The Solar Wind Interaction with the Earth's Magnetosphere: A Tutorial

C. T. Russell

Department of Earth and Space Sciences and
Institute of Geophysics and Space Physics
University of California Los Angeles

Abstract. The size of the terrestrial magnetosphere is determined by the balance between the solar wind dynamic pressure and the pressure exerted by the magnetosphere, principally that of its magnetic field. The shape of the magnetosphere is additionally influenced by the drag of the solar wind, or tangential stress, on the magnetosphere. This drag is predominantly caused by the mechanism known as reconnection in which the magnetic field of the solar wind links with the magnetic field of the magnetosphere. The factors that control the rate of reconnection of the two fields are not understood completely but a southward direction of the interplanetary field is critical to enabling reconnection with the dayside low latitude magnetosphere, resulting in magnetic flux transfer to the magnetotail. Numerical simulations suggest that the conductivity of the ionosphere controls the rate of reconnection but this has not been verified observationally. While solar wind properties ultimately control the interaction, the properties of the plasma that makes direct contact with the magnetosphere are different than those of the solar wind, having been altered by a standing bow shock wave. This standing shock is necessitated by the fact that the flow velocity of the solar wind far exceeds the velocity of the compressional wave that diverts the solar wind around the Earth. The upper atmosphere is the final recipient of all the energy and momentum that enters the magnetosphere. Coupling takes place along the magnetic field lines principally in the polar and auroral region via current systems that close across the magnetic field both at low and high altitudes and flow parallel to the magnetic field between high and low altitudes.

Introduction

The Earth has an internal dipole magnetic moment of $8x10^{15}$ Tm^3 that produces a magnetic field strength at the equator on the Earth's surface of about 30,000 nT, and at 10 Earth radii (R_E) of about 30 nT. This dipole moment is created by a magnetic dynamo deep inside the Earth in the fluid, electrically conducting core. The solar wind interaction slightly more than doubles this value on the dayside so that the pressure in the magnetic field is about 2 nPa. The sun emits a magnetized plasma consisting of mainly protons and electrons with a density of about 7 cm^{-3} at the orbit of the Earth (1 astronomical unit or AU) at a velocity of about 440 km/sec. The pressure exerted by this flowing plasma is also about 2 nPa, thus balancing the pressure exerted by the magnetospheric field. Four basic laws govern the behavior of the charges, currents, magnetic fields and electron fields in a plasma. These equations are collectively called Maxwell's laws. They together with the conservation of mass, momentum and energy govern the types and speeds of waves in the plasma. Disturbances of three types propagate in this magnetized solar wind plasma. The fast mode wave compresses the magnetic field and plasma; the intermediate mode wave bends the flow and magnetic field, but does not compress it; and the slow mode wave rarefies the field while it compresses the plasma and vice versa. The solar wind travels faster than the propagation speed of all three of these waves so when it reaches the Earth's magnetosphere the "pressure" waves needed to deflect the solar wind plasma cannot propagate upstream into the solar wind without creating a shock front. The geometry of this shock, the deflected flow, called the magnetosheath and the magnetopause, the boundary between the magnetosheath and the magnetosphere is shown in Figure 1 [1]. The fastest wave is the aptly-named fast mode wave. It does the yeoman's work in slowing, deflecting and heating the solar wind downstream of the bow shock so that the plasma can flow around the magnetosphere. Nevertheless it cannot cause all of the changes in the plasma needed to move both the plasma and the magnetic field around the bullet-shaped magnetosphere. Thus the intermediate and slow modes also play roles. The net result of these waves is a flow that moves parallel to the magnetopause. The inward force normal to the surface is transmitted by a gradient in the thermal pressure of the plasma and the outward force by a gradient in the magnetic pressure.

In order to understand how the solar wind interacts with the magnetosphere and in turn the magnetosphere reacts to this interaction we need to examine the motion of charged particles in magnetic fields and the creation of the electric and magnetic fields by these same particles. A charged particle moving perpendicular to a magnetic field experiences a Lorentz force in the direction perpendicular to the magnetic field and the velocity vector so that the particle gyrates around the magnetic field with a frequency qB/M where q is the electric change of the particle, M is its mass and B is the magnetic field in MKSA or SI units. Velocity parallel to the magnetic produces translation of the particle along the magnetic field. If the magnetic field increases as the particle moves along it, the particle experiences a force opposite the direction of motion. This slows the particle until it stops and the motion along the magnetic field reverses. In this process the perpendicular energy, $\frac{1}{2}mV_{\perp}^2$, where $V_{\perp}$ is the velocity of the particle perpendicular to the magnetic field is proportional to the magnetic field strength, maximizing where the total energy is in the perpendicular direction. This ratio $mV_{\perp}^2/(2B)$ is called the first adiabatic invariant or the magnetic moment and is a constant of the motion, if the scale length for change in the field is much less than the radius of gyration of the particle or the temporal scale for change of the magnetic field is much less than that for the gyration of the particle around the magnetic field.

Figure 2 shows on the left-hand side the gyromotion of a charged particle about a magnetic field line. If the magnetic field lines converge, as shown in the middle panel, then the conservation of the first adiabatic invariant, causes the particle to reflect and bounce back and forth along the magnetic field line. The parallel momentum, i.e. the mass times the velocity, integrated along the motion of the particle is also conserved and is called the second adiabatic invariant. If the bounce path shortens, then the parallel energy of particle increases. This process is known as Fermi acceleration, i.e. acceleration by moving magnetic mirrors. If a field line is curved and the particle moves parallel to the field line, it will drift perpendicular to the magnetic field as shown on the right. If the magnetic field strength varies with distance, such as the inverse cube falloff in a dipole field, the gyrating particle will drift perpendicular to the gradient as illustrated on the right just as for the parallel moving particle on a curved field line. Both the curvature and gradient drifts are proportional to energy. In the Earth's magnetosphere the gyrating and drifting particles lead to a current encircling the magnetosphere, aptly called the ring current. The current due to these particles causes a depression in the magnetic field on the surface of the Earth that is proportional to the energy of the particles so that 100 nT of depression is produced by 2.8×10^{15}J of kinetic (thermal) energy.

Another important drift occurs in the presence of an electric field perpendicular to the magnetic field. This drift can be understood by recalling that when particles gyrate about a magnetic field, their radius of gyration is greatest when their energy is the greatest. If an electric field is applied across a plasma, an electron or an ion will be accelerated (in opposite directions) for a period of half a gyro period. Once the particle has gyrated 180^o about the magnetic field it begins to decelerate. Since the radius gyration is greatest in the half gyro period that the particle is moving the fastest, the particles will drift perpendicular to the magnetic and electric fields.

Because electrons and positive ions gyrate in opposite directions and are also accelerated in opposite directions by the electric field, the resultant drift is the same for both and in the direction of the vector cross product **E**x**B**. Because electrons and ions drift with the same velocity, there is no current associated with this drift.

The microscopic motions of the charged particles especially in a magnetized plasma are very important to the physics of plasmas but there are circumstances where we can safely ignore these motions or average over them. This "fluid" approach to the treatment of a plasma is called the magnetohydrodynamic approach, or MHD for short. The laws that govern the behavior of this fluid are Maxwell's equations (Faraday's law, Ampére's law, Poisson's equation, and the zero divergence of the magnetic field) together with a generalized Ohm's law and the conservation of mass and momentum. The simplest generalized Ohm's law, that generally holds away from boundary regions in a collisionless plasma is that the electric field is equal and opposite to the vector cross product of the bulk velocity of the plasma times the magnetic field. These equations allow one to consider problems in terms of the pressures exerted by the plasma and magnetic field. It is important to remember that plasmas have finite mass and momentum resulting in the slow propagation of disturbances through the system relative to the speed of light. Thus responses can be far from instantaneous in a magnetized plasma such as the Earth's magnetosphere. Moreover, since there are three propagating modes that each do something different to the plasma the response of the magnetosphere to a sudden change in the solar wind can be quite complex. The fast mode compresses the plasma and the magnetic field together; the intermediate mode twists the field and the flow but does not change the density or the magnetic field strength; and the slow mode weakens the magnetic field when it compresses the density. The fast and slow waves can steepen into shocks if the wave is forced to travel at a speed greater than its natural velocity in the plasma. Since the solar wind blows against the magnetosphere with a speed much greater than that of either of these waves as illustrated in Figure 1, a shock front forms in front of the magnetosphere called the bow shock.

In the sections that follow we discuss the stresses on and in the magnetosphere and their effects, the transport of energy into the magnetosphere and its storage there, what controls the major energization events and the relationship of smaller scale disturbances, called substorms, to major magnetic storms. The strongest coupling between the solar wind and the magnetosphere occurs when their magnetic fields reconnect in regions of nearly opposite directions. The physics underlying reconnection occurs on the sub-gyroscale where the ions and eventually the electrons encounter magnetic structure that demagnetizes the charged particles so that they no longer are tied to the magnetic field and drift across it. This process allows field lines from different plasma regimes to connect. We call this process reconnection and merging interchangeably.

The Earth's Bow Shock

Before examining the physics of the magnetosphere itself we discuss briefly the bow shock. The function of this non-linear bow wave is to deflect the plasma around the magnetospheric obstacle that is shaped rather like a blunt bullet. In Figure 1 the blank area on the right is the magnetosphere that can be considered to be an impenetrable blunt body for this discussion. The curve along which the flow and the magnetic field suddenly changes from being straight to being curved is the shock front. We can understand why a bow shock forms in front of the Earth with the aid of Figure 3. The top panel shows the change in pressure in a subsonic flow as one approaches the obstacle. The pressure consists of two parts, the dynamic pressure and the static pressure. The former is proportional to the momentum flux or the mass density times the speed squared. The latter pressure is proportional to the product of the number density and the temperature and, in a magnetized plasma, with an additional component proportional to the square of the magnetic field. The total pressure remains constant but the static pressure grows as the dynamic pressure diminishes. The gradient formed by the increasing static pressure slows and deflects the flow so that it passes around the obstacle. When the flow is supersonic, the dynamic pressure exceeds the static pressure which is incapable of forming a gradient strong enough to deflect the flow. The formation of the shock heats and compresses the flow by converting dynamic pressure to thermal pressure. The subsonic flow that ensues can then establish the needed gradient in the static pressure to further slow and deflect the flow.

Where the shock forms is determined by how compressed the flow is on the downstream side of the shock (often called the high entropy side). All the material that passes through the shock front must pass between the shock and the obstacle so that if it is only weakly compressed the post shock region will have to be thick. The factors that control the compression in an ideal fluid are the polytropic index from the equation of state that governs the relation between density and temperature, and the Mach number, the ratio of the speed of the fluid and the speed of the compressional wave that deflects the flow. If the polytropic index is 5/3, the value for an adiabatic process in a monatomic collisional gas, then the solar wind plasma can be compressed by a factor of 4. If the polytropic index is 2, the value for an adiabatic process for collisional particles confined to a plane, then the solar wind can be compressed only a factor of 3 and the shock is further out from the obstacle. (Most research points to a value of 5/3 for the polytropic index but the presence of the magnetic field can make heating a solely two-dimensional process in the absence of collisions or a process that mimics collisions.). If the Mach number of the shock drops below unity as would happen if the density of the solar wind dropped (to the neighborhood of 0.1 cm^{-3} say) or if the magnetic field strength increased (to the neighborhood of about 40 nT all else being constant), then the bow shock would weaken and move away from the obstacle and disappear. The physics of the bow shock is rich with processes that heat the plasma, scatter and reflect the particles so that a foreshock is formed as shown by the shading in Figure 1 but discussing that physics is beyond the scope of this review.

The Size of the Magnetosphere

In order to determine the scale size of the magnetosphere we need to understand the pressure applied to the magnetosphere by the solar wind. Fortunately we do not have to solve the complex non-linear solar wind interaction problem to do so. We can obtain a quantitative formula for the distance from the center of the Earth to the magnetopause in a straightforward manner. Conservation of the momentum in a stream tube of varying cross-section, S, gives us

$$(\rho u^2 + nkT + B^2/2\mu_o)\, S = \text{constant} \qquad (1)$$

where ρ, u, n, T and B are the mass density, speed, number density, temperature of the solar wind and magnetic field strength respectively. This formula allows us to use the incoming solar wind dynamic pressure, ρu^2, which dominates over the thermal and magnetic pressures, in front of the bow shock instead of having to calculate these pressures in the magnetosheath downstream from the shock front, given that we know the expansion of the cross-section of the stream tube S.

