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Magnetosphere of Earth

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Magnetosphere of Earth

The region of space surrounding the Earth is called the magnetosphere and the behavior of the ionized gas (plasma) within it is dominated by the Earth's geomagnetic field. It is immersed in the continuous but highly variable SOLAR WIND stream of plasma that is ejected by the Sun. The large electrical conductivities and large spatial scales cause the frozen-in flux theorem to be both a valid and a useful approximation for much of the magnetosphere and the interplanetary space that surrounds it. This means that, although the ions and electrons of the plasmas are free to move in the field-parallel direction, the field-perpendicular plasma velocity v (the average velocity of the electrons and ions, weighted by their masses) is the same as that of the field of itself. As a result, plasma elements connected by a magnetic field line will always remain so connected. Therefore, were this theorem to apply strictly, solar wind plasma frozen into the interplanetary magnetic field (IMF) would not be able to mix with magnetospheric plasma frozen into the Earth's magnetic field: the solar wind would be deflected around the Earth and would not be able to enter the low-density magnetospheric cavity, into which the geomagnetic field is confined and compressed. To some extent, this is indeed what happens. However, most of the interesting phenomena in the magnetosphere ultimately arise from localized breakdowns of the frozen-in condition and these allow the magnetosphere to extract mass, momentum and energy from the solar wind flow. Our understanding of the magnetosphere stems largely from application of the frozen-in theorem, but with allowance for its crucial breakdowns.

In 2001, plasma tails in the Earth's magnetosphere were imaged by NASA's Imager for Magnetopause to Aurora Global Exploration (IMAGE) spacecraft, which obtained the first global views of the Earth's charged-particle populations at multiple wavelengths and energies on time scales of a few minutes—sufficient to track the dynamics of the magnetosphere. The images confirm the existence of the suspected but previously invisible 'tail' of electrified gas. The tail structure is believed to be a return flow of plasma that occurs when the solar wind buffets the magnetosphere and distorts its shape. Plasma near the boundaries of the magnetosphere is dragged with the solar wind, but then is turned around and forced back towards the Sun, moving around the Earth in tail-like flows. Although the plasma tails were expected, IMAGE discovered areas in the Earth's plasma cloud that are nearly empty of plasma. The IMAGE team calls these unexpected structures 'troughs' and research is continuing to discover how they form.

If we consider the work done in compressing a plasma element by bringing its boundaries from infinity to their present locations, we find that its energy density after the compression is synonymous with its pressure. We need to consider three important contributions to the total pressure: the pressure due to the thermal vibrations of the particles ($P_t = NkT$, where N is the plasma concentration, k is Boltzmann's constant and T is the plasma temperature); the dynamic pressure of the bulk flow of the particles ($P_v = Nmv^2$, where m is the average ion mass and v is the velocity); and the magnetic pressure ($P_B = B^2/2\mu_0$, where B is the magnetic field strength and μ_0 is the permeability of free space). Table 1 gives typical values of plasma and field parameters and of these three energy densities, in various regions of the near-Earth plasma environment, namely the interplanetary medium at the Earth's orbit, the outer magnetosphere, the inner magnetosphere (the plasmasphere) and the peak of the ionized upper atmosphere (the F region of the ionosphere). For each region, the largest energy density is in bold.

In the solar wind, the dominant energy density is that of the bulk flow of the plasma (P_v) and, as a result, 'frozen-in' means that the plasma flow drags the embedded field with it. This is the reason why the solar wind brings with it the IMF, a weak magnetic field of solar origin (see SOLAR WIND: MAGNETIC FIELD). On the other hand, throughout the magnetosphere and ionosphere the dominant energy density is that of the magnetic field (P_B) and frozen-in results in the particles being confined by the field. However, much of the fascination of the magnetosphere results from breakdowns of this frozen-in approximation. As will be discussed below, the phenomenon of MAGNETIC RECONNECTION gives localized breakdowns in current sheets and this allows the solar wind to drive a large-scale circulation (called convection) of the magnetospheric plasma and field. This convection dominates most of Earth's magnetosphere, there being only a small doughnut-shaped region surrounding the Earth, the plasmasphere, where the field and frozen-in plasma rotate with the Earth's daily spin (see MAGNETOSPHERE OF EARTH: PLASMASPHERE). Note that other planets also have both of these convecting and co-rotating parts to their magnetospheres, but the balance between the two varies. For example, most of the Jovian magnetosphere is dominated by co-rotation (see JUPITER: MAGNETOSPHERE).

Although the IMF is weak (the most common value is just 6 nT), the dependence of the magnetic reconnection on its orientation means that it plays a crucial role in the transfer of mass, energy and momentum from the solar wind flow to the Earth's magnetosphere.

