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The Earth's Magnetosphere

The outer limits of man's environment provide a readily available "astrophysical plasma laboratory."

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The magnetosphere may be defined as the region of near-earth space that is threaded by magnetic field lines linked to the earth and in which ionized gas predominates over the neutral atmosphere. It represents the outer limits of man's environment and is populated with ions and electrons from the earth's upper atmosphere, with plasma captured from the impinging solar wind, and with high-energy particles trapped in the radiation belt. Some phenomena of magnetospheric origin were known centuries before the space age began. The most spectacular one is the frequent display of polar lights or auroras (Fig. 1); other effects, though less visible, such as the magnetic storms, have puzzled scientists for hundreds of years.

Today the magnetosphere may be considered as our little private "backyard universe," where we can observe fundamental plasma processes at work that are known to occur elsewhere on a larger scale, for instance, in solar flares and other stellar surface phenomena, in galactic magnetic fields and radio clouds, and in the atmospheres of neutron stars. On a roughly equivalent dimensional scale, insights gleaned from magnetospheric studies find application in the current program for the exploration of the planets, particularly in the study of the atmospheres of weakly magnetized bodies (Mars and Venus) and the radiation environment of Jupiter. Even "earthbound" laboratory plasma physicists find in the magnetosphere and its interaction with the solar wind processes of specific interest to them, such as limits on particle confinement in a trapping magnetic field and collisionless shocks.

The magnetosphere is a significant component of the earth's total environment. It shields our atmosphere from a direct collisional interaction with the solar wind, and it shields the stratosphere at low and middle latitudes from the sometimes deadly doses of proton fluxes emitted by intense solar flares. On the other hand, its radiation belt imposes serious limitations on satellite orbit lifetimes safe for manned spaceflight. Magnetospheric processes maintain the ionization of the polar ionosphere during the long winter darkness, and, during geomagnetic storms, may cause enhancements of ionization at lower latitudes to such an extent as to impair shortwave radio communication systems. Storm-associated magnetic field variations on the earth's surface may sometimes seriously affect, even interrupt, overloaded networks of electric power lines. Changes in the density of the upper atmosphere caused by magnetospheric processes can substantially alter the drag forces on low-perigee satellites affecting their orbital stability, and it has been suggested that severe magnetospheric perturbations may affect even the earth's own rotation. The base of the magnetosphere is of potential—hopefully never real—relevance to exoatmospheric nuclear defense systems, and evidence has come to light recently (*1*) that it may influence in a subtle way the delicate balance of stratospheric and tropospheric dynamics, possibly representing one factor among the several that contribute in triggering the release of vast amounts of energy accumulated in atmospheric weather systems.

During the past 15 years, the study of the magnetosphere has undergone a highly successful stage of discovery and exploration. Investigators have obtained a morphological description of the magnetospheric field, the particle population embedded in it, and its interface with the solar wind, and have identified and are beginning to understand many of the physical processes involved (*2*). Magnetospheric physics is now ripe for a transition from the exploratory stage to one in which satellite missions and ground-based observations are planned with the specific objective of achieving a comprehensive quantitative understanding of the cause-and-effect relationships among the dynamical processes involved. For this reason, the International Council of Scientific Unions has recently invited its member countries to participate in the International Magnetospheric Study 1976–1978 (*3*), a program of internationally coordinated observations to be conducted simultaneously from spacecraft, ground-based facilities, aircraft, balloons, and research rockets. For the early 1980's, a series of magnetospheric studies have been recommended for the space shuttle (*4*), principally oriented toward artificial stimulations of magnetospheric phenomena with the objective of exploring the extent to which man himself can exert control over the space environment of the earth.

In this article I present a qualitative description of the general magnetospheric configuration and focus on some of the physical processes governing the magnetosphere that are the main targets of current research. Experimental data will not be discussed explicitly. Priority in the references has been given to reviews and monographs; the reader may find therein more complete bibliographies of original articles.

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Magnetospheric Configuration

The magnetosphere behaves like a huge "bag" of plasma and radiation that swells and contracts under the influence of the solar wind. Under the existing conditions of density, temperature, magnetic field, and bulk velocity, the solar wind (*5*) is a "collisionless" plasma flowing away from the sun at an average speed of 400 kilometers per second (supersonic with respect to the Alfvén velocity). It carries magnetic field lines from the sun, stretching them out into interplanetary space, probably far past the orbit of Jupiter. The earth's magnetic field appears as an obstacle to the flow of solar wind. The first "warning" given to a solar particle that an obstacle is being approached comes in the form of a stationary bow shock wave. Its position and shape in the "front" side of the magnetosphere are rather well determined; the geocentric distance to the subsolar point of the shock is about 14 to 15 earth radii (1 $R_e \simeq 6370$ kilometers) during quiet conditions.

Satellites and space probes have identified a transition region of compressed subsonic plasma flow, immediately behind the shock, called the magnetosheath. This transition region acts like an elastic medium, transmitting the kinetic pressure of the solar wind on to the earth's magnetic field. It confines this field into a well-defined cavity, the magnetosphere, with a "squashed" sunward side and magnetic field lines "combed" downwind into a long cometlike tail. A thin boundary, the magnetopause, separates the magnetosheath from the magnetosphere.

Figure 2 represents an artist's conception (*6*) of the magnetospheric field, its plasma populations, and associated boundaries (*7*). The average quiet-time geocentric distance to the subsolar point on the magnetopause is 11 R_e; the typical magnetic field intensity in the center of the tail "lobes" is (20 to 30) $\times 10^{-5}$ gauss. The geomagnetic tail extends far beyond the moon's orbit, possibly to a distance of the order of 1000 R_e. During severe perturbations, the magnetopause has been seen to move in to less than 5 R_e, and the field intensity of the tail may increase by a factor of 2 to 3.

The actual magnetic field configuration of the magnetosphere is determined by electric currents sustained by electrons and ions of the various particle populations. The main permanent source of the magnetospheric field is, of course, the magnetization of the earth's interior.

There are four principal external current systems: (i) magnetopause currents, which are responsible for the sharp confinement of the magnetospheric field (Fig. 2), sustained by solar wind particles deflected on, or drifting along, the boundary; (ii) the neutral sheet current dividing the magnetospheric tail into two lobes of oppositely directed fields (Fig. 2), sustained by drifting plasmasheet particles; (iii) the ring current, an east-west flow around the earth centered on the magnetic equator (Fig. 2), sustained by low-energy protons trapped in the geomagnetic field; and (iv) ionospheric currents flowing in the upper atmosphere (not shown in Fig. 2) caused by a variety of different mechanisms. To complete the picture we must add the transient currents induced in the earth's crust by external perturbations, and those flowing along magnetic field lines, which link the ionospheric current system at polar latitudes with that of the magnetosphere.

