Plasma Motions in Planetary Magnetospheres

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Before direct exploration by spacecraft, Jupiter was the only planet other than Earth that was known to have a magnetic field, as revealed by its nonthermal radio emissions. The term "magnetosphere" did not exist because there was no clear concept of such an entity. The space age provided the opportunity to explore Earth's neighborhood in space and to send instruments to seven of the other eight planets. It was found that interplanetary space is pervaded by a supersonic "solar wind" plasma and that six planets, including Earth, have magnetic fields of sufficient strength to deflect this solar wind and form a comet-shaped cavity called a magnetosphere. Comparative study of these magnetospheres aims to elucidate both the general principles and characteristics that they share in common, and the specific environmental factors that cause the important, and sometimes dramatic, differences in behavior between any two of them. A general understanding of planetary magnetospheres holds the promise of wide applicability in astrophysics, which, for the indefinite future, must rely solely on remote sensing for experimental data.

A PLANETARY MAGNETOSPHERE (*1*) IS THE REGION OF SPACE wherein the planet's magnetic field exercises a dominant influence on the motion of low-energy plasmas and energetic charged particles. Planetary magnetospheres are confined to comet-shaped cavities in the "solar wind" [the interplanetary medium composed of plasma emanating supersonically from the sun (*2*)]. This basic idea was put forth nearly a century ago by Birkeland (*3, 4*) who wrote that the "earth's magnetism will cause there to be a cavity around the earth in which the [solar wind] corpuscles are, so to speak, swept away." However, in spite of this and other independent arguments to the contrary (*5*), the view that Earth's dipole magnetic field extends unimpeded into the "vacuum" of space persisted until the early 1960s, when direct spacecraft measurements showed that the solar wind is continuously present, and confines the geomagnetic field to a cavity that extends typically about 10 R_E in the sunward direction (1 R_E = 1 Earth radius), and much farther in the antisunward direction (just how much farther is still unknown).

Of the nine planets, six are known to have fully developed magnetospheres (Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune). The necessary and sufficient condition is that the energy density ($B^2/2\mu_0$) of the planetary magnetic field ($B \sim M/r^3$ where M = dipole moment) must balance the solar-wind ram pressure ($P = \rho v^2$ where ρ = mass density and v = velocity) at an upstream planetocentric distance R_M that exceeds the planetary radius R_P:

$$R_M/R_P = [\alpha B_P^2/(2\mu_o \rho v^2)]^{1/6} > 1 \qquad (1)$$

where $B_P = M/R_P^3$ is the equatorial strength of the dipole magnetic field at the surface (or cloud tops in the case of the gaseous outer planets), and the dimensionless factor $\alpha \approx 6.5$ corrects for the various oversimplifications in the above description (*6*). Equation 1 defines the distance from the center of the planet to the nose of the "magnetopause," the boundary that separates the magnetosphere from the solar wind (Fig. 1). For typical solar-wind parameters [$\rho \sim (8 \text{ amu/cm}^{-3})/R^2$ and $v \sim 400$ km s^{-1} independent of R, where R = heliocentric distance in AU], this nose distance has respective values of 1.6, 10, 42, 19, 25, and 24 planetary radii for Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune. The observed magnetospheric dimensions are compatible with this scaling law with the exception of Jupiter, where the nose distance is observed to be highly variable with an average value about twice the nominal value owing to the presence of interior plasma with a pressure comparable to the magnetic field pressure. These planets are thus protected by their magnetic fields not only from the typical solar wind but also from any known solar-wind outburst. One might conclude that an order-of-magnitude increase of solar-wind ram pressure, a rare but not unprecedented occurrence, would push Mercury's magnetopause down to its surface. However, the magnetic induction that would accompany such an inward motion of the magnetopause would temporarily strengthen Mercury's magnetic moment so it would continue to hold off the solar wind (*7*).

Venus and Mars appear to have insufficient magnetic moments to prevent the typical solar wind from striking the planetary atmosphere; it is worth noting, however, that the resulting solar wind–ionosphere interaction (*8*) can produce an "induced" comet-like magnetosphere that mimics, in some ways, the behavior of the "intrinsic" planetary magnetospheres. Pluto has not been explored by spacecraft, nor is there a firm theoretical basis for predicting a priori the presence or absence of a magnetic moment sufficient to produce a magnetosphere. There is, as yet, no evidence that any of the planetary satellites has a magnetic moment sufficient to produce its own magnetosphere within the magnetosphere of its parent planet.

