Solar System, Magnetic and Electric Fields

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GLOSSARY

Adiabatic invariants First, second, and third adiabatic invariants are conserved quantities associated with the three periodic motions (gyro, bounce, and drift) of charged particles trapped in a magnetic mirror configuration, such as the Earth's dipole-like field.

Bow shock Collisionless shock wave in the solar wind plasma that stands in the flow, slows and heats the flow, and deflects it around all planetary obstacles.

Coronal mass ejection (CME) A large-scale eruption of the solar corona that accelerates away from the sun and produces a large (~45°) across disturbance in the solar wind. Best observed by coronagraphs viewing the limbs of the sun. Halo CMEs are CMEs moving directly at the observer and producing a disturbance in projection all around the sun.

Corotational electric field Electric field in a planetary magnetosphere associated with the rotation of the plasma at the same angular rate as the planet because of the high electrical conductivity of the plasma along magnetic field lines.

Debye length Electrical shielding length in a plasma. A test charge in a plasma cannot be sensed beyond this distance.

Field-aligned current Electric current flowing along planetary magnetic field lines connecting streamers in one part of a magnetosphere with those in another. Current system closes by flowing across the magnetic field.

Geomagnetic storm Period of several days in which currents circling the Earth in the equatorial plane of the

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magnetosphere become enhanced. The energization of these currents is caused by changes in the solar wind and interplanetary magnetic field.

Gyrofrequency Number of times per second that a charged particle orbits a magnetic field line. Depends directly on the particle’s charge and magnetic field strength and inversely as the mass of the particle.

Gyroradius Radius of orbit of charged particle in a magnetic field. Depends directly on particle mass and velocity perpendicular to the magnetic field and inversely as the charge and magnetic field strength.

Interplanetary coronal mass ejection (ICME) The disturbance in the solar wind associated with a coronal mass ejection from the Sun. This disturbed region often is preceded by a collisionless bow shock and contains embedded within it multiple magnetic flux ropes.

Interplanetary magnetic field Magnetic field of the solar wind carried out from the Sun by the solar wind flow.

Ionopause Upper boundary of an ionosphere that interacts directly with the solar wind.

Ionosphere Ionized part of the atmosphere of a planet.

Magnetic cloud Interplanetary structure in which the magnetic field is enhanced, usually quiet and slowly rotating. Remains a twisted magnetic flux tube and usually found within an ICME.

Magnetohydrodynamics Physics of magnetized electrically conducting fluids. Often applied to plasmas in situations in which they display fluid-like behavior.

Magnetopause Outer boundary of a magnetosphere confined by the solar wind.

Magnetosheath Shocked plasma behind a planetary bow shock flowing around the planetary magnetopause or ionopause.

Magnetosphere Magnetic cavity formed by the interaction of the solar wind with a planetary obstacle.

Magnetotail Long cylinder of magnetic field lines dragged out in two oppositely directed tail lobes behind a planetary obstacle.

Parallel electric field Electric field along a planetary magnetic field that is responsible for the acceleration of the electrons that cause the brightest aurora and decouple flows perpendicular to the magnetic field at different altitudes along the field line. Parallel fields also accelerate electrons into the magnetosphere from the ionosphere, and they enable reconnection by permitting the swiching of magnetic partners.

Plasma Gas, fully or partially ionized, having equal densities of electrons and ions in which the energy of motion of the particles exceeds that associated with the electric potential of the charged particles. In an unmagnetized plasma, particle motions are nearly straight lines.

Plasma frequency Natural oscillation frequency of a plasma set into motion by a small separation of the electrons and ions.

Plasma parameter Number of electrons in a cube whose side is a Debye length. “Collective” plasma behavior occurs when this number is much greater than unity. It also is a rough measure of the number of plasma oscillations between interparticle collisions.

Reconnection Process in which the magnetic topology of the magnetic field is in an element of plasma changes. For example, at the dayside magnetopause, the magnetic field lines in the postshock solar wind plasma become linked with the terrestrial field lines and accelerate the plasma on the newly joined field lines.

Solar wind Supersonically expanding upper atmosphere of the Sun that because of its high electric conductivity carries the solar magnetic field with it.

Substorm Disturbance in the night-time current systems in the terrestrial magnetosphere usually lasting a couple of hours and accompanied by enhanced auroral activity.

Sunspot cycle Eleven-year cycle in which cool, dark, magnetized regions area in the photosphere become first more frequent and then less frequent. Because the magnetic polarity pattern of sunspot groups changes every 11 years, the cycle is in actuality a 22-year cycle. This period is not exactly constant but varies slightly from cycle to cycle.

Tail lobes Two regions within a magnetotail of oppositely directed magnetic flux in which the magnetic energy density greatly exceeds the plasma pressure.

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THE STUDY of solar system electric and magnetic fields includes the investigation of the magnetic fields generated by electrical currents flowing in the interior of the Sun and the planets as well as electric and magnetic fields and their associated current systems flowing in the solar wind and in the magnetospheres and the ionospheres of the planets. Magnetic fields are generated by electric currents that arise when more particles of one charge flow in a particular direction per unit time than particles of the opposite sign. Such currents can flow in the highly electrically conducting fluid cores of the planets, which are both differentially rotating and convecting. Such currents are also found in the various plasmas of the solar system. These plasmas, or electron-ion gases, are highly electrically conducting. The material inside the Sun, its atmosphere, the expanding solar wind, and ionized material in the upper atmospheres of all the planets are plasmas. One of the more important of these current systems is the one that generates the solar magnetic field. Finally, there are currents at the atomic level in solid materials. While our usual exposure to magnetic fields of this kind is from man-made
magnets, nature also produces magnetized materials. Such remanent magnetization often preserves a record of the magnetic field at the time of the formation of the material and thus the study of magnetized rocks has led to an understanding of the magnetic history of both the Earth and the Moon.

Magnetic fields have both magnitude and direction. The most common instrument for sensing this direction is the compass. The scientific instrument for measuring magnetic fields is called a magnetometer. There are several different types of magnetometers in common use. Proton precession magnetometers measure total field strength and are frequently used in terrestrial studies. Fluxgate magnetometers measure components of the magnetic field in a particular direction and are most commonly used on spacecraft. Solar magnetic fields are sensed remotely through the splitting of spectral lines by the Zeeman effect. Magnetic fields are measured in nanotesla, gauss, and teslas (1 T = 10^4 G = 10^5 nT). The magnetic field on the surface of the Earth at the equator is about 0.31 G. In the outer reaches of the Earth's magnetosphere it is about 0.001 G or 100 nT. Outside the magnetosphere in the solar wind it is about 10 nT. The magnetic field on the surface of the Sun is highly variable but on average it has a magnitude of several gauss.

Electric fields are generated by the separation of positive and negative charges. Perhaps the most spectacular naturally occurring separation of charges is produced in convecting clouds in the Earth's troposphere leading to lightning discharges. Since electrons and ions differ greatly in mass they often react quite differently to plasma effects. The different reactions also lead to charge separations in plasmas. If an electric field is applied to a magnetized plasma in a direction perpendicular to the magnetic field, the plasma will drift in a direction perpendicular to both the applied electric field and the magnetic field. This process is referred to as "E cross B" drift. Conversely, when a magnetized plasma is observed to be drifting, there must be an electric field perpendicular to the magnetic field in the frame of reference of the observer. If an observer is moving with the plasma, she or he sees no drift and hence in this frame of reference there is no electric field. Thus the electric field in a plasma is frame dependent; it depends on the velocity of the observer.

Electric fields have both magnitude and direction. They accelerate charged particles in the direction of the electric field. The energy gained by a particle moving in an electric field is the particle's charge times the electric field times the distance traveled. The electric field times the distance is called the potential drop or potential difference between two points and dividing by the distance between them. Spacecraft designed to measure electric fields in space often carry long (up to 200 m) antennas. The common units of electric fields are volts/meter and stat-volts per centimeter. One statvolt/cm equals 3 x 10^7 V/m.

A typical electric field in the equatorial magnetosphere of the Earth is 0.2 mV/m. A typical electric field in the solar wind outside of the Earth's magnetosphere is 2 mV/m.

I. THE PHYSICS OF SOLAR SYSTEM ELECTRIC AND MAGNETIC FIELDS

A. Sources of Magnetic Fields

There are four basic equations governing the interrelationship of charges, currents, and magnetic and electric fields. These four equations are called Maxwell's laws. In an electrical resistor, current is usually directly proportional to the applied electric field. In a magnetized flowing electrical conductor, an additional term arises because of the electrical field associated with the motion of the conductor. The equation describing the relationship between the current, the electric and magnetic fields, and the flow velocity is called the Ohm's law. Maxwell's laws and Ohm's law can be combined to give what is known as the dynamo equation. This equation shows that the change in a magnetic field is the difference between the resistive decay of currents and the regeneration of the field due to fluid motion. If there is no motion in the conducting fluid, the magnetic field will decay with time. If the fluid core of the Earth froze, the terrestrial magnetic field would decay in a few thousand years. The Jovian field would decay over a few hundred million years, but the solar magnetic field decay time would be comparable to the age of the solar system. Hence, the solar magnetic field could conceivably be in part primordial, present from the time of formation of the Sun due to the compression of preexisting interstellar magnetic fields. Such a primordial field could explain only a sticky component.

