5.03 Magnetospheric Contributions to the Terrestrial Magnetic Field

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5.03.1 Introduction

The Earth's magnetic field is created and governed by processes and material in the Earth's interior. This field is not restricted to the inside, the surface, or the atmosphere of the Earth, but reaches far above the Earth into space. If that space were empty or only populated with neutral gases, there would be no consequences. However, that space is not a vacuum but, starting at a height of about 100 km, is filled with ionized gas.

The constituents of this ionized gas, a plasma of positively charged ions and negatively charged electrons, are not immobile but rather move around under the influence of externally applied and internally generated forces. This motion of charge carriers often results in a significant current flow and thus in the generation of magnetic field disturbances which can be of the same magnitude as the field generated inside the Earth at that altitude. If the spatial scale of such a current system is large enough, or if it flows close to the Earth's surface, as do for ionospheric currents, it can generate significant magnetic variations at the Earth surface.

In this chapter, we will describe the main sources of external magnetic field contributions. Nearly all of them result from an interplay between the magnetic field of the Earth and that of the Sun. They are highly variable, some changing on the scale of seconds, others on the scale of days, and typical disturbance amplitudes on the ground range between a few and some hundred nanotesla.

5.03.2 Geophysical Plasmas

A plasma is a gas of charged particles, which consists of equal numbers of free positive and negative charge carriers. Having roughly the same number of charges with different signs in the same volume element guarantees that the plasma behaves quasi-neutral. On average a plasma looks electrically neutral to the outside, since the randomly distributed particle electric charge fields mutually cancel. However, because of its sensitivity to electric and magnetic fields and its ability to carry electric currents and thus to generate magnetic fields, this fourth state of matter behaves quite different from a neutral gas.

Similar to a gaseous medium, the charged plasma particles are essentially free particles. Since the particles in a plasma have to overcome the Coulomb coupling with their neighbors, they must have thermal energies above some 10^5 K. Thus, a typical plasma is a hot and highly ionized gas. While only a few natural plasmas, such as flames or lightning strokes, can be found near the Earth's surface or below the ionosphere, plasmas are abundant in the universe. More than 99% of all normal matter (baryonic matter, not including dark matter) is in the plasma state.

Extraterrestrial plasmas have a wide spread in their characteristic parameters like density, temperature, and magnetic field. Even in the Earth's neighborhood, there are quite a number of different geophysical plasmas.

5.03.2.1 Solar Wind

The Sun emits a highly conducting plasma into interplanetary space as a result of the supersonic expansion of the solar corona. This plasma is called the solar wind. It flows with supersonic speed of about $500\,\mathrm{km\,s^{-1}}$ and consists mainly of electrons and protons, with an admixture of 5% helium ions. Because of the high conductivity, the solar magnetic field is 'frozen' in the plasma (as in a superconductor, see below) and drawn outward by the expanding solar wind. Typical values for electron density and temperature in the solar wind near the Earth are $5\,\mathrm{cm^{-3}}$ and 10^5 K, respectively. The interplanetary magnetic field strength is of the order of 5–10 nT near the Earth's orbit.

When the solar wind impinges on the Earth's dipolar magnetic field, it cannot simply penetrate it, but is slowed down and, to a large extent, deflected around it. Since the solar wind hits the obstacle with supersonic speed, a bow shock wave is generated (see **Figure 1**), where the plasma is slowed down and a substantial fraction of the particles' kinetic energy is converted into thermal energy. The region of thermalized subsonic plasma behind the bow shock is called the magnetosheath. Its plasma is denser and hotter than the solar wind plasma and the magnetic field strength has higher values in this region.

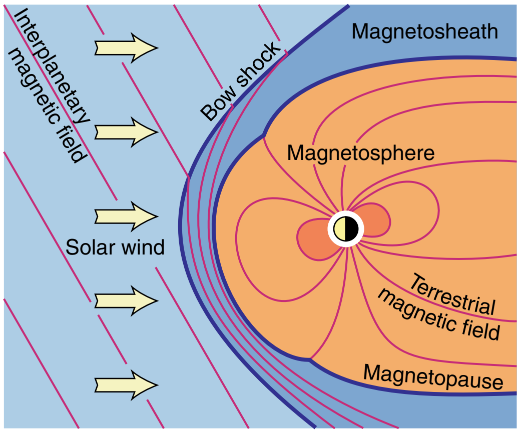

Figure 1 Solar wind interaction with the terrestrial magnetic field. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

5.03.2.2 Magnetosphere

The shocked solar wind plasma in the magnetosheath cannot easily penetrate the terrestrial magnetic field but is mostly deflected around it. This is a consequence of the fact that the interplanetary magnetic field lines cannot penetrate the terrestrial field lines and that the solar wind particles cannot leave the interplanetary field lines due to the aforementioned frozen-in characteristic of a highly conducting plasma.

The boundary separating the two different regions is called magnetopause and the cavity generated by the terrestrial field has been named magnetosphere (see **Figures 1** and **2**). The kinetic pressure of the solar wind plasma distorts the outer part of the terrestrial dipolar field. On the dayside it compresses the field, while the nightside magnetic field is stretched out into a long magnetotail which reaches far beyond lunar orbit.

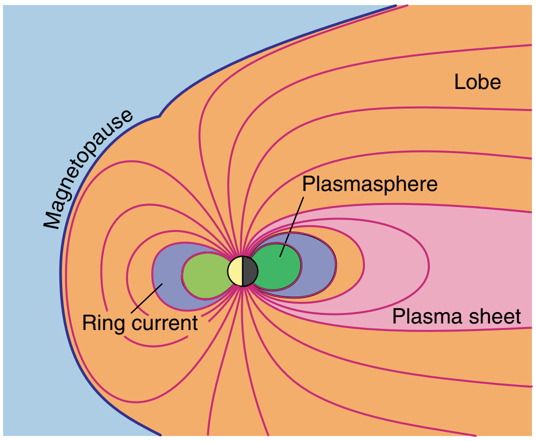

Figure 2 Plasma regions in the Earth's magnetosphere. Note that 'ring current' and 'plasmasphere' partially overlap in reality. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

The plasma in the magnetosphere consists mainly of electrons and protons. The sources of these particles are the solar wind and the terrestrial ionosphere. In addition, there are minor fractions of He^+ and O^+ ions of ionospheric origin (more prominent at lower altitudes) and some He^{2+} ions originating from the Sun. However, the plasma inside the magnetosphere is not evenly distributed, but is grouped into different regions with quite different densities and temperatures. **Figure 2** depicts the topography of some of these regions.