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Table 1. Typical plasma parameters and energy densities in the near-Earth environment.

	Main ion species	B (nT)	v (m s^{-1})	N (m^{-3})	T (K)	P_t (J m^{-3})	P_v (J m^{-3})	P_B (J m^{-3})
Solar wind at 1 AU	H^+	5	5×10^5	5×10^6	5×10^4	10^{-12}	10^{-9}	10^{-11}
Magnetosphere (convection dominated)	H^+	50	10^5	10^4	10^7	10^{-12}	10^{-13}	10^{-9}
Plasmasphere (co-rotation dominated)	H^+	5×10^3	10^4	10^9	10^4	10^{-10}	10^{-10}	10^{-5}
Ionospheric F region	O^+	5×10^4	10^3	10^{11}	10^3	10^{-9}	10^{-9}	10^{-3}

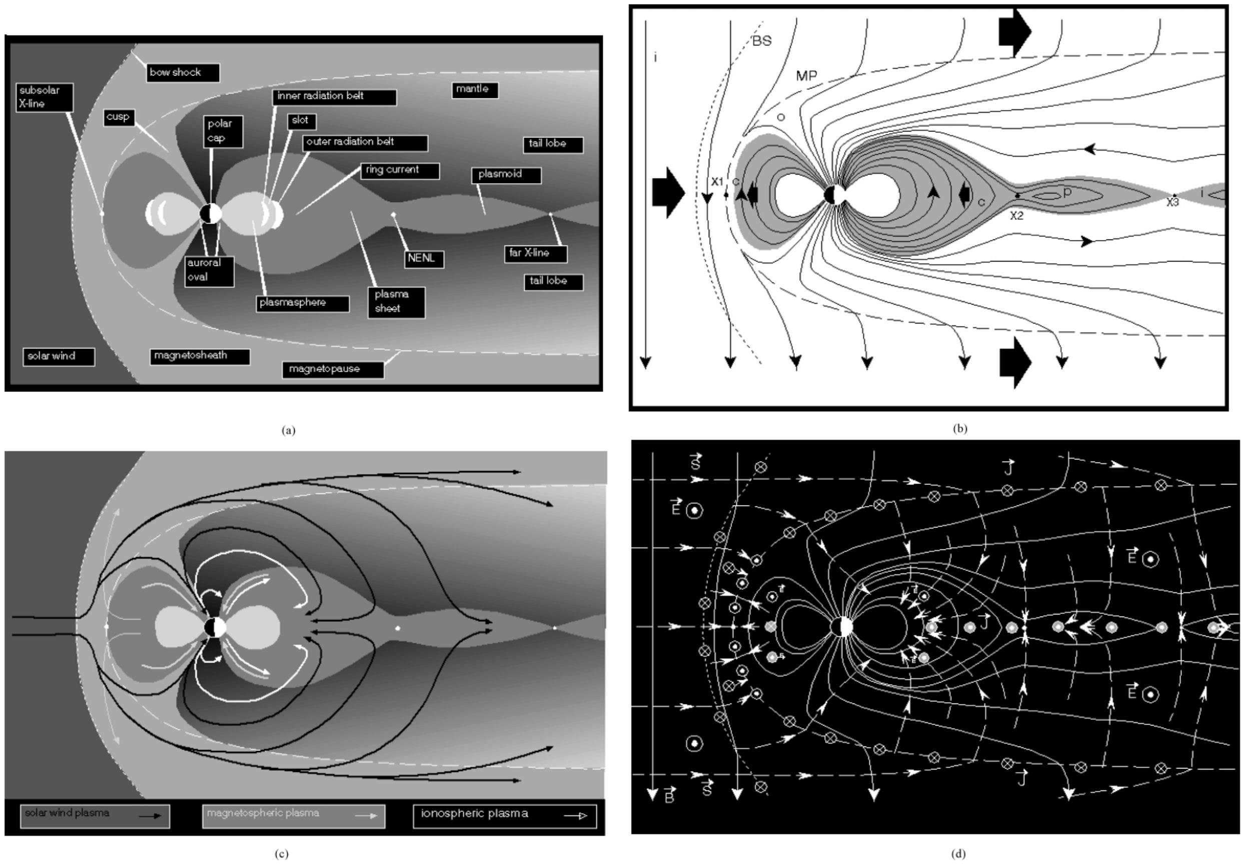

Figure 1. Four schematic views of the noon–midnight cross-section of the Earth's magnetosphere for early in the expansion phase of a substorm during southward IMF. (*a*) The names of the various regions and boundaries; (*b*) the magnetic fields; (*c*) the dominant plasma flows; (*d*) the Poynting flux ***S***, currents ***J*** and electric field ***E***.

