Geofísica Internacional (1992), Vol. 31, Num 1, pp. 5-10

The Earth's magnetosphere: an introduction

J. G. Roederer
Department of Physics and Geophysical Institute
University of Alaska, Fairbanks, Alaska, U.S.A.

RESUMEN

Desde su descubrimiento, poco después del Año Geofísico Internacional, la magnetosfera terrestre ha sido objeto de intensos estudios con satélites e instrumentos desde tierra. En la actualidad se tiene una imagen más o menos satisfactoria de las principales características estructurales y del comportamiento dinámico de las múltiples regiones que la forman. Se han propuesto procesos de micro y mesoescala para el acoplamiento entre todas esas regiones, pero no existe una descripción cuantitativa local de los flujos de masa y energía hacia, a través, y fuera del sistema. Tampoco se dispone de un conocimiento detallado de la configuración y del comportamiento dinámico del "esqueleto" básico de la magnetosfera; esto es, de las hojas de corriente y filamentos eléctricos que sostienen el campo magnético externo y todo lo que está atado a él. En este trabajo se resume el *status* actual de estas cuestiones a la luz de los planes de estudio de las componentes magnetosféricas dentro del Programa Internacional de Energía Solar-Terrestre.

PALABRAS CLAVE: magnetosfera terrestre.

ABSTRACT

Since its discovery shortly after the International Geophysical Year, the terrestrial magnetosphere has been under intensive study with satellites and ground-based instrumentation. We have a fairly good picture of its main structural features and the dynamic behavior of its multiple regions. Micro and mesoscale processes have been proposed for the coupling between these regions, but we do not yet have a global, quantitative description of the mass and energy flows into, through and out of the system, nor do we possess detailed knowledge of the configuration and dynamic behavior of the basic "skeleton" of the magnetosphere, namely the electric current sheets and filaments sustaining the external magnetic field and everything that is tied to it. The present status of understanding is reviewed in the light of current plans for the magnetospheric components of the International Solar-Terrestrial Energy Program.

KEY WORDS: magnetosphere.

BRIEF HISTORY AND CURRENT RESEARCH DIFFICULTIES

Magnetospheric Physics has gone through three phases during its over thirty years of existence. The **first phase** of discovery and synoptic study revealed the terrestrial magnetosphere as a complex and dynamic plasma structure with distinct macroscopic regions separated by thin boundary layers. We now know that this "cellular" organization is an ubiquitous feature of all cosmic plasmas in galactic and stellar systems and in the envelopes of planets and comets (Alfven's Cellular Plasma Universe). Like in a living organism, it is in the boundary layers (membranes) where the most important dynamical processes occur that govern the transfer of mass and energy from one region (cell) to another. In other words, the response of the magnetosphere as a system to outside perturbations was found to be governed mainly by interactive mechanisms residing in the boundary layers. During this first phase the principal regions and boundary layers and their typical functions and variabilities were identified and characterized.

The **second phase**, which started with the International Magnetospheric Study (IMS 1976-1979) and is now coming to a close, focused on the determination of the structure of the boundaries and the formulation of possible interactive mechanisms that regulate the magnetospheric response to characteristic features of the solar wind and the terrestrial ionosphere. It became apparent that to study the cellular structure of the magnetosphere, two quite different strategies for the experimental and theoretical investigation of the magnetosphere are necessary: a "macroscopic" study of the fundamental regions containing the bulk of mass, energy and momentum, and a "microscopic" analysis of the detailed processes in the transition layers between them. Each strategy demands a distinct approach to measurements in space (e.g., large-scale imaging vs. spacecraft cluster measurements of local properties), remote sensing from the ground (e.g., extended chains of monitoring stations vs. individual multi-instrumented facilities), and theoretical and simulation studies (e.g., global circulation models vs. simulation of localized plasma processes.)

In the **third phase**, about to begin with the international Solar-Terrestrial Energy Program (STEP 1990-1997) and expected to continue into the first decade of the next century, the magnetosphere (and the entire solar-terrestrial chain of regions) will be studied experimentally and modeled quantitatively from a global perspective as one single complex interactive plasma system.