It is instructive to compare the size of the terms in (1). The ratio of the first two terms is:

$$\rho u^2/nkT = u^2/(kT/m_i) = \gamma u^2/c_s^2 = \gamma M^2_s \qquad (2)$$

where γ is the polytropic index, c_s is the sound velocity and M_s is the sonic Mach number. The ratio of the first and third terms is

$$\rho u^2/(B^2/2\mu_o) = 2u^2/(B^2/\mu_o\rho) = 2u^2/v_A^2 = 2M_A^2 \qquad (3)$$

where M_A is the Alfven or intermediate Mach number and v_A is the Alfven velocity.

Finally the ratio of the second and third terms is

$$nkT/(B^2/2\mu_o) = \beta = 2(M_A/M_s)^2/\gamma \quad (4)$$

Since, as stated above, the solar wind flows faster than any of the three waves in the plasma and usually much faster, Mach numbers are much greater than unity. Thus equations (2) and (3) tell us that the dynamic pressure dominates over the thermal and magnetic pressures in front of the bow shock. Equation (4) indicates that, when the magnetic pressure dominates (low β), the speed of Alfven waves exceeds that of sound waves and magnetic forces dominate in the plasma frame. The intermediate wave propagates at the Alfven speed along the magnetic field. The fast mode wave propagates at a speed $(2)^{½} \{c_s^2 + v_A^2 + [(c_s^2 + v_A^2) - 4c_s^2\, v_A^2 \cos^2\theta]^{½}\}^{½}$ where θ is the angle between the magnetic field and the direction of propagation of the phase fronts of the wave. Perpendicular to the magnetic field this speed is equal to $(v_A^2 + c_s^2)^{½}$. The slow speed is $(2)^{½} \{c_s^2 + v_A^2 - [(c_s^2 + v_A^2) - 4c_s^2\, v_A^2 \cos^2\theta]^{½}\}^{½}$. The fast mode is the only mode that can transmit energy across a magnetic field.

Returning to the question of the standoff distance of the nose of the magnetopause, we now know that we can approximate the solar wind pressure contribution by the momentum flux ρu^2 diminished by a factor accounting for the expansion of the stream tube. This effect is small, roughly 10%. The magnetospheric pressure is dominated by the pressure in the magnetic field. The pressure equals $(aB_o/L^3_{mp})^2$ where a is a shape-dependent factor, equaling 2.4 for the shape of the Earth's magnetosphere as discussed below, and L_{mp} being the distance to the magnetopause from the center of the Earth. Equating the pressure to the solar wind dynamic pressure we obtain a standoff distance

$$L_{mp} = 107.4\ (n_{sw}\, u_{sw}^2)^{-1/6} \quad (5)$$

where n_{sw} is the solar wind proton number density in cm^{-3}, u_{sw} is the proton bulk velocity in km/s, and L_{mp} is the standoff distance in R_E.

The Obstacle

A magnetic field exerts a force on a plasma both through pressure gradients and curvature stresses. An equilibrium between these two forces is found in the dipole magnetic field sketched in Figure 4. In the equatorial plane the magnetic field weakens with radial distance and exerts a force on the magnetospheric plasma that is outward. The curved field lines pull with equal force in the opposite direction so there is no net force on the plasma. Since a magnetic field cannot exert a force along its length (just as you cannot push a string) there is no vertical force along the dipole axis and there is no counter balancing curvature force here. This simple description of the forces associated with a dipole magnetic field suggests that the interaction of the solar wind with a dipole magnetic field is going to be somewhat more complicated than the interaction of a supersonic bullet with air.

The first scientists to tackle this difficult problem were S. Chapman and V.C.A. Ferraro in 1930 [2] who took an infinitely electrically conducting plane to represent the solar wind plasma and pressed it against a dipole as shown in the top left diagram in Figure 5. There are bifurcations in the magnetic field above and below the equator where the magnetic field, in the noon-midnight meridian shown here, becomes zero. At these locations there are few forces on the plasma that can prevent it from entering the magnetosphere at this point and reaching the ionosphere. Because the magnetic field is zero here this region is called a neutral point. Because of its shape, it is also called the cusp or the polar cusp, a name that is in most frequent use today.

Chapman and Ferraro were able to draw this diagram by assuming that the electrical conductivity of the solar wind plasma on the left was so high that the terrestrial magnetic field was excluded from this region by currents flowing on the interface between the plasma and the terrestrial magnetic field or magnetosphere. Thus this current sheet, or magnetopause as we call it today, confines all the magnetic field lines. These magnetopause currents have an effect equivalent to placing a second dipole on the left, equidistant from the magnetopause, and then only tracing the magnetic field lines on the right. One of the forces that can prevent the solar wind plasma from entering the polar cusp is the magnetic force. Chapman and Ferraro did not consider a magnetized solar wind. As we discuss later, the solar wind is magnetized and this magnetization complicates the interaction.

In deriving equation 5 we used a shape dependent factor ‘a’. The factor for the image dipole magnetosphere is two, as you might expect from symmetry, if the magnetopause current reduced the magnetic field to zero on the solar wind side. If instead of a flat plane in front of the magnetosphere we placed a spherical superconductor around the magnetosphere, as illustrated in the upper right-hand quadrant of Figure 5, the magnetic field strength in the equatorial plane would be tripled. If one instead inserted the magnetosphere in a bullet-shaped superconducting shell approximating the shape resulting from the interaction with the flowing solar wind as shown on the bottom left, the factor becomes 2.4. Finally, for comparison with a more realistic magnetosphere containing plasma we show on the bottom right the empirical magnetosphere based on comparisons with observed magnetic fields [3].

The magnetopause currents that bound the magnetosphere are sensitive to the square root of the solar wind dynamic pressure. When the dynamic pressure of the solar wind changes, the currents increase as the magnetosphere shrinks and the magnetic field seen on the surface of the Earth rises. The time rate of change of the magnetic field is generally quite benign except in the dayside auroral zone near 60^o-80^o magnetic latitude. Figure 6 shows a plot of the time rate of change of the magnetic field for different magnetic latitudes as a function of local time for many sudden compressions of the magnetosphere showing this dayside high latitude amplification associated with the high (Hall) conductivity of the ionosphere, associated with the impact of auroral particles on the atmosphere. Values greater than about 7 nT/s can be harmful to electrical transmission systems. This did not happen during these events but it would not have taken a much larger storm to cause such problems.

Tangential Stress

The dynamic pressure determines the overall size of the magnetosphere and to zeroth order its shape, but tangential stresses also affect the shape and cause momentum transfer across the boundary. Several different mechanisms have been proposed for the source of tangential stress and momentum transfer to the magnetosphere. Figure 7 illustrates a number of the popular mechanisms. The upper left-hand panel illustrates diffusive entry. An ion enters the magnetospheric magnetic field and instead of returning to the magnetosheath with the same velocity with which it started, it becomes scattered and drifts within the magnetosphere carrying with it whatever momentum parallel to the boundary it had initially. This process relies on scattering centers that seem not to be present in the boundary layers inside the magnetosphere. The lower left panel shows a variant of diffusive entry in which an entire tube of magnetosheath plasma crosses the magnetopause into the magnetosphere. However, this mechanism is not expected to be effective because as long as there is a finite angle between the magnetosheath and magnetospheric fields the tubes cannot penetrate one another. If they do become aligned in some region, the three-dimensional geometry of the interaction causes them to be at some significantly large angle not far away from the point of alignment. Thus the two magnetized plasmas are kept separate.

The top right-hand panel illustrates momentum transfer by wave processes. In a dissipative medium, such as the ionosphere to which the magnetospheric field lines are connected, the eddies formed by the passage of a surface wave are increasingly smaller with distance from the boundary. The net result is a flow within the magnetosphere that is parallel to the magnetosheath flow. Finally, the lower left panel shows the result of boundary-wave amplitude growth via the Kelvin-Helmholtz instability when the magnetosheath velocity passes an instability threshold. The boundary shape becomes non-sinusoidal and the momentum transfer by the process discussed above proceeds at even a greater rate. This process takes place independently of whether the solar wind magnetic field is parallel or antiparallel to that of the magnetosphere, but the tangential stress on the magnetosphere clearly depends on the magnetic field orientation. There seems to be little momentum transfer that is independent of control by the north-south component of the interplanetary magnetic field.

The main mechanism by which the magnetized solar wind powers the magnetosphere was first proposed by J. W. Dungey [4, 5] as sketched in Figure 8. In the top panel the interplanetary magnetic field is southward and becomes connected to the terrestrial magnetic field at the subsolar point in a process known as reconnection. Reconnection produces open field lines with one end connected to the Earth, by combining interplanetary field lines, not connected to the Earth, with closed field lines, connected to the Earth on both ends. The resulting V-shaped magnetic fields attempt to straighten and accelerate plasma (whose origin is both in the solar wind and the magnetosphere) in the direction of the arrows shown. Then the magnetic field slows the plasma as the field lines are stretched behind the terminator. Over the dayside energy flows from the magnetic field into the plasma, but in the tail there is an electromagnetic flux of energy, called the Poynting flux, into the magnetic field from the solar wind plasma. This flux of energy is numerically equal to the vector cross product of the solar wind velocity at the boundary times the magnetic field crossing the boundary times the magnetic field parallel to the boundary divided by the permeability of free space μ_o. This process slows the solar wind moving along the boundary extracting energy from it and stores it as magnetic energy in the magnetotail. The addition of magnetic flux to the tail by this process is illustrated at the top of Figure 9. This energy is in turn tapped at a reconnection point in the tail, shown in the upper panel of Figure 8, that causes the flow of plasma into the magnetosphere proper and back down the tail. The plasma and field continue to move toward the dayside reconnection point as illustrated by the dashed lines in Figure 9 where the cycle repeats itself. In this way the magnetospheric plasma can be made to circulate even in a dissipative system as energy is continually supplied by the solar wind. Estimates of the rate of energy input into the magnetosphere during active times range up to about 2 teraWatts.

When the interplanetary magnetic field is northward reconnection can still occur but it has a quite different effect on the magnetosphere. The panel on the bottom of Figure 8 shows this situation. The interplanetary magnetic field now reconnects with the terrestrial magnetic field above and behind the poles. The reconnected field line is added to the dayside and a corresponding flux tube is removed from the nightside and transported down the tail. Effectively this transports magnetic flux from the nightside to the dayside magnetosphere. The reconnected dayside tube moves along the magnetopause boundary (in three dimensions out of the plane of the page) and replaces the flux tube that was lost down the tail. This mechanism makes a boundary layer of plasma within the magnetopause and maintains circulation of the plasma for northward interplanetary magnetic field. When the magnetic field is northward, but not due northward, this process can still proceed, but the same flux tube is unlikely to reconnect at both ends. This results in plasma circulation but no change in the magnetic flux on open and closed magnetic field lines.

Numerical simulations of the solar wind interaction with the magnetosphere indicate that the conductivity of the polar ionosphere affects the rate of reconnection at the magnetopause [6]. This can be understood in terms of the tying of the polar cap magnetic flux more firmly to the ionosphere and slowing down magnetospheric convection. If convection over the polar cap were to cease as the polar cap became ever more electrically conducting, magnetic flux would buildup in the magnetotail to such an extent that it formed the obstacle to the flow and then would cut off subsolar reconnection. There is no observational data that directly confirms or denies this conjecture because the conductivity of the polar cap is not readily observed. However, the ring current buildup seems to depend principally on the solar wind and interplanetary magnetic field and not on changes that occur in the polar ionosphere during storms.

The tangential stress in the outer magnetosphere must ultimately apply stress to the ionospheric plasma as the ionosphere is the ultimate site of dissipation in the magnetospheric system. Although there are several ways for energy to be deposited in the ionosphere from the magnetosphere, such as particle precipitation whereby energetic charged particles in the magnetosphere enter the atmosphere and are lost, or as wave transport in which waves generated in the magnetosphere propagate into the ionosphere and heat it, the most significant energy dissipation mechanism is Joule dissipation in electric currents. Figure 9 illustrates where the current systems in the magnetosphere flow. In the absence of tangential stress the magnetopause current and the tail current are dissipationless currents flowing on the surface of the magnetopause and not closing in the ionosphere. When there is a magnetic field normal to the magnetopause these currents can accelerate or decelerate the flow in the dayside and tail regions respectively. The current crossing the plasma sheet, labeled neutral sheet current, is an extension of the tail current system. It too can lead to plasma acceleration when there is a normal component of the magnetic field across the tail current sheet. The stresses applied to the plasma on magnetic field lines connected to the Earth are coupled by field-aligned currents to the ionosphere where dissipation does occur. The magnitude of the magnetopause current is such as to rotate the field direction and increase its strength from that of the magnetosheath to that of the magnetosphere. The neutral sheet current strength is of magnitude to reverse the direction of the magnetic field from the northern lobe of the tail to the southern lobe.