In the resulting magnetic field configuration, it is necessary to distinguish between two types of field lines. (i) "Closed," dipole-like, field lines near the earth emerge from low and middle latitudes of one hemisphere and return to the other. These field lines are permanently "distorted" near the earth's surface because of asymmetries in the internal magnetic field sources (*8*); farther out they suffer a day-night distortion caused by the solar wind (compression on the dayside, expansion on the nightside) and an "inflation" caused by the ring current (*9*). (ii) "Open" field lines that very likely are inter-

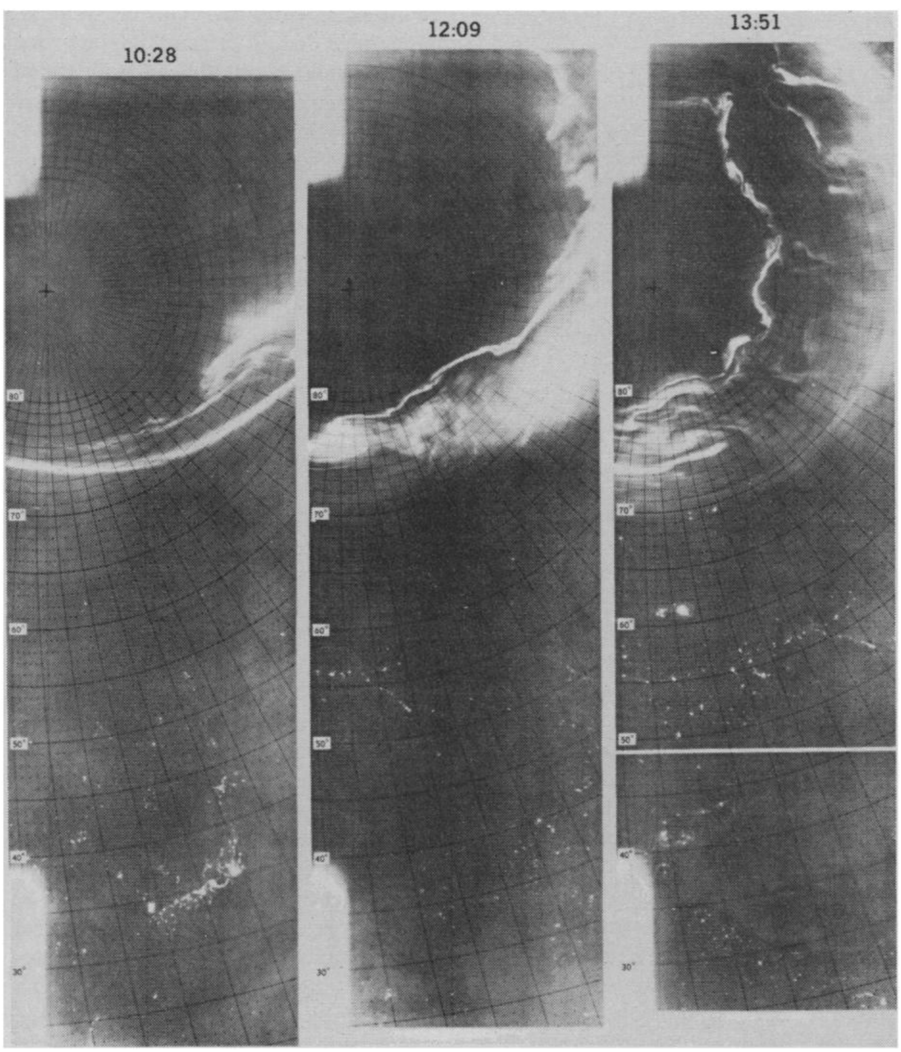

Fig. 1. Photographs of an aurora over the Soviet Union taken by a U.S. Air Force weather satellite on 8 January 1973. The numbers indicated are the universal times at the closest approach of the satellite to the geographic pole. While the time progresses from left to right, the geographic features move westward as the earth turns under the satellite orbit. Cities of Japan can be seen in the first panel; the points of light along 56° latitude in the third panel are cities along the Trans-Siberian railway. [Courtesy of G. A. Paulikas, Aerospace Corporation, Los Angeles, California]

connected with the interplanetary magnetic field through the magnetopause emerge from the polar caps and stretch out into the tail (*10*) (Fig. 2). On the nightside, the boundary between closed and open field lines is not well defined; there is evidence that some field lines may reach out into the tail to distances of 50 to 70 R_e and still be "closed" (that is, come back to the other terrestrial hemisphere). On the dayside, however, this boundary is sharp and forms so-called dayside cusps (Fig. 2), two demarcation "clefts" that extend toward the dawnside and duskside flanks of the magnetopause, probably merging with the neutral sheet somewhere in the tail. These cusps or clefts allow solar wind particles from the magnetosheath to penetrate deeply into the magnetosphere (*11*), right down into the high-latitude dayside ionosphere.

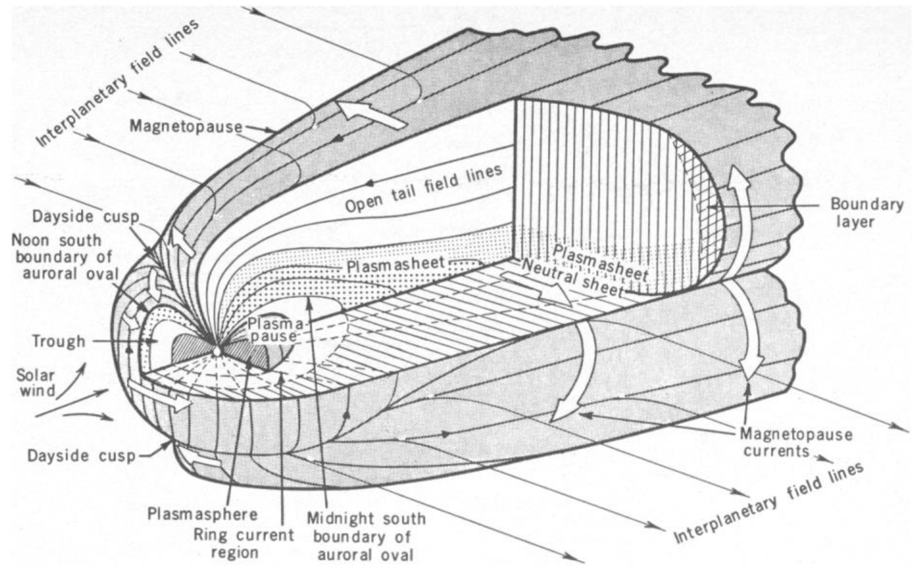

Fig. 2. Artist's conception of the magnetosphere, its plasma populations, and associated boundaries and currents (*6*).