The magnetospheric physics community is not yet fully prepared for this monumental task. On one hand, there are increasing financial constraints that impose severe limits to the possibilities for new multi-satellite missions and new major comprehensive ground-based facilities. On the other hand, there has been a narrowing of scope and field of view on part of many participants in this research. Driven by the complexities of the system, people tend to study one process while losing sight of distant connections; or they draw pictures in two dimensions (e.g., the ubiquitous noon-midnight meridian), ignoring what happens in the third dimension. Several competing models are formulated to explain one single event, but there are far fewer successes in formulating one model that explains many different events. Work done in the "distant" past is re-invented without due credit to the original authors. There is a proliferation of pet ideas, pet theories and cartoon descriptions and, sadly, considerable intolerance to new, unconventional approaches. Controversy is exciting and healthy for the development of any new research field - one just has to learn to live with it!

The magnetosphere is a highly complex, non-linear, multi-species plasma system in which "nothing is proportional to anything, and everything is coupled to everything else". In this respect it is not unlike the global atmospheric system, whose study also demands an integral approach, with similar goals of global numerical modeling and long-term prediction-making.

The magnetosphere, like the atmosphere, is a system which under the same boundary conditions or external actions can manifest different responses or achieve different states of dynamic equilibrium. Ubiquitous "creationist" scenarios like "let there be a magnetosphere immersed in a uniformly southward interplanetary field" should give way to the "evolutionist" view of a magnetosphere subjected to continually changing inputs, in which the present state depends decisively on the particular time-sequence in which these inputs have been delivered. Conversely, the magnetosphere is also a system in which different input processes can lead to the same final result, and for which the crucial question may not be **which** of several proposed processes is the "true" one, but **how much** or **how often** each one contributes.

Finally, the magnetosphere is such a highly non-linear system that simplistic models or descriptions, however self-consistent and physically "sound", may give wrong answers or lead to erroneous interpretations. This puts in question the whole issue of predictability, like in the atmospheric system. Indeed, a complex system may be inherently unpredictable within certain ranges in space and time, or its global evolution may depend in an unpredictable manner on infinitesimally small inputs or changes in boundary conditions.

Intuition and "Vorstellungsgabe" (German word for the capacity to make mental representations of things or events) are fundamental capabilities of the human brain without which scientific research, particularly theoretical research, would be impossible. An important tool to aid intuition and Vorstellungsgabe in magnetospheric physics is the concept of magnetic field lines. But field lines are **man-made** concepts - not even relativistically invariant - that can be treacherous if not handled with care. To think of field line motion is dangerous in situations in which "ideal" magneto-hydrodynamics may not apply, and our "Vorstellungsgabe" breaks down easily when we have field lines twisted in three dimensions, or with a torsion imposed by field-aligned currents.

Electric currents (and, on occasion, localized charge imbalances) are the only "real" physical entities that govern a plasma. We have grown too much accustomed to look at the magnetosphere as a bowl full of spaghetti - the field lines. We should re-train our intuition and learn to see (mentally) the complex, highly dynamical skeleton of currents, current sheets and filaments that sustains the magnetospheric field and everything that happens in it. And in considering the electric field, we should learn to see (mentally) the time-changes of the magnetic vector potential, for it is this vector potential (in the Coulomb gauge, please!) that represents the link to all currents, local and far away, and external to the system.

EVOLUTION OF A MAGNETOSPHERE

Let us perform a "thought experiment" (Einstein's "Gedankenexperiment" - the forerunner of computer simulation). Let us start by blowing an unmagnetized plasma with slowly increasing density against a magnetic dipole. Initially, when there are only a few ions and electrons coming in, nothing dramatic occurs. The particles will move under the action of the velocity vector-dependent, energy-preserving Lorentz force and be deflected as they approach the dipole. The overall result is that the incoming tenuous "plasma" is scattered into all directions. The individual trajectories may be complicated, but they are always such that at the point of closest approach, ions and electrons basically move in mutually opposite directions. Depending on the direction of incidence, some particles may end up spiraling along a magnetic field line toward one of the dipole poles, mirror close to it, spiral out again and vanish into infinity. All this is what cosmic rays do when they approach the Earth's magnetic field (unless they hit the atmosphere).

