqvist*, 1989; *Newman*, 1990]. Further, there has been considerable effort to incorporate various dissipative mechanisms in transport models [*Ganguli and Palmadesso*, 1987; *Li et al.*, 1988; *Ganguli et al.*, 1988; *Chiu et al.*, 1988; *Chen and Ashour-Abdalla*, 1990; *Wilson et al.*, 1990]. All of these studies hold the promise of an eventual synthesis of heating mechanisms with transport consequences.

An extensive new survey of the ionospheric outflow regions [*Giles*, 1993; *Giles et al.*, 1994] shows that for both heavy and light species, the dayside upwelling source region expands in latitude and local time with increasing activity. Figure 1 of the present review is derived from this work and schematically summarizes many of the results found therein. Another new result from this work is the identification of significant outflows of $M/q = 2$ ions from the auroral zone. These ions will ordinarily have been interpreted as He^{++} ions of solar wind origin, so that an ionospheric source of them has important implications for the discrimination of solar and terrestrial plasmas.

Extensive study of another data set bearing on low-energy plasma flows has appeared more recently. *Abe et al.* [1993], *Horita et al.* [1993], *Miyake et al.* [1991], *Sagawa et al.* [1991], *Watanabe et al.* [1992], and *Yau et al.* [1993] have all reported on aspects of low-energy ionospheric outflows based on the suprathermal mass spectrometer on EXOS-D (Akebono). Among the important results from EXOS-D, and of special significance to the present topic, is the observation of a persistent cold O^+ polar wind component, similar to that reported from DE 1 for conditions of high geomagnetic activity and having outflow velocities that are higher than anticipated.

The effect of hot plasma interactions with the topside ionosphere was addressed by *Ho et al.* [1992]. They found that when plasma sheet electrons are present at high altitude and electron temperature is distributed according to a heat conduction solution, the polar wind is subdued and O^+ outflow is essentially cut off. A related issue was addressed observationally by *Horwitz et al.* [1992] with focus on the polar cap photoelectron environment.

In addition to the outflow of ionospheric plasma from the polar ionosphere, another important part of the ionosphere-magnetosphere boundary is the plasmapause region. The variability of magnetospheric convection is thought to cause outer portions of the plasmaspheric plasma (H^+-He^+ dominated) to be carried off toward the dayside magnetopause, where they will be entrained in the magnetopause boundary layer flows. Apart from observational work on the magnetopause (see discussion below), there appears to have been little work in the area of assessing the importance of this source of low-energy plasma to the magnetosphere during recent years, though detached plasma regions, as defined above, were of considerable interest in the early 1970s. This is unfortunate, since a large population of light ions can be released to the dayside region by each discrete increase in magnetospheric convection.

TRANSPORT

This section deals with the plasma transport that occurs in the geopause region and therefore involves the competition between the momentum of the solar wind and the inertia of the dense ionospheric plasma. The matter of solar wind penetration into the polar cap and lobes is central to an understanding of solar wind entry into the inner magnetosphere. *Dungey* [1961] noted that reconnection of the terrestrial and interplanetary magnetic fields would produce regions of interconnecting open magnetic field lines connected to the Earth at one end and joining the IMF at the other. In such a field geometry, flow stagnation regions both at the dayside and in the magnetotail are associated with magnetic neutral lines where the field reverses direction consistent with opposing converging and diverging flow layers. At the dayside, flowing solar wind meets sunward flowing geospheric plasma, forming flows of both plasmas tangent to the magnetopause, known as the mantle. In the center of the stretched magnetic tail, mantle flows from north and south hemispheres converge, producing downstream and sunward flows emanating from a neutral sheet stagnation region.

Dungey also noted that the interconnection of interplanetary and geomagnetic field lines would upset the equilibrium of the topside ionospheric plasma. Depending on the angle between the open field line as it crosses the magnetopause and the local magnetosheath flow direction (and flow speed), a contact boundary forms between a relatively homogeneous ionospheric plasma and a penetrating solar plasma whose effective pressure can vary from the full ram pressure of the solar wind to zero. It appears that the cusp itself may be thought of as the region of maximal scalar product between the magnetosheath dynamic pressure and the local magnetic field direction at the magnetopause. Clearly, this function will be strongly peaked at locations where magnetic field lines link through the magnetopause with a component nearly parallel or antiparallel to the Earth-Sun line, that is, extending into the solar wind ram direction as they pass outward, like pitot tubes leading all the way to the ionosphere.

A dynamic equilibrium arises on such open field lines, with a contact or mixing region between the solar and ionospheric plasmas. This surface drops to its lowest altitude, nearly into the ionosphere, at the cusp center and then rises steeply as the plasmas convect antisunward over the polar cap, ultimately forming the inside boundary of the plasma mantle, continuing to mark the solar-terrestrial plasma boundary as the plasma convects antisunward and into the wake region of stretched field that forms the geomagnetic tail. Pressure balance or acoustic propagation speeds define the shape of this boundary, while diffusion determines its sharpness. By the time the boundary convects to the neutral sheet region, there will likely have been considerable mixing of the solar and terrestrial plasmas. The relevant question for the present purpose is then, where does the geopause reach the neutral sheet in relation to the stagnation region between earthward return flow and downstream flow? The answer will determine whether significant amounts of heliospheric plasma are convected into the inner magnetosphere, or significant amounts of geospheric plasma escape downstream in the solar wind.

Similar considerations apply in the low-latitude boundary layer at the flanks of the magnetosphere [e.g., *Lotko et al.*, 1987], except that one rarely if ever observes a normal component of the magnetic field there, and all local plasma entry must occur via cross-field diffusion, a process thought to be slow compared with parallel flows. We know that a low-latitude boundary layer forms and thickens as it extends antisunward along the flanks of the magnetosphere. The shape of the geopause shown in Figure 2 is strictly schematic and reflects penetration of the low-latitude boundary layer to the tail center at the same downtail distance as for the high-latitude boundary layer or mantle. Any disparity between the low- and high-latitude boundary layer flows would lead to a different geospheric shape in the tail region. Clearly, the actual shape of the geopause will be greatly influenced by, and interact strongly with, the convective flow pattern established in this region.

Flow Field Models

Models of the geopause region flow field can be constructed from empirically based models of the geomagnetic and geoelectric fields (e.g., those of *Tsyganenko* [1987, 1989], hereinafter referred to as T87 and T89). While such models are open to question in detail, there can be little doubt that they represent our best knowledge of the large-scale behavior of magnetospheric plasmas and its general variations with geomagnetic activity. It is clear that "average" configurations of the fields can never be used for an event study, but they are of great use both in understanding the general three-dimensional character of the magnetosphere and in the mapping of persistent structures between the ionosphere and magnetosphere. Tabulation and publication of the statistical variability of the fields would complement the prior publication of their mean values in such a way as to defuse the criticism that such fields describe no actual state of the magnetosphere.

The Tsyganenko magnetic field models have emerged as the most frequently used among diverse empirical or quasi-physical models. They were compared with recent observations by *Fairfield* [1991]. While noting good overall agreement, Fairfield noted that the T87 field lines in the nightside near-tail (5–15 R_E) are not stretched as much as the field lines inferred from the AMPTE CCE data set. The deficiency of stretching in the near-tail of the T87 model has been corrected to some degree in the T89 model, as was shown by *Rostoker and Skone* [1993]. The more rapid decline of Bz in the T89 model indicates increased stretching. However, the situation in the magnetotail

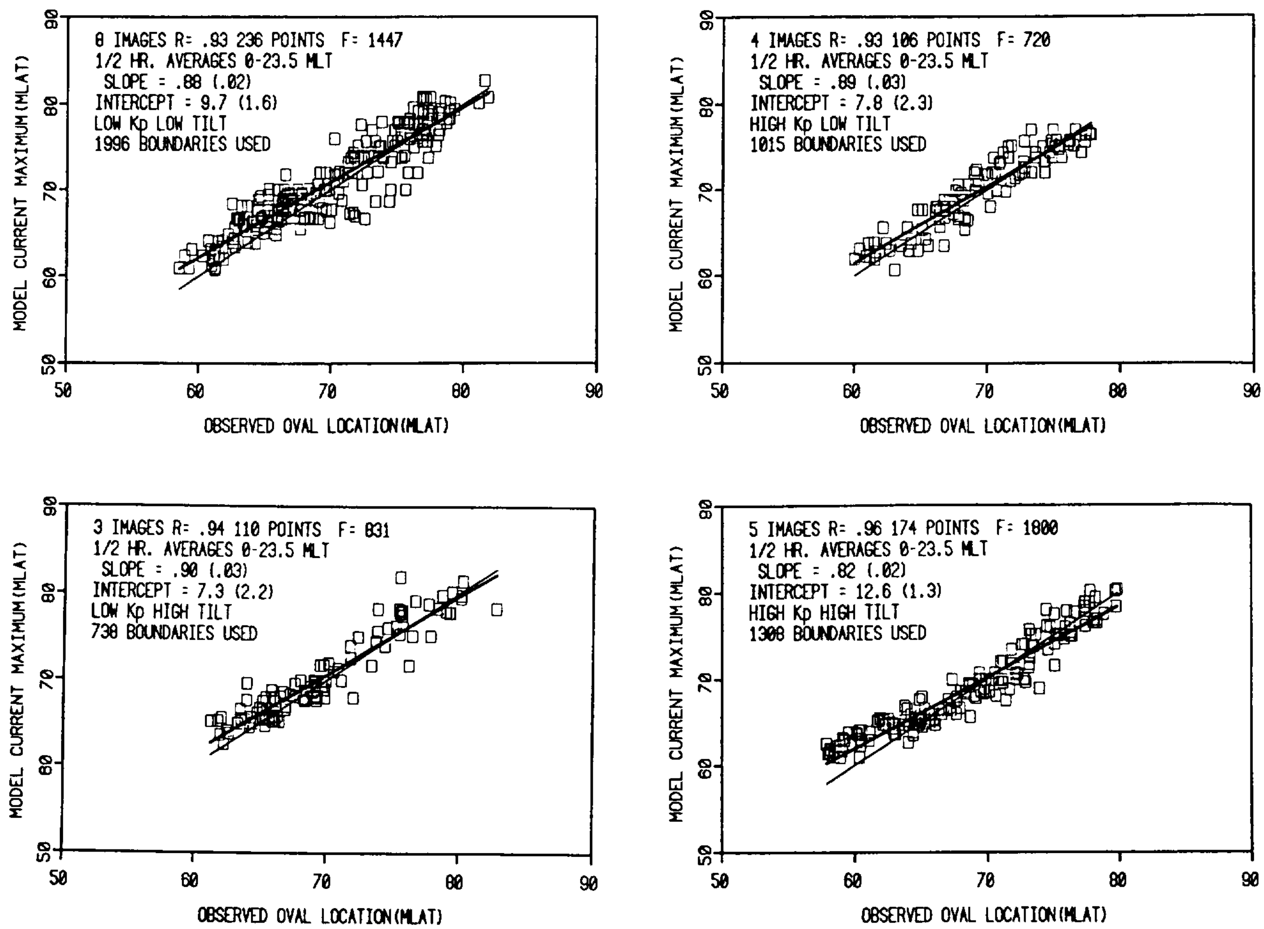

Figure 3. Correlation between the magnetic invariant latitude of the magnetic model current maximum and the oval position (Lyman-Biroge-Hopfield (LBH) bands, 130–180 nm, from the Viking imager) [from *Elphinstone et al.*, 1991, Figure 3]. Here the data have been binned by *Kp* and dipole tilt categories. *R* values in the range 0.93–0.96 should be compared with a value of 0.94 before binning and a value of 0.72 for the correlation between the model open-closed field boundary and the oval position.

is opposite to that in the near-tail, and the T87 and T89 models are both too stretched out in comparison with the ISEE data set. *Donovan et al.* [1992] pointed out that unrealistic regions of negative *Bz* occur in the T89 model under some conditions. Similarly, *Pulkkinen et al.* [1991] found it necessary to insert additional currents into the T89 model in order to successfully model the stretching of the tail field during the substorm growth phase. They noted that so stretched a field would render electron motions as well as ion motions, chaotic, a topic we will return to later. *Sergeev et al.* [1993] performed an interesting study in which they probed the near-Earth tail field using nonadiabatic particle dynamics and related particle precipitation. They also found that available magnetospheric field models seem to underestimate the amount of tailward stretching of field lines during active times.