Magnetosphere-Ionosphere Coupling

The current system ultimately responsible for the majority of the dissipation is labeled "field-aligned current" in Figure 9. This current system closes in the magnetosphere on the pressure gradients in the plasma and thus is controlled by the magnetospheric stresses. At least a part of this current closes across the magnetic field in the collisional ionosphere. These collisions heat the atmosphere and the cross-field currents accelerate the ionospheric plasma against the drag of the atmosphere. These currents attempt to force the flow in the ionosphere to follow the flow in the magnetosphere. When the stress in the magnetosphere increases, the bend in the magnetic field increases and the current flow along the field lines increases. Figure 9 describes a steady-state magnetosphere. However, transient events also can cause stress-induced current systems that close in the ionosphere. Substorms that are described below are particularly important in causing such currents.

Figure 10 illustrates the physics involved in the coupling of the magnetosphere to the ionosphere via field-aligned currents [7]. At the top of the figure is the magnetopause where the stress applied to the magnetosphere has pulled the top of a bundle of magnetic field lines into the page. These field lines are now slanted with respect to their neighbors. This shear in the magnetic field is the equivalent of a parallel current. This current that began in the "generator" region of the magnetosphere, closing across field lines in a pressure gradient and acting in the direction to slow the solar wind, now experiences a "load" in the ionosphere where it applies a stress to the ionospheric plasma in the same direction as the stress in the magnetosphere so that the ionosphere begins to flow in the same direction as the solar wind. If the plasma flows in response to this stress, then the product of the magnetic field distortion, $\delta\mathbf{B}$, and the electric field, $\mathbf{V}\mathrm{x}\mathbf{B}$, is a Poynting flux, $\mathbf{S}$, into the ionosphere. It is this energy that is dissipated in the ionosphere as Joule dissipation.

In the Earth's magnetosphere there are many types of auroral processes. Any process that causes the precipitation of energetic charged particles from the magnetosphere into the atmosphere in significant numbers is likely to cause diffuse aurora. However, the most intense discrete aurora is caused by electrons accelerated down into the ionosphere by parallel electric potential drops along magnetic field lines in upward parallel electric currents. Thus most intense auroras are in regions of velocity shear in the magnetospheric plasma. The parallel electric fields that accelerate electrons downward also accelerate ions upward. Additionally heating of the ions perpendicular to the magnetic field and the upward mirror force mentioned earlier accelerate ions upward. Moreover, there are as many regions that accelerate electrons upwards (and ions downward) as there are the reverse. Thus the ionosphere is an important source of energized plasma for the magnetosphere.

The Ring Current

The ring current consists of the current due to the eastward (electron) and westward (proton) drift in the radiation belts. Since this current does not pass through the ionosphere, it is basically dissipationless. The energy content of the radiation belt is generally fairly constant except during periods known as geomagnetic storms. The ring current causes a net decrease in the magnetic field on the surface of the Earth [8,9] as opposed to the magnetopause current that causes an increase. The energy of these circulating particles can be calculated from their effect on the ground-level magnetic field as we discuss in the next section. In major magnetic storms this energy can reach 10 or more pentaJoules and the energization rate can exceed several teraWatts, equalling and possibly exceeding the energy dissipation in the auroral ionosphere.

The disturbance, storm-time index Dst, calculated from ground based magnetic field measurements, attempts to measure the energy in the ring current particles as the average depression of the horizontal component of the magnetic field around the Earth at low latitudes. This magnetic field is also sensitive to both the magnetopause and tail currents. The effect of the currents on the dayside magnetopause is to enhance the magnetic field on the surface of the Earth. Thus a sudden compression of the size of the magnetosphere by an increase of the solar wind dynamic pressure will cause a sudden increase in the surface field and in the Dst index. The effect of the tail current system is to oppose the Earth's field and has a stronger effect on the nightside, causing a day-night gradient in the field due to external sources. Thus a sudden compression of the magnetosphere has a greater effect on the dayside of the magnetosphere than on the nightside. Overall the Dst index provides a good measure of the ring current once corrections have been made for these other current systems.

Geomagnetic Storms

A geomagnetic storm occurs when the energy content of the radiation belts, i.e. the ring current, increases to unusually large values. The conditions in the solar wind that lead to the generation of major geomagnetic storms are relatively rare and depend on the level of solar activity occurring most often when the sunspot number is a maximum. The interplanetary magnetic field must be strong and steadily southward for several hours [10]. Figure 11 illustrates the solar wind condition and magnetospheric response during the build up of a geomagnetic storm that has been chosen because it clearly illustrates the different types of responses of the magnetosphere to geomagnetic activity [11]. The top panel shows the solar wind dynamic pressure. This pressure compresses the magnetosphere and increases the field strength on the surface of the Earth but has little other effect. At this time the Dst index in the bottom panel shows an increase in association with the pressure increase caused by the change in the magnetopause current. The second panel shows the north-south or Z component of the interplanetary magnetic field during the interval. The magnetic field is slightly southward at the beginning of the interval plotted. This leads to currents in the auroral zone as seen in the fourth panel from the top. The activity in the auroral indices remains roughly constant over the entire period plotted, even though the character of the interplanetary magnetic field changes drastically in the middle of this interval.

After the pressure pulse arrives the interplanetary magnetic field strength increases and begins to have strong fluctuations in the north-south direction. This hardly affects either the auroral currents in the fourth panel as measured by the AE index, the difference between the maximum and minimum horizontal magnetic field at all local times in the auroral zone, or the ring current as registered by the Dst index. Eventually the interplanetary magnetic field becomes steadily southward and strong and lasts this way for several hours. Now the ring current builds up and the Dst plunges to values more negative than -200 nT.

We can understand the injection of energetic plasma into the ring current with a fairly simple model of the solar-wind-magnetosphere interaction [12]. The basic premise of this model is that the energy flows into the ring current from the solar wind at a rate proportional to the interplanetary electric field in the dawn-dusk direction but not when the electric field is in the opposite direction. The dawn-dusk electric field, Ey, is the rate of transport, i.e. the flux, of southward magnetic field carried toward the magnetosphere, the product of the solar wind velocity and the north-south field. The process that allows this energy flow is reconnection. Once in the ring current, the energy exponentially decays with a fixed time constant so that a fixed percentage of the ring current energy is lost per unit time. As discussed above the Dst index is the deviation of the average horizontal component of the magnetic field around the near equatorial region from the quiet day field. It has contributions from both the ring current and the magnetopause. R. K. Burton, R. L. McPherron and C. T. Russell [12] proposed the following recipe for predicting Dst from the solar wind parameters.

$$dDst/dt = F(Ey) - a\,Dst_o \qquad (6)$$

$$Dst_o = Dst - b(P)^{1/2} + c \qquad (7)$$

$$F(Ey) = d\,(Ey - 0.5) \qquad Ey \geq 0.50 \text{ mV/m} \qquad (8)$$

$$F(Ey) = 0 \qquad Ey < 0.50 \text{ mV/m} \qquad (9)$$

where $a = 3.6 \times 10^{-5}\ s^{-1}$, $b = 15.8\ nT/nPa^{1/2}$, $c = 20\ nT$; and $d = 1.5 \times 10^{-3}\ nT/(mv\text{-}m^{-1}\text{-}s)$. Equation (6) states that the rate of change of the ring current as represented by the Dst index increases due to an energy coupling function F(Ey), and decreases by a fixed percentage each minute because of loss processes. Equation (7) states that the observed Dst index consists of a ring current contribution, Dst_o, and magnetopause current proportional to the square root of the dynamic pressure of the solar wind. The parameter, c, accounts for the fact that the Dst baseline has been chosen to be zero for a typical solar wind pressure, not for zero pressure. Equation (8) and (9) are the energy coupling functions for southward and northward interplanetary magnetic fields, where Ey is the product of the outward solar wind velocity and the northward component of the interplanetary magnetic field. Here it is assumed that a threshold exists that must be exceeded before any coupling occurs.

The energy contained in the ring current [10, 11] taking account of the induction in the conducting Earth is:

$$E_{RC}[J] = 2.8 \times 10^{13} B[nT] \quad (10)$$

so that the 200 nT storm shown in Figure 11 contained about 6×10^{15} J (6PJ), which it lost to the Earth's atmosphere by charge exchange and precipitation into the Earth's atmosphere at a rate of about 2×10^{11} W. At the peak of the injection the power into the ring current was about 10^{12} W. We note that this build up of energy was not predictable from the currents in the auroral zone as can be seen by the lack of a clear relationship between the quantities plotted in the fourth and fifth panels. We note also that during disturbed solar wind conditions the convected magnetic energy in the solar wind, that is the solar wind Poynting flux, is about 10^{12} W or one teraWatt integrated over the entire dayside magnetopause. Thus reconnection would have to be 100% effective for the Poynting flux to power a magnetic storm. Instead the magnetosphere taps a small fraction of the 60 TW of mechanical energy flux that the solar wind convects toward the dayside magnetopause under disturbed conditions.

Interplanetary Magnetic Field Control of Plasma and Mass Transport

A geomagnetic storm occurs when the solar wind causes deep and intense circulation of the magnetospheric plasma and this circulation is induced by reconnection of the interplanetary magnetic field and that of the Earth. We now know that these periods of deep, prolonged circulation, associated with periods of strong reconnection, occur in response to an interplanetary disturbance associated with a large ejection of mass from the corona or a CME. When the solar wind and magnetospheric plasmas become linked, the solar wind plasma can cause day to night flows over the polar cap and magnetic energy can be stored in the tail. This is important for the substorm to be discussed below. As clear from our discussion in the section above this transport must be a strong function of the north-south component of the interplanetary magnetic field so that when the magnetic field is opposite that of the Earth the reconnection rate is strong and when it is at all parallel the reconnection rate is weak. This statement applies locally to the magnetosphere and since the magnetopause has regions of quite diverse field directions, there is always reconnection somewhere. Nevertheless, direction does matter because it is important to magnetic flux and plasma transport as to where that reconnection occurs. Examining Figure 9 we see that antiparallel solar wind and magnetospheric fields will occur in the subsolar region when the interplanetary magnetic field is due southward. When the interplanetary magnetic field is horizontal or northward the antiparallel fields that promote reconnection occur near the polar cusp. Figure 12 shows the expected region of reconnection as a function of the direction of the interplanetary magnetic field if the reconnection process acted only on antiparallel magnetic fields [13]. The triplets of numbers in each panel indicate the direction of the magnetic field in this numerical exercise. In case (001) in the upper left the magnetic field is northward and reconnection occurs behind the cusp adding magnetic flux to the dayside in the manner predicted by Dungey [5] and illustrated in the lower panel of Figure 8. If the interplanetary field is southward as in the lower left panel (00-1) of Figure 12 reconnection should take place all across the dayside transporting magnetic flux and plasma to the tail as illustrated in the top panel of Figure 8. At intermediate directions, shown on the right for horizontal fields pointing duskward (010) and for southward, duskward fields (01-1), reconnection moves to the sides of the magnetosphere and is weaker. This motion of the site of reconnection with the direction of the interplanetary magnetic field causes dawn-dusk asymmetries in the flow patterns of plasma in the ionosphere that have opposite directions in the north and south hemispheres. The variations in the direction of the interplanetary magnetic field results in the magnetospheric flows being quite dynamic.

Solar Cycle Variation in Geomagnetic Activity and the Role of Interplanetary Coronal Mass Ejections

The control of the solar wind energy transfer by the interplanetary field orientation is modulated by the solar wind speed and density and the strength of the field but the field direction usually exerts the dominant influence. The question then is when does the interplanetary magnetic field become strongest and most southward. The answer is in the interplanetary magnetic structure known as an interplanetary coronal mass ejection or ICME. These structures are the interplanetary counterparts of large eruptions of material from the solar corona observed by coronagraphs that have been called coronal mass ejections or CMEs [14]. These ejecta propagate out into the solar wind at speeds sometimes exceeding 1000 km/s, compressing and deflecting the slower solar wind ahead. The angular width of such an ejection is typically about 45^{o}. Within the ICME are smaller, 10^{o} across, magnetic flux ropes, in which the magnetic field is strong and slowly rotates. One of these flux ropes is illustrated in Figure 13.

Figure 14 shows the percent occurrence of large values of the interplanetary electric field in the dawn-dusk direction, in ICMEs at fast-slow stream interfaces and in the quiet solar wind [15]. The fast-slow stream interfaces are steady-state interactions between regions of fast solar wind flow on the sun with regions of slow flow. This interaction occurs because the solar wind speed is controlled by the sun’s magnetic structure that is tilted with respect to the sun’s rotational equator. The rotation of the sun allows the fast solar wind to catch up with and collide with the slow solar wind. Both in the pre-ICME compressed solar wind and within the ICME itself there are the large electric field values that have been proven to be effective in producing intense magnetic storms. The next leading solar wind disturbance, the interaction region between fast and slow solar wind streams coming from the sun, produces some disturbed values but not nearly as strong as those associated with ICMEs.