The ring current lies on dipolar field lines between about 4 and 6 R_E (1 Earth radius $(R_E) = 6371$ km). It consists of energetic electrons and ions which move along the field lines and oscillate back and forth between the two hemispheres (see below). Typical electron densities and temperatures in the ring current are $1\,\text{cm}^{-3}$ and 5×10^7 K. The magnetic field strength in this region is a few hundred nanotesla.

Most of the magnetotail plasma is concentrated around the tail midplane in an about 5–10 R_E thick plasma sheet. Near the Earth, it reaches down to the high-latitude auroral ionosphere along the field lines. Average electron densities and temperatures in the plasma sheet are $0.5\,\text{cm}^{-3}$ and 5×10^6 K, with magnetic fields of 10–20 nT.

The outer part of the magnetotail is called the lobe. It is threaded by magnetic field lines originating in the polar caps and contains a highly rarefied plasma. Typical values for the electron density, temperature, and the magnetic field strength are $10^{-2}\,\text{cm}^{-3}$, 5×10^5 K, and 30 nT, respectively.

5.03.2.3 Ionosphere

The solar ultraviolet light impinging on the Earth's atmosphere ionizes a fraction of the neutral atmosphere. At altitudes above 80 km, collisions are too infrequent to result in rapid recombination and a permanent ionized population called the ionosphere is formed. Typical electron densities and temperatures in the mid-latitude ionosphere are $10^5\,\text{cm}^{-3}$ and 10^3 K. The magnetic field strength is of the order of 10^4 nT.

The ionosphere extends to altitudes of about a thousand kilometers and, at low and mid-latitudes, gradually merges into the plasmasphere. As depicted in **Figure 2**, the plasmasphere is a torus-shaped volume inside the ring current. It contains a cool but dense plasma of ionospheric origin, which corotates with the Earth. In the equatorial plane, the plasmasphere extends out to about 4 R_E, where the density drops down sharply to about $1\,\text{cm}^{-3}$. This boundary is called the plasmapause.

At high latitudes, plasma sheet electrons can precipitate along magnetic field lines down to ionospheric altitudes, where they collide with and ionize neutral atmosphere particles. As a byproduct, photons emitted by this process create the polar light, the aurora. These auroras are typically observed inside the auroral oval, which is a 5–10° wide belt around 70° northern or southern magnetic latitude, containing the 'footprints' of those field lines which thread the plasma sheet.

5.03.2.4 Currents

The plasmas discussed in the last section are usually not stationary but move under the influence of external forces. Sometimes ions and electrons move together, like in the solar wind. But in other plasma regions, ions and electrons often move in different directions, creating an electric current. Such currents create magnetic fields, which distort the Earth's internal field, most intensely at higher altitudes.

Actually, the distortion of the internal dipole field into the typical shape of the magnetosphere is accompanied by electrical currents. As schematically shown in **Figure 3**, the compression of the internal magnetic field on the dayside is associated with current flow across the magnetopause surface, the magnetopause

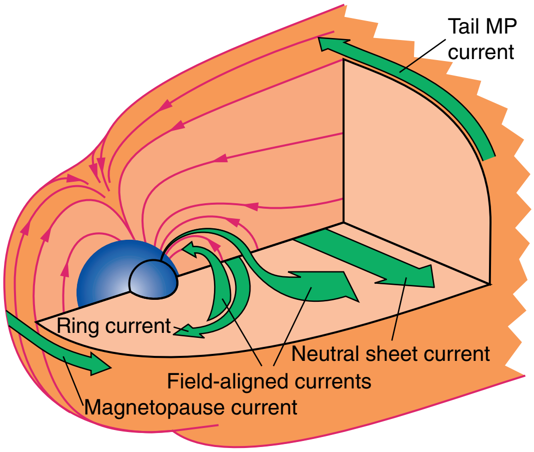

Figure 3 Magnetospheric current systems. MP current, magnetopause current. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

current. The tail-like field of the nightside magnetosphere is accompanied by the current flowing on the tail magnetopause surface and the cross-tail neutral sheet current in the central plasma sheet, both of which are connected and form a Θ-like current system, if seen from along the Earth–Sun line.

Another large-scale current system, which mainly influences the configuration of the inner magnetosphere, is the ring current. The ring current flows around the Earth in a westward direction at radial distances of several Earth radii and is carried by trapped energetic particles, which oscillate back and forth along the field lines. In addition to their bouncing motion, these particles drift around the Earth. Since the protons drift westward while the electrons move in the eastward direction, this constitutes a net charge transport and thus a current.

A number of current systems exist in the conducting layers of the Earth's ionosphere, at altitudes of 100–150 km. Most notable are the auroral electrojets inside the auroral oval, the Sq currents in the dayside mid-latitude ionosphere, and the equatorial electrojet near the magnetic equator.

In addition to the currents that flow across the magnetic field lines, currents also flow along magnetic field lines. As shown in **Figure 3**, the field-aligned currents connect the magnetospheric currents to those flowing in the polar ionosphere. The field-aligned currents are mainly carried by electrons and are essential for the exchange of energy and momentum between these regions.

5.03.3 Plasma Dynamics

The dynamics of a plasma is governed by the interaction of the charge carriers with the electric and magnetic fields. If all the fields were of external origin, the physics would be relatively simple. However, as the particles move around, they may create local space charge concentrations and thus electric fields. Moreover, their motion can also generate electric currents and thus magnetic fields. These internal fields and their feedback onto the motion of the plasma particles make plasma physics complex.

In general, the dynamics of a plasma can be described by solving the equation of motion for each individual particle. Since the electric and magnetic fields appearing in each equation include the internal fields generated by every other moving particle, all equations are coupled and have to be solved simultaneously. Such a full solution is not only too difficult to obtain, but also of no practical use, since most of the time one is interested in knowing average quantities like density and temperature rather than the individual velocity of each particle. Therefore, one usually makes certain approximations suitable to the problem studied. For studying the macroscopic interaction between the solar wind and the Earth's magnetosphere, two approaches are most useful (the most developed theoretical approach, the so-called kinetic theory of plasmas is typically needed for microphysical aspects of space plasma physics).

The simpler approach is the single-particle motion or guiding-center description. It describes the motion of a particle under the influence of external electric and magnetic fields. This approach neglects the collective behavior of a plasma, but is useful when studying a very low-density plasma, threaded by strong magnetic fields, like that found in the ring current.

The magnetohydrodynamic approach, on the other hand, neglects all single particle aspects, but includes collective effects. The plasma is treated as a single conducting fluid with macroscopic variables, like average density, velocity, and temperature. The approach assumes that the plasma is able to maintain local equilibria and is suitable to study low-frequency wave phenomena in highly conducting fluids immersed in magnetic fields.