The T87 model has been used to map the boundary of closed model field lines to the ionosphere [*Birn et al.*, 1991, 1992], leading to the derivation of "polar cap" shapes as a function of midlatitude magnetic activity (*Kp*). They suggest that the "horse collar" aurora (referring to a characteristic shape of the bright auroral oval) is related to this boundary, at low *Kp* and for northward interplanetary magnetic field. At higher activity levels the boundary becomes more circular in shape. *Elphinstone et al.* [1991], however, found from a similar study that the open-closed field boundary is poorly correlated with the aurora, compared with a better correlation between the brightest aurora and the field line that intercepts the maximum equatorial current density, as computed from the curl of the model magnetic field. As is illustrated in Figure 3, good correlation between the locations of these two phenomena exists when the data are partitioned according to *Kp* and dipole tilt, suggesting that these factors have independent but separable influences on the location of the aurora.

The identification between auroral emissivity and the peak in equatorial current density, rather than the "last closed field line," belies the traditional association of the brightest aurora with the low-latitude boundary layer and points toward the aurora as an "internal" aspect of the magnetosphere, related to the currents that stretch the tail and inflate the inner magnetosphere.

The distribution of plasma in the magnetosphere also provides significant clues as to the mean structure of the geoelectric and geomagnetic fields, through the implied transport. *Carpenter and Anderson* [1992] have synthesized an empirical model of the plasmasphere and plasmapause region from ISEE 1 and whistler data. They deliberately avoided the dusk region because of the high degree of variability seen there. D. L. Gallagher et al. (On the azimuthal variation of the equatorial plasmapause, submitted to *Journal of Geophysical Research*, 1994, hereinafter referred to as Gallagher et al., submitted) have synthesized a variety of observations into an empirical model of the plasmapause that directly confronts dusk region variability, has some surprising as well as familiar features, and evolves significantly as a function of Kp. A familiar bulge of the plasmasphere near local dusk is seen at moderate activity levels, strongly resembling the shape associated with the superposition of a uniform flow and a rigidly rotating flow. At low activity the bulge expands outward and rotates into the evening toward midnight. At higher activity the bulge shrinks and rotates into the afternoon. Presumably, this reflects a general rotation in the overall convection electric field, as it increases with higher activity. However, such a rotation has evidently not been previously reported.

On the basis of a study of DE 1 and whistler data on the dusk bulge region of the plasmasphere, *Carpenter et al.* [1992] have issued a warning that the plasmaspheric bulge is rarely, if ever, in its average state, showing diverse examples of its instantaneous states. This certainly is a valid caution in the use of any empirical model of mean conditions. *Singh and Horwitz* [1992], in a summary of their plasmaspheric refilling work, have shown local time distributions of the various types of structure seen in the outer plasmasphere. The most common distributions are the featureless (dawn) and multiple plateau (dusk) types, with significant density troughs seen fairly commonly in the nightside. A significant body of work has been reported by *Singh* [1991, 1992, 1993], in which equatorial heating of plasma or interactions with hot plasma produced by the magnetosphere promise to account for much of the variability that is seen in this region.

The T87 and T89 magnetic field models, in combination with the Heppner-Maynard ionospheric convection model [*Heppner and Maynard*, 1987] have been shown to imply a narrow, high-speed convection channel down the center of the magnetotail (T87) or a more uniform earthward convection (T89) [*Donovan and Rostoker*, 1991]. On plausibility grounds it was concluded that the T89 model was more a more credible description of the global magnetic field, given the Heppner-Maynard convection pattern.

A combination of T87 and a *Volland* [1978] ionospheric convection model, the latter having been modified to match the convection reversal with the cusp footprint in T87, was employed by *Delcourt et al.* [1992]. The result is somewhat similar to that of *Donovan and Rostoker* [1991], but the tail-center convection channel is less pronounced, and more distinct vortices are seen along with fast and distinct boundary layer flows. The differences evidently stem from the choice of Volland or Heppner-Maynard electric fields, respectively. The Tsyganenko-Volland representation of inner magnetospheric convection for $Kp = 2$ yields a stagnation region, usually associated with the dusk bulge of the plasmasphere, near ~2100 MLT, similar to that identified by Gallagher et al. (submitted).

Recently, statistical studies of field-aligned currents in the magnetosphere have been reported by *Tsyganenko* [1993] and *Tsyganenko et al.* [1993]. They have shown that the magnetic field shear associated with nightside region 1 currents is indeed observable and that the currents close remarkably close to the Earth and within the closed field part of the plasma sheet. As shown in Figure 4, this result corroborates the inference of large-scale vortices connecting the ionospheric convection cell reversals with the plasma sheet. We are learning from the empirical field models that the swept-back nature of the magnetic field is so pronounced that features we might have associated with the dawn and dusk flanks are in fact found within the magnetotail. These empirical models provide descriptions of plausible states of the magnetosphere. They are, however, unsuitable for specific event studies requiring a detailed instantaneous description.

Transport Effects on Source Entry

The three-dimensional flow field of the magnetosphere (e.g., T87 plus convection model, as shown in Figures 4 and 5) contains flows like that proposed by *Lennartsson* [1992], related to the vortices discussed above, that involve the flow of low-latitude boundary layer plasma from the equator, toward the polar lobes, then toward the center of the plasma sheet, then toward the equatorial plane, and then either toward the Earth or away from it, depending on distance downtail. However, it must be borne in mind that these are the transverse flows only [$(\mathbf{E} \times \mathbf{B})/B^2$] and that parallel motions are superposed upon these flows. Solar wind ions tend to be so energetic that they quickly mirror out of regions with a strong magnetic field gradient. Unless some means exists, such as that identified by *Delcourt et al.* [1992], whereby solar wind particles can be prevented from mirroring rapidly out of strong field regions, the majority of them appear to continue downstream in simulations based on field models.

The dispersion of ionospheric ion outflows within the lobes and as the flow is incident upon the plasma sheet has been studied by *Candidi et al.* [1988]. It does not appear that they were able to sense the presence of mantle plasma at locations earthward of $|X_{GSM}| < 23$

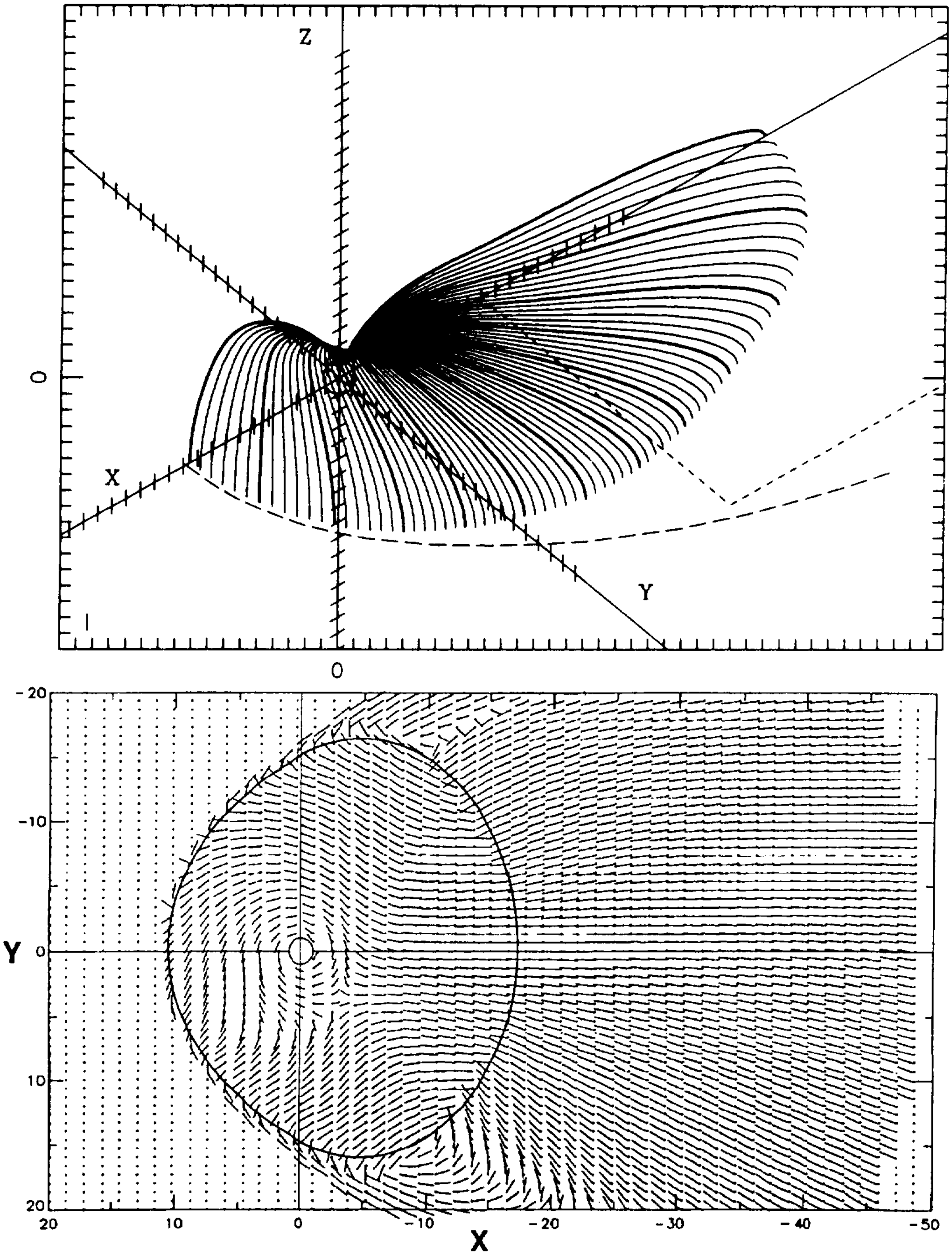

Figure 4. (top) Field lines traced from the average footpoints of region 1 current, using a modified *Tsyganenko* [1989] model ($Kp = 2$) [from *Tsyganenko et al.*, 1993, Figure 8]. Distinct region 1 current density peaks are found near $(x, |y|) = (-12, 10)$ R_E. (bottom) Equatorial convection flow field (logarithmic velocity vectors of the "wind sock" type) implied by the *Tsyganenko* [1987] (T87) ($Kp = 2$) magnetic field model and the modified Volland convection electric field used by *Delcourt et al.* [1992] in their three-dimensional particle trajectory calculations. Note shear/vortex features marked by the closed curve, which corresponds qualitatively with the region 1 current system of the top panel [*Tsyganenko*, 1993].

R_E, which suggests that the convective scale length of the diffusion process extends somewhat further into the tail than that region explored by ISEE.