One of the earliest associations of terrestrial magnetic disturbances with solar disturbances was the realization a century and a half ago that there was a geomagnetic cycle that was in step with the sunspot cycle. The reason for this correlation is that the interplanetary coronal mass ejections maximize when the sunspot number maximizes Figure 15 shows the solar cycle dependence of ICMEs, stream interactions and interplanetary shocks [16]. Interplanetary shocks turn out to have a strong correlation with ICME occurrence in the inner solar system. Thus both ICMEs and shocks track the sunspot number well. Stream interactions in contrast peak at solar minimum rather than solar maximum. Activity associated with stream interactions tends to lessen the correlation of geomagnetic activity with the sunspot cycle rather than to enhance it. To a large extent long term terrestrial space weather predictions depend on being able to predict when CMEs will be launched from the sun and predicting the properties of the resultant ICME.

Substorms vs Storms

Two basic classes of geomagnetic activity and distinguished as storms and substorms. Storms show a strong ring current and have durations that are any long or longer. Substorms are characterized by high latitude current intensifications and occur over intervals of hours, often repeating every few hours. Substorms do occur during storms, but perhaps unexpectedly this energy release is often accompanied, not by an injection of energy into the ring current, but by a loss of energy from the ring current [17, 18]. Clearly storms and substorms are both aspects of geomagnetic activity and are associated with southward interplanetary magnetic field but substorms do not cause storms and their strength is not predictive of storms. Typically substorms arise because of short time (hour long) variations in the interplanetary field. To understand their origin we look at the 1961 Dungey model [4].

Strictly speaking the Dungey model for the solar wind interaction, sketched in Figure 8, is a steady-state model, but it can readily be converted [19] to be a time-varying model as shown in Figure 15. The top panel shows the Dungey model for southward interplanetary magnetic field. The magnetic field has just turned southward and flux is being eroded from the dayside magnetosphere and moved into the polar cap or tail lobe region. Substorms occur because the various parts of the magnetosphere respond to the changing solar wind conditions only after some time delay. At the beginning of the substorm period, the merging rate, M, goes up, decreasing the dayside magnetic flux, Φ_{day}, in the bottom panel. Until reconnection begins between the two tail lobes, the magnetic flux in the tail, Φ_{lobe}, will increase. When the reconnection rate, R, in the center panel climbs rapidly, then the substorm onset has occurred returning flux first to the plasma sheet and then to the dayside. Almost by definition the substorm involves the release of energy that is much more rapid than its accumulation time. Finally, we note that even though its name suggest that a substorm is a small storm or a process that leads to a storm, there appears to be little connection between the processes that lead to substorm storage and release of energy into the auroral zone, illustrated in Figure 16, and the storm process. The substorm appears to intimately involve the tail for storage and release of energy. The storm appears to be associated with the penetration of the solar-wind induced plasma circulation deep into the magnetosphere and the resulting enhancement of the ring current.

Summary and Conclusions

The terrestrial magnetosphere is a complicated system. It acts as a buffer and an agent between the variable solar wind and the Earth's ionosphere and upper atmosphere. The magnetospheric size is controlled by the solar wind dynamic pressure. Under extreme conditions the magnetosphere can be as small as 5 R_E in radius and when the solar wind density drops to its lowest observed values it can be as large as 20 R_E. While the normal stresses are applied by the dynamic pressure, the tangential stress is applied principally by the reconnection process. The amount of reconnection at the magnetopause and its consequences depend strongly on the interplanetary magnetic field orientation. Reconnection during intervals of strongly southward field transfers magnetic flux to the tail. Reconnection above the cusp during intervals of strongly northward field can add more magnetic flux to the dayside while removing it from the tail.

Ejections of mass on the sun called coronal mass ejections can lead to intervals of prolonged southward interplanetary magnetic fields in the resulting disturbances or ICMEs. These ICMEs follow the sunspot cycle and cause the terrestrial geomagnetic cycle to follow suit. Thus accurate long term prediction of space weather depends on our ability to predict the properties of an ICME. While we do not have a complete understanding of all the processes in the magnetosphere, it is clear that the majority of the processes ultimately derive their energy from the solar wind through the reconnection process.

In addition to the academic interest in how magnetized plasmas behave, it is important to study the solar wind interaction with the magnetosphere because this interaction controls space weather phenomena. The ability to develop accurate space weather forecasts depends very much on the forecaster having a good understanding of how the magnetosphere works, i.e. on having a correct paradigm. Empiricism alone is unlikely to produce accurate predictive models.

Acknowledgments

We wish to thank Dr. Gang Lu for providing the data shown in Figure 11. This work was supported by the National Science Foundation under grant ATM98-03431.

References

[1] J.R. Spreiter, A.L. Summers, and A.Y. Alksne, Hydromagnetic flow around the magnetosphere, *Planet. Space Sci.*, *14*, 223-253, 1966.

[2] S. Chapman and V.C.A. Ferraro, A new theory of magnetic storms, *Nature*, 126-129, 1930.

[3] N.A. Tsyganenko, A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, *37*(1), 5-20, 1989.

[4] J.W. Dungey, Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47-48, 1961.

[5] J.W. Dungey, The structure of the exosphere or adventures in velocity space, in *Geophysics: The Earth's Environment*, edited by C. Dewitt, J. Hieblot, and A. Lebeau, pp. 505-550, Gordon and Breach, New York, 1963.

[6] J.A. Fedder, and J. G. Lyon, The solar wind-magnetosphere-ionosphere current-voltage relationship, *Geophys. Res. Lett.*, *14*, 880, 1987.

[7] R.J. Strangeway, R.C. Elphic, W.J. Peria and C.W. Carlson, FAST observations of electromagnetic stresses applied to the polar ionosphere in “Magnetospheric Current System,” (eds. S. I. Ohtani, R-I. Fujii, R. Lysak and M. Hesse) in press, AGU Monograph, Washington, 2000.

[8] A.J. Dessler and E.N. Parker, Hydromagnetic theory of magnetic storms, *J. Geophys. Res.*, *64*, 2239-2259, 1959.

[9] N. Sckopke, A general relation between the energy of trapped particles and the disturbance field near the Earth, *J. Geophys. Res.*, *71*, 3125, 1966.

[10] C.T. Russell, R.L. McPherron, and R.K. Burton, On the cause of geomagnetic storms, *J. Geophys. Res.*, *79*(7), 1105-1109, 1974.

[11] C.T. Russell, G. Lu, and J.G. Luhmann, Lessons from the ring current injection during the September 24-25, 1998 storm, *Geophys. Res. Lett.*, submitted 2000.

[12] R.K. Burton, R.L. McPherron, and C.T. Russell, An empirical relationship between interplanetary conditions and Dst, *J. Geophys. Res.*, *80*(31), 4204-4214, 1975.

[13] J.G. Luhmann, et al., Patterns of potential magnetic field merging sites on the dayside magnetopause, *J. Geophys. Res.*, *89*, 1739-1742, 1984.

[14] Coronal Mass Ejections: Causes and Consequences, edited by N.U. Crooker, J. Joselyn, and J. Feynman, *Geophysical Monograph 29*, AGU, Washington DC., 1997.

[15] G.M. Lindsay, C.T. Russell, and J.G. Luhmann, Coronal mass ejection and stream interaction region characteristics and their potential geomagnetic effectiveness, *J. Geophys. Res.*, *100*, 16999-17013, 1995.

[16] G.M. Lindsay, et al., On the sources of interplanetary shocks at 0.72 AU, *J. Geophys. Res.*, *99*, 11-17, 1994.

[17] C.R. Clauer, and R.L. McPherron, Predicting partial ring current development, in *Solar Terrestrial Predictions Proceedings*, *Vol. 4*, edited by R. F. Donnelly, 8-44-B-58, NOAA, Boulder, CO, 1980.

[18] T. Iyemori, Relative contribution of IMF-Bz and substorms to the Dst index, in *International Conference on Magnetic Storms*, edited by Y. Kamide, 99-104, Stelab Nagoya University, 1994.

[19] C.T. Russell and R.L. McPherron, The magnetotail and substorms, *Space Sci. Rev.*, *15*, 205-266, 1973.

Figure Captions

Figure 1. The magnetic field and the solar wind flow as they encounter the Earth's bow shock and the magnetosphere as predicted by the gas dynamic model [1]. The plane of the figure contains the magnetic field lines and the streamlines that are carried to the subsolar point. In the shaded region energetic ions accelerated at the shock can move upstream.

Figure 2. Motion of a gyrating ion in a magnetic field. On the left is the gyration of an ion about a straight field line. In the middle panel an ion is reflected by the converging magnetic field. On the right is illustrated the gradient and curvature drifts arising when the magnetic field has a radial gradient in magnitude or the field line is curved.

Figure 3. Qualitative sketch of the pressure gradient leading to the diversion of the plasma around the magnetospheric obstacle. In the top panel the velocity of the compressional wave is fast enough to create the pressure profile needed to do the deflection. In the bottom panel the pressure wave cannot move upstream and a shock has to form to do the deflection.

Figure 4. Field lines of a magnetic dipole in a plane containing the dipole axis.

Figure 5. Four magnetospheric models: (Upper left) The image dipole model; (Upper right) The spherical magnetosphere; (Lower left) The elliptical magnetosphere; (Low right) The empirical magnetosphere.

Figure 6. The time rate of change of the magnetic field at the time of the passage of shocks past the magnetosphere. The solid lines give the median values at the ground stations indicated. The largest and most dangerous values occur on the dayside of the Earth in the auroral zone.

Figure 7. Schematic illustration of four mechanisms of momentum transfer at the magnetopause.

Figure 8. The Dungey model of the reconnecting magnetosphere for northward (bottom) and southward reconnection (top).

Figure 9. A cutaway diagram of the magnetosphere showing its plasma regions and current system.

Figure 10. A schematic diagram showing how tangential stress on the high altitude magnetospheric plasma can lead to electric currents that flow along field lines and close through the ionosphere transferring the stress to the ionosphere. S, J, B, V, E represent the Poynting flux, the current, the magnetic field, the velocity of the plasma and the electric field respectively.

Figure 11. The development of a geomagnetic storm. The top panel shows the dynamic pressure in the solar wind offset by 21m to allow for the propagation time to the Earth. The next panel shows the z component of the interplanetary magnetic field in the north south direction. The middle panel is the interplanetary electric field formed from the product of the solar wind velocity and B_z. The next panel shows the auroral zone current indices AU and AL. The bottom panel shows the ring current buildup as measured by the Dst index.

Figure 12. Contours of equal angle between the shock IMF and a realistic magnetic field model for varying IMF directions. Dark regions show where the magnetic fields are nearly 180^o apart and where reconnection is expected to occur.

Figure 13. Schematic of a magnetic flux rope attached to the sun. Such ropes are consistent with the magnetic structure seen in magnetic clouds. Multiple spacecraft observations show that an individual ICME may contain several magnetic flux ropes of differing properties.

Figure 14. Occurrence of geoeffective interplanetary electric fields in ICMEs, in the region of stream interactions and in the quiet solar wind.

Figure 15. The solar cycle variation of ICME occurrence, shocks, stream interactions and sunspot number during the Pioneer Venus study period 1978-1988.

Figure 16. The near-Earth neutral point model of substorms. The top panel shows the noon-midnight meridian of the magnetosphere just after the interplanetary magnetic field has turned southward. This turning begins a cycle of flux transport. The rate of reconnection at the magnetopause is M, of reconnection in the tail is R and of convection back from the tail to the dayside is C. The fact that the time profile of these rates is different causes the amount of flux in each region to differ with time. The dayside erodes, the flux in the lobes builds up and the magnetic flux in the plasma sheet decreases until reconnection in the tail begins.