There are three main particle reservoirs in the magnetosphere: (i) a storage reservoir of "cool" plasma, consisting of protons, heavier ions, and electrons of ionospheric origin in the plasmasphere (Fig. 2); (ii) a storage reservoir of "warm" plasma—protons, electrons, and a minor proportion of alpha particles and heavier nuclei, of solar wind origin—in the plasmasheet of the geomagnetic tail (Fig. 2); and (iii) the population of "very hot" energetic particles in the radiation belt. Whereas the plasmasheet is "anchored" in the magnetospheric tail, the plasmasphere co-rotates with the earth. The plasmasheet has a rather well-defined inner edge boundary; toward the flanks of the tail it is limited by a boundary layer (Fig. 2), a region of transition to the magnetosheath plasma. The plasmasphere terminates rather abruptly at an outer boundary, the plasmapause (Fig. 2). The radiation belt extends from ionospheric altitudes out to the limit of closed field lines.

A significant characteristic of the configuration shown in Fig. 2 is that different regions of the magnetosphere and their boundaries project along field lines onto the ionosphere below. The upper atmosphere thus may be regarded as an "observing screen" onto which the effects of many phenomena occurring in the three-dimensional magnetosphere are projected. This "observing screen" appears divided into specific regions with their corresponding boundaries, each region displaying its own set of characteristic phenomena. In particular, the open field lines stretching out into the geomagnetic tail are projected onto the ionosphere defining the polar caps. The auroral oval (*12*) —a band encircling the polar caps and roughly representing the region of maximum abundance of visible auroral emissions—represents, on the dayside, the projection of the polar cusps (at 75° to 80° geomagnetic latitude). On the nightside, its equatorward boundary (located at 65° to 68° geomagnetic latitude) coincides with the projection of the inner edge of the plasmasheet (Fig. 2). (In Fig. 1 the inner edge of the plasmasheet gives rise to the diffuse circular band forming the southward edge of the auroral light emissions.)

These features are more or less locked into place in a frame of reference (the magnetosphere) fixed with respect to the earth-sun line. As the earth rotates underneath, a ground-based observer looks at these features in the same way that an azimuthal scanning radar would. The "observing screen" of the upper atmosphere can thus be monitored continuously, on a worldwide scale, from stations on the ground, and sporadically by means of instrumentation flown on airplanes, balloons, and rockets. In this way *all* countries have the opportunity of making significant contributions to magnetospheric research, regardless of their satellite launching capability. One of the most serious difficulties in this study is that the magnetospheric configuration is so very time-dependent: the magnetosphere is in a "permanent state of recovery" from a never-ending series of severe perturbations; a "steady state" is really never achieved. This complexity and the large spatial scale of magnetospheric phenomena demand a clear separation between spatial and temporal effects in the experimental observations, a fact which in turn requires that simultaneous measurements be conducted with similar instrumentation at spatially different positions, both in space and on or near the earth's surface. This is indeed the main leitmotiv of the International Magnetospheric Study 1976–1978 (*3*).

Some of the most pressing questions regarding the general configuration of the magnetosphere are concerned with the magnetic field-line connection across the magnetopause, the stability of the magnetopause, and the mechanism of transfer of particles, energy, and momentum from the solar wind to the magnetosphere. All three problems are, of course, intimately linked with the analysis of the detailed structure and dynamics of the magnetospheric boundary. In brief, there is mounting evidence from studies of the rapid access of solar flare protons into the magnetosphere (*10*) that the open field lines emerging from the polar caps must somewhere cross the magnetopause and link up with the interplanetary magnetic field that flows past the boundary, embedded in the solar wind (Fig. 2). Other effects (see next sections), pointing to an active role of the interplanetary magnetic field in causing asymmetries and triggering magnetospheric perturbations, corroborate the idea of field line connection across the magnetopause. The "escape" into the solar wind of magnetic flux emerging from the polar caps causes a tangential stress on the boundary, a

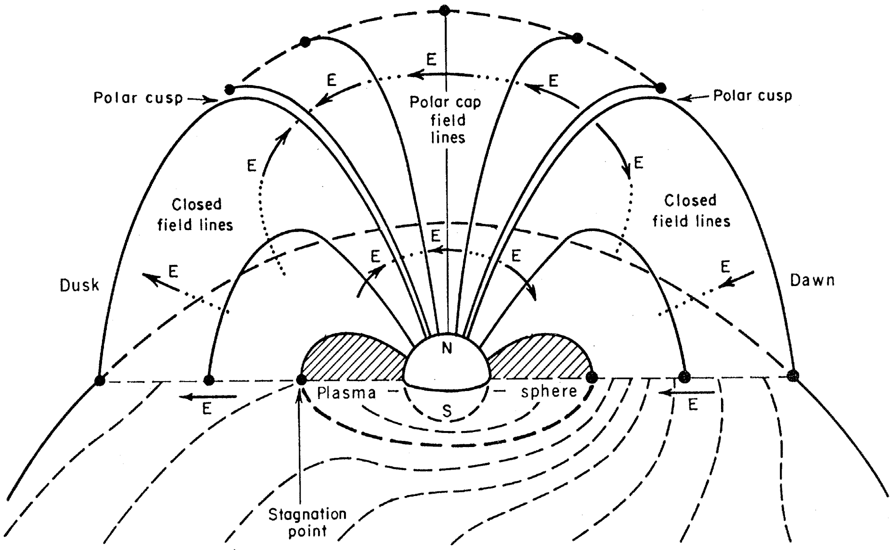

Fig. 3. A sketch of the steady-state electric field configuration on the dawn-dusk meridional plane of the magnetosphere. (Solid lines) Projections of the magnetic field lines on the dawn-dusk meridional plane; (dotted lines) electric field lines; (dashed lines) electric equipotentials on the geomagnetic equator.

force per unit area of value $B_n B_t / 4\pi$, where B_n is the (very small) magnetospheric field component perpendicular to the magnetopause and B_t is the parallel component (related to the boundary current density). The product of this stress and the (tangential) solar wind velocity, integrated over the whole magnetopause, represents the total power delivered by the solar wind to the magnetosphere, estimated at 10^{12} watts. The dissipation of this steady energy input—partly through continuous processes, partly via transient "bursts" of energy dumped into the upper atmosphere during magnetospheric substorms—is what makes the magnetosphere such a highly dynamic, restless physical system.

The transfer of solar wind particles into the magnetosphere is probably accomplished through the dayside cusps (Fig. 2). Plasma that penetrates into these magnetic "funnels" is believed to flow along the cusps as they extend to the flanks of the magnetosphere, into the geomagnetic tail. The recently discovered boundary layer (*13*) of the tail (Fig. 2), several thousand kilometers thick, filled with magnetosheath-type plasma but of slower flow speed and lower density, may play a fundamental role in the access of solar wind plasma into the magnetospheric tail. The boundary layer probably is the site of the currents which confine the tail to its cylindrical shape and, as such, could be responsible for the process of magnetic field line connection between the magnetosphere and interplanetary space. The dayside cusps are the locus of a system of field-aligned currents that could function as a key link between the dayside ionosphere, the magnetosphere, and the solar wind.