Earth's magnetosphere (Fig. 1) is the best explored, and therefore the best understood, of the planetary magnetospheres. The six known planetary magnetospheres are, in the broadest sense, similar: they all (i) are created by a central planet whose internal magnetic field extends outward to form a magnetic cavity within the supersonic solar wind, (ii) contain a population of energetic charged particles (such as Earth's Van Allen radiation belts), and (iii) produce nonthermal radio and optical emissions, most commonly in association with active aurora (Fig. 2). Such emissions have been observed from all of the magnetized planets except Mercury, where the atmosphere is extremely tenuous and such emissions, if any, are below present detection thresholds. In spite of these gross similarities, the planetary magnetospheres exhibit important differences, some of them as fundamental as the source of power and plasma that produce the observed array of magnetospheric phenomena.

Solar Wind–Driven Convection

Power for most magnetospheric phenomena is delivered through a process called magnetospheric convection, a large-scale circulation

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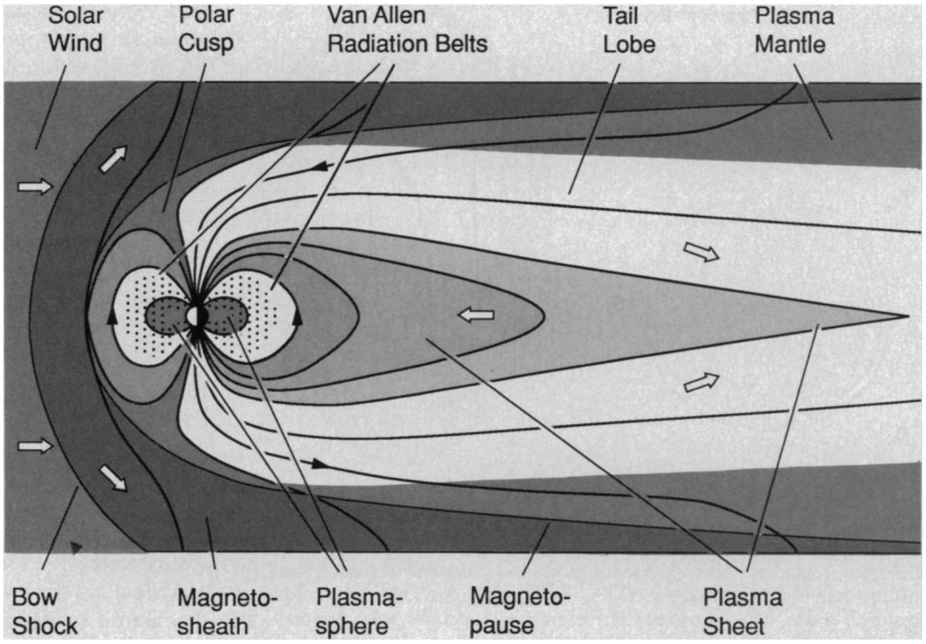
Fig. 1. Sketch of Earth's magnetosphere in the noon-midnight meridian plane, showing the location of various plasma domains described in the text. Open arrows indicate direction of plasma circulation or "convection."



of plasma within the magnetosphere. Magnetospheric convection is generally driven either by the solar wind or by planetary rotation. The solar wind is the primary driver of magnetospheric convection in the cases of Earth and Mercury (because the rotational energy source is relatively feeble) and probably also in the cases of Uranus and Neptune (because of the large misalignment of their spin and magnetic axes as described below).

Modern concepts of solar wind–driven magnetospheric convection have their foundations in two papers published in 1961. Axford and Hines (*9*) deduced from ground-based auroral observations that the solar wind drives antisunward motion of plasma in the high-latitude ionosphere, with a compensating sunward return flow at lower latitudes (Fig. 3A). Using a teardrop-shaped model of the magnetosphere (*10*), they mapped the inferred ionospheric flow pattern out along magnetic field lines to the equatorial plane of the magnetosphere to obtain a picture equivalent to Fig. 3B. Axford and Hines proposed that this convection pattern is driven by the solar wind through a viscous interaction at the magnetopause, noting, however, that the effective viscosity must exceed, by many orders of magnitude, the ordinary collisional viscosity in order to transfer enough power into the magnetosphere to account for the aurora and other associated phenomena. Dungey (*11*) made essentially the same deduction and further proposed that the required "viscosity" could be provided by magnetic tension developed along "open" magnetic field lines that link the solar wind directly to the Earth's polar caps (Fig. 4).

It is now widely recognized that Dungey's open magnetosphere mechanism provides at least 80 to 90% of the solar-wind magnetosphere coupling at Earth, although the remaining 10 to 20% remains hotly contested. The supporting evidence centers largely on the fact that the magnetosphere is more active when the interplanetary magnetic field (IMF) has a southward component, thus facilitating its interconnection with the geomagnetic field, than when it has a northward component (*12*). Other quasi-viscous momentum transfer processes, such as cross-field particle diffusion and Kelvin-Helmholtz instability, continue to merit attention, not only for their possible supporting role in terrestrial solar-wind magnetosphere coupling, but also for their potentially dominant role in other magnetospheres where the controlling parameters are different. And there remains a great deal of uncertainty, hence controversy, about the details of how an open magnetosphere actually works (*13*).