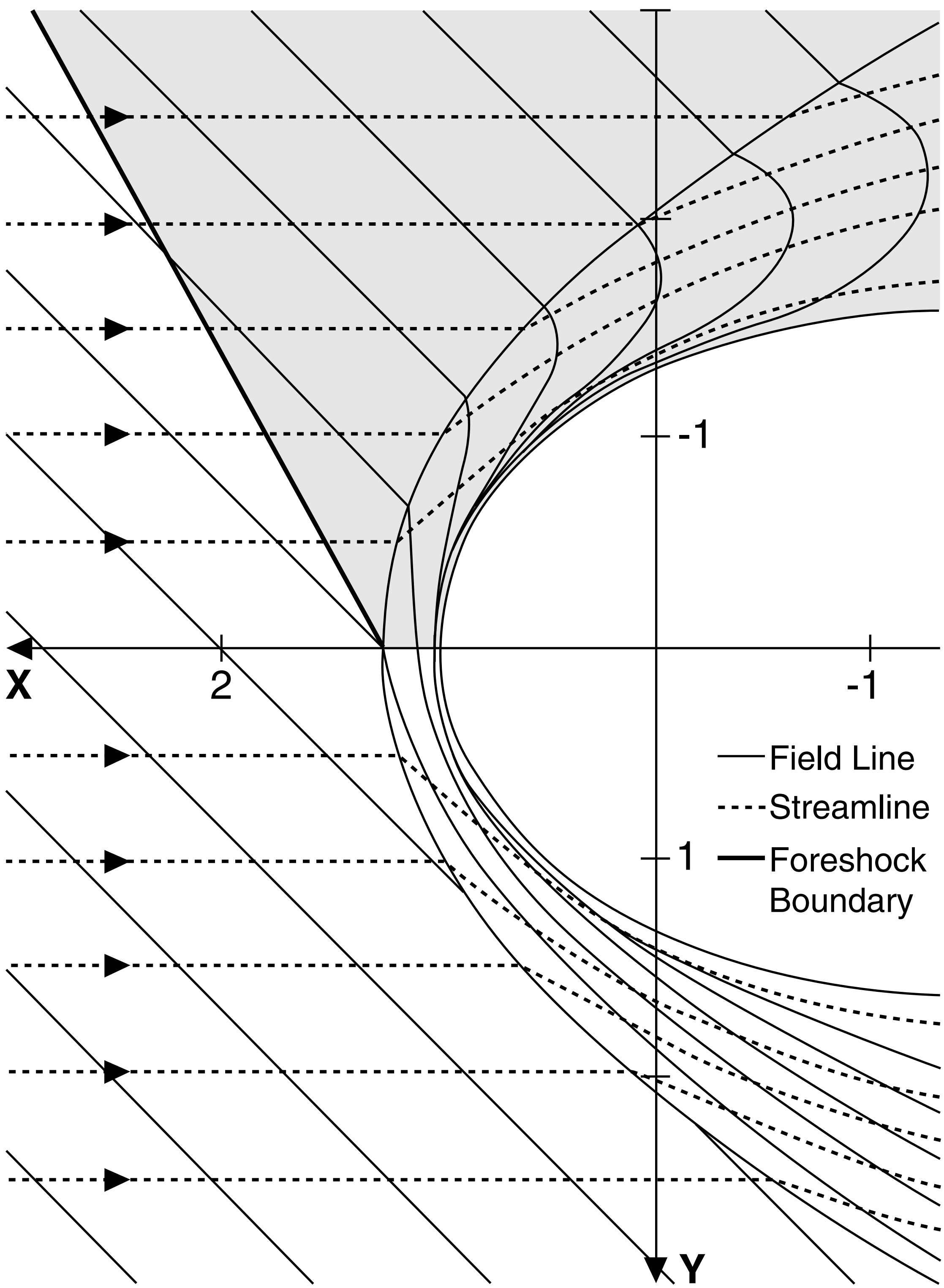


Figure 1

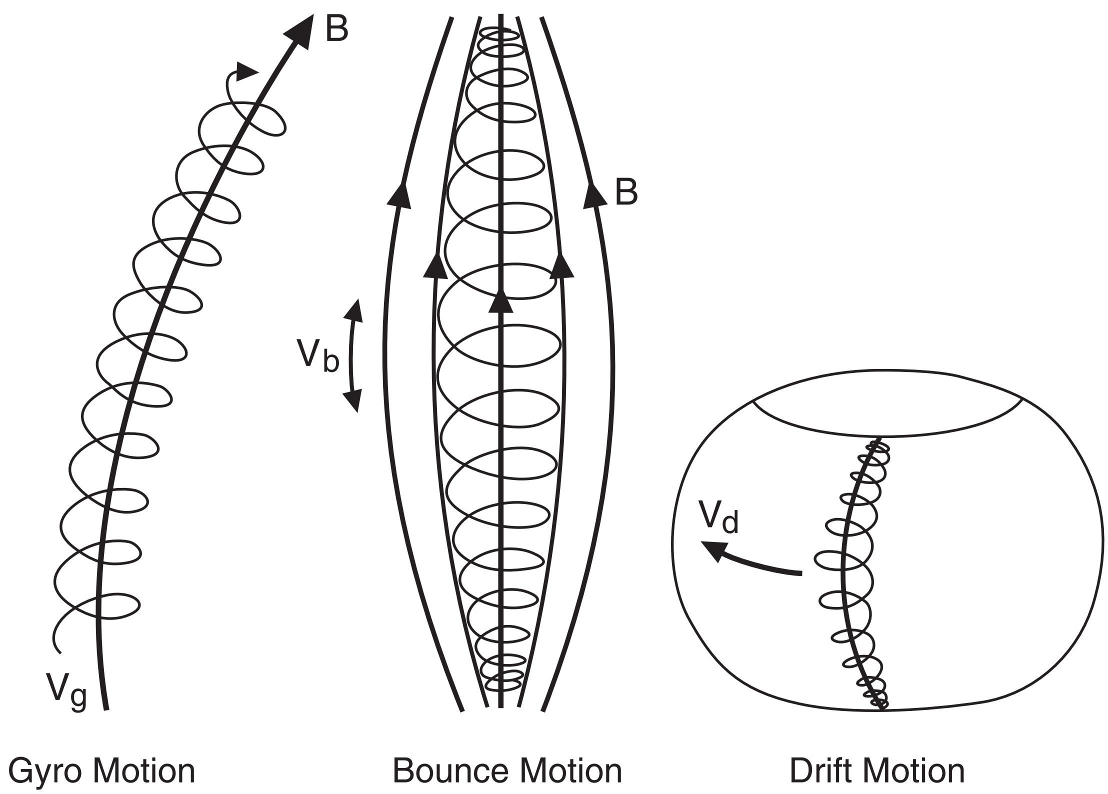


Figure 2

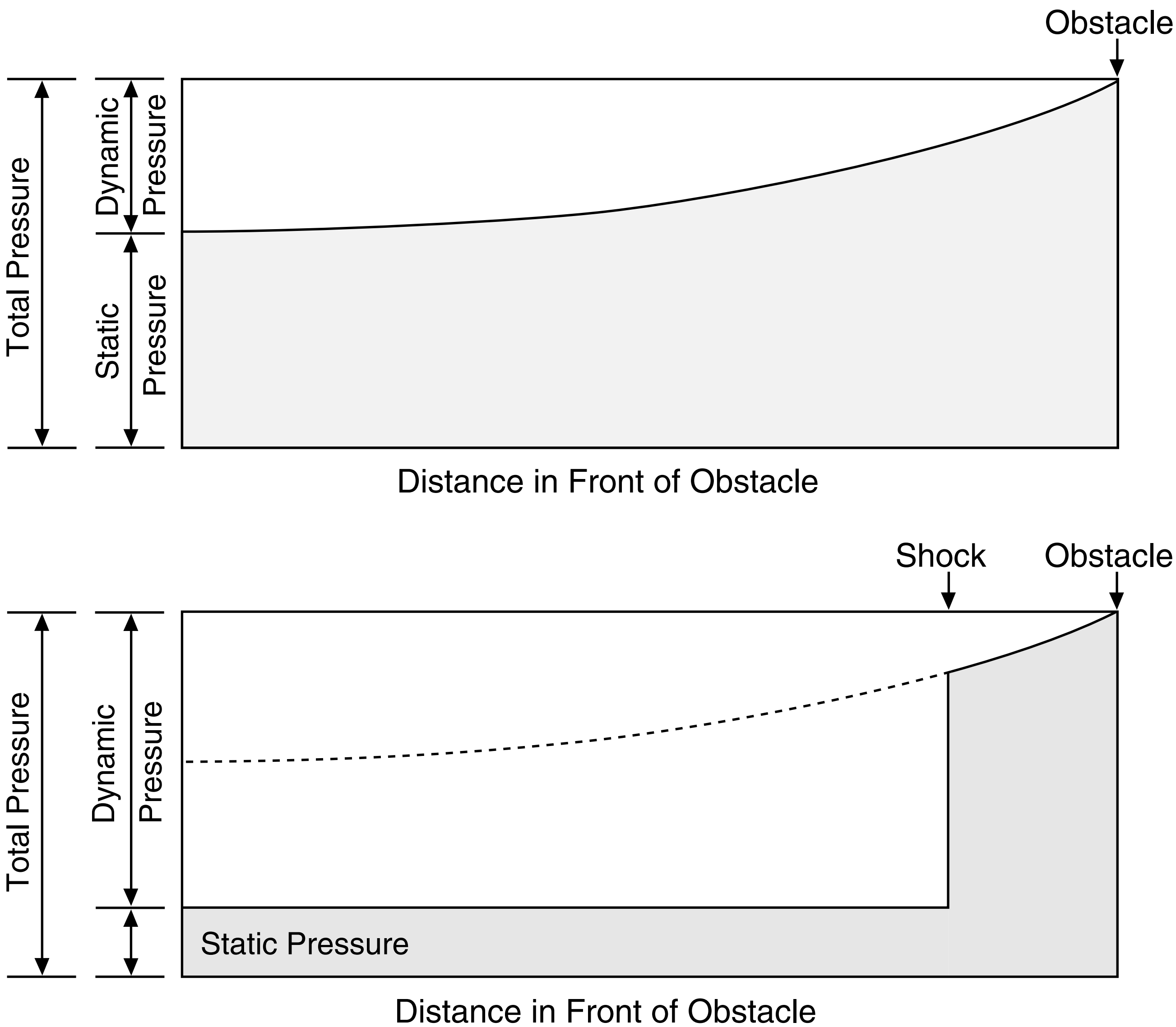

Obstacle
Total Pressure
Dynamic Pressure
Static Pressure
Distance in Front of Obstacle
Shock
Obstacle
Total Pressure
Dynamic Pressure
Static Pressure
Distance in Front of Obstacle

Figure 3

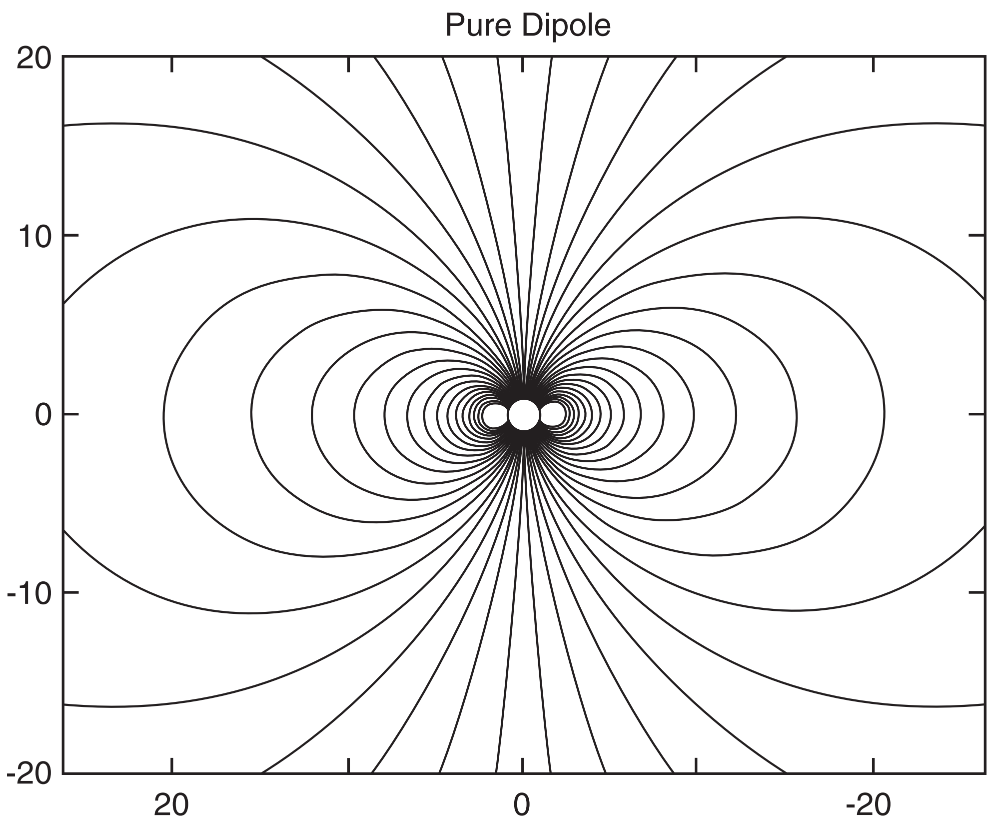
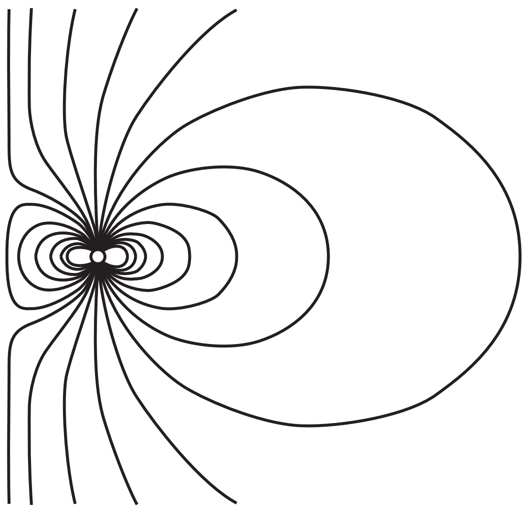
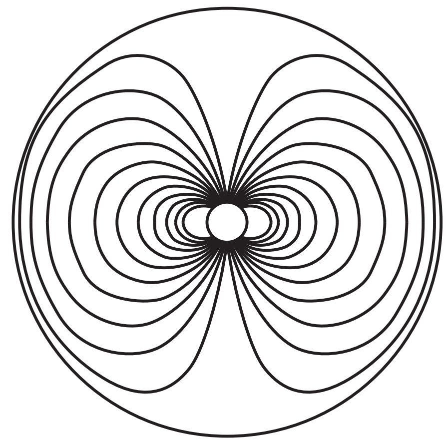