Cold dark regions on the sun called sunspots are associated with strong magnetic fields. The number and area of sunspots varies with an approximate 11-year cycle. The principal part of the solar field reverses approximately every 11 years producing a solar magnetic cycle with a length of two sunspot cycles. Because of its effect on geomagnetic records it can be shown to have continued for at least 150 years. Evidence for the solar cycle exists for over 2000 years in the available, albeit irregular, optical observations, and various proxy data, such as the fraction of the radioactive isotope of carbon, C14, measured in tree rings. This varying solar magnetic field, the magnetic field of the outer planets, and that of the Earth must be actively
maintained by a generator of magnetic fields (i.e., a dynamo).

One approach to studying dynamos is to seek patterns of motion of the conducting fluid that can generate magnetic fields. This kinematic approach is not self-consistent because it does not generate the requisite velocity field from first principles. Furthermore, the magnetic field so generated usually acts on the conducting fluid, thus altering the motion. Figure 1 shows how a planetary field might be self-regenerative if it has a conducting fluid core. The left-hand panel shows a typical planetary magnetic field with field lines confined to planes that contain the axis of rotation of the planet. Deep in the fluid core, as shown in the middle panel, this field is twisted out of these planes by differential rotation of the core. At different depths the core rotates more rapidly. This causes an azimuthal component around the rotation axis, which may become much larger than the original field sketched in Fig. 1a. We know such a differential motion, or shear, in the field lines exists in the Earth because features in the terrestrial magnetic field drift slowly westward. We also see differential motions in the solar photosphere. Sunspots move faster at the equator than at higher latitudes. This differential motion, thought to extend well down into the interior, is called the omega effect. Heating, such as produced by radioactive sources or by the freezing out of a solid inner core in the Earth or nuclear fusion in the Sun, produces rising convective cells. These rising convective cells carry the azimuthal field upward as shown in the rightmost panel in Fig. 1. The rotation of the planet causes these convective cells to twist and thus creates a component of magnetic field parallel to the initial field. This new component replaces any field lost due to resistive decay. In this way differential rotation and upward convection combine to regenerate the planetary magnetic field. This process is thought to act in the Earth, Mercury, Jupiter, Saturn, the Sun, and many stars. However, the theory of this process is not yet sufficiently developed to provide a prediction of the strength of a planetary dynamo, even if the physical and chemical structure of the interior of the planet were well known. Table I shows the properties of the dipole moments of the eight innermost planets and the Earth's moon.

One final source of planetary magnetic fields is natural remanent magnetization of solid materials. The most common means of acquiring such natural remanence is the cooling in an external magnetic field of magnetic material through one or more "blocking" temperatures below which the material can retain its acquired magnetization. Typical blocking temperatures are several hundred degrees Celsius and typical carriers of remanence are small particles of fine iron metal and nickel and the iron oxide magnetite, FeOFe2O4. It is often possible to determine the direction and magnitude of the ancient magnetizing field from rocks containing natural remanence. Such studies have been crucial on the Earth for demonstrating that continental drift and the ocean floor spreads and that the terrestrial field periodically but irregularly reverses its direction. Lunar rocks also possess natural remanent magnetism, leading to the conjecture that the Moon once possessed its own dynamo-generated internal magnetic field that ceased operating over 3 billion years ago.

B. Charged Particle Motion in Electric and Magnetic Fields

In order to understand the structure and behavior of solar system magnetic and electric fields, it is necessary to understand how charged particles move in these fields, for to a large extent, these electric and magnetic fields arise self-consistently from these same particles. As shown in the leftmost panel of Fig. 2, charged particles gyrate around magnetic field lines. The frequency of this motion is proportional to the strength of the magnetic field and the
charge on the particle and inversely proportional to the mass. A proton in a 100-eV field gyrates around the field 1.5 times per second. An electron in a 100-eV field gyrates 2800 times per second. The direction of rotation of the charged particle depends on the sign of the charge. Positively charged particles gyrate in a left-handed sense, clockwise, viewed with the magnetic field pointing toward the observer. Electrons rotate in a right-handed sense.

These circulating charged particles carry a current around the magnetic field in such a direction to reduce the magnetic field. The radius of the orbit of a charged particle, its gyroradius, is proportional to the velocity of the particle perpendicular to the field and the mass of the particle and inversely proportional to its charge and the magnetic field strength. The area enclosed by this orbit times the current due to the gyration of a particle (i.e., its charge times its gyrofrequency) is called the magnetic moment of the particle. It is equal to the energy associated with the motion of the particle perpendicular to the magnetic field divided by the magnetic field strength. If the variation in magnetic field strength is sufficiently slow in space or time, the magnetic moment of a particle is conserved. The magnetic moment is also called the first adiabatic invariant.

If magnetic field lines converge as they are shown to do in the middle panel of Fig. 2, the field strength as seen by the particle increases as the particle goes from the middle to either end of the field line. Because the magnetic moment of the particle is conserved, the perpendicular energy of the charged particle will increase until it is equal to the total energy of the particle. Because at the point where this occurs the particle has no forward velocity, and because the same forces are still acting on the particle that decelerated its forward motion, it reflects and starts moving away from this “mirror point.” A planetary magnetic field generally has two points of convergence, one in the northern hemisphere and one in the south. Thus, particles will bounce back and forth trapped between mirror points. The bounce frequency is determined by how fast the particles are moving along the magnetic field line and by the length of the magnetic field. The parallel momentum of a charged particle is its mass times its velocity measured along the magnetic field. The integral of the parallel momentum over a bounce period (i.e., the momentum summed over each portion of the path) is conserved. This quantity is called the second adiabatic invariant. If mirror points of a particle move closer together, the particle must gain energy along the field due to this conservation principle. This process is called Fermi acceleration.

In nonuniform magnetic fields, charged particles drift perpendicular to the magnetic field. If the magnetic field strength decreases with altitude as it does in the terrestrial magnetic field, the gyroradius of a particle will be larger when it is farther from the Earth in its gyromotion than when it is closer. This leads to a net drift of the particle whose direction depends on the charge of the particle. In the Earth’s magnetic field, which in the equatorial regions points northward, positively charged ions such as protons drift westward opposite to the Earth’s rotation and electrons drift eastward. This process is referred to as gradient drift. If a particle is bouncing back and forth along a curved field line as shown in the rightmost panel of Fig. 2, it will experience a centrifugal force outward as its motion is deflected by the curved field. This has exactly the same effect as a field gradient, and electrons and protons drift in opposite directions. The drift path around a planetary magnetosphere is generally closed for most nonrelativistic particles in most planetary fields if the planetary field approximates that of a dipole. This drift requires from minutes to hours, compared to seconds to minutes for the bounce motion, and milliseconds to seconds for the gyromotion. When a charged particle completes its motion around a planetary magnetosphere the path traced out by the drifting bouncing particle is a roughly spheroidal shape with open ends. This so-called drift path or shell encloses a certain amount of magnetic flux, or equivalently a certain number of magnetic field lines. The magnetic flux enclosed by the drift path, or equivalently the magnetic flux through the open ends, is conserved when the magnetic field changes slowly on the time scale of the drift motion. This conserved amount of magnetic flux is referred to as the third adiabatic invariant. If the magnetic field of the Earth, for example, increased, then the radiation belts would move outward to conserve this invariant. The gradient and curvature drift of charged particles around the Earth’s equator cause a net current to flow there, called the ring current. The ring current causes a depression in the strength of the
magnetic fields observed on the surface of the Earth. The size of this depression is linearly related to the energy of the ring current particles. If the particles in the terrestrial trapped radiation belts possessed $2.8 \times 10^{12}$ eV of kinetic energy, there would be a 100-nT depression with the horizontal component of the Earth's surface field. A geomagnetic storm is such a period of enhanced ring current.

A charged particle is accelerated by an electric field. In the case of an electric field at right angles to a magnetic field, a gyrating particle will be accelerated for one half of its gyration and decelerated in the other half. When it is moving fastest, its gyroradius is largest and when it is moving slowest, its gyroradius is smallest. Thus, it moves farther in one half of its gyration than the other. Protons and electrons gyrate in opposite directions about the field and also are accelerated on opposite halves of their gyration. The net effect is that electrons and protons drift in the same direction and at the same velocity perpendicular to both the magnetic and electric fields. In the Earth's magnetic field, which is northward in the equatorial regions, an electric field from dawn to dusk produces drift toward the Sun. Since electrons and ions drift together, there is no current associated with this drift.