The Electric Field

Considerable progress has been made in recent years in the study of the electric field of the magnetosphere. This electric field is quite difficult to measure because it is so weak (millivolts per meter or less) and so highly variable in time and space. Direct measurements from satellites have begun only in recent years (*14*); indirect techniques based on the study of energetic particle motion (*15*) and drifts of natural (*16*) or artificial (*17*) plasmas have been historically the first to provide information on the electric field. Balloon-borne measurements (*18*) of the horizontal component of the stratospheric electric field—assumed to be roughly proportional to the horizontal electric field in the overlying ionosphere—are becoming an increasingly popular and relatively cheap technique, particularly useful if measurements are carried out simultaneously over periods of many hours at different geographic locations.

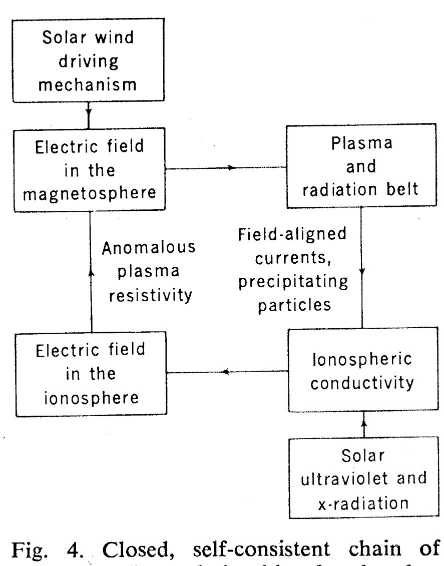

Fig. 4. Closed, self-consistent chain of cause-and-effect relationships for the electric field in the magnetosphere.

The general electric field configuration in the quiet magnetosphere is sketched in Fig. 3, with electric field vectors shown in the northern twilight (dawn-dusk) meridian. Three main regions can be identified: (i) the region of open magnetic field lines linked to the polar cap, carrying an electric field directed mainly from dawn to dusk; (ii) the region of closed field lines crossing the magnetic equatorial surface, carrying an electric field that is directed poleward on the duskside and equatorward on the dawnside; and (iii) the region of the plasmasphere with an electric field (not shown in Fig. 3) that on the equatorial plane is directed radially earthward, responsible for the earth-locked co-rotation of the plasmasphere. Electric field lines are believed to be everywhere perpendicular to magnetic field lines, in the absence of perturbations (magnetic field lines behave like almost perfect conductors, with the electric potential remaining nearly constant along a given field line but changing from line to line). Note in Fig. 3 the sudden electric field reversal across the polar cusps on the dawn-dusk meridian. Typical electric potential drops across the polar cap are of the order of 50 kilovolts. A stagnation point (reversal of the radial electric field) is believed to occur on the duskside plasmapause. Also sketched in Fig. 3 are typical (quiet-time) electric equipotential curves on the equatorial surface. All magnetic field lines passing through a given curve define an equipotential surface. The plasmapause separates the family of open equipotentials from the family of closed equipotentials that encircle the earth inside the plasmasphere. A low-energy plasma particle follows these equipotentials in its $\mathbf{E} \times \mathbf{B}/B^2$ drift motion, where $\mathbf{E}$ is the electric field vector and $\mathbf{B}$ is the magnetic field vector; the result is a general sunward convection from the tail along the open equipotentials and a co-rotational west-east flow around the earth in the plasmasphere. Over the polar caps, this drift is directed away from the sun toward the nightside; this convection is believed to contribute substantially to the maintenance of the nightside high-latitude ionosphere.

The electric field behavior on the noon-midnight meridian is more complex and appears to be more irregular. Low-altitude satellite measurements have detected multiple reversals of the electric field, probably due to motions of the polar cusps; near the midnight meridian the pronounced electric field irregularities observed in the auroral zone (which happen where the electric field switches from a poleward direction before midnight to an equatorward direction after midnight) could be related to the relatively sharp separation of convection patterns to the east and to the west, respectively (Harang discontinuity). Quite generally, the region around the midnight meridian is extremely sensitive to all major magnetospheric perturbations, and so is the electric field therein.

Some features of the electric field show distinct correlations with the interplanetary magnetic field. One of these correlations links the spatial dependence of the dawn-dusk electric field intensity in the polar cap with the azimuthal component of the interplanetary magnetic field (*14*): the electric field tends to be stronger on that side of the polar cap where interplanetary and geomagnetic field lines tend to point roughly in the same direction. As a result of this asymmetry, the whole ionospheric current system in and around the polar cap shifts toward the dawnside or the duskside, controlled by the azimuthal component of the interplanetary magnetic field. The effect of these current shifts is measurable on the earth's surface with conventional magnetometers at appropriately located high-latitude stations (*19*). As an interesting spin-off from this recent finding, it was possible to infer from ground-based magnetograms the periods of time in the past decades during which the interplanetary magnetic field was directed toward or away from the sun (*20*).

Another correlation has been found between the overall intensity of the polar cap electric field and the north-south component of the interplanetary magnetic field. During periods in which the interplanetary magnetic field is directed southward, the polar electric field may increase several times with respect to the periods in which the interplanetary field is directed northward (*21*). This process is related to the growth phase of a substorm (see below).

Both types of correlations are in support of the idea of magnetospheric field lines being connected with the interplanetary magnetic field across the magnetopause. As a matter of fact, the interplanetary field could represent the external "driving mechanism" of the magnetospheric electric field. This can be pictured in the following way: interplanetary field lines embedded in the solar wind move with the velocity $\mathbf{v}$ of the solar wind. An observer at rest in the earth's magnetosphere thus "sees" an induced interplanetary electric field $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$, where $\mathbf{B}$ is the interplanetary magnetic field vector. If the magnetic field lines are electric equipotentials everywhere, it would be possible to map this "external" electric field into the magnetosphere down to the polar ionosphere (*22*), if one knew exactly the manner in which the field lines are connected through the magnetopause. At the present time it is not at all clear whether the interplanetary magnetic field is the sole external cause of the magnetospheric electric field. The existence of a dawn-dusk electric field and associated convection pattern at *all* times, regardless of the characteristics of the interplanetary magnetic field, suggests the coexistence of another, steady-state, external driving mechanism for the electric field, probably caused by a viscous interaction of the solar wind at the magnetopause.

Dynamo effects in the ionosphere, caused by neutral winds dragging plasma across magnetic field lines, represent an additional source of the electric field in the magnetosphere. The co-rotational electric field inside the plasmasphere is entirely of such an origin.