The four diagrams of figure 1 each illustrate the magnetosphere schematically, by showing its noon-to-midnight cross-section, with the Sun to the left and the north pole of the Earth toward the top. Figure 1 is for periods when the IMF points southward, an orientation that applies for exactly half the time. (By convention, the B_z component is defined as positive northward, so figure 1 is for $B_z < 0$.) The magnetosphere is shaped by the solar wind flow, being compressed into a blunt nose on the dayside by the solar wind dynamic pressure. On the nightside, momentum transfer from the solar wind extends the magnetosphere into a long comet-like tail. The four parts of figure 1 show different aspects of the magnetosphere: (a) the names of the various regions and boundaries; (b) the magnetic fields (***B***); (c) the main plasma flows; (d) the flow of energy (Poynting flux, ***S***), the currents (***J***) and the electric fields (***E***). It must be stressed that the magnetosphere is exceedingly variable and dynamic and that some of the details in figure 1 apply at one particular time only. (Specifically, the illustrations show the situation early in what is called the expansion phase of the substorm cycle of magnetospheric behavior that is typical during southward IMF).

The solar wind is supersonic and super-Alfvénic (from table 1, the sonic and Alfvén Mach numbers are typically above 5) and so the obstacle presented to it by the geomagnetic field causes a bow shock to form (see MAGNETOSPHERE OF EARTH: BOW SHOCK), usually somewhere between about $12R_E$ and $20R_E$ upstream of the Earth. (In the magnetosphere, distances are usually measured in units of a mean Earth radius, 1 R_E = 6370 km.) The region of slowed, heated and turbulent solar wind behind this shock is called the magnetosheath. The frozen-in IMF field lines (i in figure 1(*b*)) move faster in the undisturbed solar wind than they do in the magnetosheath and, as a result, they become draped over the nose of the magnetosphere. The magnetospheric cavity is bounded by a current-carrying layer called the magnetopause (see MAGNETOSPHERE OF EARTH: MAGNETOPAUSE), the current corresponding to the change in magnetic field between the draped IMF of the magnetosheath and the geomagnetic field, according to Ampére's law. The compression of the magnetosphere by the dynamic pressure of the solar wind flow (P_v) means that the magnetopause is typically $(10–15)R_E$ away from the Earth along the Sun–Earth line. This location varies approximately as $P_v^{1/6}$, as is predicted for frozen-in plasmas by considering the balance of pressures across the magnetosheath, between the solar wind dynamic pressure (which dominates over its magnetic and thermal pressures) and the dominant magnetic pressure in the magnetosphere (see table 1). This theory was first derived by Chapman and Ferraro in 1931, in a paper which was the first to postulate the existence of the magnetosphere. In recognition of this, the currents that flow in the magnetopause boundary are called the Chapman–Ferraro currents. Observations of the interplanetary medium at the Earth's orbit over two solar cycles show that hourly averages of P_v varied from 85 nPa to below the detection threshold, with the most common value being just 5 nPa. Thus the location of the magnetopause is highly variable. The radius of the magnetosphere increases with increasing distance down the tail and approaches a limit at which the magnetopause becomes aligned with the solar wind and so no longer experiences its dynamic pressure P_v. Therefore magnetic pressure inside the far tail is balanced by the static pressure ($P_t + P_B$) of the interplanetary medium. However, observations show that there is an additional dependence of the magnetopause location on the IMF B_z component and this is not predicted by this simple theory of pressure balance between two frozen-in plasmas. Specifically, the dayside boundary moves earthward (erosion), whereas the tail radius increases (flaring), as the IMF turns increasingly southward. This shows that another process is effective. That process is magnetic reconnection as was first postulated by Dungey in 1953.

Magnetic reconnection

Figure 2 shows the basic concept of magnetic reconnection. Figure 2(*a*) shows two antiparallel fields (1 and 2), separated by a boundary which must, by Ampére's law, carry a current (of density ***J***). At a narrow current sheet, such oppositely directed fields would naturally tend to diffuse toward the centre of the current sheet where they would annihilate. However, this process is inhibited by the frozen-in plasma that is brought to the current sheet with the field and which accumulates to produce a thermal pressure that prevents any further inflow. The only way that this build-up can be avoided is for the fields to diffuse together in a localized region, as in figure 2(*b*), because then plasma can be ejected along the current sheet (at speed V_{out}). In this case, fields 1 and 2 are reconfigured to form field lines like 3 and 4, which thread the current sheet. For a magnetoplasma, there is a force (the field-line curvature force, often called