According to *Moore and Delcourt* [1992], convection across the polar cap is typically so rapid that it substantially alters the balance of forces on the polar topside ionosphere, freeing even the cold O^+ from gravitational confinement and producing a cold O^+

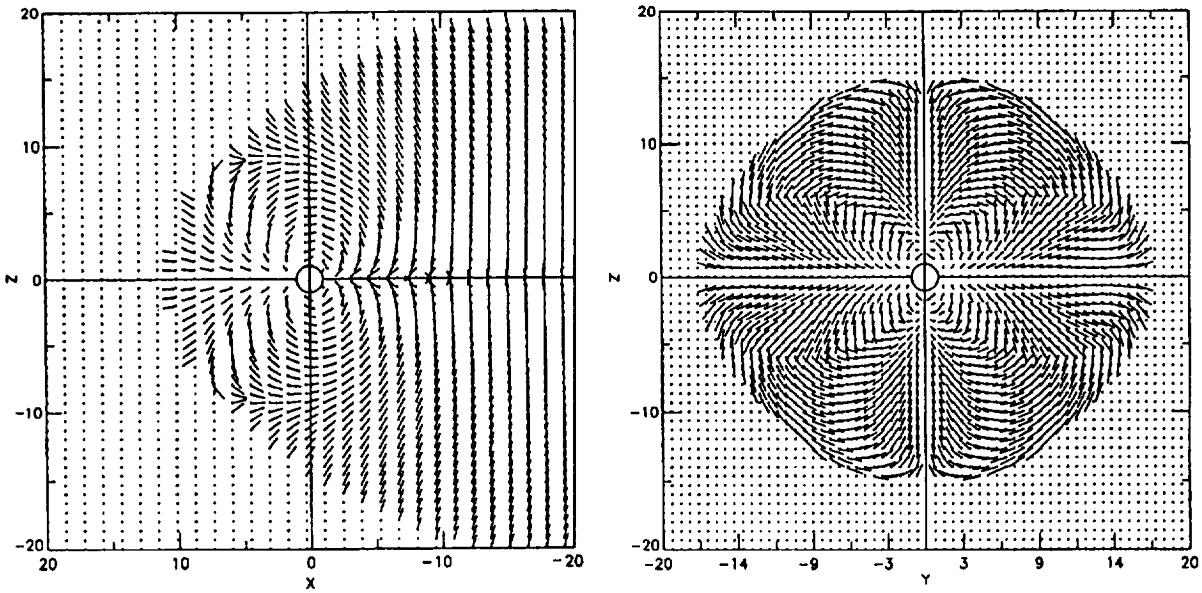

Figure 5. Similar to Figure 4, except that (left) a noon-midnight meridian flow field and (right) a dawn-dusk cross-sectional flow field are shown. These flow fields should be correlated with the equatorial flow field in Figure 4.

polar wind as an additional source of O^+ to the lobes and plasma sheet. A simple calculation was offered to test this hypothesis as it would operate above the geomagnetic pole. The magnitude of the escape speed varies with radius as

$$(v_e/v_{e0})^2 = (r/r_0)^{-1} \quad (1)$$

where v_e is escape speed and r is geocentric distance. Assuming that magnetic field lines are electric equipotentials, convection speed maps as a function of radius as

$$(v_c/v_{c0})^2 = (r/r_0)^3 \quad (2)$$

Equating the convection speed to the escape speed, it is found that the convection speed exceeds the escape speed above a "critical radius" which depends inversely on the strength of ionospheric convection:

$$r/r_0 = (v_{e0}/v_{c0})^{1/2} \quad (3)$$

With a surface escape speed of 7.9 km s^{-1} and a brisk ionospheric convection speed of 1 km s^{-1}, this yields a critical radius of only 2.8 R_E. This is the radius above which the net force associated with the gravitational and centrifugal effects on each particle is outward.

An approximation for this acceleration was included in a time-dependent, semikinetic model of polar plasma outflow, and the effects on the bulk parameter profiles and distribution functions of H^+ and O^+ were derived in recent work by *Horwitz et al.* [1994]. It was found that the steady state O^+ bulk velocities and parallel temperatures strongly increase and decrease, respectively, with convection strength. The bulk velocities increase from near 0 km s^{-1} at 4000-km altitude to ~10 km s^{-1} at 5-R_E geocentric distance for a 50 mV m^{-1} ionospheric convection electric field. The centrifugal effect on the steady O^+ density profiles depends on the exobase ion and electron temperatures T_i and T_e: for low base temperatures ($T_i = T_e = 3000$ K) the O^+ density at high altitudes increases greatly with convection, while for higher base temperatures ($T_i = 5000$ K, $T_e = 9000$ K), the high-altitude O^+ density decreases somewhat as convection is enhanced. The centrifugal force further has a pronounced effect on the escaping O^+ flux, especially for cool exobase conditions; as referenced to the 4000-km altitude, the steady state O^+ flux increases from 10^5 ions cm^{-2} s^{-1} when the ionospheric convection field $E_i = 0$ mV m^{-1} to ~10^7 ions cm^{-2} s^{-1} when $E_i = 100$ mV m^{-1}. This relationship is shown in Figure 6. The centrifugal effect also decreases the time scale for approach to steady state. For example, in the plasma expansion for $T_i = T_e = 3000$ K, the O^+ density at 7 R_E reaches only 10^{-7} of its final value ~1.5 hours after expansion onset for $E_i = 0$. For meridional convection driven by $E_i = 50$ mV m^{-1}, the density at the same time after initial injection is 30–50% of its asymptotic level. Centrifugal acceleration is a possible explanation for the large (up to ~10 km s^{-1} or more) O^+ outflow velocities observed in the middle altitude polar magnetosphere with the DE 1 and Akebono spacecraft. It is noteworthy that an effect found to be important in single particle trajectory calculations has led to a fundamental revision of semikinetic polar wind theory.

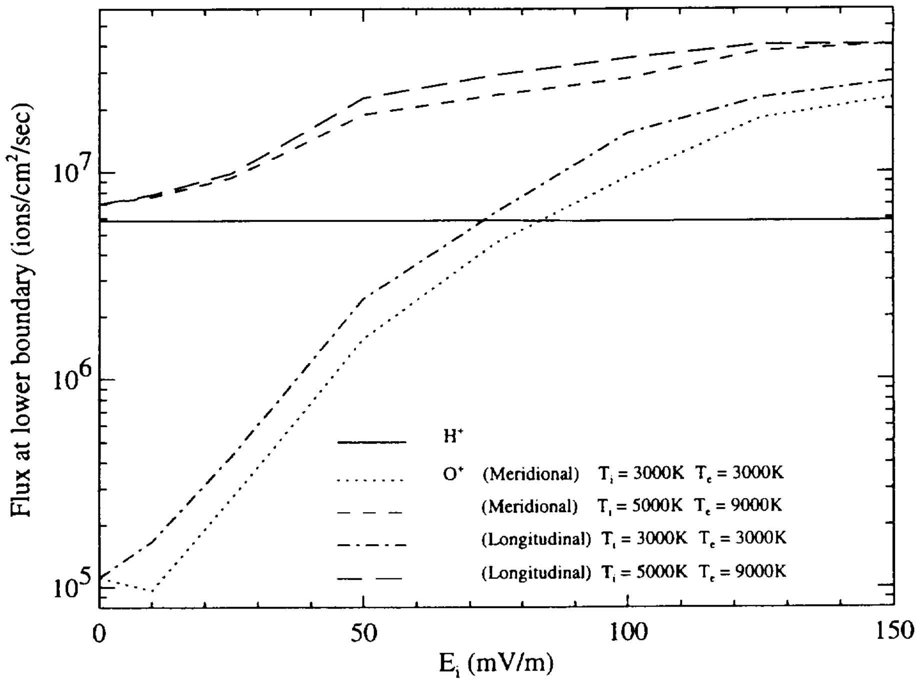

Figure 6. Centrifugal enhancement of O^+ outflow flux plotted as a function of the ionospheric electric field or convection rate, for purely meridional convection across the polar cap [from *Horwitz et al.*, 1994, Figure 7].

ENERGIZATION

A basic advantage enjoyed by the solar wind as a magnetospheric particle source is that its ions arrive at the magnetosphere with ≥ 1 keV energy, compared with the initial energy of ionospheric ions of a fraction of an eV. In this section we consider work that has explored the capacity for macroscopic magnetospheric processes to provide the accelerations required to form plasma sheet and storm time plasma populations from either solar or terrestrial source populations. These accelerations include both energization and the angular scattering required to form a hot thermal plasma sheet and storm plasmas.

Plasma Sheet Formation

The traditional view of the plasma sheet was that mantle plasma of solar origin is convected to the neutral sheet earthward of a magnetotail stagnation region, so that it is convected back toward Earth to form the plasma sheet. This view has been challenged by modeling results showing that the stagnation region must be distant (>100 R_E) for this to happen, at least for the bulk of the mantle velocity distribution. It has also been shown that the ionospheric outflows, including the cold polar wind, provide light ions to the plasma sheet and that neutral sheet acceleration is capable of generating a credible plasma sheet from such low-energy particle inputs. Suggestions have also been made and renewed (and challenged) that the heavy ion component of the plasma sheet may influence its stability and thereby the nature or degree of geomagnetic activity.

Delcourt and coworkers have independently pursued the computation of single-particle trajectories in model magnetospheric fields, with the goal of illuminating the behavior of specific ion populations, notably those emitted from the ionosphere. Considerable inspiration for this work was derived from the results of *Cladis* [1986] who showed that moderately vigorous magnetospheric convection is sufficient, in itself, to carry ionospheric O^+ from the cusp region through the polar cap and lobes to the plasma sheet, where the encounter with the neutral sheet produces field-aligned acceleration up to several keV (without recourse to the strong induced fields of *Mauk* [1986]). The emphasis of the Delcourt et al. work has been the development of fully three-dimensional descriptions of the magnetospheric fields and the resulting trajectories. Initial studies that exercised the numerical calculation (guiding center trajectories) were directed toward accounting for low-energy equatorial ion populations [*Delcourt et al.*, 1988a] and tracking the effects of convection flows associated with northward IMF [*Delcourt et al.*, 1988b].

More relevant to the present discussion, the larger problem of tracing the outflow of all known types of ionospheric outflow throughout the magnetosphere was tackled by *Delcourt et al.* [1989a, b]. In the process, a three-dimensional description was developed of the densities and mean energies that would be obtained if the ionosphere were the only source of

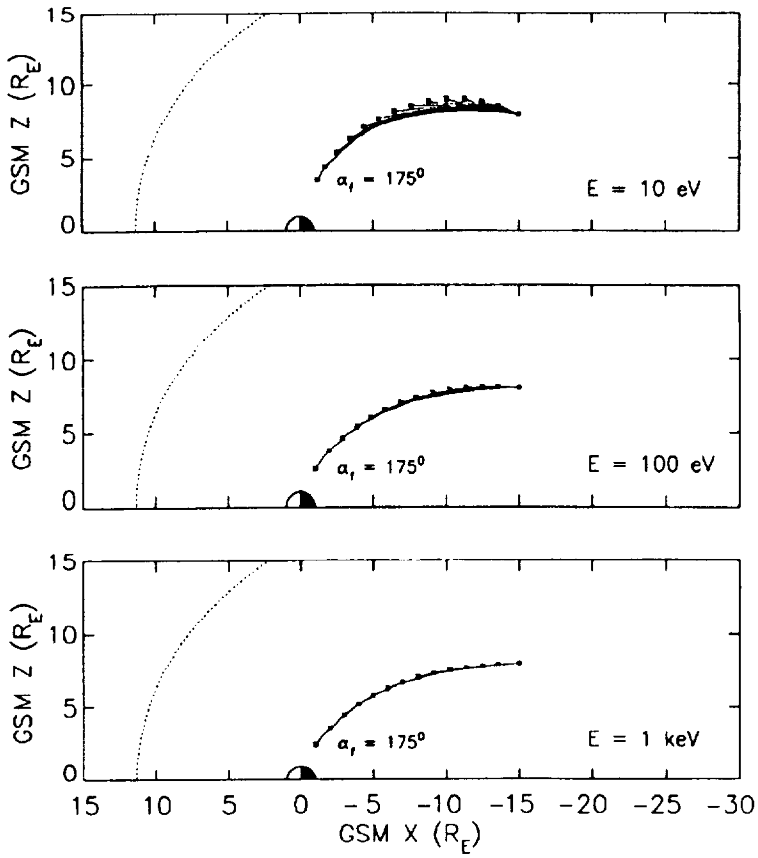

Figure 7. Backtracking of protons of varying energy and pitch angle from the injection point used by *Ashour-Abdalla et al.* [1991] to populate the plasma sheet with ions having a mean energy of 300 eV. T87 and modified Volland fields were used corresponding to $Kp = 2$.