Plasma conductivity in the ionosphere and energetic particle distributions trapped in the magnetic field control both the general configuration and local perturbations of the electric field. For instance, in regions of *localized* enhancements of the conductivity caused by auroral particle precipitation (for example, auroral arcs), the electric field $\mathbf{E}$ adjusts to the irregularity of the conductivity tensor σ (decreasing where the components of σ increase) so as to keep the current density $\mathbf{j} = \sigma\mathbf{E}$ a "smooth' function. On the other hand, when the current intensities in the auroral zone increase by orders of magnitude during magnetospheric substorms, the electric field is found to increase only a few times. This finding indicates that on these occasions the electric field is controlled mainly by an external driving mechanism and it is the current which adjusts to the large increase in ionospheric (Hall) conductivity.

Energetic particles in the radiation belt influence the electric field configuration indirectly through the electric currents (perpendicular and parallel to the magnetic field lines) that are associated with these particles. In the closed field line region (Fig. 3), the electric field is part of a self-consistent. closed chain of cause-and-effect relationships (Fig. 4), governing the strong feedback system of magnetosphere-ionosphere coupling (*23*). The requirement of self-consistency makes a quantitative theoretical study of the magnetospheric electric field (and plasma) particularly difficult.

Magnetospheric Plasma

Plasma of atmospheric origin. Ionization produced in the upper atmosphere by solar ultraviolet and x-radiation and by precipitating auroral particles (at high latitudes) may diffuse and expand along magnetic field lines to high altitudes. On open field lines (Fig. 2) this gives rise to the "polar wind" (*24*), an expansive flow of atmospheric ions and electrons from the polar ionosphere away from the earth into the magnetospheric tail and into the dayside cusps. At lower latitudes, in the closed field line region, the atmospheric ions and electrons remain trapped by the co-rotational electric field, giving rise to the plasmasphere (*25*) (Fig. 2). The typical average energy of a plasmasphere proton is 1 electron volt (this comparatively low value explains why this particle population is also called a "cool" plasma). The particle concentration is roughly constant within about 3.8 R_e, decreasing with geocentric radial distance as R^{-4} beyond that limit. The plasmasphere has a sharp outer boundary, the plasmapause (*26*), where the particle density drops suddenly by a factor of 10 to 100. Beyond the plasmapause, though still on closed magnetic field lines, plasma particles do not co-rotate anymore; they are convected along open equipotentials (Fig. 3) from the tail toward the dayside boundary of the magnetosphere. This corresponds to the "trough" region of Fig. 2.

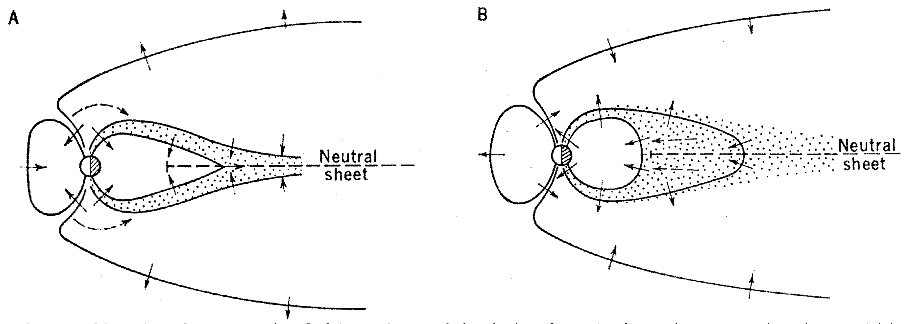

Fig. 5. Sketch of magnetic field and particle behavior during the growth phase (A) and the expansive phase (B) of a substorm. (Solid arrows) Field line and boundary distortions; (broken arrows) particle convection; (dotted region) plasmasheet.

The shape of the plasmapause is controlled by the electric field configuration, particularly the dawn-dusk electric field component. During quiet times the plasmasphere extends to geocentric distances of up to 7 R_e in the equatorial plane. Whenever the electric potential across the magnetosphere increases considerably, as happens during substorms (see next section), the region of closed equipotentials contracts, the outer layers of the plasmasphere "peel off," and the plasmapause may move in to as close as 3 R_e. It is not yet known what fraction of the plasma is convected away (toward the magnetopause) along the newly formed open equipotentials and how much is precipitated along magnetic field lines into the nightside ionosphere. After the dawn-dusk electric field has recovered to its quiet-time value, which takes 1½ to 2 hours, the closed equipotential region expands back to 6 to 7 R_e. But it takes several days for the closed equipotential region to fill with ionospheric plasma to prestorm levels. During that time two (or more) "plasmapauses" may be detected. They are the remnant sharp density gradient that had been formed close to the earth during the erosion process and the new density gradient that develops at the recovered, quiet-time limit of closed equipotentials at a larger distance.

The plasmapause exhibits important asymmetries (a bulge in the dusk-to-midnight sector) and irregularities around midnight (particularly during substorms). Since it can be adequately monitored with the ground-based technique of "whistlers" (electromagnetic waves in the kilohertz range, generated by thunderstorm lightning flashes, that propagate back and forth between hemispheres along field-aligned ducts of enhanced ionization), this method has become an important tool of magnetospheric research (*27*).

Plasma of solar wind origin. The plasmasheet (*28*) is a reservoir of "warm" plasma that extends to both sides of the neutral sheet of the tail (Fig. 2), reaching during quiet times from an earthward edge at about 10 R_e on the midnight meridian to well past the moon's orbital radius (60 R_e). It thickens toward the flanks of the tail with a dawn-to-dusk asymmetry (mutually opposite for protons and electrons). A typical average proton energy is 6 kiloelectron volts. Near its midplane, the kinetic energy density of the plasmasheet is large relative to the energy density of the local magnetic field ("high-beta" plasma). The particle distribution is nearly uniform at distances up to 1 to 2 R_e to each side of the midplane (neutral sheet). Beyond that distance, particle density and kinetic energy decrease; at about 3 R_e from the neutral sheet the very low particle density of the tail lobes is attained—the two tail regions where the magnetic field energy density dominates. It is not yet clear whether or not the entire plasmasheet population is confined to closed (but highly stretched out) field lines. The tenuous plasma in the lobes certainly lies on open field lines.

The plasmasheet is a highly dynamic region, playing a key role in the development of magnetospheric substorms (see next section). Quite generally, it is impossible to discuss the structure of the plasmasheet without specifying the time history of its perturbations. During quiet times, the flow in the plasmasheet seems to be turbulent and the particle temperature decreases gradually with time. During substorms, organized flows are detected (see next section), and considerable increases in particle energy are seen. The low-density plasma in the tail lobes, on the other hand, remains remarkably constant throughout these perturbations.

One of the most interesting magnetospheric problems is that of the steady-state maintenance of the electric current in the neutral sheet. It is not known whether this region is turbulent or not, nor is it known whether this region contains one or more neutral lines. Even the overall magnetic field geometry has yet to be established with reasonable statistical accuracy in the vicinity of the neutral sheet.