As we increase the density of the inflowing plasma, things start happening. At points of closest approach, too many ions will be moving into one direction and too many electrons into the opposite: this represents an electric current that will begin influencing the original dipole field. The result is always such that the magnetic field is compressed (increased) in the region facing the incoming particles, and extended (decreased) toward the lee. When the density of the plasma increases beyond a critical point, the initially diffuse current collapses into a thin current sheet, the **magnetopause**, which neatly separates the incoming unmagnetized plasma from the squashed dipole field. The incoming plasma is no longer scattered; it flows peacefully around the elongated magnetic cavity that has been formed, a proto-**magnetosphere**. The dynamic pressure of this flow perpendicular to the boundary balances the magnetic field pressure on the magnetospheric side; this determines the position and shape of the magnetopause. If the bulk speed of the incoming plasma is supersonic, a standing **bow shock** will appear in front of the magnetosphere. The shocked plasma flow between the bow shock and the magnetopause is the **magnetosheath.**

The magnetopause is a plasma entity in its own right; both, the external flow and the magnetospheric field share responsibility for its structure and behavior. The current lines in the magnetopause all circle around two **neutral points**, north and south; the magnetic field lines that lie inside the magnetopause converge toward these neutral points, where they turn inwards reaching down to the north and south polar regions of the dipole in two thin bundles, or **cusps.**

The story does not end there. The plasma wants to get in! At this stage of our thought-experiment one can think of several possible entry processes. Some would be continuous such as entry through the neutral points where the ram pressure has a component in the direction of the cusp field lines; small-scale diffusion; or simply the chaos of the individual phases of plasma particles as they hit the magnetopause; others would be sporadic such as density irregularities impinging on the magnetopause. This leads to new structures adjacent to the magnetopause, in which plasma particles, now detached from the external flow but keeping some memory of it, are moving inside the magnetospheric field. The **boundary layers** are thus formed, with plasma streaming along the magnetic field at the higher dipole latitudes (**entry layer and mantle**) and across it at the lower latitude flanks (**low latitude boundary layer**). Polarization charges will appear whenever the plasma has a bulk velocity component perpendicular to the magnetic field, giving rise to an **electric field** which controls the general **convection pattern** of the plasma in the magnetosphere.

Leeward, in the weakened and expanded field region, ions and electrons start drifting across the magnetic cavity in opposite directions from one flank to the other. Once there are enough particles participating, the ensuing current again collapses into a thin **tail current sheet**, which merges into the magnetopause currents at the flanks and stretches the magnetic cavity even further, forming a two-lobed **magnetotail.** The distorted magnetic field geometry in and around the tail current sheet favors the accumulation of plasma on the stretched field lines that pass through it, and the tail **plasma sheet** is formed. Plasma sheet and current sheet form a distinct plasma entity in its own right, too.

A multitude of problems appears when we begin to slowly magnetize the incoming plasma. Until now, the separation between externally flowing plasma and the magnetosphere was complete, except for the "leakage" of individual particles from outside through the magnetopause into the cavity. With a magnetic field embedded in the incoming plasma, the physics of the magnetopause will change drastically, from a mainly steady-state hydrodynamic situation (in which the magnetic field pressure inside the magnetosphere simply balances the dynamic pressure of the incoming plasma) to a complicated and not necessarily steady-state magnetohydrodynamic situation (in which the microstructure of the magnetopause plays a determining role).