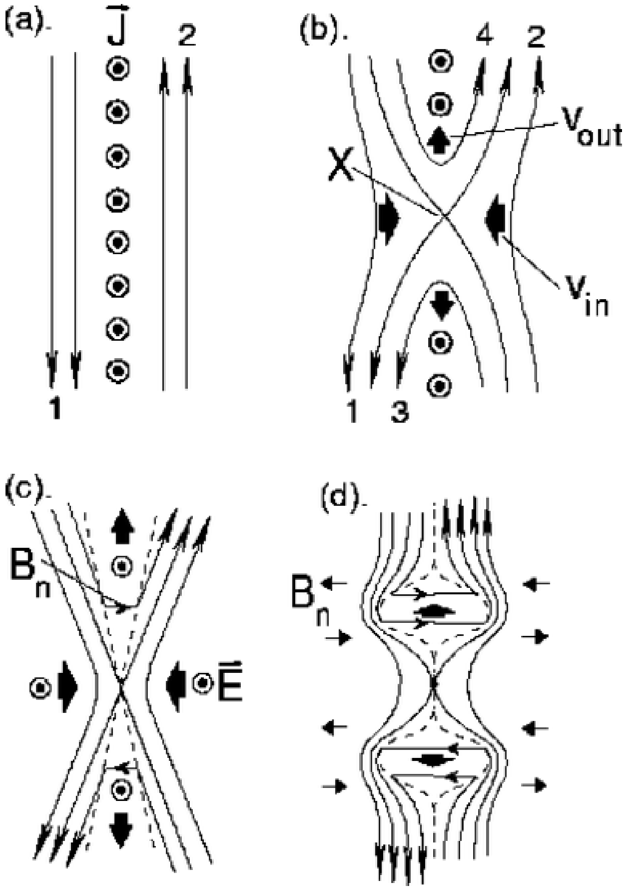

Figure 2. Magnetic fields separated by a current sheet, like 1 and 2 in (*a*), can reconfigure to produce field lines that thread the current sheet, like 3 and 4 in (*b*), a process called magnetic reconnection. The flow of magnetic flux into the current sheet (V_{in}) and the outflow along the current sheet (V_{out}) correspond to an electric field E_t, called the reconnection rate, that points in the same direction as the current ***J***. The reconnection rate is greatly enhanced by Alfvén waves (or shocks) standing in the inflow, dashed lines in (*c*). Reconnection produces a field component B_n normal to the current sheet which, like V_{out}, is oppositely directed on the two sides of the reconnection site (X). In addition, when the rate is pulsed, bulges in the outflow region are formed, as in (*d*), and the draping of the field lines over these bulges causes bipolar signatures in B_n to be seen by nearby spacecraft as the bulges pass by.

magnetic tension) which acts to straighten curved field lines and is responsible for ejecting the reconnected field lines such as 3 and 4 along the current sheet. The inflow motion of magnetic flux toward the current sheet (at speed V_{in}) and the outflow along the current sheet (at V_{out}) correspond to a boundary-tangential electric field E_{t} in the same direction as the current $\boldsymbol{J}$. This is called the reconnection rate. The frozen-in approximation applies everywhere away from the reconnection site and the equations for this limit yield $E_{\mathrm{t}} = V_{\mathrm{out}}B_{\mathrm{n}}$, where B_{n} is the boundary-normal component of the magnetic field produced because the reconnected field lines in the outflow region thread the boundary.

The situation described by figure 2(*b*) is called Parker–Sweet reconnection. However, this process is too slow to be of any significance in the magnetosphere. This is because the outflow is restricted to the thin current sheet and this limits the reconnection rate. However, theory and simulations show that wave disturbances will be formed by the field reconfiguration and these will propagate into the inflow to the current sheet. The most important are Alfvén waves, first predicted by the Nobel Laureate Hannes Alfvén, shown as dashed lines in figure 2(*c*). Between these is a wedge-like outflow region that is much broader than the thin current sheet in figure 2(*b*). This allows much greater outflow and a larger B_{n} and hence increases the reconnection rate E_{t}. This is called Petschek reconnection and it (and more complex variants allowing for other Alfvénic disturbances) gives reconnection rates that are fast enough to have fundamental effects on the magnetosphere.

Figure 2(*d*) illustrates what happens when the reconnection rate E_{t} is pulsed. Each pulse produces a pair of bulges in the reconnection outflow region (in figure 2(*d*), B_{n} and E_{t} are considered as falling to zero between the pulses in E_{t} and so between the bulges the outflow region actually vanishes). The field in the inflow regions is draped over these bulges and so a bipolar oscillation in the boundary-normal field B_{n} is seen as the bulge passes a nearby spacecraft. These have the same polarity (B_{n} pointing out then in on one side of the reconnection site, but in then out on the other) on both sides of the current sheet. Such signatures are detected at the magnetopause and are called flux transfer events.