I have already mentioned in the section titled "Magnetospheric Configuration" that a boundary layer of plasma with an antisunward flow has been recognized between the magnetosheath and the plasmasheet (*13*). This layer is several thousand kilometers thick and may well envelop both tail lobes completely (except for the region where the neutral sheet merges into the boundary). It must play a fundamental role in the transfer of solar wind plasma, energy, and momentum to the magnetosphere.

For particle number densities n and temperatures T (or energies) one finds the following qualitative relationships (*28*):

Magnetosheath		Boundary layer (and polar cusps)		Plasmasheet
n_m	$>$	n_B	$\gg$	n_P
T_m	$\lesssim$	T_B	$<$	T_P

Because of the high variability in time, it would not make much sense to quote actual numbers here. Comparison of the gradually "hardening" energy spectra of particles in the magnetosheath, the boundary layer (and polar cusps), and the plasmasheet suggests that these particles must have gone through highly selective injection and acceleration processes during their entry into the magnetosphere. In order to study these transfer mechanisms quantitatively, it is of fundamental importance to analyze and compare the behavior of *different* species of ions (protons, alpha particles, and heavier nuclei).

Waves in magnetospheric plasma. Plasma behaves like an elastic medium: it is able to transmit stress and strain from one point to another (*29*); the magnetic field acts as the physical agent tying together the constituent particles. A small perturbation can propagate along a field line as on an elastic string—this represents the so-called Alfvén waves. There is another possible mode of propagation, in which the perturbation jumps from one field line to another; this mode leads to an essentially isotropic propagation. Both modes are detected in the magnetosphere, having periods between 0.2 and 10 seconds, principally on field lines of the auroral oval. Often they appear in the form of wave "packets" traveling back and forth along a field line. They were first discovered in ground magnetometer records and given the name of magnetic pulsations or micropulsations (*30*). Longer period hydromagnetic waves are found mainly in the dayside magnetosphere (having periods of 10 to 50 seconds) and on auroral field lines (50 to 500 seconds). These ultra-low-frequency, long-wavelength modes correspond to elastic oscillations of magnetic flux tubes as a whole (roughly like air oscillations in an organ pipe). They all can be detected on the ground after they have filtered through the ionosphere. The generation mechanisms of these waves are not yet fully known or understood. Some are linked to substorm perturbations, occurring mainly during the recovery phase (see next section). The 10- to 50-second oscillations seem to be triggered by changes in the size of the magnetospheric cavity, probably caused by perturbations in the solar wind. There are other, aperiodic, hydromagnetic waves triggered by sudden compressions or expansions of the magnetopause caused by interplanetary shock waves. On ground magnetograms they appear as the so-called "sudden impulses."

The Magnetospheric Substorm

A "substorm" (*31*) is the single most important perturbation event in the magnetosphere in which magnetic energy that has been accumulated in the tail is suddenly released and dissipated in the form of particle energy. Substorms occur either in isolated form once every several hours (sometimes days) or in a rapid sequence consisting of several events per hour, often as the result of an interplanetary compression or expansion shock wave, triggered by a solar flare, impinging on the magnetosphere. This latter event represents a magnetic storm (historically, this is the reason why substorms have been called *sub*storms). Auroral particle energy release rates during big storms may be as high as 1.5×10^{13} watts, with a total energy deposited into the auroral zone atmosphere of the order of 2×10^{16} joules.

The study of isolated substorms is most important for the understanding of magnetospheric dynamics. One of the great difficulties in this study is related to the finite propagation velocity of the perturbation throughout the whole magnetosphere, which makes the accurate timing of events difficult to establish experimentally. Most scientists believe that a substorm is triggered by a southward-turning of the interplanetary magnetic field, although some controversy still persists as to whether this is a "necessary" or a "sufficient" condition, or both.

Substorms seem to proceed in several stages. The first of these is the growth phase (*31*) in which one observes (Fig. 5A): (i) a gradual inward displacement of the dayside boundary of the magnetosphere, a lowering of the dayside cusp latitudes, and an increase in the area and magnetic flux encompassed by the polar caps; (ii) an increase of the tail field intensity, an increase in the neutral sheet current density, and an earthward displacement of its inner edge; and (iii) a "stretching" of field lines into the tail, a flaring up of the tail boundary, and a gradual "thinning" of the plasmasheet. All this points to a transfer of magnetic flux tubes from the dayside magnetosphere to the tail and the accumulation of magnetic energy therein. A controversy exists (*32*) concerning the "universality" of the growth phase, the observability of its ground effects, and its timing relative to the expansive phase.

On many occasions the magnetic energy accumulated in the tail may be dissipated as it keeps coming in and nothing drastic happens; but if a certain not yet well-established threshold is reached, or when the interplanetary magnetic field ceases to be directed southward, an explosive process is triggered representing the expansive phase (Fig. 5B) of the substorm, with many effects observable on the ground (*33*). The previously enhanced neutral sheet current starts collapsing, a process that begins at its near-earth edge and propagates outward down the tail. This collapse is thought to be caused by a redirection of the neutral sheet current system *along* magnetic field lines into and from the ionosphere. This rapidly leads to a more dipole-like, less tail-like, configuration of the nightside magnetic field; the plasmasheet returns to its "normal" thickness, a restitution process that also seems to start near the earth and propagate down the tail. An intense current, the polar electrojet, starts flowing in a relatively narrow band in the auroral zone ionosphere, giving rise to intense magnetic disturbances registered at high-latitude ground observatories. There are indications that at the same time the dawn-dusk electric field in the distant magnetosphere is greatly enhanced. As a result of this enhancement, particles of the plasmasheet are convected toward the earth and accelerated. Some of these particles are precipitated into the atmosphere, producing intense auroral displays. Others are injected into magnetically trapped orbits, feeding the radiation belt (see next section). Finally a recovery phase sets in, during which the plasmasheet and the magnetic field gradually attain the quiet-time, prestorm configuration—a state which, however, really is never achieved before the next substorm sets in.

It has not yet been established with certainty what physical process causes the magnetic flux transfer from the dayside magnetosphere to the tail. Many investigators invoke a process called "field line reconnection" (*34*) between a southward-directed interplanetary field and the oppositely directed field lines on the dayside magnetopause, and a subsequent "peeling off" and "deposition" of magnetic flux into the tail. A reconnection mechanism is also thought to set in somewhere across the neutral sheet between the oppositely directed magnetic fields of the tail lobes, signaling the onset of the expansive phase of the substorm. Recent plasma flow measurements in the plasmasheet seem to lend support to this hypothesis (*28*).