Initially, when the external magnetic field is still weak, the incident (high beta) plasma will flow along the magnetopause, which will keep the two fields topologically separated: the external field lines will be draped around the boundary surface (think of a bowl of spaghetti thrown on the head of a bald person!). As the intensity of the external field increases, however, two situations are possible, depending on whether or not the local structure of the magnetopause allows for a magnetic field component perpendicular to its surface. In the first case we will have **rotational discontinuity** on the boundary, and the external field lines "hook on" to the magnetospheric field (think of a lump of spaghetti thrown on the head of a punk, getting entangled with the sticky hair). The sites where they hook on are called **magnetic merging** regions. Conceivably, they can be highly localized and transient, or extended along lines on the boundary called neutral lines. As a result of interconnection, the boundary becomes locally "transparent" to the incoming plasma and its thermal and bulk energy, to the external convection electric field, magnetic stresses, and a host of plasma waves. Field lines from the dipole that are connected to the external field passing through the magnetopause are called **open field lines.** In the second case (**tangential discontinuity**), no such magnetic interconnection exists, and we have the original picture of external magnetic field lines slipping by the magnetopause. If the first situation happens on a global scale along the entire magnetopause, we obtain an "open" magnetosphere; in the second case, a "closed" one.

It is obvious that the particular interconnection topology will depend, **inter alia**, on the direction and intensity of the external field, which thus becomes the "grand regulator" of energy, momentum and mass transfer from the external plasma to the magnetosphere. This external field will also rule the global convection pattern inside the open magnetosphere. The most favorable situation for local interconnection arises when the external field has the same direction as the polar field lines of the dipole, i.e., the dipole moment vector.

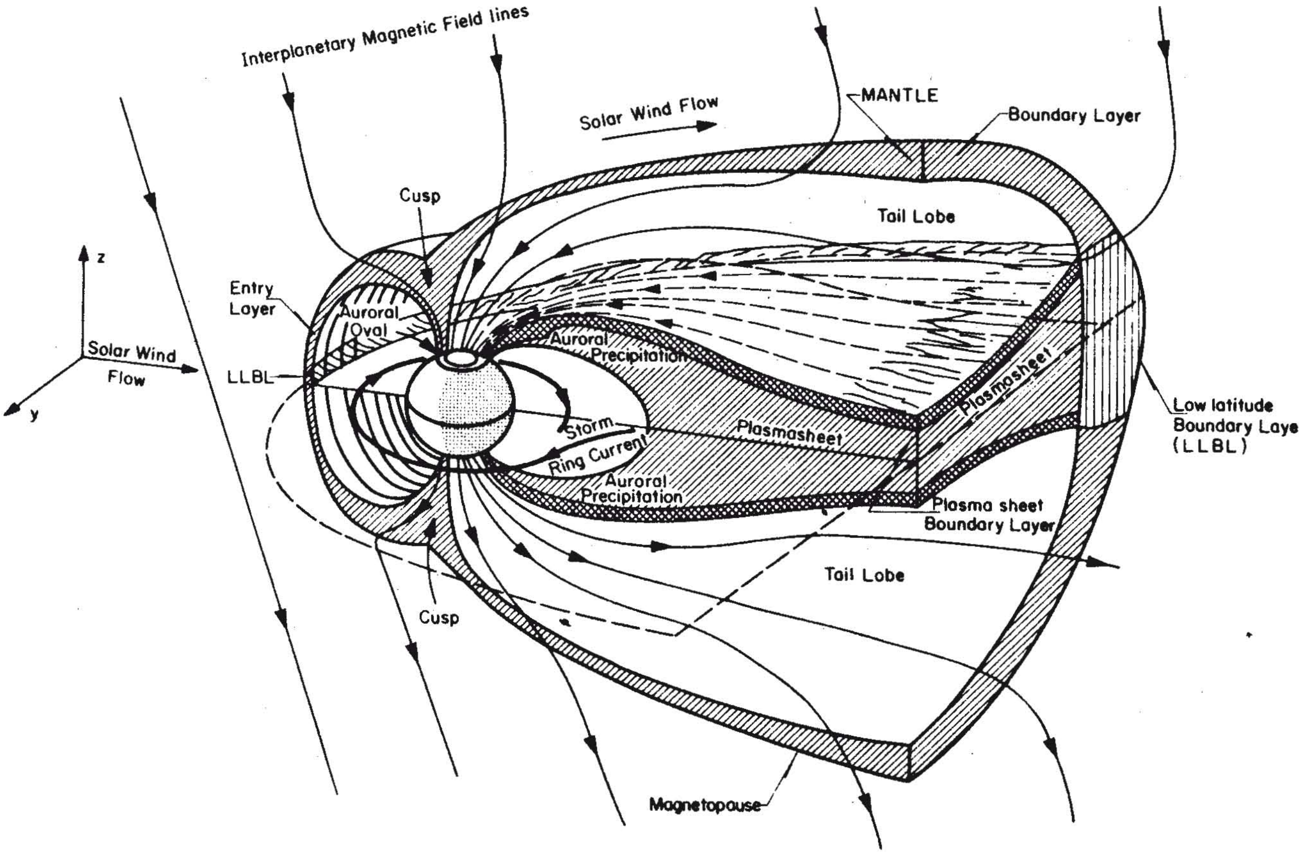
As a result of our thought experiment we have built a "real" magnetosphere . . . but it would belong to planet Mercury! Planet Earth has an **ionosphere**, so it is high time that we build one into our model. Again, big changes will occur in our system. The ionosphere offers a pool of thermal electrons and ions available for all sorts of mischief, and it offers ohmic resistivity to any electric current daring to flow into it from the magnetosphere. Magnetospheric plasma motion transverse to field lines that are connected to the ionosphere will elicit currents that flow parallel to the magnetic field in regions where the motion has a shear - the so-called **Birkeland currents.** Ionospheric resistivity will exert a drag on all convecting plasmas connected to it, and conversely, external convection will exert a drag on the ionosphere. In addition, ionospheric ions and electrons will become available as a second source of magnetospheric plasma (as soon as we have invented an acceleration mechanism to let them escape gravity).