**C. The Physics of Plasmas**

Thus far we have considered only single-particle motion. However, a gas of charged particles can exhibit collective behavior. The term plasma is usually restricted to a gas of charged particles in which the potential energy of a particle due to its nearest neighbor is much smaller than its kinetic energy. If we put a test charge in a plasma, it gathers a screening cloud of oppositely charged particles around it that tends to cancel the charge. In effect, the membership of a given particle in many screening clouds produces the collective behavior. Beyond some distance, called the Debye length, there is no observable effect of an individual charge. The Debye length is proportional to the square root of the ratio of the plasma temperature to its density. A plasma such as the solar wind with a temperature of $10^6$ K and a density of 10 per cubic centimeter has a Debye length of 740 cm. The number of particles in a cube with the dimensions of the Debye length is called the plasma parameter. The value of this parameter determines whether the ions and electrons can be treated as a plasma exhibiting collective behavior or as an ensemble of particles each exhibiting single-particle behavior. We can consider an electron-ion gas to be a plasma when the plasma parameter is much greater than 1. As illustrated in Fig. 3, in the Earth's ionosphere and the Sun's outer atmosphere (the corona) this number is about $10^6$. In the Earth's magnetosphere and in the solar wind it is about $10^{10}$.

![Figure 9: The Debye length $\lambda_D$ and the plasma parameter $\Lambda$ for plasmas of geophysical interest.](image)

The characteristic frequency of a plasma at which it would oscillate if the ions and electrons were pulled apart and allowed to move back together (a collective plasma effect) is called the plasma frequency. It is equal to $9 \times 10^7$ times the square root of the number of electrons per cubic centimeter. The maximum plasma frequency in the Earth's ionosphere is somewhat greater than about 10 MHz. The number of collisions per second in a fully ionized plasma is very roughly the plasma frequency divided by the plasma parameter. Thus, particles in plasmas can oscillate many, many times between collisions, and hence plasma processes are often referred to as collisionless processes. When the plasma parameter is large, charged particles move in almost straight lines. As the plasma parameter decreases, the individual interactions between charged particles become more important and large-scale deformations become more frequent. Eventually, for small plasma parameters, electrons become trapped in the potential wells of individual ions. This same effect occurs in metals and the interior of the Sun.

The key to understanding the behavior of the electric and magnetic fields in the solar system lies in understanding the behavior of plasmas and the various instabilities that transfer energy from one form to another in a plasma. The collective interactions allow us often to ignore the individual particle nature of a plasma and consider it to be an electrically conducting fluid. The laws governing the behavior of this fluid are Maxwell's equations, Ohm's law, and the conservation of mass and momentum. Use of these equations is called the magnetohydrodynamic, or MHD, approximation.

Plasmas in the solar system often find themselves in unstable situations in which the MHD equations would predict a rapid change of configuration. For example, there is the interchange instability in which entire magnetic flux tubes interchange position because by doing so they acquire a lower energy state. This might occur if a heavily
loaded magnetic flux tube lay on top of a lightly loaded magnetic flux tube in a gravitational field. This is analogous to the situation in which a heavy fluid sits on top of a lighter one. Another MHD instability of some importance is the Kelvin–Helmholtz or wind-over-water instability, in which surface waves on a boundary are induced by a shear in the flow velocity across the boundary. This instability is often invoked to explain magnetic pulsations in the Earth’s magnetosphere. It is analogous to the mechanism for the formation of ocean waves.

Plasmas, because they are collisionless, can have different temperatures along and across magnetic field lines. However, too large a difference can be unstable. The fire hose instability arises when the thermal pressure along a field line exceeds the sum of the pressure across a field line and the magnetic pressure. When this occurs the magnetic field lines wiggle back and forth like a fire hose whose end is not being held. An instability also occurs when the thermal pressure across a field line greatly exceeds the pressure along it. This is known as the mirror instability and it creates pockets of denser plasma along the field lines.

Many of the various plasma instabilities cause fluctuations in the plasma: oscillations in number density, in electric and magnetic field strength and direction, in the velocity of the plasma, etc. Such oscillations can also be stimulated by processes external to the plasma being studied. There are three types of magnetohydrodynamic waves: fast, intermediate, and slow. Fast waves compress the plasma and magnetic field. Intermediate waves bend the magnetic field lines but do not alter the density or magnetic field strength. Slow waves compress the plasma and magnetic field when they are decompresing the plasma and vice versa so that the total pressure, thermal plus magnetic, is nearly but not quite constant. Such waves are found throughout the solar system plasma. The velocity of an intermediate wave, also called the Alfvén velocity, is proportional to the magnetic field strength and inversely proportional to the square root of the mass density. In a plasma of nine protons per cubic centimeter and a field strength of 6 nT, which is typical of the solar wind near Earth, the Alfvén velocity is 44 km/sec. Fast and slow waves travel somewhat faster and slower than this velocity by a factor that depends on the temperature of the plasma and the direction of propagation relative to the magnetic field.

Fast and slow waves can steepen into shock waves if their amplitudes are sufficient. A shock wave is a thin discontinuity that travels faster than the normal wave velocity and causes irreversible changes in the plasma. Such a collisionless shock is analogous to the shock produced by a supersonic aircraft flying through a collisional gas, air. The process of shock formation is described as steepening because the passage of a fast or slow wave alters the plasma so that a following wave will travel faster and thus catch up with the first wave. Thus the trailing parts of a wave catch up with the leading part and a steep wave front is formed. This process is similar to the steepening of ocean waves as they approach the shore. The steepening of shock waves in a plasma is limited by collective processes occurring in the plasma over sometimes rather short scale lengths, such as the ion gyroradius. Many of the processes occurring in collisionless shocks generate plasma waves, both electromagnetic waves that transport energy and electrostatic waves that do not. These waves, oscillating at and above frequencies in the neighborhood of the gyrofrequencies of the ions and electrons, heat the plasma and equalize the pressures along and across the field. The thickness of collisionless shocks is often a fraction of the ion inertial length, which is the velocity of light divided by the ion plasma frequency (a factor of 43 less than the electron plasma frequency mentioned earlier if the ions are protons). Numerically, this is equal to 228 km divided by the square root of the number of protons per cm$^2$. In a typical solar wind plasma near the Earth a shock will be about 40 km thick.

Collisionless shocks are found in front of all the planets, forming standing bow waves much like the bow wave in front of a boat. Such a wave occurs because the solar wind must be deflected around each of the planetary obstacles. However, the velocity of the solar wind far exceeds the velocity at which the pressure needed to deflect the flow can propagate in the solar wind. The only streams by which a planet can deflect the supersonic solar wind is to form a shock wave that slows down, heats, and deforms the flow.

Solar flare-initiated blast waves also cause shocks in the solar wind that are swept out past the planets. When they reach the Earth, such shock waves cause sudden commencements in the Earth’s magnetic field that are observed by surface magnetometers. A sudden compression followed by an injection of energy into the Earth’s ring current is called a sudden storm commencement, or SSC. Otherwise a sudden compression of the Earth’s magnetic field is called a sudden impulse, or SI. Sometimes shock waves propagating toward the Sun, or reverse shocks, are carried outward by the very supersonic solar wind. These can cause negative sudden impulses in which the Earth’s surface magnetic field suddenly decreases. It was the occurrence of the negative and positive sudden impulses in the Earth’s magnetic field that originally led to the postulate that collisionless shocks could exist in the solar wind plasma. In ordinary gases, shocks require interparticle collisions to heat the gas across the shock front. In a collisionless plasma, this heating occurs both through oscillating magnetic and electric fields and through a steady-state
process by which a small fraction of the ions get reflected by the shock and thus attain a high thermal energy relative to the flowing solar wind.

D. Conductivity and Electric Field Sources

As noted above, in a plasma without collisions, an electric field perpendicular to a magnetic field causes a drift of both the electrons and the ions in the same direction and hence to the electrical current. In the dense plasmas of plan-
etary ionospheres and the solar photosphere, collisions either with other charged particles or with neutral parti-
cles occur frequently enough that the collisions modify the response of the plasma to an applied electric field. When collisions occur much more rapidly than either the electro-
one or ion gyrofrequencies, the charged particles are no longer controlled by the presence of the magnetic field. The charged particles are then said to be unmagnetized and the electric field drives a current parallel to the elec-
tric field as in an ordinary conductor. The ions are unmag-
etized at intermediate collision frequencies because of their lower gyrofrequency. They drift parallel to the elec-
tric field, while electrons, because their gyrofrequency is much higher, are magnetized and drift perpendicular to the magnetic field. Thus, there is a component of current carried by electrons perpendicular to the applied electric field and a component of current carried by ions parallel to the electric field. The ratio of proportionality between the current and the applied electric field is called the conduc-
tivity of the plasma. The conductivity perpendicular to the magnetic field and parallel to the electric field is called the Pedersen conductivity. The conductivity perpendicular to both the magnetic and electric fields is called the Hall con-
ductivity. The conductivity parallel to the magnetic field is called the direct or longitudinal conductivity. At some altitudes in the terrestrial ionosphere the Hall conductivity greatly exceeds the Pedersen conductivity and electric current flows mainly perpendicular to the applied electric field.