The Radiation Belt and Wave-Particle Interactions

During substorms, large fluxes of electrons and ions from the plasmasheet can be injected deep into the magnetosphere and left there in magnetically trapped orbits. In this process the particles enter a region of gradually increasing magnetic field; as a result they are betatron-accelerated. A typical plasmasheet proton of a few kiloelectron volts at 10 R_e increases its energy by a factor of 10 when it is conveyed to, say, 7 R_e. The plasmasheet is the main source of radiation belt particles, and the substorm is the main injection mechanism. An exception is the high-energy (> 30 megaelectron volts) protons trapped close to the earth's atmosphere at geocentric distances less than about 2 R_e, which are believed to be injected by a quite different mechanism, that is, as decay products of energetic "albedo" neutrons emitted from nuclear reactions caused by cosmic-ray bombardment of the earth's atmosphere. During the early 1960's and until just a few years ago, man-made energetic (megaelectron volt) electron fluxes from fission products released during high-altitude nuclear explosions predominated over the natural electron background in the radiation belt in an extended region of the magnetosphere. Studies made with these artificially injected trapped particles provided much of the early information on radiation belt physics, until the high-altitude nuclear tests of the major powers stopped in late 1962.

Natural radiation belt particles (electrons, protons, and heavier ions) consist of those stably trapped particles whose motion is defined entirely by the confining magnetic field. These high-energy particles are comparatively easy to detect, and, for this reason, they have been under study since the first artificial satellites were launched. The radiation belt configuration and dynamics are now quite well known and understood (*35*), especially by comparison with our still rather meager knowledge of the plasma in the magnetosphere. Radiation belt electrons (about 100 kiloelectron volts to several megaelectron volts in energy) are located predominantly in two toroids known as the inner zone and outer zone (Fig. 6) (*36*). Radiation belt protons are distributed throughout the magnetosphere, with the highest energy particles (hundreds of megaelectron volts) being dominant in the region of the inner electron belt and the lowest energy protons (a few tens of kiloelectron volts) being dominant in the region of the outer zone. The motion of these lower energy protons (and electrons of similar energies) is determined both by the terrestrial magnetic field and by the electric field.

Geomagnetically trapped particles move with three periodicities (*37*): a cyclotron motion around a field line, a bounce motion up and down along a field line between two conjugate "mirror points," and a drift motion around the earth (protons and ions westward, electrons eastward). In addition, they are subject to a series of interactions which actually control the dynamics of the radiation belt (*35*). These include: (i) adiabatic effects, determined by very slow, temporal variations of the magnetic field or by large-scale static field asymmetries; (ii) quasi-adiabatic effects, caused mainly by the transient variations in the electric and magnetic fields during a substorm; and (iii) stochastic diffusion, controlled by fluctuations in the electric and magnetic fields or by interactions with atmospheric atoms and ions.

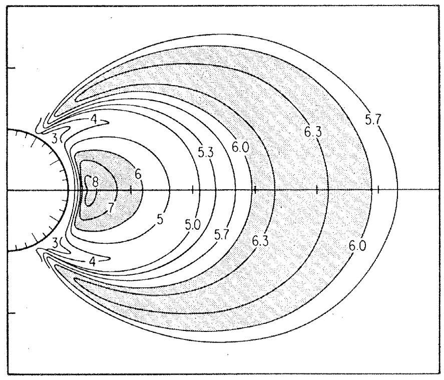

Fig. 6. Average omnidirectional isointensity contours of radiation belt electrons with an energy of 0.5 megaelectron volt (*36*). Numbers are the decimal logarithms of the omnidirectional intensities (particles per square centimeter per second).

Adiabatic effects are well understood, particularly those related to magnetospheric field asymmetries (*35*) (for example, day-night asymmetry and slow time variations due to the external currents, and static distortions due to the earth's internal field anomalies). A recently studied time-dependent adiabatic effect of importance is related to the slow secular decrease of the magnetic dipole moment of the earth (0.16 gauss-R_e^3 per century). This causes the ultrastable high-energy protons of the inner radiation belt to slowly approach the earth and be absorbed by the atmosphere (*38*).

The study of quasi-adiabatic effects requires a detailed knowledge of electric and magnetic field behavior during magnetospheric perturbations that is not yet available. Diffusion processes are better known (*39*). Some lead to what is called radial diffusion, whose net effect is a transport of particles across field lines from the external source toward the earth. In this process particles always gain energy via betatron acceleration. Other diffusion mechanisms lead to pitch angle diffusion, that is, a scattering of the angle between the particle velocity and the trapping field, whose net effect is a transport of particles from the magnetospheric equator into the atmosphere.

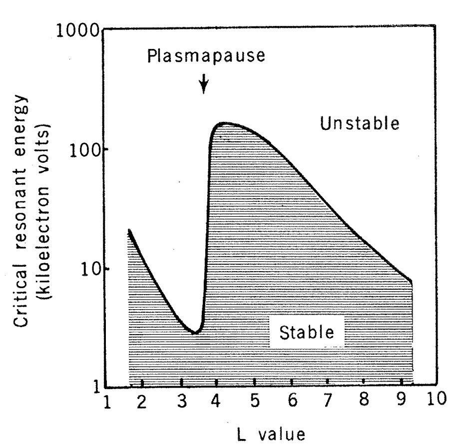

Fig. 7. Critical resonant energy defining the limit of stability for particles trapped in the magnetosphere (*40*), as a function of geocentric distance *L* (in earth radii).

Radial diffusion is caused mainly by random fluctuations in the electric field; magnetic field fluctuations also contribute, but to a lesser extent. These fluctuations seem to occur everywhere in the closed field line region of the magnetosphere, but the radial dependence of their effectiveness (diffusion coefficient) decreases very rapidly as one approaches the earth. This type of radial diffusion is responsible for the radial distribution of trapped electrons and protons and for their reshuffling after major substorm injections.

The most important pitch angle diffusion process in the magnetosphere is caused by resonant interactions between trapped particles and various types of waves that abound in the magnetosphere. Right-hand-polarized, very-low-frequency (kilohertz) electromagnetic "whistler" waves, mentioned earlier, interact with trapped electrons of appropriate cyclotron frequency. Left-hand-polarized, ion-cyclotron waves, also guided nearly along field lines, similarly interact with protons. In these resonance interactions, which are possible whenever the frequency of the wave (as seen by the bouncing particle) is an integral multiple of the particle's cyclotron frequency, energy is exchanged between the particle and the wave. This wave-particle interaction can lead to the development of an instability in the collective behavior of trapped particles. When this happens, the wave amplitude grows exponentially as a result of the energy exchange with the resonating particles while the particles suffer pitch angle scattering in such a way as to line up along the field line and precipitate into the atmosphere. To a first approximation, this instability would continue in effect until enough particles had disappeared so that the particle flux could level off at a certain maximum value permitted for stable trapping.