5.03.3.1 Single-Particle Motion

In a situation where the charged particles do not directly interact with each other and where they do not affect the external magnetic field significantly, the motion of each individual particle can be treated independently. This single-particle approach is only valid in very rarefied plasmas where collective effects are negligible. Furthermore, the external magnetic field must be much greater than the magnetic field produced by the electric current due to the charged-particle motion.

The equation of motion for a particle of charge q under the action of the Coulomb and Lorentz forces can be written as

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad [1]$$

where m represents the particle mass and $\mathbf{v}$ the particle velocity. Under the absence of an electric field and a homogeneous magnetic field, eqn [1] describes a circular orbit of the particle around the magnetic field, with the sense of rotation depending on the sign of the charge. The center of the orbit is called the guiding center. The gyroradius of the particle orbit increases with the particle's momentum and decreases for stronger magnetic fields. A possible constant velocity of the particle parallel to the magnetic field will make the actual trajectory of the particle three dimensional and look like a helix (see **Figure 4**).

Taking the electric field into consideration will result in a drift of the particle superimposed onto its gyratory motion. Since, due to the high mobility of electrons, parallel electric fields can typically not be maintained in geophysical plasmas. Solving eqn [1] yields

$$\mathbf{v}_{\mathrm{E}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \qquad [2]$$

The $\mathbf{E} \times \mathbf{B}$ drift is independent of the sign of the charge and thus electrons and ions move together with the same speed in the same direction.

Figure 5 shows the acceleration and deceleration effect of a perpendicular electric field and explains the $\mathbf{E} \times \mathbf{B}$ drift in an intuitive way. An ion is accelerated in the direction of the electric field, thereby increasing its gyroradius. But it is decelerated during the second half of its gyratory orbit, now with a decreasing gyroradius. The changing gyroradii shift the position of the guiding center in the $\mathbf{E} \times \mathbf{B}$ direction. The electrons are accelerated when moving antiparallel to the electric field and decelerated when moving parallel. But since their sense of gyration is also opposite, their guiding centers drift into the same direction.

Up to now we have assumed that the magnetic field is homogeneous. This is definitely not the case in the magnetosphere, where the magnetic field has gradients and field lines are curved. This inhomogeneity of the magnetic field leads to a 'magnetic' drift of charged particles. As visualized in **Figure 6**, in a magnetic field configuration with a gradient in field strength, the gyroradius of a particle decreases in the upward direction and thus the gyroradius of a particle will be larger at the bottom of the orbit than during the top half. As a result, ions and electrons drift into opposite directions, perpendicular to both $\mathbf{B}$ and ∇B. Since ions and electrons gyrate in the opposite sense, ions and electrons also drift in opposite directions. The gradient drift

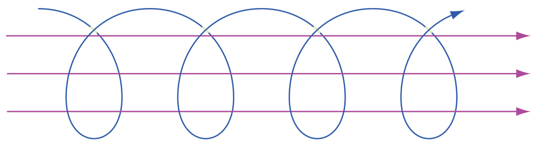

Figure 4 Ion orbit in a uniform magnetic field. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

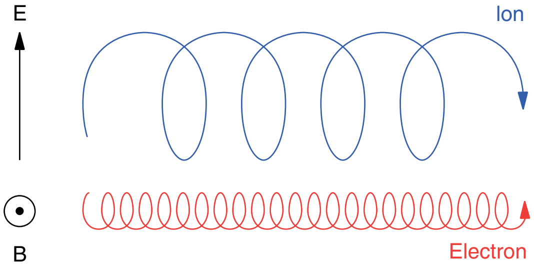

Figure 5 Particle drifts due to an electric field. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

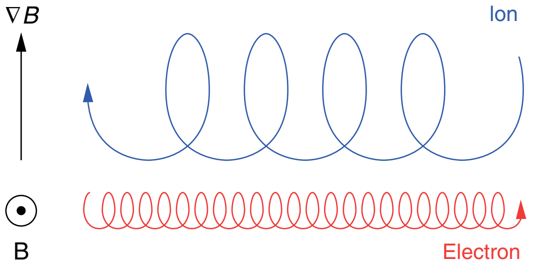

Figure 6 Particle drifts due to a magnetic field gradient. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

velocity is proportional to the perpendicular gyratory energy of the particle, $W_\perp = (1/2)mv_\perp^2$: more energetic particles drift faster, since they have a larger gyroradius and experience more inhomogeneity of the field. The opposite drift directions of electrons and ions lead to a transverse current.

The ‘gradient’ drift is only one component of the particle drift in an inhomogeneous magnetic field. When the field lines are curved, a ‘curvature’ drift appears. Due to their parallel velocity, the particles experience a centrifugal force. The curvature drift velocity is proportional to the parallel particle energy and perpendicular to the magnetic field and its curvature. It again creates a transverse current since ion and electron drifts have opposite signs.

In a cylindrically symmetric field, like in a dipole field, gradient and curvature drifts can be combined to

$$\mathbf{v}_B = \mathbf{v}_\nabla + \mathbf{v}_\mathrm{R} = \left(v_\parallel^2 + \frac{1}{2}v_\perp^2\right)\frac{\mathbf{B}\times\nabla B}{\omega_\mathrm{g} B^2} \qquad [3]$$

where $\mathbf{v}_\nabla$ and $\mathbf{v}_\mathrm{R}$ are the gradient and curvature drift velocity, ω_g gives the gyrofrequency, and the subscripts $\perp$ and $\parallel$ denote components perpendicular and parallel to the ambient background field, respectively. The transverse current associated with this full magnetic drift creates the magnetospheric ring current, mentioned above and further detailed below.

5.03.3.2 Trapped Particles

In slowly varying magnetic and electric fields, not only the total energy of a particle, $W = W_\parallel + W_\perp$, is constant, but also the magnetic moment of a particle, $\mu = W_\perp / B$, does not change with time. Quantities like μ are called adiabatic invariants and are not absolute constants like total energy or total momentum, but change only very slowly.

Since the magnetic moment is invariant and the total energy is a constant of motion, only the ratio between perpendicular and parallel energy increases or decreases along the guiding center trajectory. In a converging magnetic field geometry, a particle moving into regions of stronger fields will have its transverse energy increasing at the expense of its parallel energy. If there is a point along the field line where all of the particle energy is in $W_\perp$, the particle cannot penetrate any further along the field line into the stronger field region. Actually, it does not stop, but is pushed back by the parallel component of the gradient force, the so-called mirror force, $-\mu\nabla_\parallel B$, from this mirror point.