The complexity of the situation is bad enough, but "you ain't seen nothing yet", as Reagan used to say. Up to now the system is still basically in a state of dynamic equilibrium, except for the possibility of accumulation and quasi-periodic unloading of magnetic or kinetic energy for certain conditions of external magnetic field and plasma flow. The real fun begins when rapid changes occur in the incoming plasma. Yet for this brief introduction, we'll leave things where we are. To my knowledge, our thought experiment of **gradually** building the integral magnetospheric systen has never been converted into a computer experiment (a plasma simulation), although a lot could be learned quantitatively from this. The thought experiment has, however, provided us with the qualitative basis for a brief review of the main structure of the real terrestrial magnetosphere in a quiescent state.

BASIC PLASMA STRUCTURE OF THE QUIESCENT MAGNETOSPHERE

Figure 1 shows a sketch of the principal plasma regions in the real magnetosphere. These regions are defined above in the discussion of our "thought experiment". Not shown explicitly in the figure is the incoming plasma, or **solar wind.** Typical densities of the solar wind are 1 - 10 ions/cm^3, and flow speeds are highly variable, from 200 to 600 km/s at 1 a.u. Ion temperatures range from 2 x 10^4 to 2 x 10^5 K; electron temperatures are somewhat higher. The dominant ion species is hydrogen; the dominant minor ion species is He^{++}, an important "tracer" to identify the solar wind contribution to magnetospheric plasmas. The magnetic field in the solar wind (**interplanetary magnetic field,** IMF) is basically organized into sectors of sunward or antisunward spiral configurations in the ecliptic; but it is highly variable and its vector can assume any direction. The magnitude can range from a few nano-Tesla to 15 nT.

Behind the bow shock, not shown in the figure, the **magnetosheath** represents the shocked solar wind with increased density (2 - 50 ions/cm^3) and temperature (5 x 10^5 to 5 x 10^6 K for ions), and reduced speed (200 to 500 km/s). A hot plasma component has also been found, the



origin of which may be heating at the bow shock and/or magnetospheric plasma leaking out through the magnetopause. As the plasma flows away from the subsolar point along the tail, it accelerates from the sub-Alfvenic values; at the Moon orbit (60 Re) it is found to have properties similar to the solar wind. Except for the region near the subsolar point, the magnetic field in the magnetosheath is similar in magnitude and direction to that of the impinging solar wind.