Collisions couple the neutral and ionized atmospheres of planets, including the Earth. Motions of either one cou-
ples into the other. Neutral winds are driven by solar heat-
ing. At low altitudes in the terrestrial ionosphere where both ions and electrons are unmagnetized these collisions simply carry both the ions and electrons along with the neutral wind and cause a drift of the plasma. At high alti-
itudes, the collisions cause the electrons and ions to drift in opposite directions perpendicular to the direction of the wind resulting in a current perpendicular to the wind asso-
ciated with the differential flow of the ions and electrons. At intermediate altitudes the electrons are magnetized and the ions unmagnetized so that there is an electron current perpendicular to the wind and the magnetic field, and an ion current parallel to the wind. Thus, neutral winds as well as applied electric fields can drive currents. These currents cause variations in magnetic records taken on the surface of the Earth. Variations associated with the normal solar-heating-driven convection of the ionosphere have been called S0 variations because they are in phase with the Sun and are present on quiet days. Daily variations at geomagne-
tically active times are called S1 variations. Variations caused by the effects of lunar gravitation on atmospheric circulation at quiet times are called L0 variations. The S0 variations are caused by both solar gravitation and heat-
ing effects, whereas L0 variations are due to gravitational tides only.

The electrons and ions that surround a planet and com-
prise its ionosphere can be set in motion from above as well as below. The expanding solar atmosphere, or solar wind, flows by the planets at an exceedingly high veloc-
ity, about 400 km/sec on average. Despite the fact that this solar wind is very tenuous, it can couple into a plane-
tary ionosphere or magnetosphere by viscously dragging on the magnetopause which couples to the ionopause, the outer boundary of the ionosphere. In a magnetized ino-
osphere like the Earth’s ionosphere, such motion is equi-
alent to an electric field as discussed above. Because the parallel conductivity along magnetic field lines is quite high, there is little potential drop along the field lines and the potential drop appears across field lines in the lower ionosphere, driving current there in the complex manner discussed in the previous paragraph. In short, drag at high altitudes in a planetary magnetic field can cause circu-
lation in the ionosphere. This, in turn, leads to complex current patterns at low altitudes.

Because the solar wind is magnetized, there is an ad-
ditional component to the drag on a planetary magne-
tosphere in addition to the normal particle and wave transfer of momentum across the boundary. When the interplanetary magnetic field has a component antiparallel to a planetary magnetic field where the solar wind and planeto-
etary magnetosphere first come into contact, the two fields can become linked in a process called reconnection. This process increases the drag on the magnetized planetary plasma, leads to a long magnetized tail behind the planet, and causes ionospheric flow across the polar cap, which returns at lower latitudes. This process of reconnection is believed to be the primary controlling mechanism for almost all of geomagnetic activity, except for sudden im-
pulses in ground magnetograms that are associated with shocks in the solar wind passing the Earth.

Because the Earth rotates and the terrestrial magnetic field lines are good electrical conductors, the plasma on the field lines tends to rotate with the Earth. The electric field associated with this rotation is called the corotational electric field. The motion of plasma due to the drag of the
Solar wind, which at high latitudes is directed away from the Sun over the polar caps, is toward the Sun at lower latitudes. The electric field associated with this motion is called the convection electric field. The combination of the two fields produces a plasma circulation pattern in the Earth's equatorial magnosphere as shown in Fig. 4. In this figure the large arrow labeled E represents the direction of the convection electric field. It is perpendicular to the magnetic field, which is out of the page and to the direction of flow, or convection, of the plasma, which is indicated by the streamlines labeled with smaller arrows. Most of these streamlines are open and carry low-energy plasma from the nightside of the magnosphere to the dayside and out through its boundary. A subset of the streamlines in the inner magnosphere is closed. In this region the plasma rotates with the Earth, both being supplied by and losing particles to the Earth's ionosphere along magnetic field lines.

II. THE SOLAR WIND

When during a solar eclipse the moon blocks all the light from the photosphere, light scattered from electrons in the solar corona can be seen. The density of the solar corona is very structured, and this structure is controlled by the solar magnetic field that changes significantly from month to month, passes through quiet phases every 11 years, and reverses polarity just after every period, producing a 22-year magnetic cycle. The corona is also hot, so hot that it expands supersonically into interplanetary space. It reaches a velocity of typically 440 km/sec well before reaching Mercury and continues at this velocity well beyond Pluto. The density of the solar wind falls off as the inverse square of the heliospheric distance, so that at the orbit of the Earth, one astronomical unit (AU) from the Sun, there are about seven electrons and seven protons in every cubic centimeter with a temperature of about 100,000 K. Electrons and ions do not collide under these conditions and therefore are frozen to the magnetic field line on which they began their journey from the Sun. The energy density in the flowing solar wind is much greater than that in the magnetic field so the magnetic field does not act as a brake on the flow, rather the plasma drags out the magnetic field. The thermal velocity of the ions is much less than the radial bulk flow of the plasma, but not so for the much lighter electrons, which can communicate with the Sun along the stretched-out spiral magnetic field. Thus, one should visualize the electrons as streaming (back and forth) along the magnetic field line while the protons move radially outward with no contact with the Sun, dragging the field line with them. Time variations on the Sun may change the density of electrons on the field line at the surface of the Sun, but the electric potential due to the existence of an excess charge at any point adjusts the velocities of the electrons just the right amount to maintain charge neutrality. The thermal velocities of the electrons are not distributed according to a Maxwellian distribution, nor are they the same along and across the field. This complicates the radial variation of the effective temperature of the electrons and the angular distributions.

Much like the Earth, the Sun's magnetic field has a north pole and a south pole whose locations switch periodically, about every 11 years. There is also a magnetic equator. Unlike the Earth, the magnetic equator tilts significantly over the course of the 11-year sunspot cycle and unlike the Earth, the strength of the higher order moments of the magnetic field can be very strong. At the orbit of the Earth much of this complexity is seldom seen. What is important is the polarity of the dipole moment and the tilt of the magnetic equator or, as it is more commonly called, the heliospheric current sheet. As the sun rotates relative to the Earth it carries this current sheet past the Earth in a 27-day cycle producing a characteristic ionospheric pattern of the magnetic field as the Earth moves above and below the current sheet. This pattern is referred to as the sector structure of the interplanetary magnetic field. Since the magnetic field is connected to the Sun at one end, it
forms a spiral pattern as it expands. The strength of the radial component of the magnetic field decreases as $r^{-2}$ and of the tangential components as $r^{-1}$, resulting in a magnetic field spiral that becomes tighter and tighter as it converges outward. At the orbit of the Earth the angle of the magnetic field to the radial direction from the Sun is about 65°. The solar wind velocity varies with heliomagnetic latitude, being about 800 km/sec above about 20°. When the magnetic equator is tilted with respect to the rotational equator, the fast solar wind regions will catch up with the preceding slow solar wind. This collision causes a pileup in the collisionless solar wind because one magnetized plasma region cannot penetrate another except under special circumstances. This collision is called a stream-stream interaction and it compresses the field strength and the plasma density and the causes deflections to the east and west. These regions in turn have greater influence on the magnetosphere when they arrive close to the larger densities and magnetic fields. The most effective disturbances from the Sun are those associated with coronal mass ejections (CMEs), in which large segments of the corona come flying off accompanied by a strong magnetic field. This fast plasma flow with its strong steady fields is very effective at producing a disturbed terrestrial magnetosphere. These disturbances in the solar wind have been called interplanetary coronal mass ejections (ICMEs) to distinguish them from the causative disturbance whose properties we do not fully understand. ICMEs often drive a leading bow shock in the solar wind. They also often contain multiple magnetic flux ropes or magnetic clouds that are twisted tubes of strong magnetic flux, containing perhaps as much as 50 earth-magnetic flux tubes (TWe) of magnetic flux. It is the interaction of these twisted tubes of magnetic flux that cause the largest geomagnetic disturbances or storms.