The evidence for magnetopause reconnection is extensive and compelling. The motion and orientation of the current sheet are variable and, as a result, we have not yet been able to detect, on a routine basis, two of the direct consequences of reconnection, namely the boundary-normal magnetic field B_{n} and the boundary-tangential electric field E_{t}. However, this should soon be possible with the four-satellite Cluster 2 mission. On the other hand, the accelerated flows along the current sheet (V_{out}) have been observed and their direction depends on the IMF orientation in a way that has only been explained as the effect of the curvature force on newly reconnected field lines. In addition, application of the tangential stress balance test has shown that the speed of the accelerated flows is also as predicted for reconnected field lines. Magnetospheric and magnetosheath plasmas are free to flow along the reconnected field lines that thread the magnetopause and this has been observed using ion species that are known to be of solar and of terrestrial origin. Furthermore, characteristic ion distribution functions (the distribution of velocities in three dimensions) were predicted from reconnection theory and these have subsequently been seen for the mixing particle populations on both sides of the magnetopause. Field-aligned electron flows show that field lines do thread the magnetopause current sheet and so B_{n} is not zero. This local evidence is in addition to the many aspects of the global behavior of the magnetosphere, some of which are discussed in the following sections, which are uniquely well explained by reconnection.

The magnetosphere during southward IMF

Without reconnection, all geomagnetic field lines would connect the ionospheres of the two hemispheres without ever passing through the magnetopause. Examples of such closed field lines are labelled c in figure 1(*b*). Figure 1(*b*) also shows how draped interplanetary field lines in the magnetosheath (i) can, if they point southward, reconnect with the northward-pointing closed field lines at a reconnection site in the dayside magnetopause (X1) and generate open field lines (o) which do thread the magnetopause. In the magnetosheath and in the interplanetary medium, open field lines are still frozen into the solar wind flow and this sweeps them antisunward so they form the long geomagnetic tail (see MAGNETOSPHERE OF EARTH: GEOMAGNETIC TAIL). The oppositely directed fields in the two tail lobes are separated by a cross-tail current sheet, shown in figure 1(*d*). Also shown are the Chapman–Ferraro currents in the magnetopause which circulate around the cusps (thus, in the noon–midnight cross-section shown in figure 1, the Chapman–Ferraro currents are from dawn to dusk in the low-latitude magnetopause but from dusk to dawn on the edges of the tail lobe antisunward of the cusps). Rapid conversion of closed to open field lines by reconnection at X1 causes the erosion of dayside magnetopause. The consequent accumulation of the open flux in the tail lobes causes the tail flaring.

The growth of the open magnetic flux in the tail cannot continue indefinitely. The magnetic energy density P_B stored in the lobes increases, as does the corresponding current which flows across the central region of the tail. After about 45–60 min of rapid reconnection at X1, called the substorm growth phase (see MAGNETOSPHERE OF EARTH: SUBSTORMS), this current becomes unstable in the near-Earth region (roughly $10R_{\mathrm{E}}$ down the tail from the Earth) and is diverted so that it passes through the ionosphere. This current system is called the current wedge and its appearance marks the onset of the substorm expansion phase. During quiet times, open field lines may be closed again (at a slow rate) by reconnection at a far X-line in the cross-tail current sheet, such as X3 in figure 1(*b*). Close to the time of substorm onset, reconnection commences much more rapidly at a new site like X2, called a near-Earth neutral line (NENL). Between X2 and X3 a magnetic island or flux rope called a plasmoid forms and is disconnected from the Earth when X2 has 'eaten' its way through the closed field line region and so has started to reconnect open lobe field lines (shortly after the time depicted in figure 1). The plasmoid moves down the tail and is ejected into the interplanetary medium. The lobe field lines have been stretched out by the solar wind flow and when they are reconnected at X2 they snap Earthward because of the field-line curvature force. This causes the energy that was stored in the tail lobe to energize the plasma, giving the plasma sheet (see MAGNETOSPHERE OF EARTH: PLASMA SHEET. When particles energized in an expansion phase hit the Earth's upper atmosphere they cause it to emit light and greatly enhance auroral displays on the nightside of the Earth. This is called an auroral substorm. These particles also increase the electrical conductivity of the auroral ionosphere, making it easier for it to carry the currents of the current wedge. The currents also deposit much energy in the upper atmosphere. The disturbance subsequently fades away in the substorm recovery phase.