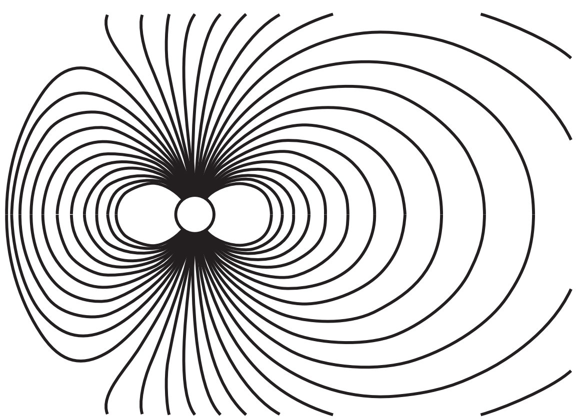
Figure 4



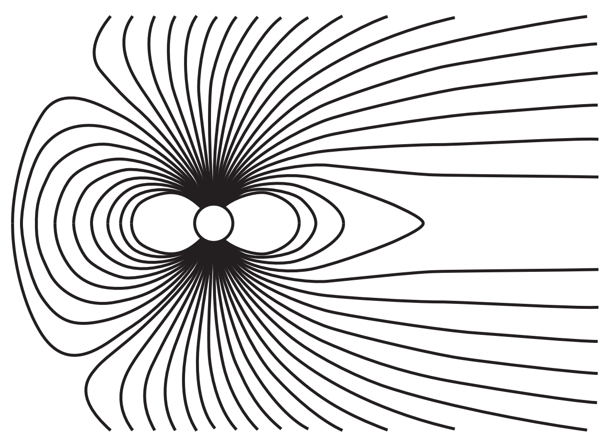
Planar Magnetopause



Spherical Magnetopause

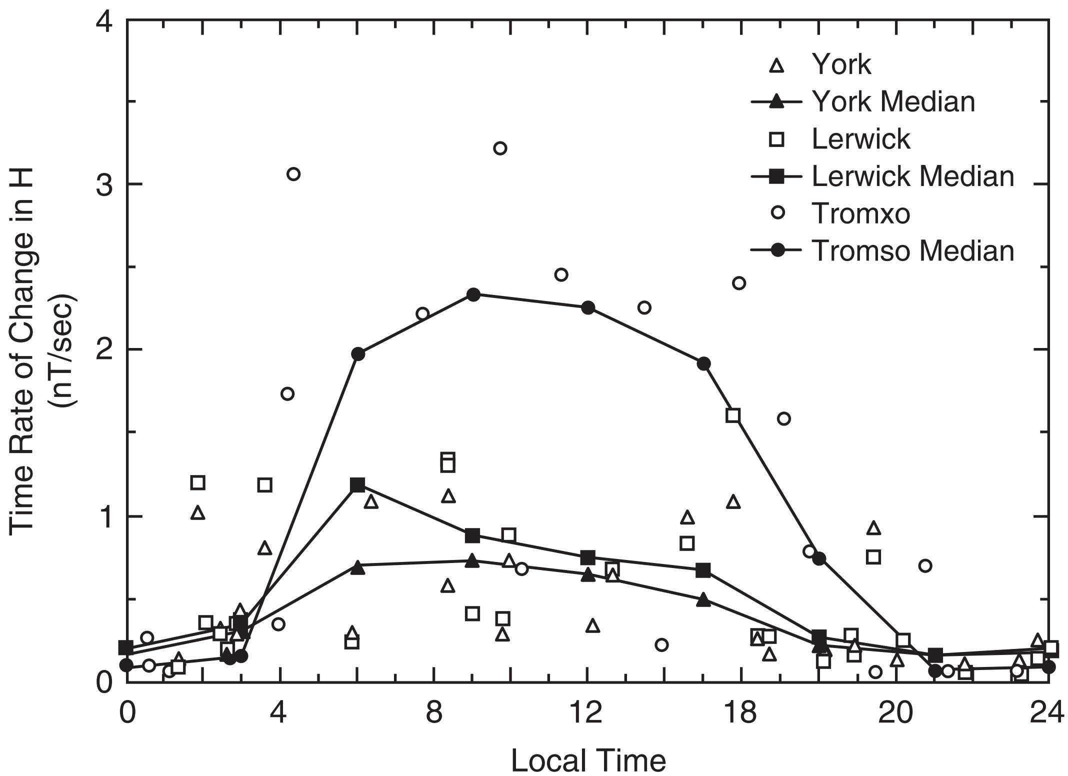


Elliptical Magnetopause



Empirical Magnetosphere

Figure 5



Time Rate of Change in H
(nT/sec)
Local Time
York
York Median
Lerwick
Lerwick Median
Tromxo
Tromso Median
0
1
2
3
4
0
4
8
12
18
20
24

Figure 6

Sources of Viscosity at the Magnetopause

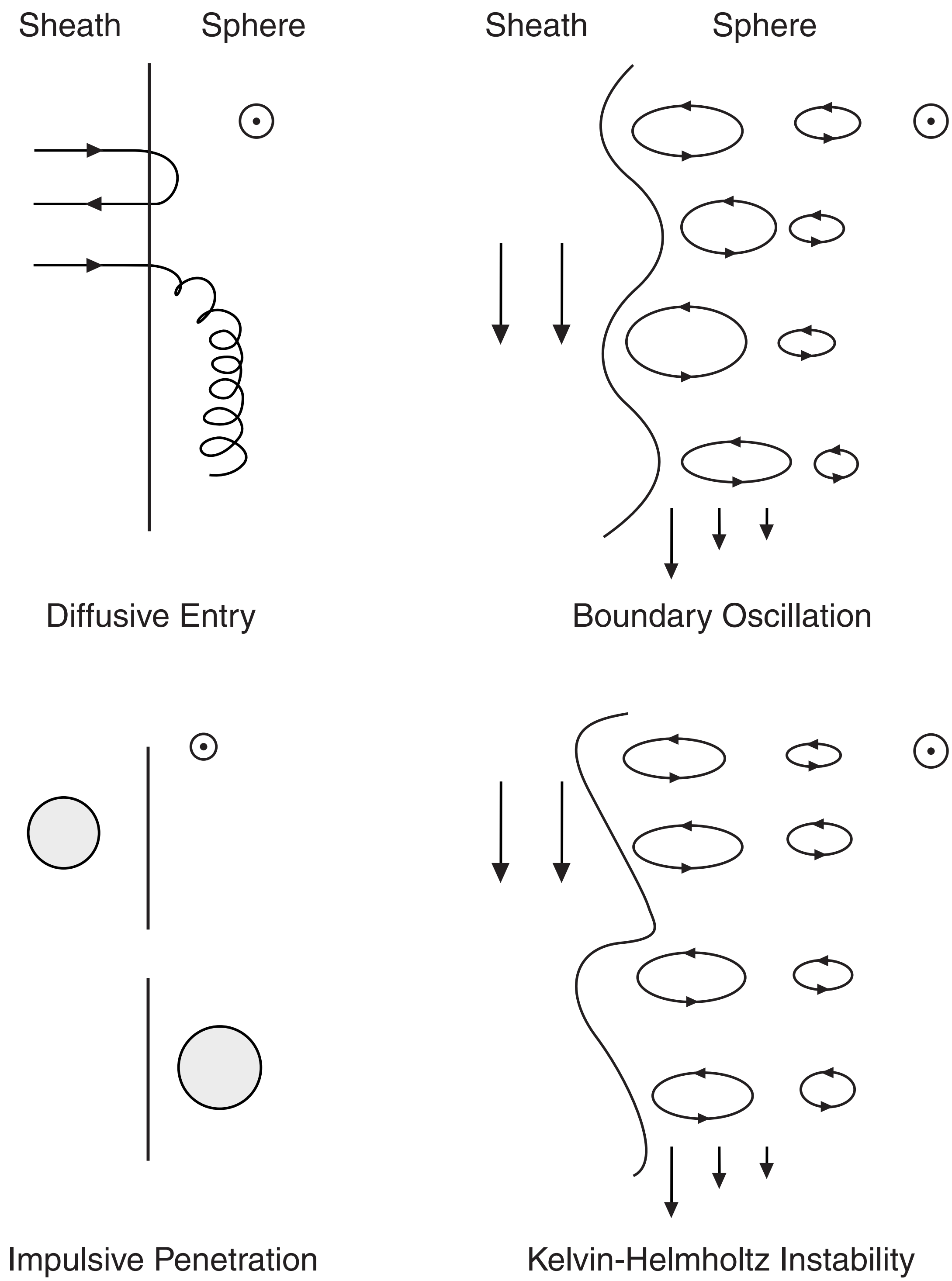
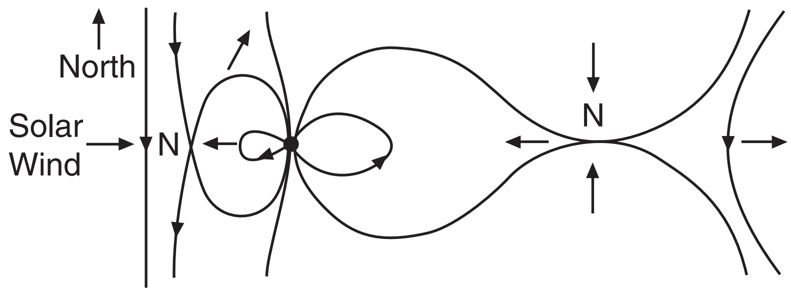