III. PLASMA INTERACTIONS WITH UNMAGNETIZED ATMOSPHERELESS BODIES

The simplest interaction of a plasma with a solar system body is that with an unmagnetized atmosphereless body, as in the interaction of the solar wind with the Earth's moon. The electrons and ions in the solar wind strike the lunar surface and are absorbed, leaving information about the solar wind energy implanted in the lunar soil but undergoing no equatorial plasma processes. This process leaves a cavity behind the Moon. The solar wind attempts to close behind the Moon to fill in this cavity. As illustrated by Fig. 5, the closure depends on the direction of the interplanetary magnetic field relative to the direction of the solar wind flow. If the magnetic field is aligned with the flow, the cavity behind the Moon is filled with magnetic flux and the cavity closes only slightly, so that pressure balance with the solar wind pressure is maintained. If the magnetic field is perpendicular to the flow, then the solar wind closes slowly behind the Moon as plasma flows along field lines at the thermal speed. The thermal speed is the average random velocity of the particles relative to the drift or bulk velocity of the flow. The Moon is not completely unmagnetized. It possesses remanent magnetization from an earlier epoch. Some regions are coherently magnetized over hundreds of kilometers and sufficiently so that they have enough magnetic pressure to deflect the solar wind when the solar wind flow is tangential to the lunar surface in the region known as the solar wind limbs, or terminator. This deflection causes a disturbance to be launched into the solar wind, but it is not strong enough to form a shock. These disturbances have been called limb compressions. The Moon has an ionizing outer shell, but its interior, being much hotter, is quite electrically conducting. The size and conductivity of this highly conducting region are such that it would take at least many days to perhaps hundreds of years for a magnetic field to diffuse from outside the core to the interior of the core. Thus magnetic observations can be used to probe the interior lunar electrical conductivity. One way to do this is to use measurements obtained when the Moon is in the near-vacuum conditions.
of the geomagnetic tail lobes. A satellite, such as one of the Apollo 15 and 16 satellites, flying in low-altitude lunar orbit can measure the distortion of the field caused by its exclusion from the lunar core. A second technique is to measure the frequency spectrum of magnetic fluctuations in the solar wind on a spacecraft and then measure the frequency spectrum of magnetic fluctuations seen on the lunar surface as was done during the Apollo program. The alternation of the frequency spectrum can be used to determine the conductivity profile of the Moon. In particular, this technique can sound the conductivity profile in the cooler outer layers of the Moon. Its sensitivity is limited by the accuracy of the intercalibration of the two instruments used.

Two of the moons of Jupiter, Europa and Callisto, also appear to have an interior electrically conducting layer, but in the cases of these two bodies the layer is thought to consist of salty water rather than a metallic or molten core. At both bodies the time-varying magnetic field associated with the rotation of its tilted dipolar magnetic moment is nearly completely excluded from the interior of the moon indicating that the conducting layer is close to the surface. The thickness of the subsurface oceans of Europa and Callisto is thought to be of the order of 100 km.

Plasmas interact with the moons of Jupiter and Saturn. Except for Titan and to a lesser extent Io, these moons have almost no atmosphere. Energetic charged particles from the radiation belts of these planets impact the surfaces of these moons and sputter atoms from them. These atoms then become ionized and join the plasma surrounding the planets. Such sputtering also occurs in planetary rings. The collision of energetic particles with moons and rings is a significant loss process for the radiation belts of Saturn and to a lesser extent the radiation belts of Jupiter.

Dust particles, both those in rings and those not in the rings, can become electrically charged. For small dust particles, the charge can significantly alter their motions because the particles will feel the forces of the planetary elastic and magnetic fields as well as gravity. For instance, a planetary electric field is typically such as to enforce current in the plasma in the planetary magnetosphere with the rotation of the ionosphere of the planet, whereas the orbital velocity of uncharged particles varies with radial distance. So, to, will interplanetary and cometary dust be affected by the motional electric field of the solar wind.

Finally, the interaction of the solar wind with an asteroid should resemble the interaction with the Moon except that perhaps the cavity will not be as well defined because the asteroids are all smaller than the Moon and hence gyrodynamics effects become more important. If the asteroid has a magnetic field, as might an asteroid that is a nearly extinct comet, then its interaction region would be quite large and its interaction processes quite different from those described above. We defer such discussions to Section V.

IV. PLASMA INTERACTIONS WITH MAGNETIZED BODIES

There are at least seven strongly magnetized bodies in the solar system, Mercury, the Earth, Jupiter, Saturn, Uranus, Neptune, and the moon Ganymede. Each of these bodies provides us with a different aspect of the interaction of flowing plasma with a magnetic field. Mercury has a small magnetosphere, or magnetic cavity, both in absolute terms and relative to the size of the planet. Mercury also has no atmosphere or ionosphere. The Earth has a sizable magnetosphere as well as a well-developed atmosphere and ionosphere. Jupiter is a rapidly rotating planet with an immense magnetosphere and a strong source of plasma deep in the magnetosphere. Saturn has a smaller but also rapidly rotating magnetosphere. However, its plasma sources are not as strong as Jupiter’s sources. Uranus has a magnetic dipole axis that is at an angle of 60° to its spin axis, but, since its rotation axis is presently nearly aligned with the solar wind flow, it has an almost Earth-like interaction. Neptune’s moment, tilted at 47° to its rotation axis, which is almost perpendicular to the solar wind flow, undergoes large changes in its angle of attack to the solar wind in the course of each day. Finally, Ganymede, the solar system’s largest moon, has a magnetic moment large enough to create its own magnetosphere inside that of Jupiter.

A. Solar Wind Interaction with Mercury

Mercury is the smallest of the terrestrial planets, with a radius of 2439 km, intermediate between the Earth’s moon and Mars in size. It rotates more slowly than the Moon, rotating with a period of 59 days compared to the Moon’s 28 days. It is heavily cratered like the moon but differs from the Moon in its lack of synchronicity of rotation and orbital periods and in its density, which is 5.4 g/cm³ compared to the Moon’s density of 3.3 g/cm³. The high density indicates that Mercury has a significant iron core. This core apparently is sufficient to sustain an active dynamo despite the small size and slow rotation of the planet. Mariner 10 passed through the nightside magnetosphere of Mercury twice, in March 1974 and 1975, and detected a magnetic field arising from a planetary dipole magnetic moment of strength 4 ± 2 × 10²⁴ G-cm³. Figure 6 shows a sketch of the solar wind interaction with Mercury and the field lines in the Mercury magnetosphere. The zone of the magnetopause is only about 0.35 Mercury radii.
FIGURE 6 The solar wind interaction with Mercury illustrating the large fraction of Mercury’s magnetosphere occupied by the planet.

$R_m$ above the surface of Mercury. The bow shock is at about $0.9R_m$ above the surface at the subsolar point. The magnetic field strength on the surface of Mercury is 300–500 nT. Its instantaneous value depends on variations in the solar wind pressure relatively more than the magnetic field at the surface of the Earth depends on these variations. Variations observed in the magnetic field during the passages of Mariner 10 past the planet have been interpreted in terms of a dynamic magnetosphere controlled to a large extent by internal processes, but there are few observations on which to judge. The magnetopause and bow shock seem similar in basic properties and structure to these terrestrial boundaries.

B. Solar Wind Interaction with the Earth

The Earth, like Mercury, presents a magnetic obstacle to the solar wind. The Earth’s magnetosphere, though, is about 20 times the size of Mercury’s magnetosphere, being about 200,000 km wide at the dawn–dusk or terminator plane. Furthermore, at the feet of the field lines of the terrestrial magnetosphere there is a dynamically significant ionosphere. In front of this magnetosphere stands a bow shock wave much like that of Mercury, both in relative location and in microstructure. The closest approach of the bow shock to the center of the Earth under typical solar wind conditions is about 92,000 km or about 14.5 Earth radii. Under similar conditions the boundary of the magnetosphere (i.e., the magnetopause) lies at about 70,000 km or 10.9 Earth radii.

The Earth’s dipole magnetic moment is $8 \times 10^{22}$ T·m$^3$, which corresponds to a surface field of about 31,000 nT at the equator of the Earth and twice this at the poles. There are contributions from higher order terms such as the quadrupole and octupole terms. The relative importance of these higher order terms diminishes with altitude so that for most purposes we can consider the field in the inner magnetosphere to be dipolar. The Earth’s internal dynamo is not steady. The most noticeable surface field change is a slow westward drift, but on much longer scales, millions of years, the field reverses. These reversals provide a useful clock for geophysical studies. Their existence also suggests that the Earth was not always so well shielded from the solar wind as it is today.

Figure 7 shows a noon–midnight meridian cross section of the terrestrial magnetosphere. The solar wind, after passing through the bow shock, flows through a region known as the magnetosheath and around the magnetopause. The electrons and protons in the magnetosheath near the magnetopause are reflected by the Earth’s magnetic field. In this encounter with the Earth’s magnetic field they turn 180° about the field line and escape from the magnetopause. The current associated with this gyroconvection self-consistently generates the proper electric current to bound the Earth’s magnetic field under ideal conditions. Thus, plasma cannot directly enter the Earth’s magnetic field in the subauroral region. The magnetic field inside the boundary has a pressure equal to the...
dynamic pressure of the solar wind outside the magnetosphere.

Behind the Earth, a long magnetic tail stretches for perhaps 1000 Earth radii or more. If there were no viscosity in the solar wind interaction, the magnetopause shape would be determined only by normal stresses perpendicular to the magnetopause, and the resulting shape would be a teardrop. Viscosity is presently thought to be supplied in part by the Kelvin–Helmholtz instability discussed above and in part by the process of reconnection discussed below. As the flow in the magnetosheath passes above and below the polar regions, it passes a weak point in the magnetospheric field that marks the beginning of the tail. The two regions, one in the north and one in the south, are called the polar cusps. In these regions, solar wind plasma can reach all the way down to the ionosphere. Plasma can enter the magnetosphere here and form a boundary layer that has been called the plasma mantle. In a reconnecting magnetosphere the plasma can drift across the tail to a null field point, called the X-point, where it is accelerated. There, some of it enters the closed field region of the magnetosphere. The process of reconnection effectively couples the electric field of the solar wind into the electric field of the magnetosphere. Since motion of magnetized conductors is equivalent to electric fields, we may also view this as the motion of the solar wind causing motion of the terrestrial plasma. However, this coupling of the two magnetized fluids cannot occur without breakdown of the very high conductivity of the fluids at least in some limited region.