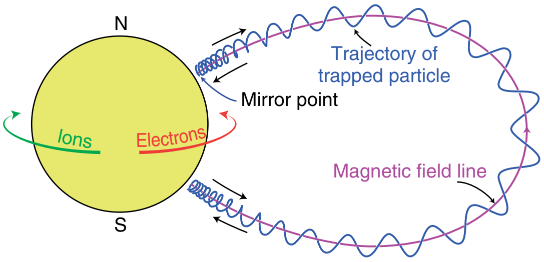

Figure 7 Trajectories of particles trapped on closed dipolar field lines. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

A dipole magnetic field has a field strength minimum at the equator and converging field lines in both hemispheres. In such a configuration, particles will be trapped and bounce back and forth between their mirror points in the Northern and Southern Hemispheres (see **Figure 7**). The particles do not only gyrate and bounce, but undergo a slow azimuthal drift due to the combined effect of the gradient and curvature of the dipole magnetic field as described in eqn [3]. The ions drift westward while the electrons move eastward around the Earth. It is the current associated with this drift that constitutes the ring current.

5.03.3.3 Collisions and Conductivity

So far only the motion of single particles in external and slowly variable electromagnetic fields has been considered, but any interaction between the particles has been neglected. Interaction in plasmas is, however, unavoidable and collective effects constitute the very nature of plasma physics. The simplest kind of interaction between particles is a direct collision. The partially ionized plasma of the terrestrial ionosphere is a good example for such interactions. Here collisions between charged and neutral particles create electrical resistivity and current flow.

In the presence of collisions a collisional term has to be to added to the equation of motion [1] for a charged particle under the action of the Coulomb and Lorentz forces. Assuming all collision partners are at rest, then

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B}) - m\nu_\mathrm{c}\mathbf{v} \qquad [4]$$

The collisional term on the right-hand side describes the momentum lost through collisions occurring at a frequency ν_c. It is often called frictional term since it impedes motion.

The friction term introduces a differential motion between electrons and ions and thus a current, even in homogeneous magnetic fields. In fact, the above equation reduces to a generalized Ohm's law

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad [5]$$

which is valid in all geophysical plasmas where the typical collision frequencies are low, and σ is the plasma conductivity.

While treating the plasma conductivity as a scalar is warranted in the dilute magnetospheric plasma, there is one place where we have to take the anisotropy introduced by the presence of a strong magnetic field into account. This is the lower part, the so-called E-region, of the partially ionized terrestrial ionosphere, at about 100–130 km altitude, where abundant collisions between the ionized and the neutral part of the upper atmosphere might even interrupt the cyclotron motion of electrons and/or ions, leading to an anisotropic conductivity tensor and a different form of Ohm's law:

$$\mathbf{j} = \sigma_{||}\mathbf{E}_{||} + \sigma_{\mathrm{P}}\mathbf{E}_{\perp} - \sigma_{\mathrm{H}}(\mathbf{E}_{\perp} \times \mathbf{B})/B \qquad [6]$$

The Hall conductivity, σ_{H}, determines the Hall current in the direction perpendicular to both the electric and magnetic field. The Hall conductivity maximizes near 100 km altitude, where the ions collide so frequently with the neutrals that they are essentially at rest, while the electrons already undergo a somewhat impeded $\mathbf{E} \times \mathbf{B}$-drift. The Pedersen conductivity, σ_{P}, governs the Pedersen current in the direction of that part of the electric field, $\mathbf{E}_{\perp}$, which is transverse to the magnetic field. The Pedersen conductivity maximizes near a height of 125 km, since here the ions are scattered in the direction of the electric field before they can start to gyrate about the magnetic field. The element $\sigma_{||}$ is called parallel conductivity since it governs the magnetic field-aligned current driven by the parallel electric field component, $E_{||}$.

5.03.3.4 Convection and Merging

While collisions play an important role in the ionosphere, most space plasmas are essentially collisionless. Hence, the conductivity in the magnetospheric or in the solar wind plasma is near infinite. As in a superconductor, magnetic field lines are frozen in the plasma and both move together under the action of external forces. In particular, under the influence of an external electric field, the so-called flux tubes, bundles of field lines filled with plasma, simply drift following eqn [2]. On the other hand, if forces are exerted on the magnetic field lines leading to a motion of the flux tubes, an electric field will be generated. The latter is often called convection electric field.

However, there is an exception. Under certain conditions, especially in the thin and intense current sheets of the magnetopause and the magnetotail neutral sheet, strong plasma waves or inertial effects may substitute collisions and lower the conductivity to a finite value. In this case, the magnetic field lines can diffuse through the plasma. This rarely has major consequences, except for a situation as depicted in **Figure 8**.

Consider a magnetic topology with antiparallel field lines frozen into the plasma, as depicted in the left-hand diagram of **Figure 8**. If the flux tubes are stagnant and do not move, nothing will happen. However, when plasma and field lines on both sides move toward each other, the situation may change. When the conductivity becomes finite in a small volume of space, the magnetic field can vanish due to diffusion at a particular point. This results in the X-type configuration shown in the middle panel of **Figure 8**, with the magnetic field being zero at the center of the X, the magnetic neutral point. The result will be the situation depicted on the right-hand side of **Figure 8**. Plasma and field lines are being transported toward the neutral point from either side. At the neutral point the antiparallel field lines are cut into halves and the field line halves from one side are reconnected with those from the other side. The merged field lines are then expelled from the neutral point. The merged field lines will be populated by a mixture of plasma from both sides.

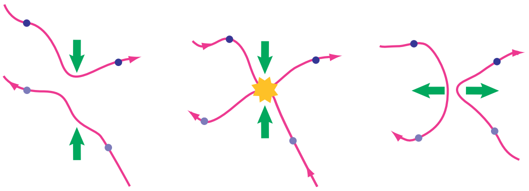

Figure 8 Magnetic field line reconnection.

5.03.4 Low- and Mid-Latitude Currents

The ions and, to a lesser degree, also the electrons in the ionospheric E-region are coupled by collisions to the neutral components of the upper atmosphere and follow their dynamics. Atmospheric winds and tidal oscillations of the atmosphere force the E-region ion component to move across the magnetic field lines, while the electrons move much slower at right angles to both the field and the neutral wind. The relative movement constitutes an electric current and the separation of charge produces an electric field, which in turn affects the current. Because of this, the E-region bears the name dynamo layer, the generator of which is the atmospheric wind motion. This wind-driven dynamo causes two current systems in the equatorial and mid-latitude ionosphere whose 'external' magnetic variations alter the geomagnetic field measured on the Earth's surface. A third current system results from electric and magnetic drifts of magnetospheric particles, the ring current. It is concentrated in the equatorial region of the Earth's magnetosphere.

5.03.4.1 Sq Current

The relation between current, conductivity, electric field, and neutral winds can be seen by replacing $\mathbf{E}_\perp$ with $\mathbf{E}_\perp + \mathbf{v}_n \times \mathbf{B}$ in the Ohm's law given above. For mid- and low-latitude dynamo currents, the dominant driving force for the current is actually the $\mathbf{E} \times \mathbf{B}$ field induced by the motion of ions, which are coupled to the neutral atmosphere via collisions and thus move with the neutral wind, across the magnetic field. (For auroral oval current systems discussed later, the neutral wind term is usually much smaller than the electric field term and can be neglected.)