Figure 7

Interplanetary Field Southward



Interplanetary Field Northward

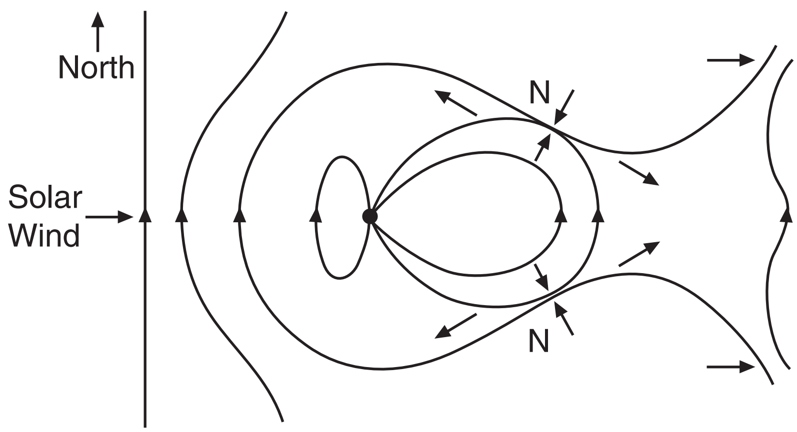


Figure 8

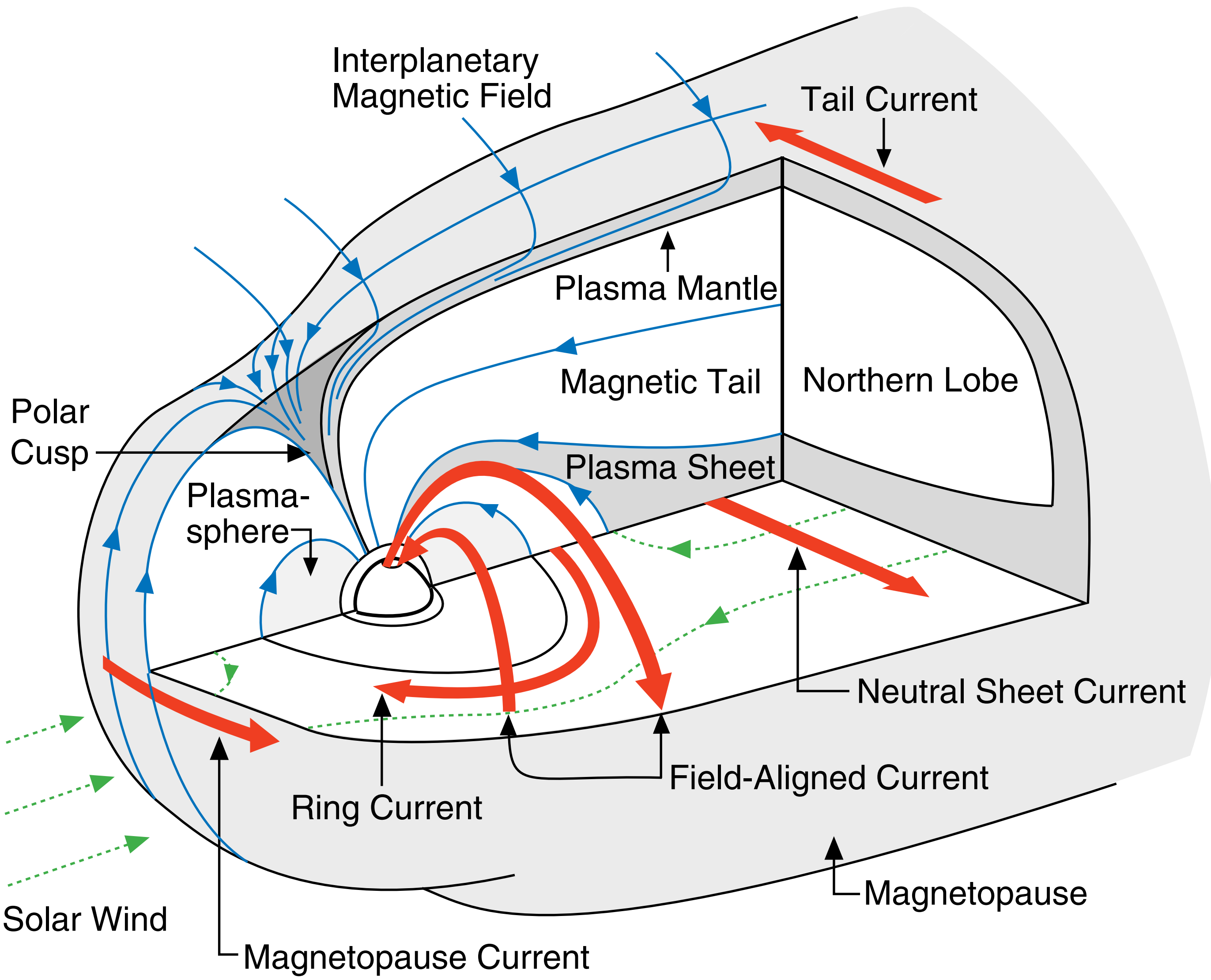

Interplanetary Magnetic Field
Tail Current
Plasma Mantle
Magnetic Tail
Northern Lobe
Polar Cusp
Plasma-sphere
Plasma Sheet
Neutral Sheet Current
Field-Aligned Current
Ring Current
Magnetopause
Solar Wind
Magnetopause Current

Figure 9

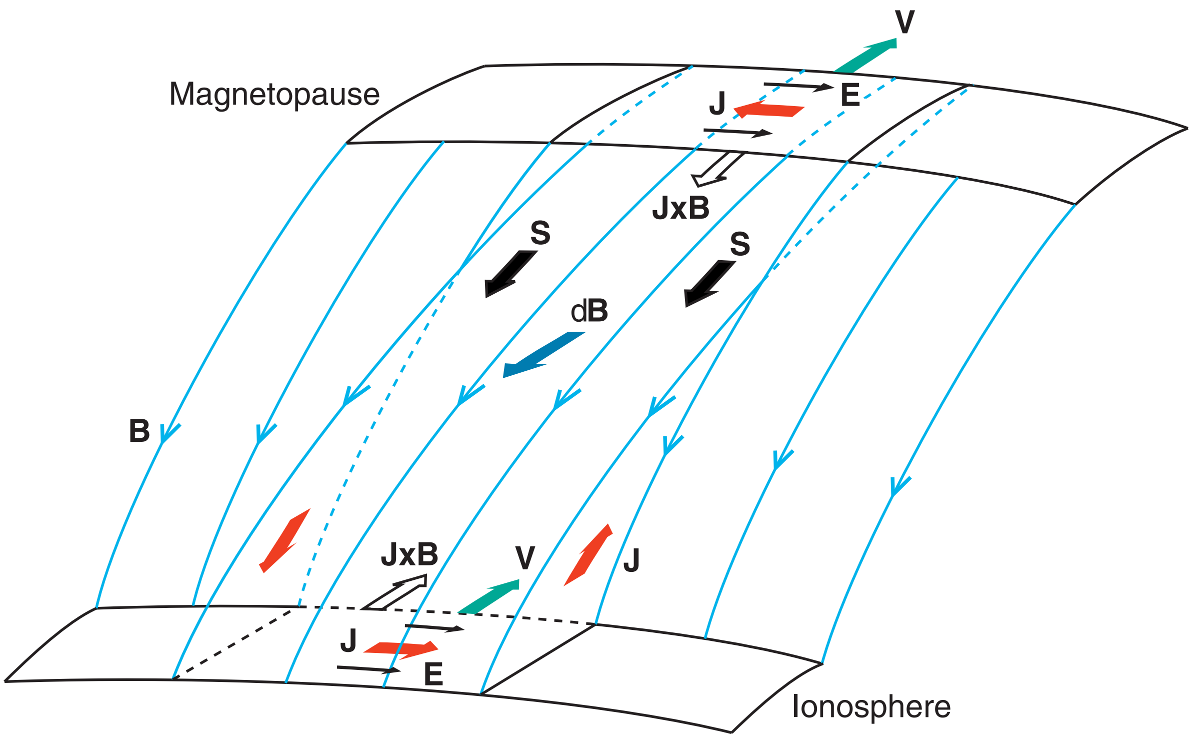


Figure 10

What geomagnetic activity responds to what solar wind input?

AE roughly the same for weak IEF
oscillating IEF
strong IEF
Ring current responds to strong IEF

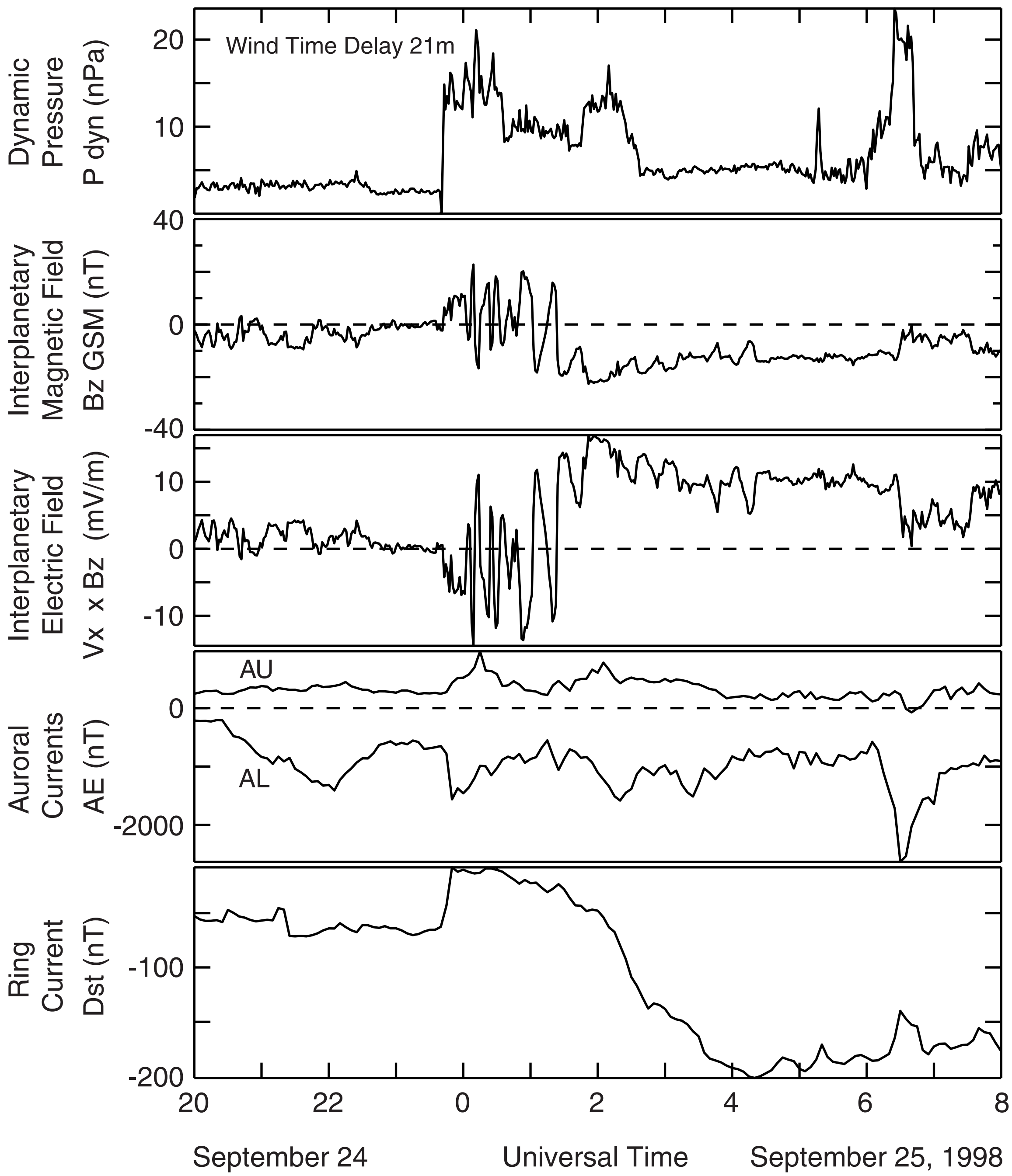


Figure 11

Where does Reconnection occur?

What does it do there?