It is possible for the rates of open flux generation and destruction (at the magnetopause and in the tail) to be the same, in which case a steady circulation of magnetic flux is established (this is called a convection bay or a steady convection event). Open magnetic flux is dragged antisunward until it is closed by tail reconnection at X3, after which it moves sunward, passing the Earth on both the dawn and the dusk flanks before returning to be re-opened at the dayside magnetopause reconnection site X1. However, the strength and orientation of the IMF usually fluctuate on time scales down to a few seconds whereas information about consequent changes in the magnetopause reconnection rate takes typically 30–60 min to reach a tail reconnection site. Thus a more usual behavior of the magnetosphere is for the rates of open flux generation and destruction to be out of balance. Periods of dominant magnetopause reconnection cause the open flux to increase and are the substorm growth phases discussed above. These are compensated for by periods when the destruction of open flux dominates (the expansion and recovery phases). Cycles of substorm growth, expansion and recovery are the usual behavior of the magnetosphere when $B_z < 0$. Typically, these phases are each 30–60 min long. However, when the IMF is continuously southward, the cycle period can become shorter than for 'isolated' substorms caused by a temporary swing of the IMF to southward.

The ionosphere, at the base of the magnetosphere, is incompressible, in the sense that the magnetic field there is dominated by currents in the Earth's interior and is roughly constant in magnitude. Near its peak ionization density, the frozen-in approximation still applies and ions and electrons circulate with the field lines (ionospheric convection). The antisunward transfer of open flux across the poles is matched by a return sunward flow outside the polar cap: this corresponds to the sunward motion of the magnetospheric field lines closed in the tail and moving back towards the dayside magnetopause past the dawn and dusk flanks of the Earth. The associated transpolar voltage (by Faraday's law, the same thing as the antisunward magnetic flux transfer rate) can be as large as 150 kV during periods of strongly southward IMF.

The plasma that enters the magnetosphere through the dayside magnetopause is hotter and denser than it was in the solar wind, owing to the effect of the bow shock. It is accelerated towards the Earth on crossing the dayside boundary by the field-line curvature force on newly-opened field lines and can precipitate directly into the Earth's upper atmosphere through two funnel-shaped regions called the cusps (see MAGNETOSPHERE OF EARTH: DAYSIDE CUSP). These are narrow in latitude because the solar wind plasma which crosses the magnetopause antisunward of the cusp is less dense and cooler. In addition, the effect of the curvature force on these field lines which have been open longer is to slow the plasma on crossing the boundary: this mantle plasma is mainly swept into the tail with the open field lines and very little precipitates into the polar cap, poleward of the cusp, as in figure 1(*a*). The solar wind electrons heat the electrons of the cusp ionosphere and these give rise to a characteristic red AURORA by colliding with the atomic oxygen of the upper atmosphere (at ionospheric altitudes the atmosphere is called the thermosphere), causing it to emit 630 nm light. The more energetic particles that precipitate from the plasma sheet excite the atomic oxygen to produce predominantly green (557.7 nm) and ultraviolet (296 nm) auroral light in a band that surrounds the polar cap and is called the auroral oval.

In the lower ionosphere around 130 km altitude (the 'E region'), the density of neutral thermospheric gases is much higher and collisions with the moving charged particles give rise to differences in ion and electron motions. This contrasts with the F region (roughly 200–500 km) where the frozen-in approximation applies and ions and electrons move together. There must be currents flowing parallel to the convection electric field (the Pedersen currents) and these cause ohmic heating of the ionosphere and thermosphere. There will also be currents flowing perpendicular to the electric field (Hall currents) that are the main cause of deflections of the geomagnetic field at the Earth's surface. Hall currents can circulate in closed loops, but this is not true for Pedersen currents which must link to the magnetospheric current systems via field-aligned or Birkeland currents (named after the scientist who first postulated their existence). Two sets of Birkeland currents are required: the region-1 currents are between antisunward convection in the polar cap and sunward convection in the auroral oval, whereas the region 2 currents are on the equatorward edge of the region of sunward convection. In addition, there are two sources of field-aligned current (with associated E region current, F region convection, magnetic deflections and energy deposition in the atmosphere). These are associated with the opening and with the destruction of open flux. The former dominates on the dayside of the polar ionosphere and is directly driven by the solar wind–magnetosphere interaction. The latter dominates of the nightside and is driven by the release of magnetic energy stored in the geomagnetic tail.

The ionosphere is incompressible, in the sense that the magnetic field there B_i is effectively constant. Therefore, as the total open flux, $F = A_\mathrm{pc}B_i$, increases during the substorm growth phase, the polar cap area A_pc also increases. This expansion of the polar cap causes the auroral oval on closed field lines outside the polar cap to migrate to lower latitudes. The nightside aurora is usually at high latitudes (for example over Canada in the North American continent and northern Scandinavia on the European continent). During extremely disturbed periods called magnetic storms, caused by enhanced solar wind with prolonged and strong southward IMF, the auroral oval can expand as far as middle magnetic latitudes (for example, Texas in the USA and southern Britain in Europe).