Details aside, it is widely agreed that the solar wind drives antisunward convection on tail lobe magnetic field lines that are connected to the IMF (Fig. 4) and, to a lesser extent, on field lines of the low-latitude boundary layer (LLBL) just inside the magnetopause (Fig. 3B). Whether or not the field lines in this LLBL also connect to the IMF is one of the important "details" still under investigation. The convection system can be characterized either by the plasma bulk velocity **v** or by the electric field **E**, the two being related by the ideal magnetohydrodynamic (MHD) approximation

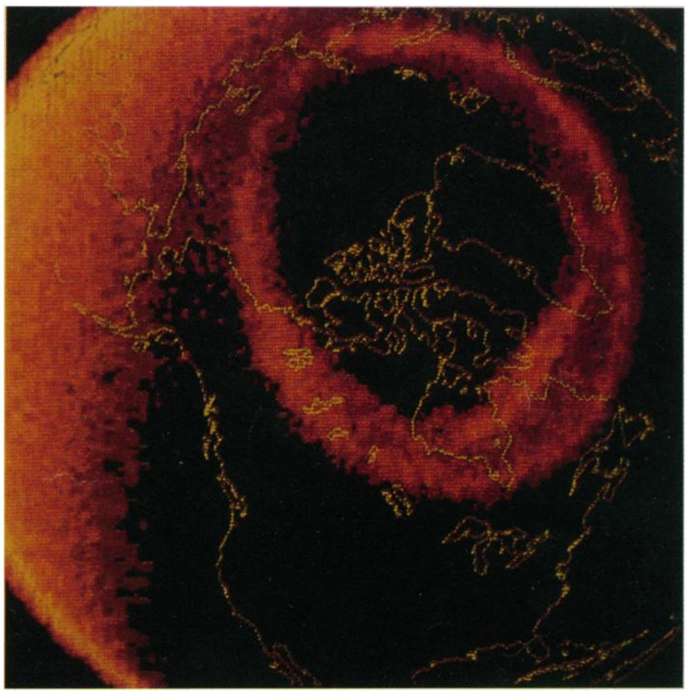


Fig. 2. Ultraviolet image of Earth obtained by a spin-scan photometer on the DE-1 satellite on 8 November 1981 (*41*). Scattered sunlight from the dayside hemisphere is visible on the left. The northern auroral oval is illuminated in this image primarily by the 130.4-nm line of atomic oxygen excited by the impact of electrons precipitating from the magnetosphere. [Reprinted with permission of the American Geophysical Union]

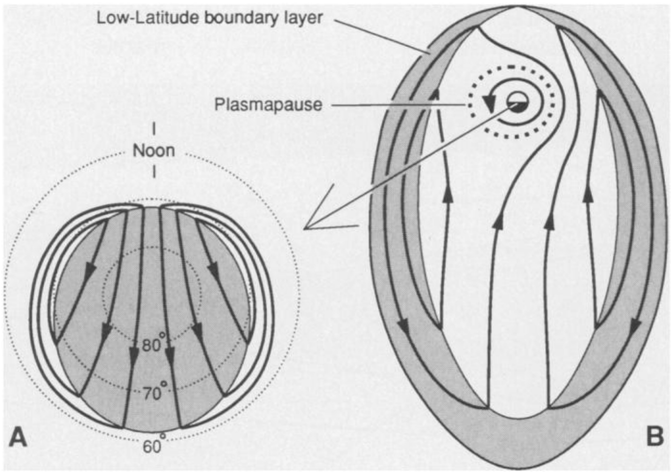


Fig. 3. (**A**) Sketch of the average plasma circulation pattern in the high-latitude ionosphere, comprising antisunward flow within the polar cap (shaded) and a return flow toward the sun at lower latitudes. (**B**) The inferred circulation pattern in the magnetospheric equatorial plane, obtained (*9*) by mapping the pattern of (A) along magnetic field lines within a teardrop model of the magnetosphere. In this model the polar cap maps to the low-latitude boundary layer of the magnetosphere. Inside the plasmapause, corresponding to surface magnetic latitudes of less than about 60°, the plasma essentially corotates with Earth.

$\mathbf{E} + \mathbf{v}\times\mathbf{B} = 0$ (the frozen field condition, where **B** is magnetic field). The $-\mathbf{v}\times\mathbf{B}$ electric field imposed on the magnetosphere by the solar wind drives not only the antisunward flow of the polar cap ionosphere, but also a compensating sunward return flow in the "auroral oval" at latitudes just equatorward of the polar cap. The polar cap ionosphere maps to the tail lobes and perhaps the LLBL, while the auroral oval maps to the magnetotail plasma sheet and its earthward extension, the ring current, the details of this mapping being likewise uncertain. The establishment of the return flow in the plasma sheet is by no means trivial, a point to which we shall return.