The most important dynamo effect at mid-latitudes is the daily variation of the atmospheric motion caused by the tides of the atmosphere, that is, the diurnal and semi-diurnal oscillations, which are excited by the heating of the atmosphere due to solar radiation. The current system created by this tidal motion of the atmosphere is called solar quiet or Sq current. This current system creates daily magnetic variations, records of which are obtained at many different magnetic observatories distributed across the globe. These recordings can be used to construct the Sq current system. More sophisticated methods use measured wind patterns, conductivities, and disturbance magnetic fields and calculate electric fields and currents based on Ohm's and Biot–Savart's laws.

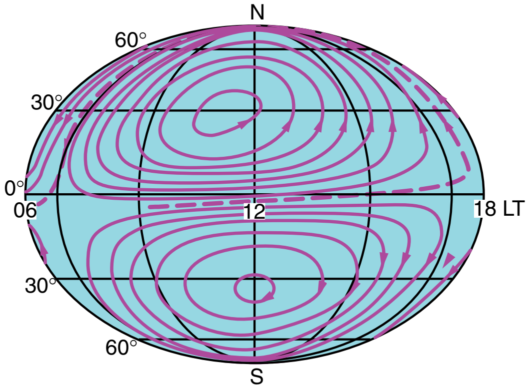

Figure 9 Dayside view of the Sq current system. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

Figure 9 presents a global view of the average Sq current system from above the terrestrial ionosphere: the lines give the direction of the current while the distance between the lines is inversely proportional to the height-integrated current density. The Sq currents form two vortices, one in the Northern and the other in the Southern Hemisphere, which touch each other at the geomagnetic equator. In accordance with the day–night contrast in the low- and mid-latitude E-region conductivities, the Sq currents are concentrated on the dayside.

5.03.4.2 Equatorial Electrojet

At the geomagnetic equator, the Sq current vortices of the Southern and Northern Hemispheres touch each other and form an extended nearly jet-like current in the ionosphere, the equatorial electrojet. However, the electrojet would not be so strong if it were formed only by the concentration of the Sq current. The special geometry of the magnetic field at the equator together with the nearly perpendicular incidence of solar radiation cause an equatorial enhancement in the effective conductivity which leads to an amplification of the jet current.

Since the magnetic field lines in the equatorial ionosphere are directed northward and parallel to the Earth's surface, the eastward ionospheric electric field drives an eastward Sq Pedersen current and a Sq Hall current, which flows vertically downward at the equator. As shown in **Figure 10**, the latter causes a charge

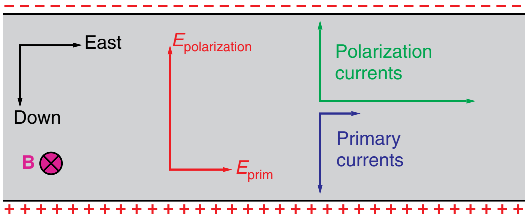

Figure 10 Eastward current enhancement at the magnetic equator.

separation in the equatorial ionosphere with negative charges accumulating on the top boundary and positive charges accumulating at the bottom of the highly conducting layer. This space charge distribution creates a secondary polarization electric field, directed vertically upward. The polarization electric field drives a vertical Pedersen current opposing the Hall current until it compensates it. Since the Hall conductivity is typically about 4 times higher than the Pedersen conductivity, the polarization field must also be 4 times stronger than the primary electric field. Moreover, the polarization electric field generates a secondary Hall current component flowing eastward, about 16 times stronger than the primary eastward Pedersen current, thus explaining the amplification of the equatorial electrojet current above the equator.

The strong horizontal jet current causes a magnetic field disturbance which weakens the horizontal component of the terrestrial magnetic field at the Earth's surface over a distance of about 600 km across the equator (similar to the effect of the ring current field; see below). Typical disturbance fields near the noon magnetic equator are of the order of 50–100 nT.

5.03.4.3 Ring Current

The westward drift of trapped ions and the eastward drift of trapped electrons around the Earth, depicted in **Figure 7**, represent a giant current loop of 1–10 MA, that can significantly alter the terrestrial field even at the Earth's surface.

Applying the magnetic drift velocity given in eqn [3] to the Earth's dipole field, one can calculate the current density caused by n particles with energy W circulating around the Earth at a certain radial distance or particular L-shell

$$j_{\mathrm{d}} = nev_{\mathrm{B}} = \frac{3L^2 nW}{B_{\mathrm{E}} R_{\mathrm{E}}} \qquad [7]$$

where L is measured in R_{E} but is dimensionless, B_{E} is the equatorial magnetic field on the Earth's surface, and j_{d} results as an azimuthal current flowing in the westward direction.

Integrating over all energies, applying Biot–Savart's law, and then integrating over all L-shells, several symmetries in the equations lead to the simple expression

$$\Delta B_{\mathrm{d}} = -\frac{\mu_0}{4\pi}\frac{3U_{\mathrm{R}}}{B_{\mathrm{E}} R_{\mathrm{E}}^3} \qquad [8]$$

field disturbance at the Earth's center, where U_{R} is the total energy of all ring current particles. The minus sign accounts for the fact that the disturbance field of the westward ring current is directed opposite the terrestrial dipole magnetic field.

The total magnetic field perturbation caused by the ring current must also include the diamagnetic contribution due to the cyclotron motion of the ring current particles. Again, symmetries result in a simple expression

$$\Delta B_{\mu} = \frac{\mu_0}{4\pi}\frac{U_{\mathrm{R}}}{B_{\mathrm{E}} R_{\mathrm{E}}^3} \qquad [9]$$

This disturbance adds to the terrestrial dipole field, since the Earth's dipole moment and the magnetic moments of the ring current particles are co-aligned. The total magnetic field depression caused by the ring current, $\Delta B_{\mathrm{R}} = \Delta B_{\mathrm{d}} + \Delta B_{\mu}$, at the Earth's center is

$$\Delta B_{\mathrm{R}} = -\frac{\mu_0}{2\pi}\frac{U_{\mathrm{R}}}{B_{\mathrm{E}} R_{\mathrm{E}}^3} \qquad [10]$$

This is the famous Dessler–Sckopke–Parker relation, which directly relates the total energy contained in the ring current to the magnetic variation measured on the Earth's surface.