plasma. Their conclusions begin with a realization that nearly all of the H^+ emitted by the ionosphere was lost from their system, which was admittedly artificial in that it did not extend beyond 17 R_E geocentric distance. This limits greatly the conclusions which can be drawn concerning ionospheric H^+ contribution to the plasma sheet and storm plasma, since such a contribution would evidently require that H^+ travel quite far downstream to return through the plasma sheet. However, the most important conclusion of this work was that the simulations reproduced the observed increasing keV O^+ content of the plasma sheet with increasing magnetic activity. Moreover, the results exhibited a clear plasma sheet boundary layer signature consisting of intense earthward-directed ion beams, which were almost entirely attributable to the heated cleft ion fountain outflow originating in the dayside auroral zone (distinct from the cold polar wind). Though the single-particle, adiabatic guiding center approach is incapable of thermalizing these boundary layer streams into a central plasma sheet, it seems clear that the gross features of O^+ transport are described by this uncomplicated model and associated assumptions and inputs.

Single-particle motions of outflowing ionospheric ions in mean fields were asserted to account for the general characteristics of the plasma sheet, for example, the earthward streaming boundary layers [*Moore et al.*, 1989]. This argument was weak in that the guiding center motions being considered could not account for the isotropy in the central plasma sheet, tending to produce streaming and counterstreaming instead. An unspecified form of pitch angle diffusion was needed to transform the boundary layer streams into the isotropic central plasma sheet.

It has been shown [*Ashour-Abdalla et al.*, 1991, 1993; *Peroomian and Ashour-Abdalla*, 1994] that the chaotic ion motions given by the full equations of motion lead naturally to a degree of energization and isotropy appropriate to the central plasma sheet, in addition to structuring of the boundary layer streams. A solar wind source (mantle plasma) was invoked in this work, and it was assumed to fill the lobes completely, providing solar wind plasma directly to the "first closed field lines" of the plasma sheet. This assumption was not defended by tracing particles backward to plausible magnetopause entry points, and it is in direct conflict with the entry boundary result of *Delcourt et al.* [1992]. Moreover, such backward tracing can be shown to lead to ionospheric source regions, as shown in Figure 7. Though these authors disagree fundamentally on the origin of the plasma incident on the plasma sheet, there is apparently agreement that any plasma delivered there will be processed into an isotropic plasma sheet with earthward streaming boundary layers, solely under the influence of the stretched magnetic field and convection (M. Ashour-Abdalla, private communication, 1993).

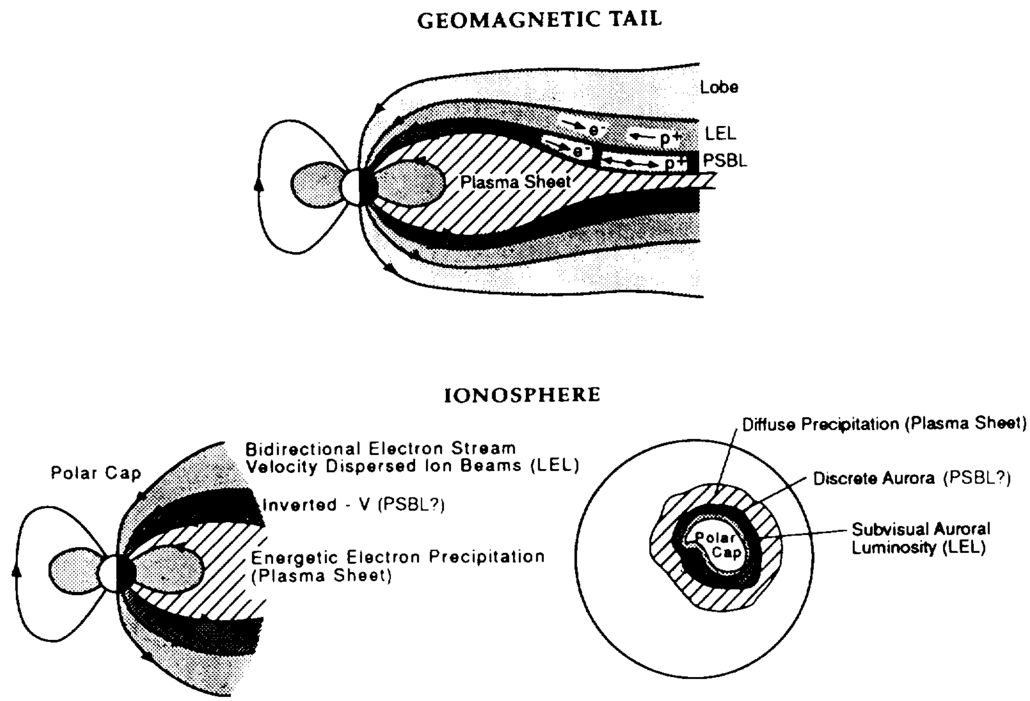

Figure 8. A schematic diagram that summarizes various features observed by the authors near the PSBL [from *Parks et al.*, Figure 13]. The proposed relations of the tail features to those in the ionosphere are indicated in the lower panels.

Single-particle trajectory studies also have pointed toward the development of velocity space structuring of boundary layer flows into multiple beamlets. These structures may be unstable to plasma waves. *Chen* [1992] has reviewed the work on nonlinear and chaotic charged particle behavior in the magnetotail and has also predicted detailed structures in particle distribution functions, citing the observations of *Huang et al.* [1989] in support of this prediction.

Previous work on ionospheric outflows has been extended by using the long T87 magnetic field to track trajectories as far as 70 R_E downtail [*Delcourt et al.*, 1993, 1994], for the first time accounting for the outflowing low-energy protons. Polar wind and dayside upwelling H^+ were found to provide the largest fluxes of ions to the plasma sheet in quiet times and moderately active times, respectively. With increasing convection speed, the faster superthermal ions begin to reach the highly stretched but closed parts of the neutral sheet, while the slower ions are recirculated in the inner magnetosphere without significant acceleration. Another aspect of this work is that the plasma sheet formed from low-energy protons is thinner than it would be for a higher-energy source population. This results from "centrifugal trapping" of the ions near the neutral sheet by the strong curvature of the $\mathbf{E} \times \mathbf{B}$ convection paths in that vicinity. There is the suggestion here that the nature of the source feeding the plasma sheet may influence its thickness during the substorm cycle.

The three-dimensional particle distribution functions in the plasma sheet boundary layer (PSBL), modeled by *Burkhart et al.* [1992], exhibit a "D" or "bean-shaped" distribution. This result is quite similar to that derived earlier by, among others, *Lyons and Speiser* [1982]. However, in the new work an instability is identified that prevents ion motions from carrying cross-tail current when a threshold is exceeded, leading to catastrophic loss of neutral sheet equilibrium. Three-dimensional plasma observations show just this sort of distribution in the plasma sheet boundary layer [*Nakamura et al.*, 1991, 1992]. An interesting sidelight of this work is that several reported cases showed an additional cold ion component of comparable density that had a bulk velocity dramatically different from that of the high-speed components.

Parks et al. [1992] have reported observations of another structure outside the plasma sheet boundary layer, which they refer to as the low-energy layer, or LEL, shown schematically in Figure 8. Since they found the low-energy ions to be earthward streaming in this layer, it may be suspected that they have not yet found the lowest-energy lobe ion streams, which must be streaming antisunward through the lobes. Such tailward low-energy streams have been recently observed outside the plasma sheet proper from Geotail by *Mukai et al.* [1994]. While there is unquestionably a low-energy layer outside the plasma sheet, backtracking of particle motions from this layer will not closely follow magnetic field lines because of strong convective motions that crucially influence the low-energy particles. The resulting velocity dispersive effects at moderate energies have been recently confirmed by the analyses of *Onsager et al.* [1991] and *Galperin and Feldstein* [1991] and the observations of *Saito et al.* [1992]. The lowest-energy particles will have originated from the ionosphere or the very lowest energy component of the mantle, according to *Delcourt et al.* [1992].

The earthward convection of plasma has been studied using ideal MHD arguments to compute the pressure profile and self-consistent magnetic field geometry [*Hau*, 1991]. The derived equilibria tend to contain broad minima in the magnetic field intensity in the near-tail, similar to the T89 empirical field model. The effect of angular anisotropy on ideal MHD neutral sheet equilibria has also been examined [*Hau*, 1993]. Allowing for anisotropy does not relieve the problem of excess plasma pressure that tends to arise from earthward convection. However, plasma initially becomes fire hose unstable ($P_{\parallel} > P_{\perp}$) and then only evolves to a "pancake" distribution inside 10 R_E.

An assumed ionospheric source of O^+ ions was simulated using a single particle tracking code with full equations of motion [*Cladis and Francis*, 1989, 1992]. The plasma pressure in the inner plasma sheet was found to build up to values greater than the magnetic field energy density, a condition that was hypothesized to trigger the substorm instability. Theoretical arguments have also been advanced [*Swift*, 1992] for heavy ion destabilization of the plasma sheet. However, in counterpoint to these theoretical studies suggesting a heavy ion effect on plasma sheet stability, observational studies based on a study of ISEE 1 data suggest that the dynamism of the magnetotail seems to be uncorrelated with the amount of O^+ that it contains [*Lennartsson et al.*, 1993].

Ring Current Injection

A space storm is defined by the growth of substantially enhanced storm plasmas and associated ring current over a period of a few hours, followed by a recovery period during which the ring current decays over a few days. Given a plasma sheet consisting of hot isotropic plasma convecting slowly (subsonically) toward Earth, like that produced by the steady state single particle simulations, it appears that a cross-tail current system forms self-consistently through the quasi-adiabatic heating of that plasma, forming an earthward pressure gradient [*Spence et al.*, 1987, 1989]. To date, single-particle simulations have not taken the step of computing the perturbed magnetic field from the particle distribution and resultant current to achieve fully three-dimensional computational self-consistency, but there is optimism that the result will be favorable when the computational resources required can be brought to bear.

Spectacular images of the substorm expansion phase aurora have been obtained from spaceborne imagers by *Nakamura et al.* [1993]. They interpreted the auroral imagery in terms of an earthward convection channel and two vortices in the near-tail. This interpretation is highly reminiscent of the (steady state) picture of nightside plasma flow afforded by the combined magnetic and electric field empirical models, suggesting that highly dynamic periods represent a transient intensification of the steady state circulation.

It appears possible that a realistic ring current can be developed from such a plasma sheet simply by sufficiently increasing the rate of convection. The natural adiabatic compression of the plasma sheet as it is convected into the inner geosphere by enhanced convection is sufficient to produce a plausible ring current. To the extent that there are purely "driven" space storms, such a model may indeed be a reasonably comprehensive description of them. On the other hand, a large body of evidence and thought indicates that purely "driven" storms may be unusual and that the more general case involves significant storage and rapid release of energy in the form of potential energy of the geotail magnetic field. These individual cycles of storage and relief are known as substorms, with the implication that a full storm comprises multiple substorms. This situation is somewhat reminiscent of the atmospheric storm analogy mentioned earlier. In general, severe atmospheric storms (with electrical and tornadic activity) involve significant storage and release of energy in the form of latent heat of evaporation over storm cell development timescales and in the form of electrostatic storage and release on shorter timescales.