The global dynamics of this convection system is related intimately to the flow of electric current through the system. The conduction current in the ionosphere obeys a straightforward Ohm's law relationship and is therefore dissipative ($\mathbf{j}\cdot\mathbf{E}>0$ in the reference frame of the neutral atmosphere, where **j** is current density). The ionospheric conduction current is connected by Birkeland (magnetic field–aligned) currents to transverse ($\perp\mathbf{B}$) currents in the magnetosphere. The latter are not directly related to **E** by an Ohm's law relationship, but are instead associated, through the MHD equation of motion, with pressure gradients or acceleration of the plasma, or both. Deceleration of the solar wind in the vicinity of the tail magnetopause provides the "dynamo" current ($\mathbf{j}\cdot\mathbf{E}<0$) for the magnetosphere "circuit," extracting from the nearby solar wind the energy that ultimately is expended by all the "dissipative" ($\mathbf{j}\cdot\mathbf{E}>0$) elements of the circuit. The latter include, in addition to the ionospheric conduction current, the cross-tail current, which provides the earthward acceleration and heating of plasma-sheet plasma, and the "partial ring current," that is, the azimuthally asymmetric part of the ring current carried by trapped particles drifting around the Earth.

In Mercury's magnetosphere, where the electrical conductivity of the atmosphere is negligible, the dynamo currents presumably couple only to the magnetotail and partial ring currents, giving rise to what might be considered a "pure" solar wind–magnetosphere interaction, in which the only role of the planet is to provide the requisite magnetic dipole moment. In Earth's magnetosphere, the situation is wonderfully enriched (or horribly complicated, depending on one's point of view) by the ionosphere, which is sufficiently conductive to couple significantly both to the dynamo currents (*14*) and to the magnetotail/ring currents (*15*). Sorting out these current systems is an active topic of both observational and theoretical research.

On a global scale, the connecting Birkeland currents can be assumed to flow without resistance ($\mathbf{E}\cdot\mathbf{B} \approx 0$), but in localized regions the requisite Birkeland current density taxes the available flux of charge carriers in the ambient plasma, resulting in potential drops of a few kilovolts along the magnetic field. This occurs almost exclusively in regions of upward Birkeland current (*16*) because the flux of electrons available to carry a Birkeland current is larger at the low-altitude, ionospheric end of a given magnetic flux tube than at the high-altitude, magnetospheric end. (Positive ions are much less mobile than electrons and carry a negligible fraction of the Birkeland current.) The resulting magnetic field–aligned potential drops, although a relatively minor fraction of the total cross-magnetosphere potential drop, are responsible for the most dramatic manifestation of magnetospheric convection, the discrete aurora.

As we noted earlier, the establishment of the return (sunward) flow at auroral latitudes, as required by a given direct (antisunward) flow in the polar cap, is not trivial. Faraday's law requires that, in a steady state or a long-term average sense, the electromotive force (EMF) along the magnetotail X-line should be equal and opposite to that across the dayside X line (Fig. 4), that is, magnetic flux should exit the nightside polar cap at the same rate as it enters the dayside polar cap. Empirically it is found (*12*) that, on the convection timescale (~1 hour), the nightside EMF responds quite nonlinearly to changes in the dayside EMF, and theoretical arguments (*17, 18*) indicate that the process of sunward convection in the magnetotail may be intrinsically sporadic even if the flow imposed on the dayside is constant. The sunward flow in the plasma sheet does not occur smoothly and continuously but rather in the form of a series of events known as magnetospheric "substorms," lasting typically ~1 hour and occurring typically a few times per day. The manifestations of a magnetospheric substorm include the downtail ejection of a major piece of the plasma sheet (a "plasmoid") with the attendant partial collapse of the magnetotail configuration, injection of plasma into the ring current, diversion of current from the near magnetotail into the ionosphere, and expansion and intensification of auroral displays with their associated magnetic perturbations and nonthermal radio emissions. The substorm