It is important to have a clear idea of the implications of a finite flow speed in the magnetosheath. For instance, it takes a magnetosheath discontinuity anywhere between 7 and 10 minutes to travel from the "nose" of the magnetosphere to the dawn-dusk meridian, and it takes it 15 - 22 minutes to reach 20 Re down the tail. In other words, it is impossible to "switch on" a given solar wind condition for the entire near-Earth portion of the magnetosphere! In order to "immerse" the principal part of the magnetosphere (say, from the subsolar point to 60 Re down the tail) into a more or less uniform IMF, the duration of that condition measured on a spacecraft upstream must be at least 30 - 40 minutes.

The **magnetopause,** the true outer boundary of the global Earth system within which everything is physically tied to our planet, is only 400-800 km thick (5 - 10 ion Larmor radii at typical magnetosheath particle energies). It is identified as a clear signature of the magnetic field in the subsolar point region; along the flanks, plasma observations must be invoked to determine the magnetopause. Because of its small thickness and highly dynamic behavior, the internal structure of the magnetopause is extremely difficult to determine experimentally. Localized filamentary currents have been identified, as well as layered structures during conditions of northward IMF.

The main approach of magnetopause studies usually consists of (mostly highly simplified) simulation studies and theoretical formulations (often "back-of-the-envelope") followed by attempts to verify pertinent predictions with the retrospective analysis of experimental data. Large-scale, quasi-stationary reconnection at the magnetopause during episodes of southward-directed IMF is one example of an over-simplified (yet intrinsically complicated) theoretical scenario that has been around for three decades, but for which clear experimental evidence has been stubbornly elusive. Global, all-encompassing, "smooth" models of the magnetopause may indeed be utterly unrealistic. If we could see the magnetopause, it would appear to us as a most ugly object: full of pock marks, oozing pimples, wobbly wrinkles, holes ripped open by slippery, twisted flux tubes, and many other unappealing features. Since the magnetopause is the most important "membrane" in our cellular plasma system, it is crucial to characterize and understand all small-scale processes occurring on this ugly but fascinating boundary.

The omnipresence of a magnetospheric **boundary layer** beneath the magnetopause is a clear indication that solar wind plasma has access to the magnetosphere at all times regardless of the particular state of solar wind parameters. The IMF modulates, but certainly does not determine, the entry of solar wind plasma. Diffusive transport through the magnetopause, small-scale, localized reconnection events (flux transfer events, see later), impulsive entry of plasma filaments (plasma transfer events, see later) are probably coexisting processes of entry. The flow in the boundary layer is generally anti-sunward and the plasma is characteristic of the magnetosheath (although hot magnetospheric plasma is also present at lower latitudes). The inward (earthward) edge of the boundary layer has been called the **geopause** because it may represent the contact boundary between regions dominated by solar wind plasma and the colder and more homogeneous plasma of ionospheric origin. A more mundane view, at least of the low latitude portion of this transition boundary, is that it represents a general convection reversal region between the outer anti-sunward flow and the sunward flow in the inner magnetosphere.

The boundary layer can be divided into several characteristic regions. The **entry layer, distant cusp** and **mantle** are found at high latitude regions (Figure 1), containing magnetosheath plasma flowing mostly along the magnetic field. It is believed that most of the plasma enters the magnetopause on the day side into the entry layer, where the flow can be sporadic and quite turbulent. The entry layer is believed to feed the mantle via the polar cusp, which acts as a velocity spectrometer, sending lower energy particles to the deeper layers of the mantle. The distant cusp, lying under a depression in the magnetopause around which the magnetopause currents circle, shows smoother and more constant flows of freshly entered magnetosheath plasma that, because of the particular field topology there, has direct access to the ionosphere along the cusp field lines. In the mantle, plasma densities range from 0.5 to 50 ions/cm^3, ion temperatures from 5 x 10^5 to 8 x 10^6 K, and the bulk speed is typically 100 - 300 km/s. The thickness of the mantle varies considerably (from a few thousand to 20,000 km), and is strongly dependent on the direction of the IMF, increasing during the magnetically active periods of a southward-directed field and nearly vanishing for a northward IMF. It thus seems that plasma entry along sporadically interconnected field lines on the dayside magnetopause (flux transfer events) is an important mechanism feeding the boundary layer at high latitude.