An extensive recent review of substorm research has been provided by *Fairfield* [1992]. It provides a helpful guide to the concepts and terminology discussed below, drawing a clear distinction between "driven" and "unloading" aspects of substorms. The "driven" aspect relates to changes in the relatively steady solar wind driving of the magnetosphere. Globally, substorms develop over timescales of the order of a few tens of minutes, though longer active periods are certainly common. The "unloading" aspect relates to abrupt changes of magnetic field that, when observed at a specific location in the magnetotail, typically include a abrupt phase, lasting on the order of 1 or 2 min. This distinction is used as a basis for organizing the work discussed below. *Lui* [1991] also sought to synthesize the various concepts of magnetospheric substorms into a unified description. Following *Lui et al.* [1991, 1992], emphasis has been placed upon the nature of the instability that grows into the magnetic field reconfiguration during dipolarization.

Some workers [e.g., *Mauk and Meng*, 1983] might go as far as to assert that plasma circulation in the inner geosphere is negligible except on those occasions when impulsive energy releases ("dipolarizations," or relaxations of the stretched magnetic field, also known as substorms) drive flows into that region. This view is probably too extreme, since considerable direct and indirect evidence exists of low-speed flows and electric fields in the plasmapause region [e.g., *Angelopoulos et al.*, 1993]. It is clear that both driven and "unloading" phenomena are important in the occurrence of severe space storms. It is likely that the unloading aspect of the system becomes active when the rate at which the system is driven exceeds the rate at which energy can be continuously dissipated, leading to buildup of excess energy. Thus the harder the system is driven, the more it unloads, in close analogy with the electrostatic activity of thunderstorm convection cells.

Fast dipolarization events imply large rates of change of the magnetic field and therefore significant induced electric fields. Inductive acceleration of ions in the plasma sheet was treated by *Mauk* [1986] and, with the addition of macroscopic magnetic field-aligned electric fields, by *Mauk* [1989]. The findings of the latter study amplify those of the former, that dipolarization events occurring in the near-Earth plasma sheet lead to an induced electric field and curvature drifts that result in dramatic field-parallel accelerations of preexisting ion populations. With guidance from high-altitude electric field observations, representative results include the acceleration of proton populations with characteristic energies of tens of eV to form bidirectional streaming populations with characteristic energies of up to several keV.

In an elaboration of the basic three-dimensional single particle description of the magnetosphere, *Delcourt et al.* [1990a, b] have examined the effects of including substorm magnetic field dynamics in their model, building on the work of *Mauk* [1986, 1989]. In order to maintain a complete three-dimensional field structure in which to run trajectories, the Mead-Fairfield empirical magnetic field model [*Mead and Fairfield*, 1978] was evolved by interpolation between active (stretched) and quiet (closer to dipolar) states. To control the rate of collapse and therefore the strength of the induced motions and associated electric fields, high-altitude electric field observations of *Aggson et al.* [1983] were used as a guide. To create a population of ions that would be tracked through the dynamic fields, cleft ion fountain O^+ ions were launched so as to be distributed along their steady state trajectories when the field collapse was initiated. In the course of this work, it was noted that the conditions for validity of the guiding center approach were violated in some regions, not only because of field curvature and finite gyroradius effects, but principally because of magnetic field changes on gyroperiod timescales, which also lead to nonadiabatic behavior, even for equatorially trapped particles that are unaffected by local field curvature. Therefore a switch to integration of the full equations of motion became necessary, reducing the rate at which trajectories could be computed.

The results of this study include energization of ions to hundreds of keV, which is, of course, what is needed to create plasmas that carry significant ring current. Also, the acceleration turned out to produce in this case a wide range of pitch angles, so that the "thermalization" required to create a plausible central plasma sheet or storm plasma may be an intrinsic result of a single-particle approach. Moreover, the results exhibit an earthward and duskward moving front or boundary between accelerated ions and others that are relatively unaffected by the dynamic fields. This appears to correspond well with commonly observed features of substorm injections in the evening magnetosphere. The rate and direction of motion of the front needs further study with larger numbers of particles, but it appears to be radial at the rate at which field lines are displaced earthward during the dipolarization, plus westward at a speed corresponding to the gradient drift of the ions. This study builds significantly on the earlier work of Mauk and Cladis and clearly indicates that commonplace events in the magnetotail are capable of forming plasma sheet and storm plasma populations using only the ionospheric particle source.

A similar approach was applied to initial particle populations reflecting the cold polar wind H^+ and heated upwelling O^+ outflows [*Delcourt et al.*, 1991; *Delcourt and Moore*, 1992]. H^+ is adiabatically accelerated during dipolarizations in the inner plasma sheet, whereas O^+ responds in a highly nonadiabatic manner in that region, leading to large energy gains. Nonadiabatic H^+ behavior was suggested but not demonstrated to occur in the more distant plasma sheet.

A new global three-dimensional MHD simulation [*Usadi et al.*, 1993] nicely illustrates the general features of substorms as macroscopic disconnections of the plasma sheet, produced by transient reconnection in the mid–plasma sheet. *Hesse and Birn* [1991] and *Birn and Hesse* [1991] showed results from two-dimensional MHD simulations in which they paid particular attention to the dipolarization of the inner magnetosphere. For a scenario driven by enhanced reconnection at a neutral line, they showed that the dipolarization is evident first closer to the Earth and then progressively farther tailward, owing to the pileup of convected flux near the Earth. It is important to note that in these simulations the timescale for the dipolarization at a given location is comparable to the total time for the dipolarization to propagate through this simulation. *Steinolfson and Winglee* [1993] and *Winglee and Steinolfson* [1993] performed complementary MHD and particle simulations, also finding plasmoid formation but emphasizing solar wind pressure increases as a perturbative influence in producing the plasmoid. Interestingly, these authors stressed the agreement between the two techniques, rather than their complementarity.

Additional evidence for tailward expansion of the current sheet disruption in the near-Earth magnetotail was provided by *Lopez et al.* [1993], who correlated it with the poleward expansion of aurora observed simultaneously. *Kistler et al.* [1993] showed field line crossing distances inferred from the AMPTE CCE magnetometer data. The data support these simulation results in the region beyond 17 R_E. The inner field lines start earthward somewhat ahead of the tailward lines during a "dipolarization" event. Again in these observations, dipolarization at a given location occurs over a timescale comparable with the substorm timescale for this region.

The convection electric field (a direct measure of convection velocity), as measured by the potential drop across the polar cap, changes on relatively slow timescales commensurate with the total duration of substorms [*Weimer et al.*, 1992]. *Baumjohann et al.* [1991] showed an interesting superposed epoch analysis of AMPTE Ion Release Module (IRM) data that clearly delineates, on coarse timescales, the earthward flow and heating of the plasma sheet that is associated with substorm onset.

Further observational support has been found for the view that dipolarization events progress tailward [*Jacquey et al.*, 1991, 1993]. However, at geosynchronous orbit the evidence was for a front propagating earthward and eastward at 20–160 km s^{-1}, in agreement with an earlier study based upon observations from a cluster of spacecraft [*Moore et al.*, 1981]. *Kan* [1991] took issue with the causality of substorm theory and simulation results, suggesting that the dipolarization collapse is a consequence of field-aligned current system changes. However, he also suggested an earthward propagating injection front in the inner plasma sheet.

New attention has been given to the dipolarization phenomenology in substorms by *Angelopoulos et al.* [1992]. As Quinn, Mauk and coworkers have previously (referring to them as "convection surges"), they noted that intense flow bursts (hundreds of kilometers per second) occur with timescales of a few minutes in association with dipolarization events. The timescale relevant to these events is much shorter than the overall substorm duration.

A new perspective on substorm dipolarization events was provided by the RIMS instrument on DE 1 [*Liu et al.*, 1994]. Large impulsive plasma flows are seen even at low altitudes of ~3 R_E. At these altitudes the observed flows are poleward across the magnetic field and outward along the field at some 50 km s^{-1} in each direction, implying field line displacement of a fraction of an Earth radius during the events. The poleward motion at midlatitudes has previously been seen in the electric field by *Aggson and Heppner* [1977]. Interestingly, this bulging of the field lines at midlatitude is a feature of the T89 magnetic field relaxation from high to low activity but is not seen in the T87 field. Figure 9 shows the interpretation of these results in terms of the shape change of the magnetic field lines.

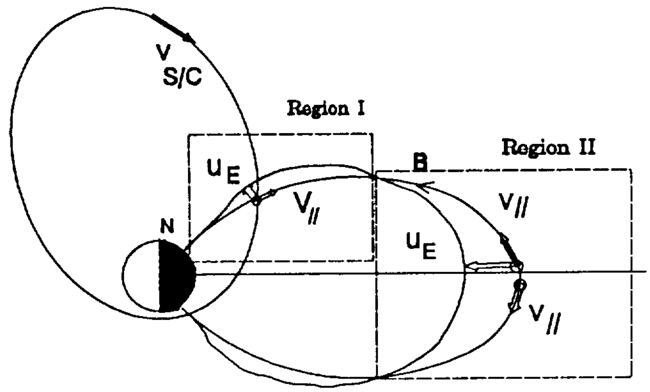

Figure 9. Schematic illustration of the field shape change and associated plasma flow associated with a substorm dipolarization event, as seen from the DE 1 spacecraft [after *Liu et al.*, 1994, Figure 4]. The motion of the spacecraft is indicated by V_{sc}, while the observed plasma flow is indicated by $V_{\parallel}$ and u_E. Both the initial and final shapes of the inferred field lines are shown to illustrate simultaneous inward motion near the equator with outward motion at higher latitudes.

Impulsive plasma flows are uncorrelated with tail lobe energy density changes, according to *Huang et al.* [1992], who found little evidence for unloading of energy during the substorm, at least from the reservoir of open flux in the lobes. This suggests that energy can be released in the tail by flux transfer from the lobes without abrupt reconnection of open flux, by changes in the configuration of the closed flux. Alternatively, it may be that the lobes adjust to flux gain or loss primarily by changing their volume, with little or no field pressure change.

A potentially crucial aspect of the plasma energization during substorms is shown in Figure 10 [*Kistler et al.*, 1992]. The total (field plus plasma) pressure increases in the inner magnetosphere while decreasing further out in the tail. This suggests that there are compressive phenomena where there is net pressure increase and rarefactive phenomena where there is a decrease. The boundary between opposite responses is near 10 R_E. The implication is that this represents the boundary across which both magnetic flux and plasma are transported during a substorm, filling the inner region at the expense of the outer region.