5.03.4.4 Storms and Sudden Commencements

The ring current and its associated disturbance field is not a stationary feature. At times more particles than usual are injected from the magnetotail into the ring current, mainly by an enhanced duskward solar wind electric field induced into the magnetotail. This way the total energy of the ring current is increased and the additional depression of the surface magnetic field can clearly be seen in near-equatorial magnetograms, as shown in **Figure 11**. For about 1 day, the equatorial terrestrial field was depressed by more than 150 nT. Strong depressions of the terrestrial field, up to 2–3% of the total surface field in extreme cases, have been noticed in magnetograms long

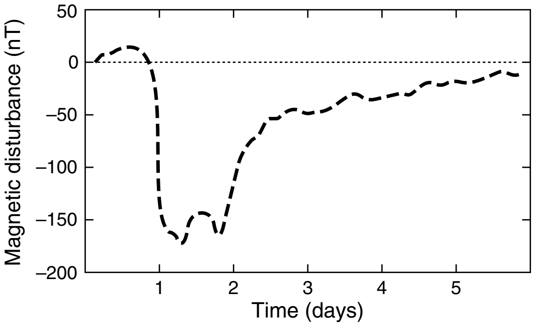

Figure 11 Magnetic field variation during a magnetic storm. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

before one knew about the ring current and have been called magnetic storms.

A magnetic storm has two distinct phases. For some hours or days, an enhanced electric field injects more and more particles into the inner magnetosphere, building up the strong storm-time ring current and the associated magnetic disturbance field. After a day or two, the electric field amplitude and the rate of injection return to the normal level. The disturbance field starts to recover, since the ring current loses more and more storm-time particles. This recovery phase typically lasts several days.

The depression of the terrestrial dipole field given in eqn [10] is reflected in the Dst index. This index represents the average disturbance field at the Earth's equator and is calculated on the basis of hourly averages of the northward horizontal component recorded at four low-latitude observatories – Honolulu, San Juan, Hermanus, and Kakioka. All four observatories are 20–30° away from the dipole equator to minimize equatorial electrojet effects and are about evenly distributed in local time (longitude).

At each observatory, a magnetic perturbation amplitude is calculated by subtracting from the hourly averages a quiet time reference level and the Sq field, both of which vary with local time. All four magnetic disturbances are then averaged to further reduce local time effects and multiplied with the averages of the cosines of the observatories' dipole latitudes, to obtain the value of the ring current field at the dipole equator.

Magnetograms like in **Figure 11** often also show a positive excursion of the horizontal field magnitude, right at the beginning of the storm. This excursion is the magnetic signature of the solar wind impinging faster than usual onto the magnetopause. The position of the dayside magnetopause is essentially determined as the surface of equilibrium between the magnetic pressure of the terrestrial magnetic field and the kinetic energy of the solar wind. Whenever the speed of the solar wind increases, the terrestrial field has to be compressed and thus the magnetopause has to recede to a new equilibrium position. If such a sudden compression of the dayside magnetospheric field occurs at the beginning of a magnetic storm, it is called storm sudden commencement (SSC), whereas when it is not followed by a storm, it is called sudden impulse (SI).

5.03.5 High-Latitude Currents

Intense ionospheric current systems are also flowing in the high-latitude ionosphere. However, in this region, the magnetic field lines are oriented approximately perpendicular to the ionospheric layers and so-called field-aligned currents connect the ionospheric currents to those flowing in the magnetosphere. Hence, the electrodynamics in the high-latitude E-region is coupled and even governed by the dynamics of the magnetosphere at large.

5.03.5.1 Magnetospheric Convection

The concurrent drift of plasma and field lines as one entity is called convection. Due to the infinite conductivity, the electric field is zero in the frame of reference moving with the plasma at a velocity $\mathbf{v}_c$. However, according to eqn [2], an observer in the Earth's fixed frame of reference will measure a convection electric field

$$\mathbf{E}_c = -\mathbf{v}_c \times \mathbf{B} \qquad [11]$$

Hence, the flow of the magnetized solar wind around the magnetosphere represents an electric field in the Earth's frame of reference. Since the solar wind cannot penetrate the magnetopause, this electric field cannot directly penetrate into the magnetosphere. However, when the interplanetary magnetic field has a southward component, the northward-directed terrestrial field lines at the dayside magnetopause can merge with the interplanetary magnetic field.

As depicted in **Figure 12**, when a southward-directed interplanetary field line encounters the magnetopause, it can merge with a closed terrestrial field line, which has both 'foot points' on the Earth. The merged field lines will split into two open field

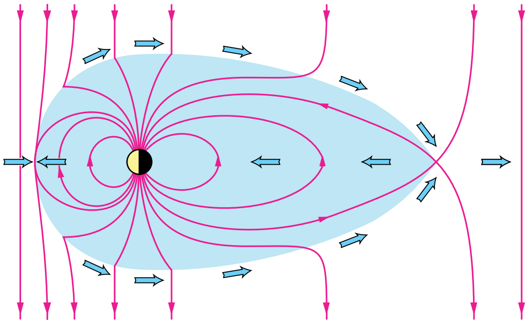

Figure 12 Reconnection and convection cycle in the magnetosphere. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

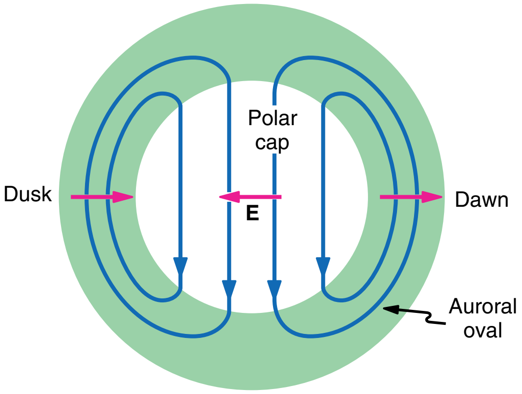

Figure 13 Convection and electric field in the high-latitude ionosphere. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

lines, each of which has one end connected to the Earth and the other stretching out into the solar wind. Subsequently, the solar wind will transport this field line across the polar cap down the tail and due to the stiffness of the field line, the magnetic tension, the magnetospheric part of the field line (inside the shaded region), will also be transported tailward. At the nightside end of the magnetosphere the two open field line halves will meet again and reconnect, leaving a closed but stretched terrestrial field line in the magnetotail and an open solar wind field line downtail of the magnetosphere. Due to magnetic tension, the stretched tail field line will relax and shorten in the earthward direction. During this relaxation it transports the plasma, to which it is frozen, toward the Earth.

For an observer on the Earth, the sunward transport of plasma in the magnetosphere caused by magnetic merging at the Earth's magnetopause is equivalent to an electric field. The total potential difference between the dawn and dusk magnetopause or, equivalently, across the polar cap corresponds to about 50–100 kV. For a cross section of the magnetosphere of about 30 R_E, this amounts to a dawn-to-dusk directed field of some 0.2–0.5 mV m^{-1}.