The **low latitude boundary layer** (LLBL) lies behind the magnetopause at low latitudes and contains magnetosheath-like plasma flowing tailward in a direction mostly perpendicular to the magnetospheric field. Thus the physics of the LLBL is quite different from that governing the high latitude boundary layers. The densities are similar to those of the latter, but the temperatures are higher (2 x 10^6 - 2 x 10^7 K for ions). It is important to note that this plasma coexists, but is not mixed (temperature-wise), with much hotter magnetospheric plasma. The thickness behind the subsolar point varies from 2,000 to 10,000 km and increases gradually along the flanks down the tail. At the lunar orbit (60 Re) it may reach 30,000 km. What is crucial is that, in stark contrast to the high latitude boundary layers, both the thickness and the density **increase** during periods of northward IMF (i.e., during low magnetic activity). Moreover, there is a small but persistent bulk flow component perpendicular to and away from the magnetopause all along the LLBL. All this indicates that the plasma entry process responsible for the formation of the LLBL is efficient at all times (apparently more so during quiet times), and that it is not restricted only to the dayside magnetopause near the subsolar point. Plasma transfer events are a candidate.

In the biological analog used in the first section, the **plasma sheet** is the nucleus of the magnetospheric cell, controlling many global-scale processes occurring in the latter. It separates the two lobes proper of the tail, which have greatly reduced densities (less than 0.1 ions/cm^3). The plasma sheet contains the cross-tail current sheet (also called **neutral sheet**) which separates the two halves of the tail with oppositely directed magnetic fields ranging from 20 - 50 nT (at 20 Re). The plasma sheet works as the great plasma reservoir of the magnetosphere that feeds many different components of the magnetosphere, such as the aurora, the ring current, the radiations belts, several types of field-aligned currents, and the plasmoids claimed to be seen travelling down the tail at substorm time (plasma structures on closed field line loops detached from both Earth and solar wind). Ion densities in the plasma sheet vary from 0.1 to 1 per cm^3; the temperatures range from 5 x 10^6 to 5 x 10^7 K and are 3-5 times higher than those of the electrons.

An important fraction, sometimes more than half, of the plasma in the plasma sheet appears to be of ionospheric origin (for which O^+ ions are the characteristic tracers), ejected from the cusp regions and convected through the lobes. The rest is of magnetosheath origin (He^{++} tracer), either from the mantle via convection through the lobes, or from the LLBL, or, more likely, from both. Ion bulk velocities are highly variable in direction and magnitude. They range from 10 to 1,000 km/s, and can exhibit high-speed streaming. On the average, the bulk velocity is about 10 km/s, directed earthwards. The neutral sheet is 1 - 3 Re thick, with current densities of about 10^{-8} A/m^2; overall, this relatively large value is necessary to produce the up to 100 nT reversal of the magnetic field from one lobe to the other. The ions do not behave adiabatically in the vicinity of the neutral sheet, and a special "pseudo-adiabatic" physics had to be developed for this system. Understanding the dynamics of the cross-tail current sheet is of primordial importance for the understanding of the principal large-scale instability of the magnetosphere, the **substorm**.

Finally, the plasma sheet has its own **plasma sheet boundary layer** (the nuclear membrane!), with frequently strong field-aligned earthward streaming of ions, and field-aligned currents (sometimes in sheets of opposite directions). The highly variable plasma characteristics of this boundary layer can be quite different from those of the underlying plasma sheet. There are indications that this boundary layer may represent plasma ejected from an acceleration region downstream in the plasma sheet that is operating at all times.

The description of the active magnetosphere requires an extra review paper. The understanding is still quite fluid, and we must look forward with interest to the international Solar-Terrestrial Energy Program (STEP), that has just begun. Indeed, with STEP, the era of multi-point measurements in the magnetosphere will start, with multiple satellite missions and a complementary continuous ground-based program with chains of magnetic and optical sensors, and large multi-instrumented radar facilities. Only such a concerted international effort will provide the necessary information to elucidate the intricate, complex and dynamic processes governing the magnetosphere.

J. G. Roederer
Department of Physics and Geophysical Institute
University of Alaska, Fairbanks,
AK 99775-0800, U. S. A.