An important hybrid simulation has been reported [*Rogers and Christiansen*, 1992], in which fields are self-consistent but ions are handled as single particles. Simulating only a small volume in the inner neutral sheet, realistic solutions were found that generate earthward propagating "Alfvénic noise." When the simulation is subject to increased convection, it first stretches the taillike magnetic field, then develops a dipolarization transient that is much like that observed. Results of this simulation are reproduced in Figure 11. As observed, the transient has a short timescale compared with overall event timescales when viewed at a specific location. It propagates

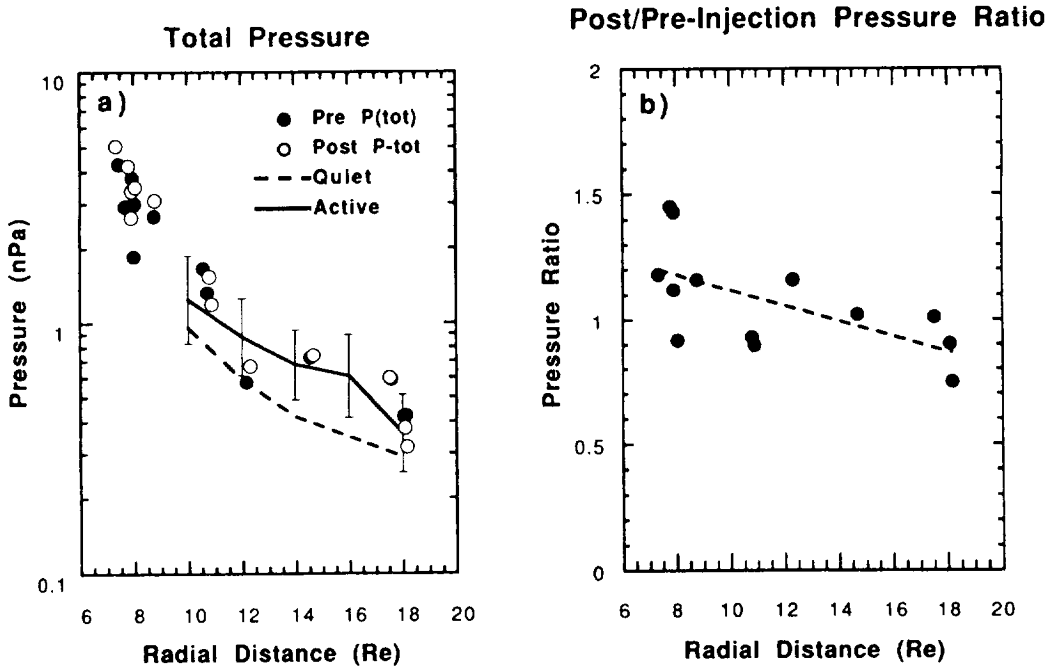

Figure 10. (a) Preinjection (solid circles) and postinjection (open circles) total pressure as a function of radial distance. Also shown is the average total pressure for quiet times ($AE \leq 100$) and disturbed times ($AE \geq 200$), using the AMPTE IRM tail survey data set. The error bars, shown for the disturbed data only, indicate the standard deviation of the data. The standard deviations are similar for the quiet data. (b) Ratio of the postinjection to preinjection total pressure for each of the substorm injection events, again as a function of radial distance. After *Kistler et al.* [1992, Figure 7].

earthward over the longer timescale. This simulation may relate to the specific inner magnetospheric phenomenology that is at odds with the MHD behavior of the plasma sheet. Occurring within the limited simulation region in a region of closed magnetic field lines, it may be closely related to the cross-tail current instability of *Lui et al.* [1991, 1992].

Recent successes in understanding the origins of energetic substorm ions are certainly very encouraging. However, there remains much to do to achieve a capability to predict full storms or individual substorms. Moreover, there is an outstanding mystery as to the mechanism through which electrons are accelerated in the tail and in the inner magnetosphere. Some possibilities, which need further investigation, have been suggested:

1. The stretching of the tail is so severe that (as was suggested by *Pulkkinen et al.* [1991] and *Lyons* [1984]) nonadiabatic electron behavior occurs, with resultant enhanced energy gains. Recently, *Schriver et al.* [1994] performed single particle trajectory studies that lend additional credence to this prospect.

2. Auroral electron acceleration at low altitudes could be contributing significantly to the keV electrons of the plasma sheet if, as seems likely, they are not entirely lost in the atmosphere but "leak" out of the edges of auroral arcs, especially as the arcs move.

3. The earthward propagating injection fronts may have a "heating" effect on the electrons through which they propagate. Evidence exists that this is true at least in the high-energy tail of the electron distribution. Parallel electric fields can also be generated as part of the dipolarization process [*Mauk*, 1989] and may be capable of producing accelerated electrons in the equatorial plasma.

LOSSES

Losses of both mass and energy strongly influence the evolution of energetic plasmas and consequently that of space storms as well. They limit the severity of storms and control the decay of storm time plasmas when activity subsides. Mass loss processes affecting the geopause region include convective or diffusive transport through the magnetopause boundary layer into the downstream solar wind and plasmoid ejection from the magnetotail. Energy loss and dissipation processes that affect this region include charge exchange conversion of fast ions into escaping or precipitating fast neutrals (leaving behind cold ions) and thermalization (including precipitation) of superthermal plasma populations such as the plasma sheet and storm plasmas.

Boundary Layer

An interesting complement to the inward boundary layer diffusion of solar wind plasma lies in recent

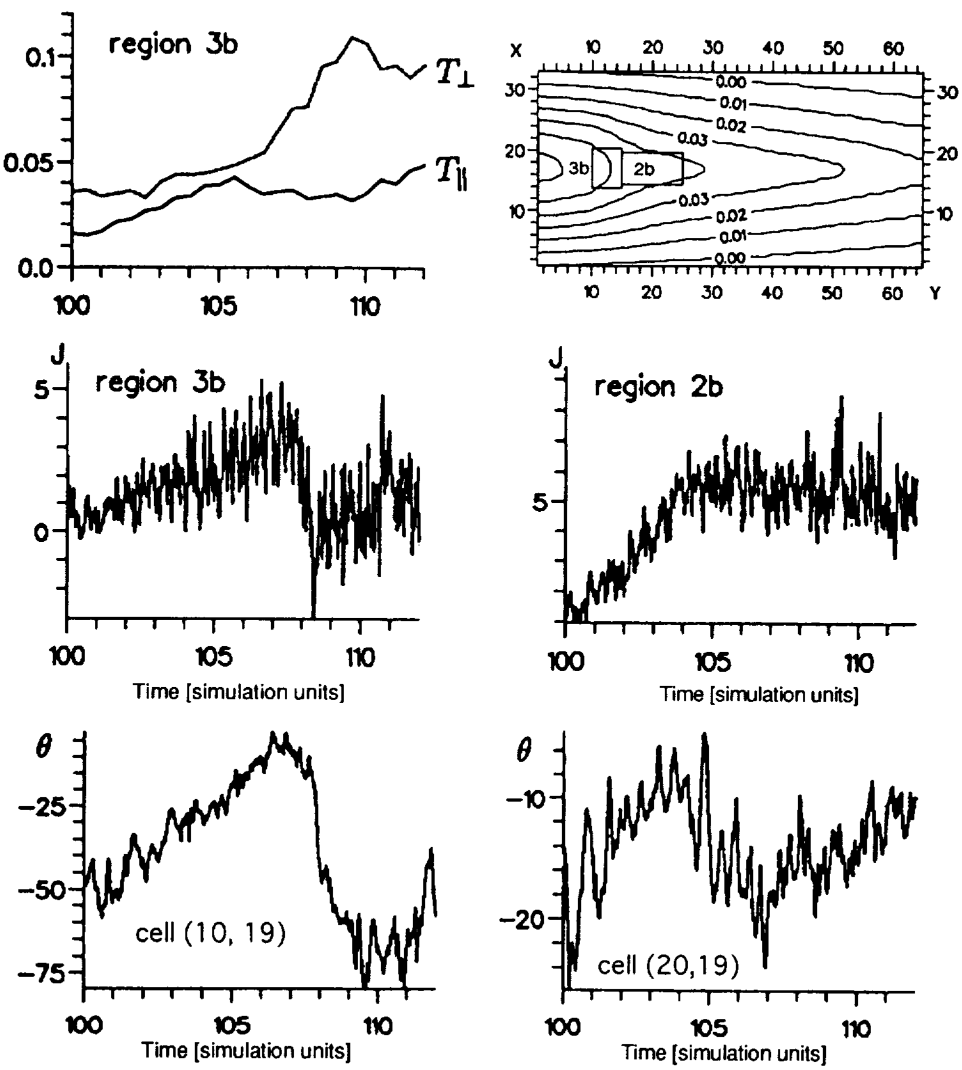

Figure 11. Response of a simulated current sheet to an enhancement of the convection electric field [from *Rogers and Christiansen*, 1992, Figures 1 and 7]. (top left) Time history (in simulation time units) of temperature changes in region 3b during a transient dipolarization event. (top right) "Steady state" magnetic field configuration prior to enhancement of convection. Two subregions used in this figure are indicated. (middle) Time history of the cross-tail current density in regions (left) 3b and (right) 2b. (bottom) Time history of the inclination angle of the magnetic field ($\theta = -90$ for purely poleward field) coordinates (left) $(x, z) = (10, 19)$ in region 3b and (right) $(x, z) = (20, 19)$ in region 2b. The dipolarization may be seen to proceed from larger to smaller x, becoming larger and more abrupt as it progresses from $x = 20$ to $x = 10$ (region 2b to region 3b).

observations of direct injection of low-energy ionospheric ions into the low-latitude boundary layer [*Lockwood et al.*, 1988; *Fuselier et al.*, 1989a, b], which appears to occur by a combination of convection to the dayside magnetopause and field-aligned injection from the conjugate auroral ionosphere. A related observation is that of energetic ions of magnetospheric (and certainly to some degree ionospheric) origin being transported outward into the boundary layer [*Mitchell et al.*, 1987] and leaking out across the magnetopause and into the magnetosheath flow [*Sibeck et al.*, 1987a, b]. Such ions are also the source of a controversy concerning the origin of energetic ion populations seen upstream of the Earth's bow shock [*Möbius et al.*, 1987; *Sibeck et al.*, 1988].

In addition to energetic particles, geospheric plasma is also transported to the dayside magnetopause. There it is subject to rapid downstream motion in the boundary layer. In the process, it mingles diffusively with the magnetospheric mantle, joining the mantle plasma in its downstream motion. Depending on whether or not a particular streamline closes in the geotail, this geospheric plasma may be lost entirely or recycled into hot plasma return flows. Modeling efforts are well behind observational work in this area.

Plasmoid Ejection

Ionospheric escape into the solar wind is a real possibility, which would lead to a significant mass loading of the solar wind flow over some distance scales, analogous to the ion tail phenomenon in comets (but not to the cometary pickup ion phenomenon, since the rate of formation of new ions outside the magnetopause is negligible). A much larger loss of ionospheric plasma is likely in the downstream lobe region. That portion of the neutral sheet lying beyond a neutral line and consisting of interplanetary field lines that are strongly draped downstream in the solar wind must arise from the requirement that the interplanetary field accelerate some distant magnetotail population back up to the macroscopic solar wind speed. The Maxwell stresses in such a region are in the same direction as the plasma flow and are inconsistent with a plasma inflow having a large antisunward velocity component. The plasma inflow population that is accelerated downstream may be a volume of heliospheric plasma that has been decelerated during its contact with and coupling to the geospheric plasma, or it may be a volume containing primarily geospheric plasma that is inherently moving more slowly than the solar wind, or, as seems likely, it may be a volume containing a mixture of the two.

Mass loading of the magnetotail by ionospheric outflows may contribute to the instability of the tail, which forms plasmoids in the following way: Enhanced coupling of the magnetosheath with the ionosphere may lead to a region (parcel) of enhanced density (geospheric) plasma moving antisunward at excessive speed. Some part of this parcel may be captured on closed plasma sheet field lines and disturb the Maxwell stress equilibrium there. A magnetic neutral line may then form that cuts off the plasma parcel from the closed field lines restraining it and leads to a reversal of the Maxwell stresses, so that the parcel begins to experience an acceleration downstream. The result would produce a dramatic temporary enhancement of ionospheric transport across the geopause boundary, suggesting that enhanced solar wind coupling may increase not only the amount of ionospheric plasma in the magnetosphere, but also the amount transported downstream in the solar wind. This potential for downstream escape has barely been explored by modelers.