The net result of this process is flow in the outer magnetosphere, but the deep interior of the magnetosphere is relatively unaffected by these flows and continuous to corotate with the Earth. In this interior region, the ionoplasmic plasma, which is continually upwelling from the dayside ionosphere, can build up in density to a level at which the upwelling is matched by an equal downward flow. This high-density region of cold ionospheric plasma is called the plasmasphere. In this region the magnetic field is quite dipolar in character and the electric field is simply that necessary to make the plasma rotate uniformly.

The strongest coupling between the solar wind and the magnetosphere is through the process known as reconnection. This process can be steady state, slowly varying, or highly temporally varying. First we examine the case of steady-state reconnection. Then, we examine how variations in the reconnection rate lead to dynamic magnetosphere and finally we examine the effects of temporally and spatially patchy reconnection. Figure 8 shows the field lines in an idealized solar wind–magnetosphere interaction. In the top panel, the interplanetary, or solar wind, field lines are in the direction opposite those in the Earth's magnetosphere. Due to a breakdown in electrical conductivity at the "nose" of the magnetosphere, the interplanetary and planetary magnetic fields join at this point. The flow of the solar wind carries the ends of these joined field over and under the magnetosphere, pulling the magnetospheric field lines over the poles. These field lines sink in the tail until they meet in the center of the tail at the X-point where they reconnect once more. Here they form a closed field line, which touches the Earth at both ends, and also an interplanetary field line that does not touch the Earth at all. This interplanetary field line flows away from the Earth. The newly closed field line flows toward the Earth, around the Earth out of the plane of the figure, and then joins up with a new interplanetary magnetic field line.

When the interplanetary magnetic field is northward, parallel to the Earth's magnetic field, as in the bottom panel, reconnection apparently can still occur at high latitudes behind the polar cusps. This reconnection removes flux from the magnetotail and adds it to the dayside...
magnetosphere if the same field line connects to both the North and South of the magnetotail. Otherwise, the magnetosphere is simply stirred by this process but no net flux transfer occurs.

The processes sketched here are steady state. If, instead, as occurs in practice, the rates of reconnection and hence flux transfer from one region to another vary and vary differently, flux can build up in one region or another. The sequence that frequently occurs is a sudden increase in the dayside reconnection rate with a southward field in the solar wind. The magnetic flux in the magnetotail increases until the reconnection rate in the tail increases to remove the flux from the tail. This latter rate of reconnection can exceed the rate that built up the flux enhancement in the tail. This generates rapid flows and high electric fields as plasma is accelerated both toward and away from the Earth.

The accelerated plasma, in addition to filling the radiation belts and adding energy to the ring current flowing in the magnetospheric equator, also powers the auroral displays. Auroras occur when energetic particles from the magnetosphere collide with neutral atoms and molecules, putting their electronic shells into an excited state from which they later decay by giving off light. During these times, flows in the outer magnetosphere can well exceed the flows possible in the ionosphere at low altitudes. This can occur only if the magnetic field line has less than infinite conductivity, and therefore electric fields can appear parallel to the magnetic field lines. In such situations, particles bouncing on flux tubes become accelerated in the “parallel” electric field and cause further auroral displays as they excite atmospheric atoms by collision. The overall sequence of events in the Earth’s magnetosphere and ionosphere at such times is usually referred to as a magnetospheric substorm.

Even this complex process is an oversimplification. In practice, the reconnection process appears to be very unsteady. This unsteadiness appears to lead to the formation of magnetic islands on both the dayside and the nightside. This unsteadiness also leads to oscillations in the magnetospheric plasma inside the magnetosphere, adding to those oscillations that may be associated with the Kelvin-Helmholtz instability. Yet another source of waves is the region of space upstream of the Earth’s bow shock yet connected to it by field lines. Beams of particles escaping from the bow shock generate waves. These waves are blown back toward the Earth by the supersonic solar wind. If the waves are generated in just the right region, they can be carried to the magnetopause and also add to the oscillations in the magnetosphere. Thus the magnetospheric field lines are almost always vibrating to some degree. Some of these vibrations can occur at resonances of the field line and large standing waves build up. Often the oscillating electric field associated with these waves far exceeds the background or steady electric field value. However, typically, the magnetic amplitude is at most a few percent of the background field.

The presence of these oscillating electric and magnetic fields has very significant consequences for the trapped energetic charged particles in the Earth’s radiation belts. In a dipolar field such as the Earth’s, charged particles have three separable periodic components of motion: gyration around the magnetic field, bounce motion back and forth along the field, and drift around the Earth. As discussed earlier, in Section 1.B, these three components of motion are associated with three conserved quantities or adiabatic invariants. These quantities remain unchanged unless the assumptions about the constancy of the fields in which the particles move are violated. The lowest frequency oscillations in the magnetosphere, with periods of many minutes to hours, can violate the third adiabatic invariant, that associated with the drift of particles around the Earth causing them to diffuse inward or outward. Fluctuations with periods of seconds to minutes can resonate with the bounce motion causing particles to mirror at different points. Fluctuations at periods of milliseconds to seconds can resonate with the gyro motion of particles causing particles to have different helical paths along the field and to enter the atmosphere rather than bounce back along the magnetic field line. A very important set of these resonant wave-particle interactions are known as wave-particle instabilities. If waves at the resonant frequency do not exist, they may be spontaneously generated by the plasma if the net effect of the waves on the particles includes a transfer of energy to the waves. For example, if an electron traveling along a magnetic field with some energy across the field and some energy along the field meets a right-handed electromagnetic wave head on, it would resonate with the wave if the particle velocity along the magnetic field caused the wave to appear to the particle to be oscillating at its gyrofrequency. This resonance would cause energy to be transferred from the parallel motion to the perpendicular motion of the electron or vice versa depending on the phase of the interaction. This resonant oscillation also would transfer energy from the wave to the particle in the former case and from the particle to the wave in the latter. If, for a given resonant parallel electron velocity, there are more electrons with energy predominantly perpendicular to the field than along the magnetic field, this random resonance will cause a net diffusion from the perpendicular energy state to the parallel one. Since this liberates energy from the electron, the wave gains energy. This process is but one example of a wave-particle instability. There are many such instabilities in the magnetospheric plasma causing both electromagnetic waves and
electrostatic waves. These instabilities help the magnetosphere regulate itself and return to an equilibrium configuration when disturbed.

C. Solar Wind Interaction with Jupiter

The magnetosphere of Jupiter is immense. It could easily contain the Sun and its corona. If one could see it in the night sky, it would appear to be much larger than the full Moon. It also rotates very rapidly, because the planet rotates rapidly and there is good electrical connection between the planet and the magnetosphere. Furthermore, the magnetosphere is filled with heavy ions that appear to come mainly from the solar wind. These characteristics combine to provide Jupiter with a very interesting and different magnetosphere than that of the Earth.

The reason for the enormity of the jovian magnetosphere is that the planet's intrinsic magnetic moment of $1.5 \times 10^{22}$ T·m$^3$ is over 16,000 times greater than that of Earth and that the solar wind that confines the magnetospheric cavity is over 25 times weaker. The resulting average distance to the magnetopause at the subsolar point is 70 planetary radii. The bow shock at the subsolar point is on average 85 jovian radii. The surface magnetic field of Jupiter has a greater contribution from higher order terms (quadrupole, octupole, etc.) than the surface field of the Earth. This is at least in part due to the fact that the conducting core of Jupiter, in which the dynamo currents flow, is relatively close to the surface of Jupiter than is the Earth's core to the surface of the Earth.

Well inside the jovian magnetosphere, at 5.9 jovian radii, orbits the moon Io with its sulfuric volcanoes. These volcanoes release into the jovian magnetosphere sulfur monoxide, sulfur dioxide, sodium, and other gases, which in turn are ionized and become part of the trapped plasma of the jovian magnetosphere. Spouting from Io, the other satellites, and the jovian rings also adds atoms and ultimately plasma to the jovian magnetosphere. Because the jovian field lines are good electrical conductors, the plasma is forced to corotate with the solid body of the planet over much of the magnetosphere. This acceleration is accomplished through an electrical current system closing through the jovian ionosphere and the magnetospheric plasma joined along field lines. This current system also flows most strongly near Io as Jupiter attempts to force the newly created ions into corotation. These processes are thought to generate large potential drops along the field lines in the vicinity of Io. These electrical potential drops can accelerate charged particles to high energies and may be responsible for some of the radio emissions from Jupiter at decametric (10 m) wavelengths. At decametric wavelengths (10 cm) radio emissions are due to synchrotron radiation from the intense fluxes of relativistic electrons near the planet. Auroral emissions are also observed at Jupiter and are thought to be caused in much the same way as terrestrial auroras.