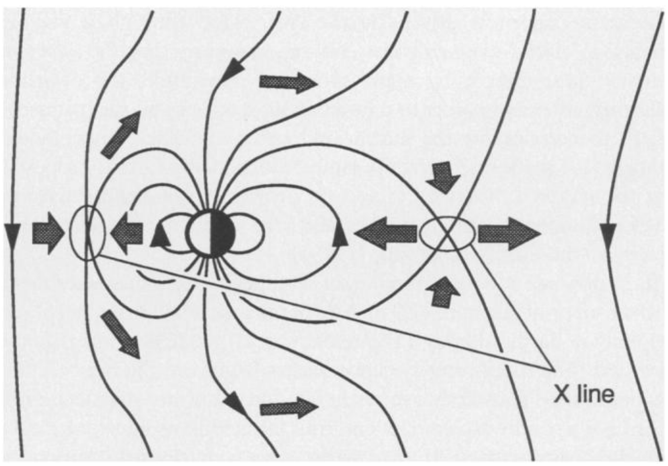


Fig. 4. Sketch of the magnetic topology of Dungey's "open" magnetosphere model (*11*) in the noon-midnight meridian plane. In this model, magnetic field lines from the northern and southern polar caps extend into the solar wind. Interconnection of geomagnetic and interplanetary magnetic field lines occurs through a process called magnetic merging at the dayside X line, and disconnection occurs through the same process at the nightside X line. The tension of these interconnected magnetic field lines transfers solar-wind momentum into the high-latitude magnetosphere, driving the plasma circulation pattern indicated by large arrowheads.

phenomenon is a lively, complicated, and often controversial research topic, made all the more interesting by the possible analogy with astrophysical flare phenomena such as solar flares in which magnetic energy is thought to be accumulated through a slow convection process, then released in a sudden burst of plasma acceleration and heating.

Magnetospheric convection, and the attendant substorm phenomena, are diminished when the IMF direction tends toward northward, as is expected in the context of the open magnetosphere model of Fig. 4. During such quiet intervals, the magnetosphere appears to revert to another mode of solar-wind interaction that, although less energetic than the substorm mode, is no less enigmatic. This northward IMF mode is just beginning to be studied in earnest, with the aid of global auroral imaging from polar-orbiting satellites (*19*).

Centrifugally Driven Convection

Another source of power for planetary magnetospheres is the kinetic energy of planetary spin. Jupiter, and probably Saturn, derive power for their magnetospheres by slowing the spin of the planet (albeit imperceptibly). They are thus analogous, in principal, to astrophysical systems (such as pulsars) in which power is extracted from the spin of the central body (the neutron star). As described above, convection in Earth's magnetosphere is driven by the flow of the solar wind past the magnetosphere; internal forces arising from injection of fresh plasma and its motion within the magnetosphere (centrifugal and coriolis accelerations, for example) are small compared to the force exerted by the solar wind. In contrast, it is widely accepted that the solar wind has negligible effect on magnetospheric plasma motions at Jupiter and (perhaps) Saturn; the prevailing view is that plasma motion in these magnetospheres is driven by centrifugal force. [However, there are alternative views (*20*).]

Plasma is supplied to Earth's magnetosphere both by the ionosphere and by the solar wind, with roughly equal contributions from each source, although the strength of both sources, and hence their ratio, varies with time. The total rate of injection of plasma ions into Earth's magnetosphere is of the order of 10^{26} ions s^{-1} (*21*). Protons are usually (though not always) the predominant ion, so the average magnetospheric mass-loading rate is roughly ~ 0.2 kg s^{-1}. In contrast, the rate at which plasma is injected into the inner magnetosphere of Jupiter by its satellite Io is estimated to be at least 10^3 kg s^{-1} (*22*). This large mass-loading rate, combined with the substantial size and rapid spin of the Jovian magnetosphere, leads to an entirely different convective process in which the centrifugal force on the magnetospheric plasma far exceeds the forces exerted by the solar wind.

Gas escaping from Io is ionized to form a plasma torus surrounding Jupiter. This torus tends to corotate with Jupiter because of its electrodynamic coupling to Jupiter's ionosphere. The torus, located at a Jovicentric distance of about 6 R_J (1 R_J = Jupiter's radius), contains nearly 10^9 kg of plasma. Jupiter's 10-hour spin period implies an outward centrifugal acceleration of $1.3g$ at this distance, while the inward gravitational acceleration is less than $0.1g$ (where g = 9.8 m/s^2 is the acceleration of gravity at Earth's surface). The injection of new plasma at an average rate $dm/dt \sim 10^3$ kg s^{-1} must be balanced by an outflow of old plasma at the same average rate, resulting in a residence time $m/(dm/dt) \sim 10$ days. (Alternative mechanisms for removing the plasma, such as recombination or absorption by Io or Jupiter, are too slow to have much effect.) This outflow comprises a magnetospheric convection system that, although its specific pattern remains undefined, is known to transfer power from Jupiter to its magnetosphere (*23, 24*). Saturn has several potential plasma sources within its magnetosphere, including the icy satellites and rings as well as Titan's atmosphere. The relative importance of these sources remains controversial (*25*), and theoretical discussions of rotationally driven convection have concentrated almost exclusively on Jupiter, probably because it has a single, dominant plasma source (the Io torus) whose properties can actually be monitored by Earth-based spectroscopic observations (*26*).