Charge Exchange

For some time it has been known that charge exchange of energetic ions on geocoronal hydrogen is the principal loss mechanism for the energetic storm time ions. *Roelof et al.* [1985] found that the resultant energetic atoms are seen by suitably instrumented spacecraft tens of Earth radii away from the Earth. Much of this "loss" is energy loss rather than mass loss because much of the mass returns to the atmosphere. The rate of loss is significantly dependent on species and energy owing to the variation of the charge exchange cross sections.

Recently developed models of the recovery phase of space storms account in some detail for ring current decay by this mechanism, assuming strong pitch angle diffusion [*Fok et al.*, 1993]. In more recent work, *Fok et al.* [1995] have accounted for the evolution of the storm plasma as a function of ion pitch angle, owing to these losses. An example of the transient dispersion and decay of the ring current so calculated is shown in Plate 1. Drift dependence on pitch angle produces field alignment of the pitch angle distributions in some regions that competes against the losses, which are largest for field-aligned ions that mirror low in the geocorona. Charge exchange losses erode the pitch angle distributions, producing strong minima along the field direction that are reasonably well described by the form $A \sin^n(\alpha)$, where α is the equatorial pitch angle. This type of modeling is now moving toward the inclusion of pitch angle diffusion produced by observed wave power spectra. This will in general moderate the pitch angle anisotropies and enhance the energy loss rates, thereby modifying the time history of storm recovery.

Thermalization

Thermalization of storm plasma energy occurs through both fast neutral and direct ion bombardment of the atmosphere and ionosphere. The less dense regions of these media are strongly influenced by this energy. The resultant electron heating leads to stable auroral red arcs [*Kozyra et al.*, 1987], while ion heating in the topside ionosphere and plasmasphere is also substantial.

Losses of storm plasma energy via Coulomb collisions with the low energy or core plasma have been found to significantly affect the storm time plasmas, in spite of conventional thinking that the system is "collisionless" [*Fok et al.*, 1993]. Both energy degradation of the storm time ions and bulk heating rates for the core plasma result. In both cases the effects are significant and competitive with other processes, depending to some degree on the ion species involved. In the future, such modeling efforts must consider the effects of this energy on the low-energy media and resultant potential feedback effects as superthermal phenomena alter the thermal environment. To do this properly will require multidimensional models of field-aligned thermal plasma transport that account for ionospheric plasma flow on field lines of time-dependent arbitrary shape and convection paths, including centrifugal and other inertial effects such as those found by *Horwitz et al.* [1994] and flux tube volume effects such as those found by *Guiter and Moore* [1994].

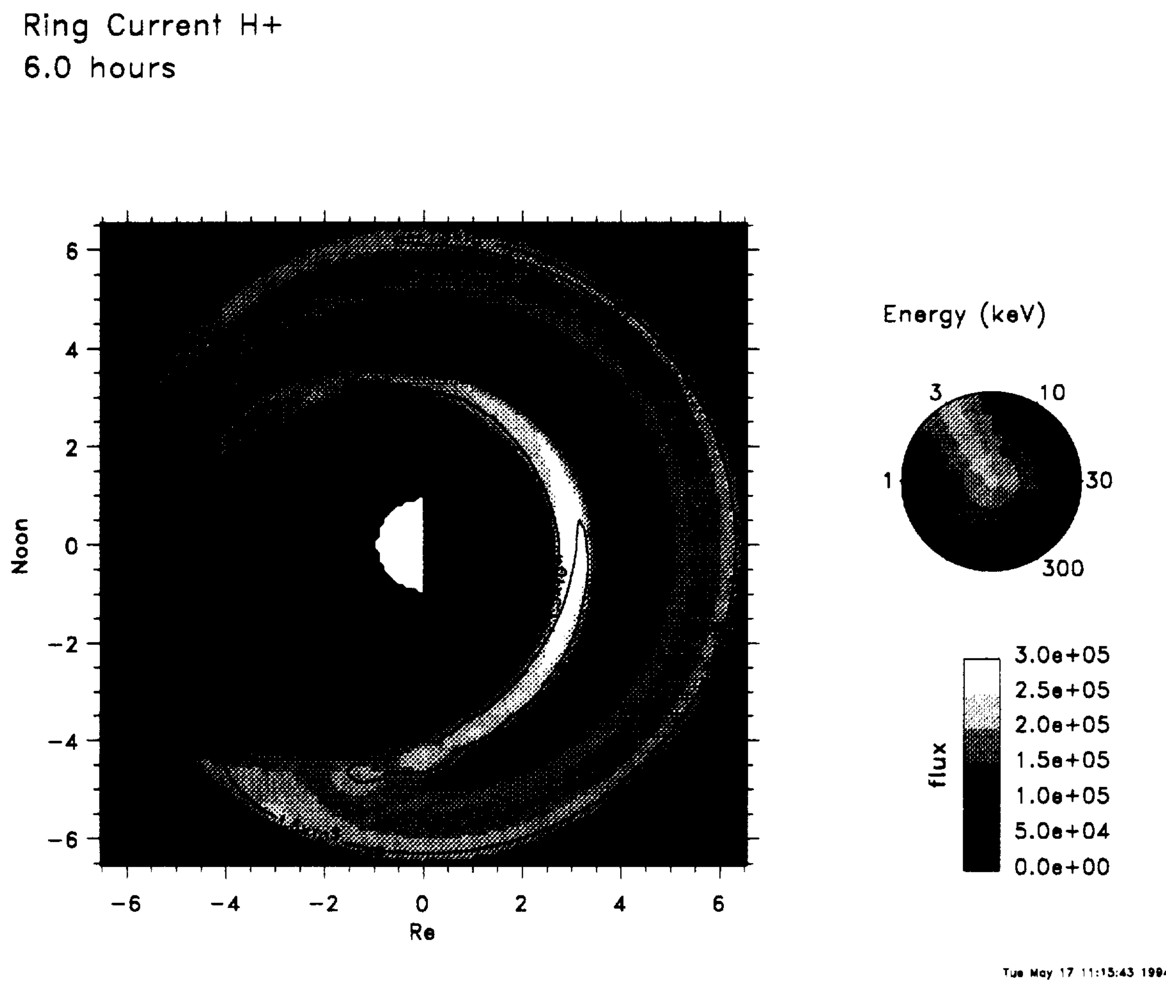

Plate 1. A depiction of the transient recovery phase storm plasma during its early dispersion (6 hours after main phase) from a main phase injection region localized near midnight [from *Fok et al.*, 1995, Plate 1b]. In this presentation, low energy fluxes are represented by red intensity, medium energy fluxes by green, and high energy fluxes by blue, as indicated in the color wheel, so that a flat energy distribution produces a gray color. Red, green, or blue dominance in a particular pixel indicates low, medium, or high energy dominance, respectively.

DISCUSSION

The origins of magnetospheric plasma, and particularly the protons, remain somewhat ambiguous. There is a consensus based upon the observed O^+ content of storm time hot plasmas that the geosphere and heliosphere contribute comparably to magnetospheric hot plasmas, each source responding to varying conditions. However, the hot plasmas outside the plasmasphere are not homogeneous in composition, and it is certain that geospheric H^+ is also an important component of the hot storm plasmas. At a minimum, our understanding of the magnetosphere needs elaboration through recognition that a boundary exists, within which the geosphere dominates and outside of which the heliosphere dominates (i.e., the geopause of Figure 2). Though advocates might assert that the geopause lies closer to the plasmapause or to the magnetopause, it is clear that the geopause must lie between the two, that its shape and size vary greatly, and that the entire outer region of open convection in the magnetosphere constitutes a "geopause region." The geopause doubtless moves and changes shape with geomagnetic activity and solar changes, as is suggested by the results of *Sharp et al.* [1985]. Moreover, the actual position of the geopause may depend on whether it is defined in terms of density, mass density, or partial pressure.

In the geopause region, solar and magnetospheric plasmas are strongly coupled by virtue of sharing the same magnetic flux tubes, either through direct interconnection of the geomagnetic and interplanetary fields or through the cross-field diffusion of plasma across flux tubes. The energetic heliospheric plasma experiences an electrodynamic drag (**J** × **B** force) on its motion, while the geospheric plasma experiences a corresponding but opposite acceleration force. This suggests an alternate definition of the geopause: the geopause is the locus of the pivotal balance points, on each flux tube, between solar wind forcing and geospheric plasma inertia. This can also be expressed in generator and load terminology. The geopause is the boundary between plasma that is being decelerated to create electrical energy ($\mathbf{j} \cdot \mathbf{E} < 0$, heliospheric plasma) and plasma that is being accelerated through the dissipation of electrical energy ($\mathbf{j} \cdot \mathbf{E} > 0$, geospheric plasma). The flux-tube-aligned current circuit that flows between the two plasmas is reflected in distortions of the magnetic field that correspond to the Maxwell stresses set up by the divergent tendencies of the two plasmas cohabiting the common flux tube.

As the flux tube stresses achieve a compromise between the influences of the two plasmas, the plasmas intermingle through diffusion along the flux tube to a degree that cannot be easily anticipated without a comprehensive theory of field-aligned transport of both plasmas that does not yet exist. For example, it is possible that an electrostatic contact surface could be formed that would tend to partition them from each other. On the other hand, at least some of the electrons are required to intermingle along the flux tube in order to carry the required field-aligned currents.

The cusp is the region of deepest direct penetration of heliospheric plasma. The cusp responds dramatically to increased solar wind ram pressure. It increases in size and becomes a more copious source of both solar and ionospheric plasma to the mantle, polar caps, and lobes. Changes in the dayside merging rate also lead to size changes in the cusp. Heliospheric plasma also enters gradually into the low-latitude boundary layers either through diffusion or direct entry near the subsolar region.

Owing to the nature of plasma circulation in the magnetotail, which could be described as a dual counterrotating egg beater in a wind (see Figure 5), solar wind entering the boundary layers across even the low-latitude parts of the magnetopause tends to be carried through the lobes toward the center of the plasma sheet. However, only the slowest solar wind particles (the low-speed "tail" of the solar wind velocity distribution) appear to be carried rapidly enough toward the central plasma sheet to gain entry to the return channel of convection back toward the Earth. An "entry boundary" can be defined that delineates the inner edge of the mantle flow. This boundary is in fact a conceptual model of the geopause, defining the inner limits of majority concentrations of heliospheric plasma.

It has been demonstrated that even the lowest-energy polar wind outflows from the ionosphere are transported to the plasma sheet and accelerated immediately to auroral particle energies by nonadiabatic neutral sheet acceleration effects. Moreover, a new form of trapping, effective only for particles with small parallel velocities, has been discovered to play a large role in the confinement of low-energy plasma. This strongly suggests that thickness of the plasma sheet, known to thin prior to substorm onsets, may be influenced by the entry energies of particles supplying it with plasma.

Many researchers continue to see value in empirical field models, in spite of their obvious shortcomings. Though it can be argued that the magnetosphere is never in its mean state, such models serve well to tie together disparate observations. They have provided important tools for treating the transport of plasmas into the magnetosphere, both from the solar wind and from the ionospheric sources. They are beginning to incorporate more realistic features, including field-aligned currents. However, there is still a need for models that do a better job with magnetopause current systems and with the neutral sheet current distribution in the near-tail.

The evolution of magnetic and electric field models appears to be in the right direction: more stretch through deeper penetration of the neutral sheet current and the inclusion of additional current systems. Out of these models has come a recognition that the boundary layer vortices, which had been thought to be centered in the dawn and dusk low-latitude boundary layer, are instead found within the plasma sheet, where their associated region 1 currents can be seen as a vortical shear in the magnetic field. One of the most robust results to appear in this area is that auroral emissions map to the region of greatest equatorial current in the Tsyganenko models.