5.03.5.2 Ionospheric Convection

The motion of the flux tubes across the polar cap due to magnetic merging depicted in **Figure 12** also moves the ionospheric foot point of the flux tube and the plasma tied to it across the polar cap to the nightside. Similarly, the sunward convection of magnetospheric flux tubes leads to a sunward convection of the foot points of these flux tubes in the dawn- and dusk-side high-latitude ionosphere, inside the auroral oval. This leads to a two-cell convection pattern in the polar ionosphere, depicted in **Figure 13**.

The convection pattern is equivalent to an electric potential pattern. Cold particles will drift along these contours: drawing equipotential contours and drawing $\mathbf{E} \times \mathbf{B}$ drift trajectories of the plasma is equivalent. Hence, we can take the two-cell convection pattern as a two-cell pattern of equipotential contours, which is equivalent to an ionospheric electric field that is directed toward dusk in the northern polar cap. Inside the Northern Hemisphere auroral oval the electric field is directed toward the pole on the dusk side, while it has a southward direction in the morning hours.

Since the ionospheric conductivity is a tensor with three different components (see previous section), three types of currents will be generated by the convection electric field. The first type is the field-aligned currents flowing parallel to the magnetic field into and out of the ionosphere. Second, there are the Pedersen currents which flow perpendicular to the magnetic field lines and parallel to the ionospheric convection field. Finally, Hall currents will flow perpendicular to both the magnetic and the electric field.

5.03.5.3 Auroral Electrojets

Since particles precipitating into the auroral oval cause significant ionization, its conductivity is much higher than that of the polar cap. As a result, the high-latitude current flow is concentrated inside the auroral oval, where it forms the auroral electrojets.

The auroral electrojets are the most prominent currents at auroral latitudes. They carry a total current of some million amperes. This is the same order of magnitude as the total current carried by the ring current, discussed in the previous section, but since the auroral electrojets flow only 100 km above the Earth's surface, they create the largest ground magnetic disturbance of all current systems in the Earth's environment. The disturbance fields have typical magnitudes of 100–1000 nT, but may reach 3000 nT during the largest magnetic storms.

It is important to distinguish between the convection auroral electrojets, shown in the left-hand panel of **Figure 14**, and the substorm electrojet on the right-hand side. The convection electrojets consist of eastward and westward electrojets. These are primarily Hall currents which originate around noon where they are fed by downward field-aligned currents. Typical sheet current densities range between 0.5 and 1 A m^{-1}. The eastward electrojet flows in the afternoon sector and terminates in the pre-midnight region where it partially flows up magnetic field lines and partially rotates northward, joining the westward electrojet. The westward electrojet flows through the morning and midnight sector and typically extends into the evening sector along the poleward border of the auroral oval where it also diverges as upward field-aligned currents.

Similar to the ring current, which is 'measured' by the Dst index (see previous section), the auroral electrojet indices AE, AU, and AL were introduced as a measure of global auroral electrojet activity. The indices are based on 1 min samples of the northward component trace from auroral zone observatories located at 65–70° magnetic latitude with a longitudinal spacing of 10–40°. Referenced to a quiet-day level, the data of all observatories are plotted as a function of universal time. The upper and lower envelopes are defined as AU and AL, while AE is defined as the separation between the upper and lower envelopes. The upper and lower envelopes are thought to represent the maximum eastward and westward electrojet current, respectively, while AE represents the total maximum electrojet current.

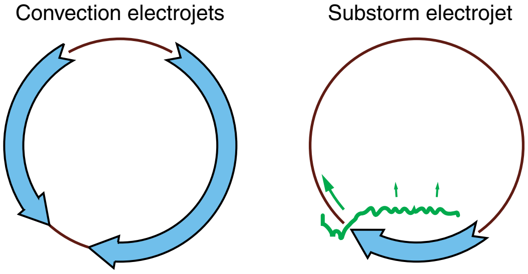

Figure 14 Auroral electrojets. The green line and arrows in the righthand panel indicate the boundary of the west- and northward expanding substorm auroral bulge. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

5.03.5.4 Substorms

Convection is not a stationary process: magnetic merging between interplanetary and terrestrial field lines at the dayside magnetopause does not occur all the time, but only for southward-oriented interplanetary field lines, and is typically not in equilibrium with reconnection in the magnetotail. Only part of the flux transported into the tail is reconnected instantaneously in the deep tail and convected back to the dayside. The remaining field lines are added to the tail lobes, where they increase the magnetic flux density and, hence, enhance the cross-tail current in the neutral sheet. After some tens of minutes these intermediately stored field lines are suddenly reconnected at tail distances of 20–25 Earth radii and their magnetic energy is explosively released. The sudden reconnection of previously stored flux tubes has rather dramatic effects on the magnetospheric plasma and associated phenomena like aurora and magnetospheric and ionospheric currents. These effects, which last for 1–2 h, are summarized as magnetospheric substorm.

A substorm starts when the dayside merging rate is distinctively enhanced, typically due to a southward turning of the interplanetary magnetic field. The flux eroded on the dayside magnetopause is transported into the tail. Part of the flux is reconnected and convected back to the dayside magnetosphere. The enhanced convection causes enhanced current flow in the convection electrojets and an associated growth of the AE index.

The other part of the flux is added to the tail lobes. After 30–60 min, too much magnetic flux and thus magnetic energy has been accumulated in the tail. The tail becomes unstable and must release the surplus energy. This is the time of substorm onset and the beginning of the substorm expansion phase. At substorm onset, the aurora suddenly brightens and fills the whole sky. During the following 30–60 min, rather dramatic changes are seen in the auroral zone currents.

The sharp AE index seen in **Figure 15** to values of about 500 nT indicates that the ionospheric current flow is strongly enhanced. The unloading of

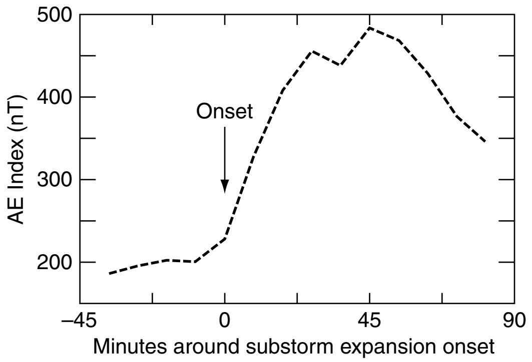

Figure 15 Variation of AE index during a substorm.

magnetic flux previously stored in the magnetotail leads to the formation of a substorm electrojet with strongly enhanced westward current flow in the midnight sector. The substorm electrojet is concentrated in the region of active aurora and expands westward during the course of the expansion phase. In contrast to the convection electrojets, where any increase is caused mainly by an increasing convection electric field, the strength of the substorm electrojet current is mainly determined by a strong increase in ionospheric conductance due to strong particle precipitation in the bright substorm aurora.