The power deposited in the magnetosphere by this plasma outflow is easily estimated (*23, 24*). Viewed in a reference frame that corotates with the planet, the torus is suspended in a centrifugal potential field $-\Omega^2 r$, where Ω is the angular rotation rate and r is the distance from the rotation axis to an element of torus plasma. The torus plasma falling outward through this centrifugal potential at a rate dm/dt releases power at a rate

$$P_t = (dm/dt) \int_{r_1}^{r_2} \Omega^2 r \, dr = (dm/dt)\Omega^2(r_2^2 - r_1^2)/2 \qquad (2)$$

where r_1 is the distance at which plasma is injected and r_2 is the outermost distance at which effective corotation of the plasma with the planet is enforced. No detailed theory has been put forth showing how this potential energy is tapped to power the broad array of magnetospheric phenomena, but an obvious connection is the Birkeland (magnetic field–aligned) currents that must flow as the torus plasma moves outward through the Jovian magnetic field (*27, 28*).

We can apply Eq. 2 to the specific example of Jupiter for which we have confidence that the power that drives magnetospheric phenomena is drawn principally from the kinetic energy of planetary spin and not from the solar wind. If we take $dm/dt \sim 10^3$ kg s^{-1}, $\Omega = 1.76 \times 10^{-4}$ rad s^{-1} (corresponding to Jupiter's 10-hour spin period), and respective values for r_1 and r_2 of 6 R_J and 20 R_J, we obtain $P_t \sim 3 \times 10^{13}$ W, which appears to be sufficient to drive the broad array of observed magnetospheric phenomena (*22*). It is interesting to note that an additional amount of power P_t is required to maintain corotation of the plasma to the distance r_2. Thus, power is extracted from Jupiter's kinetic energy of rotation at a rate $2P_t$.

The form of the resulting convection system has not yet been determined (*29*). Theoretical effort has focused on three principal mechanisms: (i) the eddy diffusion process involves a turbulent

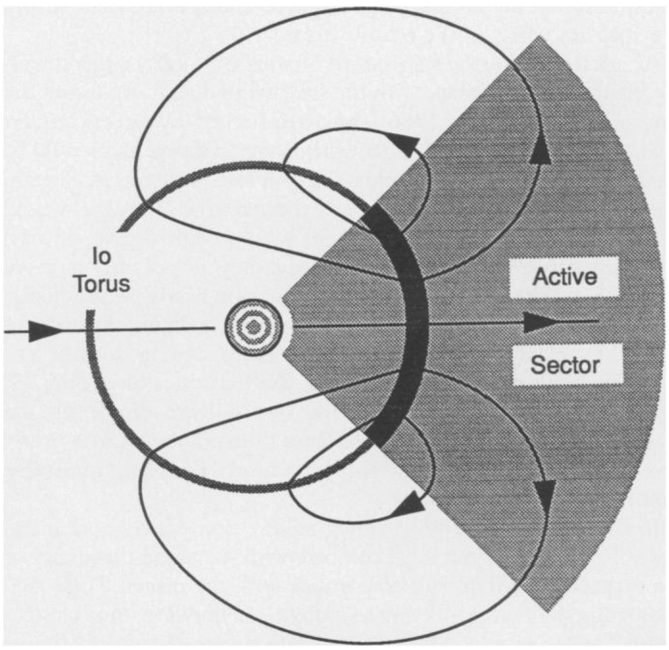


Fig. 5. Streamlines of the corotating convection pattern proposed to account for spin-periodic behavior of the Jovian magnetosphere (*22, 32*), viewed in the magnetospheric equatorial plane. A persistent longitudinal asymmetry of the Io plasma torus (*33*) drives plasma outflow within the overdense active sector and a compensating inward return flow at other longitudes. The flow pattern, like the torus asymmetry that drives it, corotates with Jupiter.

interchange of mass-loaded magnetic flux tubes from the torus with less dense magnetic flux tubes from the surrounding magnetosphere, resulting in a net outward mass transport (*30*); (ii) in the transient convection scenario, small mass-loaded flux tubes break away from the torus and "fall" outward through a less dense background (*31*); (iii) corotating convection is a proposed large-scale circulation pattern (Fig. 5) that corotates with the magnetosphere (*22, 32*), and is driven by the observed longitudinal asymmetry of the inner part of the plasma torus (*33*). To determine which of these theoretical scenarios (if any) best describes the transport of plasma out of the Io torus, we need synoptic observations of the type to be provided by the Galileo spacecraft upon its late 1995 arrival at Jupiter.

Jupiter's magnetosphere, presumably by virtue of its large size and rapid spin, exhibits certain properties of astrophysical pulsars (*22*). Specifically, (i) it derives its power from the spin kinetic energy of its central body, (ii) its magnetospheric plasma is derived from internal sources (both its ionosphere and the Io torus), (iii) its electromagnetic emissions, from radio to ultraviolet frequencies, exhibit spin-periodic modulation, and (iv) it is a source of cosmic-ray particles (namely electrons with energies up to 30 MeV), whose release is modulated at the planetary spin period. The power loss relationship derived for astrophysical radio pulsars, $P \propto M^2\Omega^n$ where M = magnetic moment and $n \mp 3.5 \pm 0.5$, extrapolates quite well to Jupiter, whose magnetic moment is typical of that assumed for neutron stars but whose spin rate is smaller by orders of magnitude (*34*).