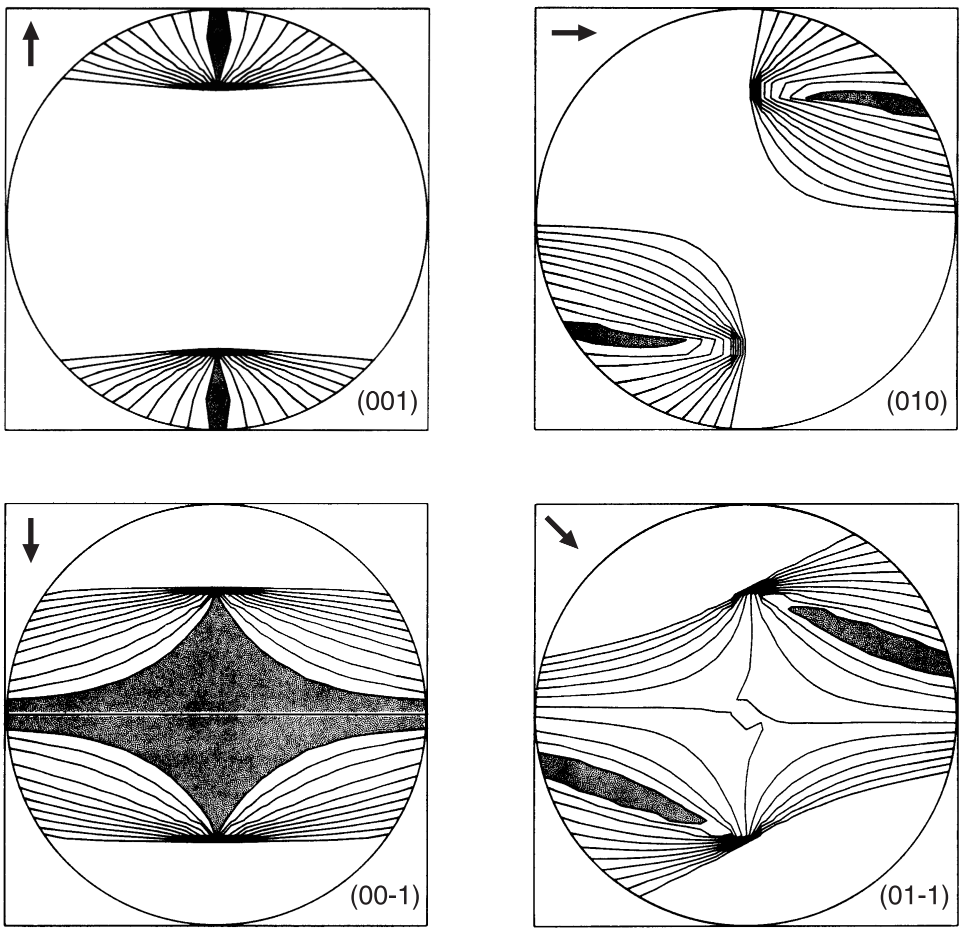


Figure 12

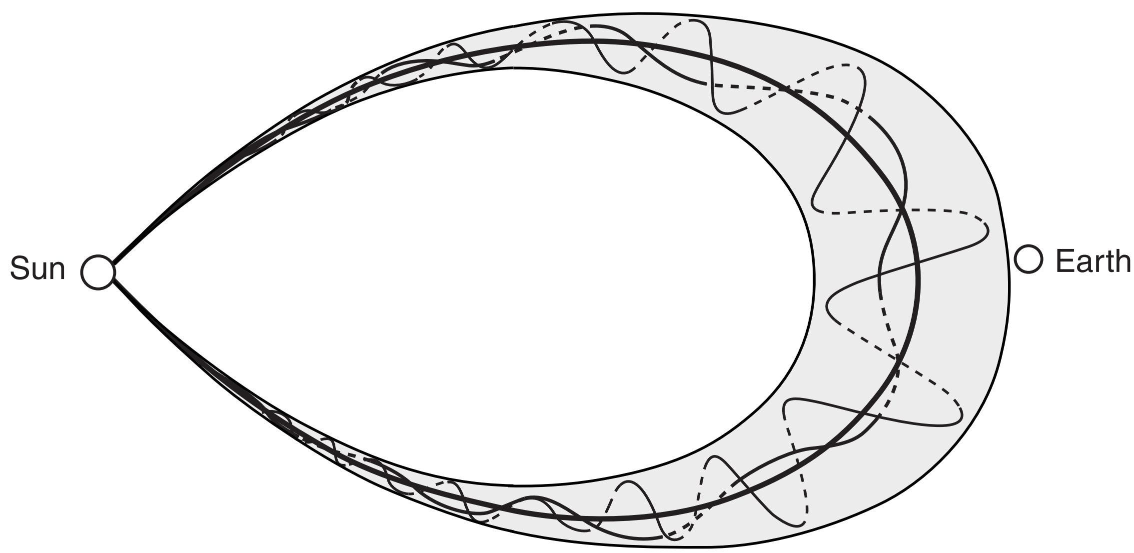
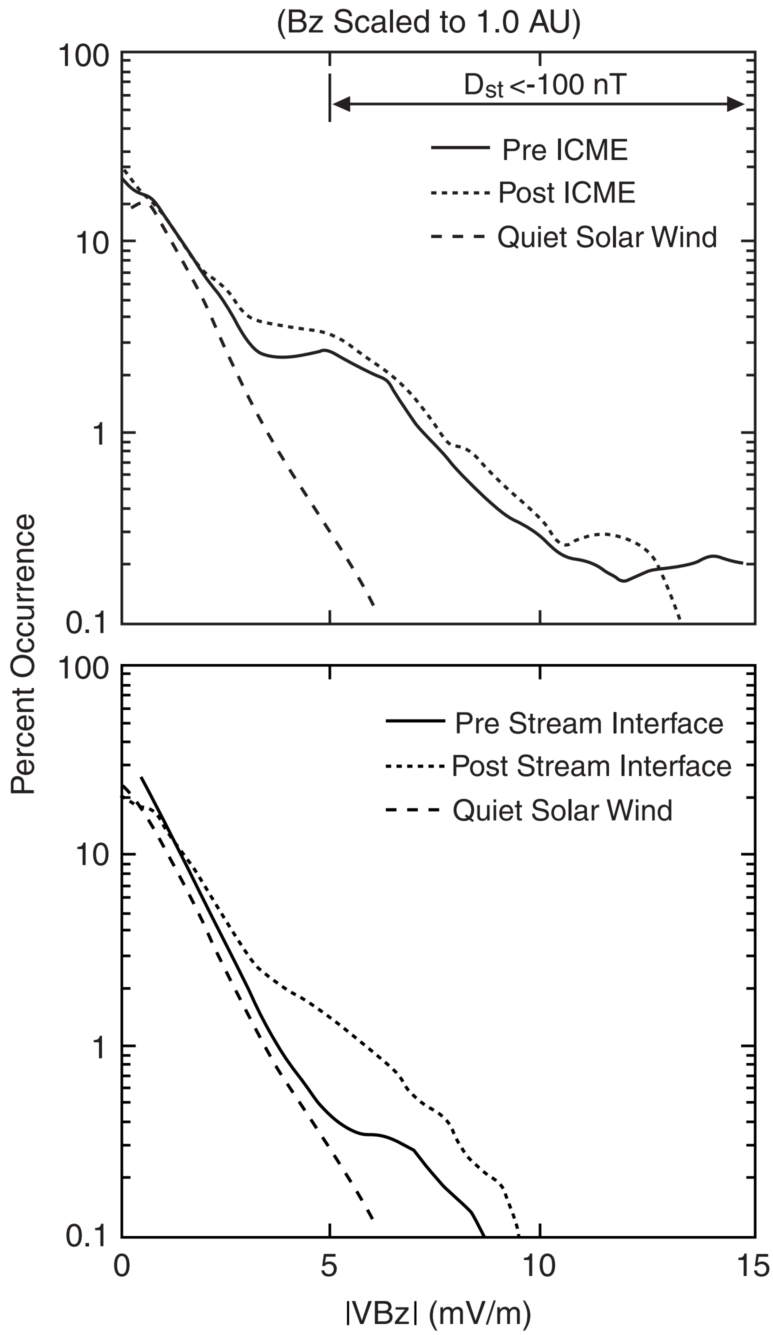


Figure 13



(Bz Scaled to 1.0 AU)
D_{st} <-100 nT
Pre ICME
Post ICME
Quiet Solar Wind
Pre Stream Interface
Post Stream Interface
Quiet Solar Wind
Percent Occurrence
100
10
1
0.1
0
5
10
15
|VBz| (mV/m)

Figure 14

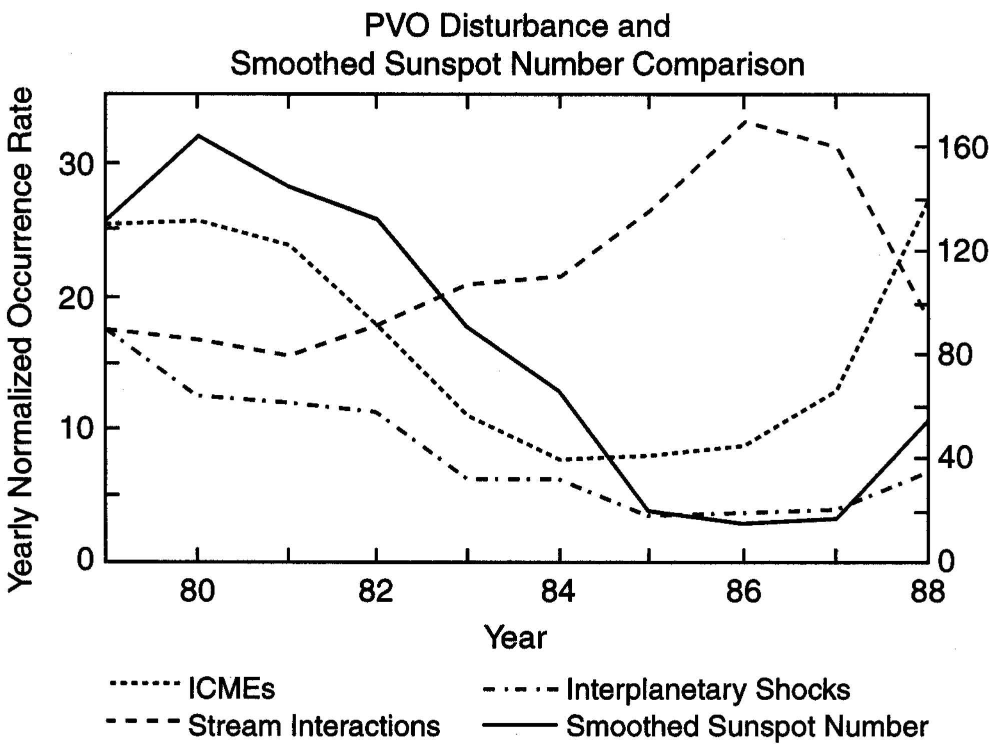

PVO Disturbance and
Smoothed Sunspot Number Comparison
Yearly Normalized Occurrence Rate
0
10
20
30
0
40
80
120
160
80
82
84
86
88
Year
ICMEs
Stream Interactions
Interplanetary Shocks
Smoothed Sunspot Number

Figure 15

Substorm Model (ca 1973)

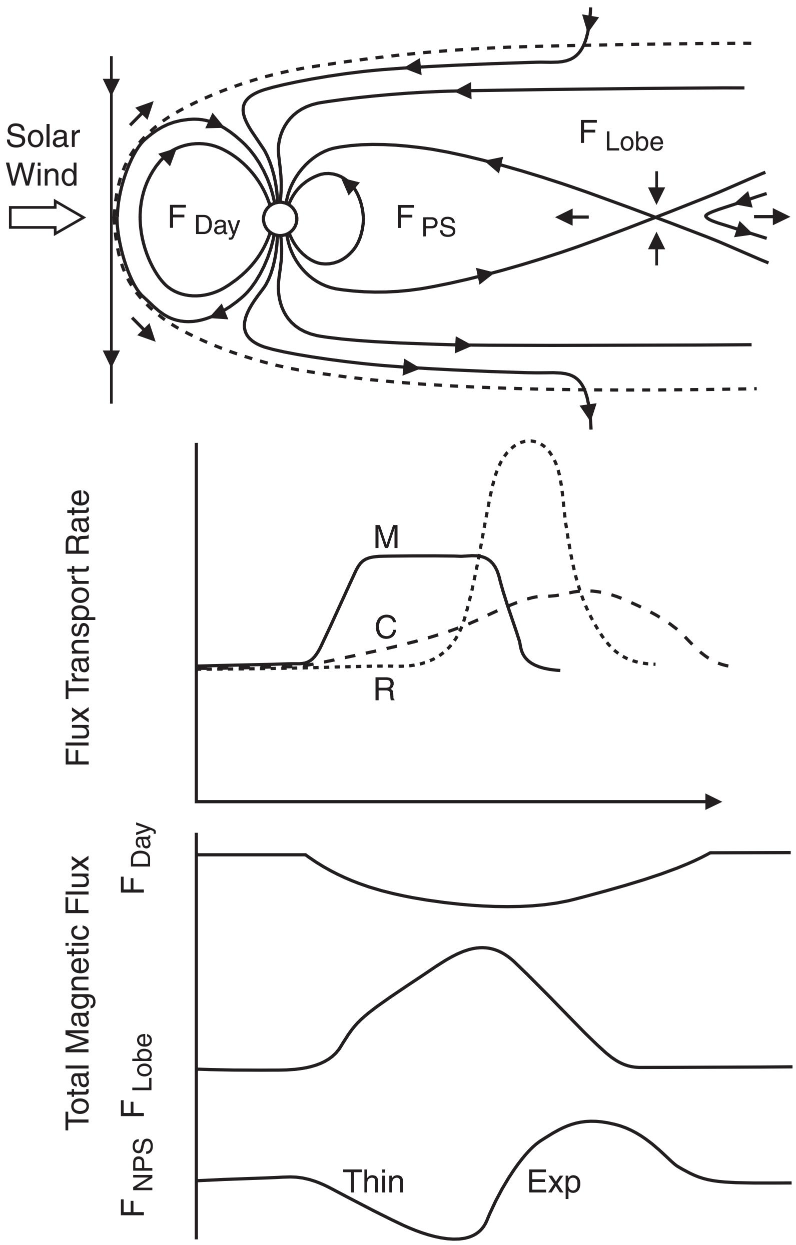


Figure 16