The centrifugal force on the plasma in the jovian magnetosphere far exceeds the gravitational force over much of the magnetosphere. On the front side of the magnetosphere the solar wind opposes this centrifugal force and near-static equilibrium is reached. If too much mass is added to flux tubes, then they can interchange their positions (via the interchange instability) with lighter flux tubes further out in the magnetosphere, but generally the flow corotates azimuthally with the planet.

As illustrated in Fig. 9, one major effect of these rapidly rotating mass-loaded magnetic field lines is that of stretching the magnetospheric cavity from the more common spherical shape to a more disk-like shape. This effect can be seen in observations of the magnetic field and of the location of the bow shock. The streamlined shape of the disk-shaped magnetosphere allows the shock to stand closer to the magnetopause.

The plasma added to the magnetosphere at Io at an average rate of perhaps 500 kg/sec moves slowly outward at a rate of only meters per second at first but reaches a velocity of over 40 km/sec at a distance of about 50 jovian radii. Thus many months are required for the transport of plasma to the distant magnetosphere where it can be lost down the tail, but most of this time is spent traversing the inner magnetosphere. Since in a collisionless plasma the

![FIGURE 9 The magnetic field lines in the noon–midnight meridian of the jovian magnetosphere showing the current sheet associated with centrifugal force exerted by the plasma added to the magnetosphere by the moon Io.](image)
charged particles are constrained to stay on the same magnetic field lines in the absence of parallel electric fields, the outward motion of the plasma that is needed to maintain a steady-state density profile also transports outward the magnetic flux. Since Jupiter's internal dynamo is producing a rather constant magnetic flux, the outward plasma transport would soon deplete the magnetic flux of the planet if there were no way to separate the plasma from the magnetic field. Two mechanisms can do this: particle scattering that causes some particles to move parallel to the magnetic field and enter the neutral sphere, and reconnection of oppositely directed magnetic fields across the magnetosphere that forms magnetized islands of ions with no net magnetic flux. Subseem, similar to those in the Earth's magnetosheath have been reported. These liberate a similar amount of magnetic flux from the ions as was loaded with plasma at Io, about 80,000 Wb/sec on average. Once emptied of their plasma these magnetic flux tubes move buoyantly back to the interior of the Jovian magnetosphere much like a stream of air bubbles rising from the bottom of a sealed jar with a small hole in the bottom.

The size of the Jovian tail is immense. It is about 200 R_J (14 million km) across or more than 40 times the width of the Earth's tail. It is at least 4 AU long, extending all the way to Saturn.

D. Solar Wind Interaction with Saturn

The magnetic moment of Saturn is a factor of 32 less than that of Jupiter but it is immersed in a solar wind whose pressure is a factor of 4 less than that at Jupiter. The net result is a Saturn magnetosphere that, while it is only one fourth of the size of that of Jupiter, still dwarfs the magnetosphere of the Earth. Saturn's magnetosphere seems to be less inflated than that of Jupiter. The intrinsic magnetic field of Saturn is highly unusual. The surface magnetic field strenght at the equator is 0.21 μ T, not much different than that of Earth. However, the magnetic moment of Saturn is almost perfectly aligned with the rotation axis, whereas the magnetic dipole moments of the Earth and Jupiter are tilted by about 10° to the rotational axes of the planets. The sizeable tilt of planetary dipole magnetic fields is thought to be essential to the dynamo process. Thus, the alignment of the Saturn magnetic moment is quite puzzling. The contribution to the surface field by the higher order moments is much less than that at Jupiter indicating that the depth at which the dynamo is acting at Saturn is greater than at Jupiter.

Saturn has many small and intermediate-sized moons and a well-developed ring system. These bodies are bombarded by the radiation belt particles, mass is spattered from their surfaces, and mass is added to the magnetic field lines. The Saturn ionosphere, like the Jovian ionosphere, attempts to accelerate this plasma to corotational velocities. However, the mass-loading rates in the inner magnetosphere are not as large as at Jupiter and little distortion of the magnetosphere results. The one large moon of Saturn, Titan, orbits at the outer edge of the magnetosphere at 20 Saturn radii. Its dense atmosphere does strongly interact with the corotating magnetospheric plasma. However, the resulting distortion of the overall shape of the magnetosphere is much less than Io's effect on the Jovian magnetosphere. Again, this is evident from the direction of the magnetic field in the magnetosphere of Saturn and the location of the bow shock relative to the magnetopause.

The radiation belts of Saturn are much more benign than those of Jupiter and the radio emissions are much less intense. The rings absorb the charged particles as they diffuse radially in toward the planet. Because it is the particles in the innermost part of a planetary magnetosphere that are most energetic, the rings play a significant role in reducing the particle and radio flux. Ring particles can become electrically charged. It is thought that some of the exotic behavior of the rings such as the appearance of radial spokes in the rings may be the result of the effects of Saturn's magnetic and electric fields on these charged dust particles. The Cassini spacecraft launched in 1997 is scheduled to orbit Saturn in 2004 and extend our understanding presently based on three Pioneer and Voyager flybys.

E. Solar Wind Interaction with Uranus and Neptune

Voyager 2 flew through the magnetospheres of Uranus and Neptune in January 1986 and August 1989, respectively. The magnetic moment of Uranus is a factor of 12 smaller than that of Saturn, and the best-fit offset dipole field is tilted a surprising 59° to the rotation axis. The magnetic moment of Neptune is a factor of two smaller than that of Uranus and tilted at 47° to the rotation axis. The radiation belts of both planets are quite benign. Otherwise, the magnetospheres are quite terrestrial in configuration, with a standing, very high Mach number, bow shock in front and a long magnetic tail in the antisolar direction.

F. Interacting Magnetospheres of Jupiter and Ganymede

The Ganymede magnetosphere shown in Fig. 10 differs greatly from that of the Earth shown in Fig. 7. First, the velocity of the Jovian magnetospheric plasma past Ganymede is slower than that of the compressional wave that is required to deflect the flow around Ganymede. Thus the compressional wave can run far ahead of Ganymede so that the flow is deflected gradually around Ganymede and
no bow shock is formed. Second, the external magnetic conditions are relatively constant so that the Ganymede magnetosphere is quite steady with no substorms-type processes. Third, the strong external field limits the magnetosphere to a nearly cylindrically symmetric tube that wobbles with the nodding of the external Jovian field as the Jovian tilted dipole rotates. Finally, there is no cold plasmasphere in the inner part of the Ganymede magnetosphere. The ionosphere and slow rotation compared to the transport velocity induced by the Jovian magnetosphere are just too weak to produce such a feature. Nevertheless, it has some of the character of the terrestrial magnetosphere: a polar cap whose magnetic field lines connect to the external, flowing plasma and a region of closed field lines that intersect the surface of the body on both ends.

V. PLASMA INTERACTIONS WITH IONOSPHERES

A planetary ionosphere is the ionized upper atmosphere of a planet or moon, usually caused by solar ultraviolet radiation, but often impact ionization caused by charged particles plays an important role. If a body has an ionosphere, it also has a neutral atmosphere. The plasma also can interact directly with the neutral atmosphere. Thus, it is often difficult to separate those effects due to the interaction of a magnetized plasma with a conductor (the ionosphere) and those due to charged particle–neutral particle interactions. This is particularly true for the interaction of the moon to

and the Jovian magnetosphere. Nevertheless, in the next two sections we attempt just that. In this section, we discuss the interaction of the solar wind with Venus and then with Mars, both of which are probably dominantly, but not exclusively, controlled by ionospheric behavior.

A. Solar Wind Interaction with Venus

The planet Venus has been visited by many spacecraft including the long-lived Pioneer Venus orbiter, one of whose objectives was to study how the solar wind interacted with the Venus ionosphere. Figure 11 shows schematically the interaction of the solar wind with Venus. Despite the fact that Venus has no detectable intrinsic magnetic field, the solar wind is deflected about the planet and a bow shock formed. The ionospheric pressure balances the solar wind pressure to stand off the solar wind. The pressure of the solar wind is applied to the planetary ionosphere through a compression and pileup of magnetic field lines over the forward hemisphere of the planet. Magnetic field does penetrate the ionospheric barrier in two ways. First, bundles of magnetic field about 20 km across break through the ionopause and slip into the planetary ionosphere. The ionosphere sweeps these flux ropes to the nightside. However, as they move through the ionosphere, these tubes can become highly twisted and form links like a highly twisted rubber band.

The magnetic field also can diffuse and convect into the ionosphere. Usually the rate of diffusion is small enough that any field that enters the planetary ionosphere is swept away by ionospheric flows although, at the subsolar point, downward motion of the ionospheric plasma also can transport magnetic flux from the ionopause to low altitudes. When the solar wind pressure is high, especially when it exceeds the peak ionospheric pressure, diffusion
and downward transport of magnetic flux can become fast enough to magnetize the Venus ionosphere with a horizontal field of up to ~150 eT's strength. At such times ion-neutral collisions in the atmosphere help support the ionosphere against the solar wind pressure. The magnetic field that enters the Venus ionosphere from the solar wind still has its ends in the solar wind and is dragged antiparallel by the solar wind flow. This process contributes to the formation of a magnetic tail behind Venus.