Hybrid Magnetospheres

Uranus and Neptune form a separate class of obliquely rotating magnetospheres in which the magnetic dipole axis is grossly misaligned with the planetary spin axis. (The angles are 60° and 47°, respectively, compared to ≤11° in all other known cases.) Because of this misalignment, the magnetospheres of Uranus and Neptune are "hybrids" in the sense that rotational and solar-wind effects can, and probably do, coexist. This is especially true of Uranus which, in addition to the misalignment of magnetic and spin axes, has a spin axis that lies nearly in the ecliptic plane.

By good fortune, the spin axis of Uranus was nearly aligned with the planet-sun line (hence with the solar-wind direction) during the Voyager 2 encounter in 1986. Thus, before the Voyager encounter, given the natural assumption that the magnetic dipole axis would be found to be essentially parallel to the spin axis (as it was in all cases then known), it was confidently expected that Voyager would discover a "pole-on" magnetosphere with a high degree of axial symmetry. Instead, the configuration at any given time is more nearly "Earthlike," with the solar wind striking nearly perpendicular to the planetary dipole, although the whole configuration rotates about the planet-sun line once per Uranus day in a most un-Earthlike fashion. Neptune's spin axis, like Earth's, is tilted only 23° from the ecliptic pole, but because of the large dipole tilt the magnetospheric configuration oscillates diurnally between a nearly pole-on geometry at one extreme and a nearly Earthlike, transverse geometry at the other.

In the "normal" Earthlike configuration, convective motion imposed by the solar wind must compete with the natural tendency of the magnetospheric plasma to corotate with the planet. These two competing influences give rise to a physical boundary, the "plasmapause," inside of which the plasma motion is predominantly corotational, and outside of which it is dominated by the sunward return flow imposed by the solar-wind interaction at high latitudes (Fig. 3B). Earth's plasmapause has a mean radius ~5 R_E, about half the distance to the dayside magnetopause. For Jupiter and Saturn the nominal plasmapause distance is outside the dayside magnetopause, indicating that the entire magnetosphere, with the possible exception of its tail, should be dominated by corotation, as observations indeed suggest. Uranus and Neptune would likewise be corotation-dominated in this sense if their magnetic configurations were "normal." The configurations, however, are such that the influence of the solar wind can penetrate much deeper within these magnetospheres than the nominal plasmapause distance.

Indeed, Uranus probably has little or no plasmasphere at all when it is near solstice, as it was during the Voyager encounter. (The plasmasphere is the region enclosed by the plasmapause.) Any solar wind–induced convection pattern is fixed with respect to the planet-sun line, which maintains a fixed direction in the corotating frame of reference, as well as in the noncorotating planet-fixed frame, if the spin axis is aligned with the planet-sun line. Thus, a solar wind–induced convection system can be established in the corotating frame itself—the frame in which the plasma would otherwise be at rest (*35*). Corotation is, so to speak, orthogonal to the solar wind–induced convection pattern and thus has no first-order effect on that pattern. Data from the brief Voyager encounter with Uranus are insufficient either to confirm or to rule out the presence of a vigorous solar wind–induced convection system, but its presence is consistent with the observed paucity of plasma in this magnetosphere: any plasma deriving from internal sources, such as satellites, would be quickly swept away by such a convection system before a substantial plasma population could be established.

The case of Neptune is a bit more subtle. On the basis of the geometry alone we would expect a plasmapause to form, as at Earth, because the planet-sun line does not remain fixed in the corotating frame. On the other hand, if solar wind–induced convection is associated with magnetic interconnection, as at Earth (Fig. 4), the strength of that convection system is expected to oscillate at the planetary spin period because, unlike the terrestrial case, there is a systematic diurnal variation of the degree to which Neptune's magnetic field is able to interconnect with an IMF of a given direction, the latter direction tending to remain fixed for many rotation periods at Neptune's orbit. This spin-resonant amplitude modulation of the convection system enables it to penetrate the otherwise impenetrable plasmapause (*36*), and to establish a flow pattern that is fixed in the corotating frame when averaged over many rotations. As with Uranus, the data from the brief Voyager encounter with Neptune are consistent, albeit not uniquely, with the presence of a vigorous solar wind–induced convection system penetrating well inside the nominal plasmapause distance.