The magnetosphere during northward IMF

Reconnection can still take place at the magnetopause when the IMF points northward. However, this reconnection is generally not at low-latitude sites such as X1 in figure 1(*b*) (in this context, meaning between the cusps) and does not result in the generation of open flux. Often northward-IMF reconnection takes place poleward of the cusps and is between the draped IMF in the magnetosheath and lobe field lines that were opened during a prior period of southward IMF. In such cases, the reconnection acts to reconfigure already-opened flux, as opposed to generating new open flux. The reconfigured open field lines may be dragged sunward by the field-line curvature force before being returned to the tail lobe by the solar wind flow. This stirring on the polar cap can give some directly driven energy deposition but, because no new open flux is generated, it does not contribute to the storage of magnetic flux and energy in the tail.

The state of the magnetosphere depends critically on its recent history. When the IMF turns northward after a period of prolonged and strong southward orientation, it will take time to destroy the accumulated open flux in the lobe. Reconnection in the tail will continue and will act to gradually reduce the tail lobe flux in a series of weakening substorms. Because the ionosphere is incompressible, the loss of lobe flux causes its ionospheric projection, the polar cap, to shrink in size (the area A_pc decreases) and the aurora is found at increasingly higher latitudes. Sun-aligned auroral arcs may be seen in the polar cap, on either the dawn or the dusk side of a shrunken open field line region but sometimes bifurcating that region. The continuing tail reconnection drives ionospheric flow and gives a transpolar voltage which varies with the substorm phase, with a peak value that gradually decays over a period of about 10 h as the tail lobe flux decreases.

Effects of the dawn–dusk component of the IMF

When open field lines are formed with an IMF that has a non-zero dawn–dusk component (B_y), the curvature force acting to straighten them causes asymmetric motions towards dawn or dusk which are different in the two hemispheres and which depend on the polarity of B_y. This causes dawn–dusk asymmetries in the ionospheric flow and currents and means that the tail lobes are asymmetrically loaded with open flux, causing a twisting of the tail and the current sheet separating the two lobes. This twist becomes more exaggerated with increasing distance down the tail. These hemisphere-dependent asymmetries have opposite senses when the IMF B_y component points toward dawn compared with when it is toward dusk.

Energy flow in the magnetosphere

Figure 1(*d*) shows the flow of electromagnetic energy (Poynting flux $\boldsymbol{S}$). The frozen-in theorem means that the antisunward flow of the solar wind and the open flux, and the sunward flow of the closed flux, both correspond to a large-scale dawn-to-dusk electric field in the Earth's frame and this, along with the distribution of magnetic field ($\boldsymbol{B}$) shown in figure 1(*b*), gives the $\boldsymbol{S}$ ($= \boldsymbol{E} \times \boldsymbol{B}/\mu_0$) shown as dashed curves in figure 1(*d*). Poynting's theorem shows that a net inflow of $\boldsymbol{S}$ corresponds to a local increase in magnetic field (with consequent gain of stored magnetic energy density, P_B) and/or ohmic heating of the particles (when $\boldsymbol{J}$ has a component parallel to $\boldsymbol{E}$). Conversely, there is a loss in P_B and/or energy is extracted from the particles ($\boldsymbol{J}$ is oppositely directed to $\boldsymbol{E}$) where there is a net outflow of $\boldsymbol{S}$. Note that at the time depicted in figure 1(*d*), magnetic energy previously stored in the tail lobes during the growth phase is being lost and deposited as heat in the plasma sheet, particularly its inner edge (the ring current (see MAGNETOSPHERE OF EARTH: RING CURRENT)) and in the ionosphere.

At the dayside magnetopause (at latitudes below the magnetic cusps) the dawn-to-dusk electric field ***E*** is in the same direction as the magnetopause current ***J*** and thus this current sheet is a sink of Poynting flux and/or magnetic energy density. This is the source of the energy required for the accelerated ion flows along the magnetopause.

On the other hand, at the tail magnetopause (antisunward of the cusps), ***J*** is oppositely directed to ***E***. This means that energy is extracted from the particles (the solar wind flow) and this region is a source of Poynting flux and/or of magnetic energy. Therefore this part of the magnetopause is where the energy extraction from the solar wind takes place. (Note that the reconnection which makes this energy extraction possible takes place in a different region of the magnetopause, between the cusps.)

In the central current sheet of the tail, the dawn–dusk electric field associated with the sunward return of re-closed field lines gives ***J*** aligned with ***E*** and so particles are energized (to give the plasma sheet and ring current energies). Thus this region is a major sink of Poynting flux. Another major sink is the ionosphere–thermosphere, where Pedersen currents flow in the E region parallel to ***E***, giving energy deposition.