Wave-particle instability can develop only under the following two conditions: the initial particle pitch angle distribution must be anisotropic, peaking at 90° to the field line, and the particles' initial energy must surpass a critical value E_c, roughly given by the ratio of the local magnetic energy density to the local plasma number density (*40*). The first condition is indeed met by the plasmasheet particles injected during substorms. One can qualitatively analyze the second condition by considering the radial dependence of the ratio that yields E_c (Fig. 7). In general we may draw the following conclusions from Fig. 7:

1) Particles with energies greater than about 100 kiloelectron volts are subject to wave-particle instability throughout the whole magnetosphere, and their maximum fluxes are limited everywhere to the corresponding values predicted for stable trapping.

2) Particles with energies of the order of 10 kiloelectron volts—which constitute the bulk of the trapped particle population in the magnetosphere—are stable only between the plasmapause and 7 to 9 R_e. This is precisely the region occupied by electrons of the outer radiation belt and ring current protons (Fig. 2). Beyond 7 to 9 R_e we have a region of strong diffusion which projects along field lines onto the equatorward edge of the auroral oval (Fig. 2) (see also the diffuse bands in Fig. 1). This is precisely where the main bulk of auroras occur. On the other hand, this particle population is "eroded" by the plasmasphere just behind the plasmapause: when these particles are convected or when they diffuse earthward past the plasmapause, they trigger wave emissions through a wave-particle instability and are subsequently precipitated into the atmosphere. This enhanced precipitation of protons gives rise to luminous effects in the upper atmosphere at mid-latitudes, known as subauroral red arcs.

3) Particles with energies of less than a few kiloelectron volts are stable everywhere. These particles belong to the thermal plasma population of the magnetosphere.

A quantitative description of these processes is now emerging. Many unknowns remain, however, concerning theory and experimental verification. For example, no exhaustive experimental identification of the waves responsible for the above processes has yet been made. Another important problem is related to the following: all major acceleration processes in the magnetosphere have the property that the increase in the energy of a particle is always proportional to the increase of the magnetic field intensity at the particle's "mirror point." Thus, when a plasmasheet particle is convected or radially diffuses toward the earth, or both, the maximum possible increase of the magnetic field experienced by the particle when it reaches the inner belt is at the most 1000 times the initial field. A typical plasmasheet proton with an energy of a few kiloelectron volts thus could achieve an energy of only a few megaelectron volts. Yet higher energy protons are detected in the inner belt. Since the cosmic-ray albedo neutron decay source can explain successfully only the proton population with energies of $\gtrsim$ 30 megaelectron volts (*41*), one must assume that protons with energies between 1 and 30 megaelectron volts do originate in the plasmasheet but that they have undergone several cycles of inbound acceleration and outward energy-conserving diffusion.

Future Goals

During the past 15 years, the study of the earth's magnetosphere—man's immediate plasma and radiation environment—has undergone a successful stage of discovery and exploration. Investigators have obtained a morphological description of the magnetospheric field, the particle population embedded in it, and its interface with the solar wind, and have identified and are beginning to understand many of the physical processes involved. Quite generally, the magnetosphere reveals itself as a region where we can observe some of the fundamental plasma processes at work that are known to occur elsewhere in the universe.

Now it is time for a transition from the exploratory stage to a stage in which satellite missions and ground-based, aircraft, balloon, and rocket observations are planned with the specific objective of achieving a quantitative understanding of the physical processes involved. Some of the principal targets of current research are the following: the electric field in the magnetosphere; the dynamics of the two main plasma reservoirs (plasmasphere and plasmasheet) and their boundaries; the interaction between trapped particles and waves; the transfer of particles, energy, and momentum from the solar wind to the magnetosphere; and the development of a fundamental instability, the magnetospheric "substorm." It is expected that research carried out as part of the International Magnetospheric Study 1976–1978 will solve many of the problems involved, particularly those related to the timing of dynamical changes during substorms, the identification of spatial locations for these changes, the nature of magnetospheric boundaries, and the energy budget in the solar wind–magnetosphere–ionosphere system. Several basic quantitative questions concerning intricate closed loops of cause-and-effect relationships controlling this system will, however, remain unanswered. The space shuttle in the 1980's will offer a unique opportunity to study systematically on a large scale these puzzling strong feedback loops because it will be possible to introduce small, man-made perturbations of known initial conditions with orbiting particle accelerators, plasma injectors, and high-power transmitters for wave injections.

Paradoxically, magnetospheric research has come under criticism in recent years, particularly in discussions of research priorities involving other space-oriented disciplines. A frequent argument is that, since no important new discoveries can be expected in the magnetosphere, the meager space research funds should be dedicated to more "exciting" topics—it is left up to each individual to interpret the meaning of "exciting." In my opinion there remain many exciting—though perhaps not so "glamorous"—problems to be studied in the magnetosphere, all related to the quantitative understanding of fundamental physical processes that govern the earth's outer environment, and, on a larger scale, that of the sun and other stars. Another factor adversely affecting the further development of magnetospheric research is the dwindling general support of the "pure" sciences. Both public and official attention is being directed away from fundamental scientific research under the pressure of demands for so-called "relevance," a trend that is pervading many fields of pure science, distorting the original goals toward what in many cases are outright phony lists of "more relevant" and "more society-oriented" spin-offs. In my opinion, *any* inquiry is "relevant," no matter what the particular target, as long as the effort contributes positively to the understanding of our world and of man's place in it. Where would astronomy, mathematics, physics, philosophy, or, as a matter of fact, science as a whole be today, if more enlightened sectors of humanity had not in the past allowed scholars to pursue their quest for truth for the sake of the truth and nothing but the truth?

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Genetic Control of the Cell Division Cycle in Yeast

A model to account for the order of cell cycle events is deduced from the phenotypes of yeast mutants.

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Mitotic cell division in eukaryotes is accomplished through a highly reproducible temporal sequence of events that is common to almost all higher organisms. An interval of time, *G1*, separates the previous cell division from the initiation of DNA synthesis. Chromosome replication is accomplished during the DNA synthetic period, *S*, which typically occupies about a third of the cell cycle. Another interval of time, *G2*, separates the completion of DNA synthesis from prophase, the beginning of mitosis, *M*. A dramatic sequence of changes in chromosome structure and of chromosome movement characterizes the brief mitotic period that results in the precise separation of sister chromatids to daughter nuclei. Mitosis is followed by cytokinesis, the partitioning of the cytoplasm into two daughter cells with separate plasma membranes. In some organisms the cycle is completed by cell wall separation.

Each of these events occurs during the cell division cycle of the yeast, *Saccharomyces cerevisiae (1)* (Fig. 1). However, two features which distinguish the cell cycle of *S. cerevisiae* from most other eukaryotes are particularly useful for an analysis of the gene functions that control the cell division cycle. First, the fact that both haploid and diploid cells undergo mitosis permits the isolation of recessive mutations in haploids and their analysis by complementation in diploids. Second, the daughter cell is recognizable at an early stage of the cell cycle as a bud on the surface of the parent cell. Since the ratio of bud size to parent cell size increases progressively during the cycle, this ratio pro-

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