Model plasma distributions are at a relatively rudimentary stage of development, but efforts to use them for wave propagation studies have been made. Strong interest exists in the exploitation of plasma imaging to reveal the global dynamic behavior of magnetospheric plasmas and fields during transient events such as substorms and storms. This is a significant part of the motivation for the proposed Magnetosphere Imager Mission [*Williams et al.*, 1992].

Studies of particle nonadiabaticity and nonlinear dynamics in the neutral sheet region have shown that both the formation of an isotropic central plasmasheet and the formation of boundary layer streams are direct consequences of the chaotic nature of particle orbits. There is considerable agreement between the particle distributions predicted and those observed in the boundary layer and central regions.

A "low-energy layer" is seen immediately outside the plasma sheet boundary layer. New observations from Geotail show that low-energy, ionospheric, anti-sunward streaming plasma is seen just outside the plasma sheet boundary layer, similar in some respects to the scenario suggested by recent single particle modeling efforts, but contrary in others. The magnitude of the cross-field flows seen are so large that they must be quite localized to the center of the tail to be consistent with observed cross-polar cap potentials.

In existing empirical field models, the ring current appears as a steady feature of the magnetosphere that is only subtly distinguished from the neutral sheet

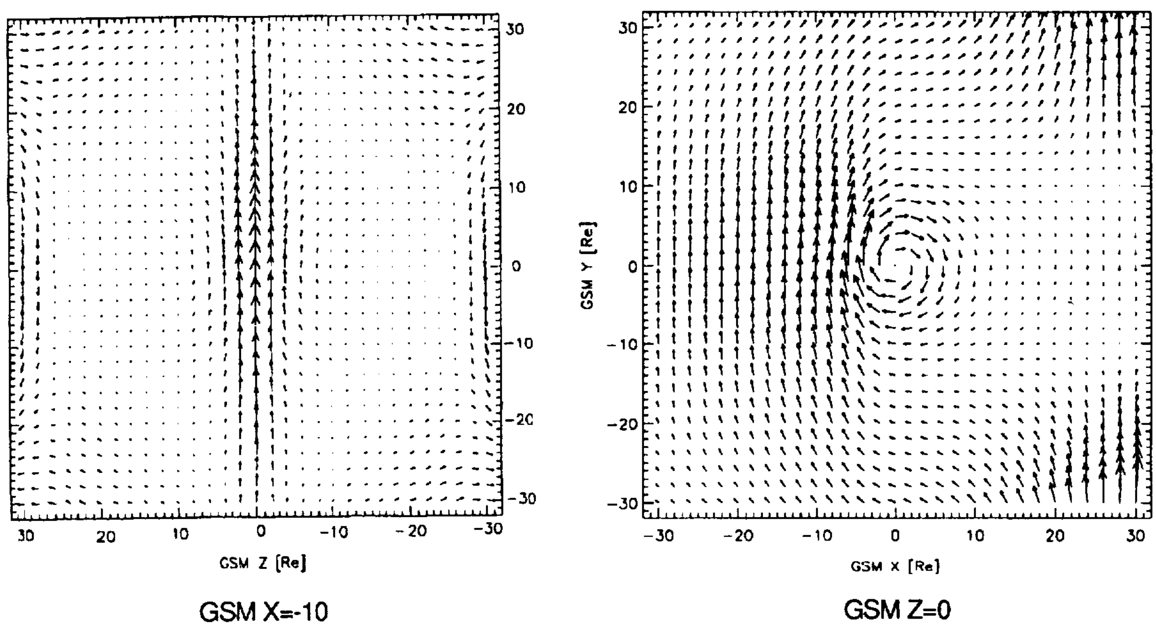

Figure 12. The geospheric current system, obtained as the curl of the *Tsyganenko* [1987] magnetic field model corresponding to a moderate activity level ($Kp = 3$). The current flow field is depicted as arrows of length proportional to the current density, in (left) the $X_{GSM} = -10\ R_E$ plane and (right) the equatorial plane.

current of the magnetotail. Figure 12 shows the combined current system as derived from the T87 model. It reveals a cross-tail current that shades continuously into a ring current that closes through the dayside rather than flowing to the flanks of the magnetopause. Observations and theoretical concepts continue to indicate that the plasma sheet has a macroscopic instability leading to substorm dipolarizations that in turn remove cross-tail current and add to the closed ring current. Heavy ion inputs from the ionosphere may contribute to this instability, but it is also influenced by solar wind factors including but not limited to the rate of coupling into convective circulation. Convection is clearly observed to increase during substorms, over timescales commensurate with the substorm auroral timescale, and with the changes in the plasma sheet associated with substorms. However, additional observations confirm that the fundamental substorm event is a collapse of the tail field, which appears locally as a "dipolarization," with associated convection surges or bursty bulk flows. The induced electric field associated with these events accelerates ions to high energies, suggesting an alternate term for them: induction surges.

Beyond approximately 10 R_E in the tail, dipolarization occurs with a time scale of several minutes to a few tens of minutes at individual locations, and is observed to spread tailward over a similar timescale. The net change in plasma plus field pressure in this region is a reduction. MHD simulations contain this behavior in the region earthward of the neutral line, which spreads tailward in an expansion fan wave.

Inside approximately 10 R_E, dipolarization occurs in 1–2 min at individual locations and is observed to propagate earthward over a timescale of approximately 10 min or more. The net change in plasma plus field pressure is an increase in this region. A new hybrid simulation contains this inner magnetospheric behavior, which is understood as an instability of the neutral sheet geometry to strong convection through it. Given the rapid dipolarization collapses, induced electric fields directly accelerate the energetic ions of the inner plasma sheet and storm plasmas, from whatever plasma is available as working material.

The region near 10 R_E in the nightside is a zone of special significance, separating the rarefactive tail from the compressive inner magnetosphere. This newly appreciated feature seems to merit a name, so we propose that it be called the injection port because it is the aperture through which current and plasma are injected into the inner magnetosphere, where the current is transformed from neutral sheet current to ring current. The injection port is an aperture in a purely conceptual boundary between the tail and the inner magnetosphere, as illustrated schematically in Figure 13.

In Figure 13 the role of the dipolarizations and the injection port is to move plasma from a buildup in the cross-tail current to an enhancement of the closed ring current, while reconfiguring the inner magnetosphere in a compatible way to better support closed drifts of energetic particles, that is, to make it more azimuthally homogeneous or, in other words, less stretched in the midnight sector. The net result is that current

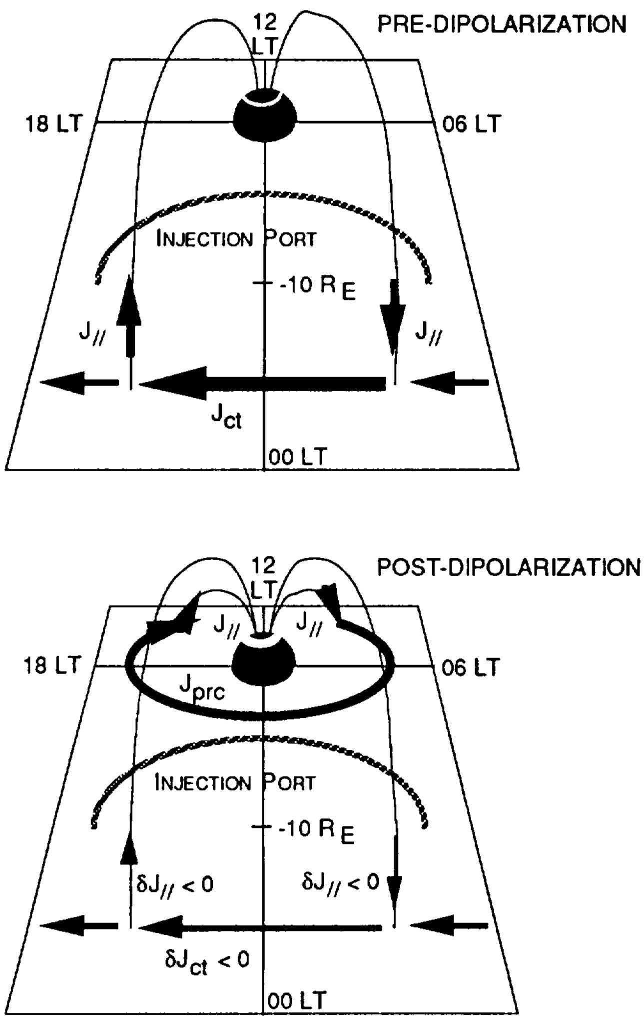

Figure 13. Schematic of the proposed "injection port concept, showing the special significance of the region near 10 R_E in the tail. In this concept the current disruption consists of a redistribution of current toward the Earth, with a net increase inside the "port" and a net decrease outside it.

streamlines that previously would have linked the magnetopause boundary layers are wrapped around the dayside to form a closed ring current.

It is tempting to speculate that the geopause has an interaction with the injection port, that is, that a motion of the geopause outward through the injection port region might destabilize the region to dipolarizations. A number of theoretical arguments have been advanced in support of heavy ions as a cause of instability, but it is also possible that a relatively cold ion supply to the plasma sheet might be destabilizing, independent of any mass composition effects. In light of the results indicating that a cold ion plasma sheet would be thin, this idea deserves more study.

CONCLUSIONS

Terrestrial matter in the plasma state dominates a larger region of space than was suspected when the "space age" began. Contrary to early popular accounts of the aurora and radiation belts, more matter escapes from Earth into space than is acquired from the solar wind, and the energetic plasmas that produce the aurora and damage spacecraft are largely of local origin, though energized by the solar wind. The net mass loss over geologic time is very difficult to assess, because solar wind conditions are known to have varied significantly but no record exists over such long timescales. It seems possible that this mass loss rate has influenced the evolution of our atmosphere. The region within which terrestrial matter is dominant should, by established convention, be referred to as the geosphere. Its outer limit, the geopause, is now known to lie well beyond the boundary that was originally thought of as the outer limit of ionospheric plasma, the plasmapause. Because of the highly dynamic nature of the geopause region, the location of the geopause is likely to be variable. Owing to the ambiguous origins of protons in the geopause region, the geopause will be similarly difficult to identify.

Severe space storms, which regularly damage spacecraft, interfere with communications, and trigger power grid failures, occur in the geopause region. The geopause is analogous in some ways to the air-sea interface. It is the interface across which the supersonically expanding heliospheric plasma delivers momentum and energy to the terrestrial plasma, exciting it into motion, "evaporating" it into space, and dissipating considerable amounts of power in thermal forms while generating energetic particles through repeated storage and rapid release of electromagnetic energy. Recent simulation efforts have reproduced some aspects of this cycle of storage and release on injection timescales. This suggests that the basic injection-scale phenomenon is earthward motion and closure of some cross-tail current to form the ring current. It is hoped that recognition of the geopause as a momentum transfer boundary will foster better understanding of the development of such space storms.

As the geopause position has migrated outward in our thinking, many phenomena formerly thought to occur in the boundary layers near the magnetopause now appear to occur deeper inside the magnetosphere; for example, the region 1 current system, the auroral precipitation peak, and the onset region for substorms. This trend is consistent with the thesis presented here that the geopause is the focal region of magnetospheric energy dissipation and release. While it has been known for some time that the intensity of the solar wind and the orientation of its magnetic field jointly control the occurrence of severe space storms, it increasingly appears that the reason for this control is the resultant modulation of the strength of coupling to the outermost plasmas of the geosphere. As in other geophysical contexts, the greatest dissipation is found at the boundary between sources and sinks of energy and momentum, the geopause.

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