Particle sources and sinks

As mentioned above, the opening of field lines by magnetopause reconnection allows magnetospheric particles to escape into the magnetosheath and magnetosheath particles to enter.

Most of the magnetosphere takes part in the convection. As discussed above, during this circulation, field lines are opened by magnetopause reconnection, allowing some of the magnetospheric plasma to escape. However, the small torus-shaped plasmasphere does not take part in this circulation and, instead, co-rotates with the Earth. The fact that these field lines are never opened allows higher densities to build up. The plasma is mostly supplied from the ionosphere and is produced by photoionization of upper atmospheric gases by solar electromagnetic radiations (in the x-ray and EUV wavelength ranges). The location of the boundary of the high plasmaspheric densities, the plasmapause, is set not only by the location of the boundary between co-rotation and convection but also by the time constant for re-filling flux tubes which have been emptied by briefly taking part in the convection cycle during periods of enhanced transpolar voltage.

The other major source of magnetospheric plasma is the magnetosheath. Solar wind ions crossing the dayside magnetopause are accelerated toward the magnetopause and precipitate in the cusp down field lines that are convecting away from the reconnection site. Faster particles arrive first and thus closer to the reconnection site thereby giving a plume of particles dispersed by this velocity-filter effect. Particles with a velocity vector close to the magnetic field direction precipitate into the cusp ionosphere, but those with a larger gyration component to their motion are ‘mirrored’ in the converging field. These move back up the field lines and are dispersed by the convection into the tail lobe. Some observations have been interpreted as showing solar wind ions on closed field lines in the low-latitude boundary layer (LLBL). Diffusion is an inadequate mechanism for this entry, as are most other proposed mechanisms, and some scientists argue that the LLBL is on open, rather than closed, field lines. Another possibility is that the LLBL could be on field lines re-closed by lobe reconnection in both hemispheres during northward IMF ($B_z > 0$). Mantle plasma that crosses the lobe magnetopause flows away from the Earth and into the tail. In addition, the LLBL and cusp regions of the ionosphere are heated by the directly driven energy deposition and by solar wind particle precipitation and respond by giving upflows of ionospheric ions. These too are dispersed by the convection, according to their field-aligned velocity before arriving in the central plasma sheet. Thus ions of both solar and ionospheric origin collect and are accelerated Earthward in the plasma sheet at the centre of the tail. The flows of charged particles in the magnetosphere discussed above are illustrated in figure 1(*c*). The upflows mean that the ionosphere is a significant source of plasma, especially for the inner magnetosphere.

Close to the Earth, the gradients and curvature of the geomagnetic field cause ions to drift westward, whereas the electrons drift eastward. This gives the westward ring current around the Earth. This motion means they are crossing equipotentials and both are further accelerated. The most energetic of such particles form the outer radiation belt (see MAGNETOSPHERE OF EARTH: RADIATION BELTS). Closer to the Earth, these particles are lost by interaction with VLF whistler waves, which scatter them in pitch angle so that they precipitate into the atmosphere and are lost. This loss gives the ‘slot’ region between the two belts. The inner radiation belt is made up of COSMIC RAYS that have hit the Earth and its atmosphere and are then trapped in the geomagnetic field.

The importance of the magnetosphere

Magnetic reconnection allows the Earth’s magnetosphere to extract of order 2% of the incident energy of the solar wind flow when $B_z < 0$, of which two-thirds is returned to the interplanetary medium (much of it in the form of plasmoids). Nevertheless, the remaining third has significant effects on the magnetosphere, the ionosphere and the neutral upper atmosphere, as well as on a large number of operational systems, such as communications and navigation systems, power distribution networks, radars and satellites. The energy deposited in the auroral ovals causes winds and composition changes in the thermosphere which propagate all over the globe, perturbing the ionosphere (in ionospheric storms). The enhanced ring current and auroral currents in magnetic storms cause magnetic deviations and induced currents and voltages at ground level. These effects are global and highly variable on time scales of minutes up to the 11 yr SOLAR CYCLE. Some of the variability arises from fluctuations in the solar wind flow (including major events such as SOLAR CORONAL MASS EJECTIONS), some from the variations in the direction of the IMF and others from intrinsic time constants of the coupled magnetosphere–ionosphere–atmosphere system. Processes such as reconnection, collisionless shocks, particle acceleration and turbulence all have applications in other disciplines of science, ranging from astrophysics to the development of fusion reactors. The magnetosphere provides an excellent natural laboratory where these effects can be studied on a variety of spatial scales, by both remote sensing and *in situ* observations, and where the plasma is disturbed by neither container boundaries nor diagnostic probes.

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