The solar wind interaction with Venus is solar-cycle dependent with the bow shock farthest from the planet at the peak of the solar cycle when the solar ultraviolet radiation is the strongest. At solar minimum when the solar ultraviolet radiation and the Venus ionosphere are weaker the solar wind penetrates closer to the planet and more directly interacts with the neutral atmosphere. Thus, at solar minimum the ionosphere is more strongly magnetized and fewer electrons and ions are transported toward midnight to support the nighttime ionosphere.

B. Solar Wind Interaction with Mars

The exploration of the planet Mars has been plagued with many problems and only recently has our understanding of the solar wind interaction with Mars approached our understanding of the interaction with Venus. This new understanding derives first from the 1989 Russian Phobos mission that provided 3 months of data from an initial elliptic orbit and then a circular orbit close to the moon Phobos. It also derives from the 1997 U.S. Mars Global Surveyor (MGS) mission that used aerobraking at altitudes below 140 km. These missions both reveal a very Venus-like interaction in which the solar wind interacts with the planetary ionosphere and any planetary magnetic field plays at most a very minor role. MGS additionally provided evidence for patches of strong surface remanent magnetization that show that, although Mars does not presently have an active dynamo, it once did.

VI. PLASMA INTERACTIONS WITH NEUTRAL GAS

The epitome of the interaction of a plasma with a neutral gas is the formation of a cometary tail in the solar wind. A cometary nucleus evaporates when it is close to the Sun. The expanding cloud of neutral gas is ionized by the solar ultraviolet radiation as well as by charge exchange with the solar wind and by impact ionization. This ionization makes the solar wind heavier and it slows down. However, the ends of the magnetic field lines are not affected and they continue to move at a rapid rate antiparallel. This stretches the field lines out in a long magnetic tail behind a comet. In this section we will discuss our present understanding of comets. Then we examine the same processes as they occur at Venus, Io, and Titan. The major difference in the interactions with these three bodies is that their neutral atmospheres are gravitationally bound to them. This restricts the region of mass addition.

A. Solar Wind Interaction with Comets

For purposes of understanding the solar wind interaction with comets, the cometary nucleus can be thought of as a reservoir of frozen gases and dust. The gas may be locked up in a lattice of other material. Such an assemblage is called a clathrate. When the gas is warmed up by the approach of the comet to the Sun, it evaporates, expanding supersonically and carrying dust particles with it. The evaporation can occur from a limited region of the nucleus and form a jet, or it can occur rather uniformly. The resulting cloud of dust orbits with the comet, although light pressure changes the effective force of gravity on the dust so that the dust follows a slightly different path trailing out behind the comet. This dust cloud forms what is known as a type II cometary tail. The neutral gas expands to great distances up to several million kilometers or more in an active comet, with an emission rate that may exceed 10^20 molecules per second. The neutral hydrogen in this cloud extends to millions of kilometers as can be determined from observations of the solar Lyman α scattered from the neutral hydrogens and forming a bright ultraviolet halo about the comet. The neutral gas becomes ionized by solar ultraviolet radiation, by charge exchange with solar wind ions, and by impact with solar wind electrons. Photoionization simply adds mass to the solar wind, as does impact ionization. Charge exchange does not add mass to the flow if the charge exchange is symmetric (i.e., between nuclei of the same species). However, a fast ion turns into a fast (400 km/sec) neutral in this process, so momentum is removed from the solar wind. If the charge exchange is between a solar wind proton and a heavy neutral atom such as oxygen, the solar wind plasma gains mass. All these processes lead to a slowing down of the solar wind flow because the electric field of the solar wind immediately accelerates the newly created ion up to the speed of the flow across the magnetic field. Since momentum is conserved, this acceleration of the ion must be accompanied by a slight deceleration of all the neighboring ions.

The energy of the solar wind flow is converted to energy of gyromotion of the decelerated heavy ions. Ions with energies of the order of 100 keV may be detected millions of kilometers from a comet. Near the comet the energy density in the picked-up ions may significantly exceed the energy density in other constituents in the plasma.
large amount of energy in these heavy ions in 0x0 leads to plasma instabilities and much turbulence downstream of the nucleus.

The interaction with a comet creates a slow spot in the solar wind. Well away from this slow spot, the solar wind is moving at an undisturbed rate. Since the fast regions and slow regions are linked by the magnetic field lines, the magnetic field gets stretched out, forming a long tail. This long tail is filled with ions, at least in its central region, and can often be readily seen in bright comets. This is a type 1 or ion tail. Figure 12 shows the magnetic field lines obtained in computer simulations of Comet Halley for four different conditions, slow, normal, and fast solar wind velocity, and, on the bottom, normal velocity but enhanced mass addition rate.

If a comet is weak, there is no formation of a bow shock wave. However, if the comet is strong, the solar wind is unable to accommodate the added mass, a shock wave is formed, and the incoming flow is deflected around the heaviest mass-loading region. The newly added mass may, in fact, have enough pressure to create an ionopause and a magnetic field void in the interior of the interaction region. Such a void was observed at closest approach to Halley by the Giotto spacecraft.

Missions to comets—Giotto at both Halley and Grigg-Skjellerup; VEGA 1 and 2 at Halley; and EEE-3 at Giacobini-Zinner—encountered strong ultralow-frequency wave turbulence. The VEGA 1 and 2 spacecraft at closest approach to Halley also saw ion condensations, indicative of the mirror instability, in which ions form pockets of high density and low magnetic field strength surrounded by regions of strong magnetic field and low ion density.

The tails of comets undergo many dynamic events as they encounter changing solar wind magnetic field orientations and changing solar wind conditions. The most dramatic of these is the so-called tail disconnection event, where the type 1 ion tail appears to be torn away from the comet. Undoubtedly, the behavior of the ion tail at these times is strongly affected by the tension in the bent magnetic field lines. This tension acts to accelerate the ion tail plasma to the ambient solar wind velocity.

B. Formation of the Venus Magnetotail

The neutral atmosphere of Venus is gravitationally bound to the planet. However, both the hydrogen and oxygen in the Venus atmosphere have hot components that can emit many thousands of kilometers in altitude before returning to the planet. As the solar wind passes through this so-called exosphere, it can pick up mass just as in the cometary interaction described above. This added mass can further slow down the solar wind and add magnetic flux to the Venus tail. Measurements behind Venus reveal a well-developed magnetic tail with two lobes as in the Earth's tail and a diameter of 4 Venus radii. However, at Venus the location of these two lobes depends on the orientation of the interplanetary magnetic field because they are formed by the deflection of this field around the obstacle to the solar wind flow.

C. Plasma Interaction with Io

The interaction of the Jovian magnetospheric plasma with the moon Io is the engine that drives the dynamics of the Jovian magnetosphere, its aurora, and radio emissions. The tenuous, volcanically derived atmosphere of Io becomes ionized by photoionization, charge exchange, and impact ionization. As illustrated in Fig. 13, the strong Jovian magnetic field links this plasma to the rapidly rotating Jovian ionosphere. A current system is established that accelerates the newly added plasma to the angular speed of the ionosphere, which is much greater in linear
D. Plasma Interaction with Titan

The interaction of the Saturnian magnetosphere with Titan is much less eccentric than that of Io with the Jovian magnetosphere because the magnetic field at Titan is very weak compared to that at Io and the ionization rates much lower. Titan’s atmosphere is dense, not tenuous, and is less sensitive to any preexisting volcanic activity or outgassing of the planet. As a result, any variability of the interaction of the Saturnian magnetosphere with Titan should depend more on the solar wind than on changes at Titan. The most recent passage of Voyager by Titan revealed strongly bent magnetic field lines and associated field-aligned currents. Many sources of interaction should resemble the solar wind interaction with Venus, rather than Jupiter’s interaction with Io. Further study of the interaction of Titan with the Saturnian magnetosphere will be obtained with the Cassini mission.

VII. CONCLUDING REMARKS

Plasmas in the solar system are complex entities in part because the currents, fields, and particle distributions are all interdependent physical parameters, linked through Maxwell’s equations and the laws of classical mechanics and gravitation. Often intuition based on our observation of neutral gases and fluids fails us so that we find these plasma behaviors in quite unexpected ways. Much of the present understanding of space plasmas is based on a symbiotic relationship between theory and observation and assisted in recent years by large-scale computer simulations. This relationship will have to continue as we explore and attempt to understand the distant reaches of our solar system. The most distant reach of the solar system,
as far as electric and magnetic fields are concerned, is the heliopause, where the solar wind is stopped. Here the pressure of the galactic plasma, including its cosmic rays and magnetic field, is sufficient to balance the dynamic pressure of the solar wind. Our spacecraft have not reached the heliopause yet, but we expect that, if they keep operating, one of the Pioneer or Voyager spacecraft will one day penetrate this boundary, probably before the end of this century.

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