Future Directions

The Earth's magnetosphere is one link of a complicated chain of cause and effect extending from the sun to the Earth. Disturbances in the solar corona generate dynamic variations in the solar wind, which in turn trigger magnetospheric phenomena that affect the dynamics of the ionosphere and thermosphere, effects that are readily observable from the ground. There are even suggestions that solar wind/magnetospheric phenomena may affect weather and climate (*37*), although the associated energy inputs to the troposphere are minuscule compared to solar radiant heating, and none of the suggested mechanisms is presently considered viable. In any case, it is clear that the dynamic state of the magnetospheric plasma environment has important effects not only on the operations of Earth-orbiting spacecraft but also on ground-based communications and power transmission systems. Thus it is a matter of practical importance as well as scientific curiosity to improve our understanding of the terrestrial magnetosphere.

In the inner magnetosphere, where the magnetic field is roughly dipolar and the plasma flow is subsonic and sub-Alfvenic (that is, below the Alfven wave speed), the physics governing the magnetosphere and its coupling to the ionosphere is relatively well understood. Computer simulation of this region has reached a level of sophistication that allows realistic theoretical predictions and comparisons with in situ observations (*15*), given a realistic set of time variable boundary conditions at the high-latitude boundary of this region, which corresponds roughly to the auroral oval. Poleward of this boundary the physics is less well understood, and we cannot yet specify from first principles a poleward boundary condition for the low-latitude calculation, much less to model the two regions together as a self-consistent interactive system.

Global simulation models of the magnetosphere have been constructed (*38*) on the basis of time-dependent solutions of the "ideal" collisionless MHD fluid equations that should, in principle, govern the magnetospheric plasma behavior on macroscopic length scales. The word "ideal" is in quotes because neither the simulations nor the real magnetosphere behave as ideal fluids. (A precise solution of the ideal MHD equations, even if it were feasible on the scale of the magnetosphere, would be rather boring. It would have an impermeable magnetopause with none of the exchange of mass, momentum, energy, and magnetic flux that makes the real magnetosphere so interesting.) In the MHD simulations, non-ideal behavior is introduced either by artificially large collisional transport coefficients (resistivity, viscosity, and so forth) or by purely numerical diffusion. In the real magnetosphere, non-ideal behavior results from a rich variety of non-MHD processes occurring primarily in boundary regions where gradient length scales become comparable to intrinsic plasma length scales. Examples include magnetic merging at the dayside magnetopause (the process that establishes the rate and geometry of interconnection between the geomagnetic field and the IMF), the solar flare-like disruption of the magnetotail associated with magnetospheric substorms, and the magnetic field–aligned electrostatic acceleration of auroral primary particles in regions of supercritical Birkeland current density. Until these processes are better understood, we have little guidance as to how, or even if, their effects can be represented by transport coefficients in a global fluid simulation.

The next few years will bring significant new opportunities for advancing our understanding of the interaction between the solar wind and Earth's magnetosphere. The International Solar Terrestrial Program (*39*) involves the coordination of five new spacecraft dedicated to making simultaneous multipoint measurements of the complicated, time variable system. In parallel with this ambitious spacecraft observational program, a program of suborbital observations, data analysis, and theoretical modeling, known as the Geospace Environment Modeling (GEM) program (*40*), will proceed through a series of observational and theoretical "campaigns" toward the ultimate development of a magnetospheric "general circulation model" analogous to the large numerical models used to study weather and climate.

The magnetospheres of Jupiter and Saturn are also due for closer scrutiny in the next several years. Two spacecraft are already enroute to Jupiter: Ulysses, which will utilize a Jupiter flyby in February 1992 to achieve its polar heliocentric orbit, and Galileo, which will orbit Jupiter after dropping a probe into its atmosphere in December 1995. Meanwhile, the International Jupiter Watch promotes increasingly sophisticated and coordinated Earth-based observations of the Jovian system including the highly dynamic Io plasma torus. Cassini, presently scheduled for launch in 1996 and Saturn arrival in 2002, is essentially a Saturn analog of the Galileo/Jupiter mission except that the probe will enter Titan's, rather than Saturn's, atmosphere. A Mercury orbiter is also under consideration by NASA; if approved, this would be the first spacecraft mission to another planet that was motivated primarily by magnetospheric objectives.

Unlike terrestrial laboratories, planetary magnetospheres are large enough to serve as laboratories for in situ study of the behavior of cosmic plasmas and magnetic fields and their attendant particle acceleration and electromagnetic emission. Thus far, however, there has been little application of the power of magnetospheric physics, as developed over the past three decades, to the solution of the problems of remote astrophysical plasmas. Although some general concepts have been adopted in certain astrophysical applications, a vigorous, synergistic interchange cannot yet be said to exist. Past experience in solar system plasma physics ought to give us a sense of humility if not apprehension. Concepts and theories developed using remote sensing data were startlingly denied when spacecraft arrived to show by direct, in situ measurements how the given phenomena actually worked. It is this experience with direct spacecraft measurements that makes plausible the expectation that magnetospheric physics has much to offer astrophysics.

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