Since the substorm electrojet is governed by the strong increase of the conductivities inside the region of bright aurora, the situation is similar (except for directions) to that in the equatorial electrojet described in the previous section. However, in the present case, the polarization electric field and thus the enhancement of the westward current is not so strong, since field-aligned currents will remove part of the space charge deposited at the boundaries of the highly conducting channel.

Another difference between the convection and substorm electrojets is that in the case of the convection electrojets, the field-aligned currents are distributed over a wide local time range. In the case of the substorm electrojet, the jet itself and its field-aligned currents are much more concentrated in the midnight sector, forming a current wedge as depicted in **Figure 16**. The effects of this current wedge, in particular the magnetic disturbance associated with the field-aligned currents, can be seen also at mid-latitudes.

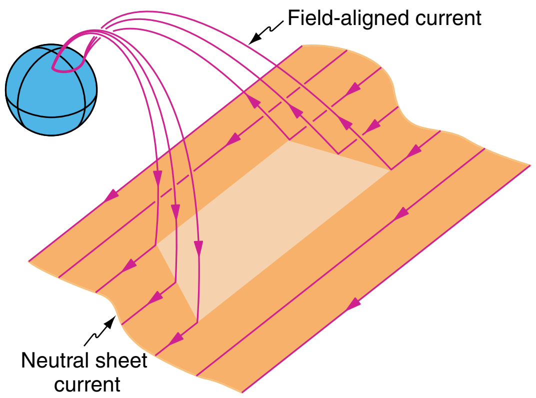

Figure 16 Substorm current wedge. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

5.03.6 Geomagnetic Pulsations

As with any medium, a plasma carries waves in many different frequency ranges, from as low as millihertz to as high as several tens of kilohertz. Typically, the higher-frequency waves can only be observed in the plasma itself, but the ultralow-frequency (ULF) waves, in particular, generate fast fluctuations of the Earth's surface magnetic field in the frequency range from a few millihertz up to a few hertz, corresponding to oscillation periods from several hundred seconds to a fraction of a second. These are the so-called geomagnetic pulsations, known of for about a century.

In most cases, the pulsating disturbance fields observed are associated with shear Alfvén waves. These waves constitute the simplest wave solutions of the magnetohydrodynamic equations and represent simple string-like oscillations of mass-loaded magnetic field lines. Shear Alfvén waves are purely transverse waves, that is, all variations have only components that are perpendicular to the ambient magnetic field. The magnetic component of this type of wave is parallel to the plasma velocity variation while the wave electric field points perpendicular to the magnetic and velocity variations.

An Alfvén wave may propagate parallel to the ambient field with the Alfvén velocity, v_A, which is essentially a 'magnetic sound' velocity, given by

$$v_A^2 = \frac{B^2}{\mu_0 nm} \qquad [12]$$

In the Earth's magnetosphere, typical Alfvén velocities range from some hundreds to several thousands of kilometers per second.

The ULF range, and hence the pulsations, are conventionally divided into five intervals, Pc1–Pc5,

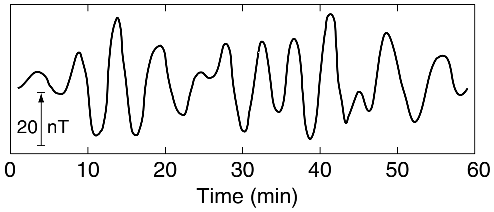

Figure 17 Ground magnetic disturbance of a Pc5 pulsation.

for continuous pulsations, and into two intervals, Pi1 and Pi2, for irregular pulsations. The class of continuous pulsations covers quasi-sinusoidal oscillations of narrow spectral bandwidth, as shown in **Figure 17**. They may have a comparably long duration from several minutes up to hours. Pc pulsations can generally be observed over a wide latitudinal and longitudinal range on the Earth's surface and in the magnetosphere. The irregular pulsations, in contrast, are shorter-lived, sometimes comprising only a few oscillations decaying in time.

5.03.6.1 Pc5 Pulsations

The Pc5 pulsations shown in **Figure 17** are caused by standing oscillations of magnetospheric field lines. For a standing wave, the length of the field line between the two reflection points in the ionosphere must be a multiple of half the parallel wavelength. Hence, each particular field line has a number of distinct eigenfrequencies or Alfvénic resonances. Since the length of the field lines increases with latitude, the resonance or eigenfrequency decreases with latitude. For an average Alfvén velocity of $1000\,\mathrm{km\,s^{-1}}$, the fundamental resonance frequency on closed field lines ranges between 1 and 100 mHz and falls into the Pc3–Pc5 range.

Figure 18 schematically shows how the dipolar field configuration changes for two fundamental types of field line resonances. The foot points of the field lines are fixed in the ionosphere, but the field lines may either perform a 'breathing' motion (fundamental odd mode) or a 'wobbling' motion (even mode). In addition to these poloidal modes, the field lines can also exert toroidal oscillations, in which case the oscillation of the field line and the plasma bulk flow are purely azimuthal. Pc pulsations often are a mixture of poloidal and toroidal oscillations.

Pc5 pulsations are resonant oscillations of field lines. They are excited and driven via surface waves traveling along the magnetopause. These surface waves are caused by a Kelvin–Helmholtz instability excited by the flow of the solar wind around the magnetosphere and represent an evanescent wave mode. Being surface waves, their amplitude is strongly damped away from the magnetopause, yet they can still set the field line with a matching eigen- or resonance frequency into oscillation. All other field lines, whose resonance frequencies do not match, are only marginally excited and do not contribute to the pulsation.

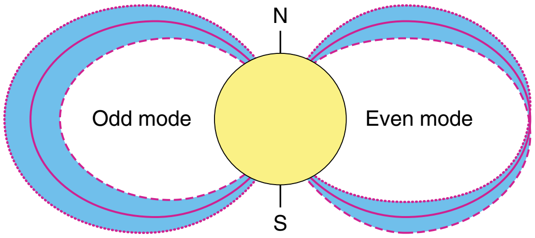

Figure 18 Fundamental poloidal field line resonances. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

Pc4–Pc5 pulsations might also be excited by packets of trapped particles bouncing up and down a field line, as long as the bounce period of these particles, which depends mainly on their energy, matches the eigenperiod of the field line.

5.03.6.2 Pi2 Pulsations

The short-period irregular Pi2 pulsations are associated with the development of the substorm current wedge described in the previous section. Whenever field-aligned currents are suddenly switched on somewhere in the magnetosphere, they must be transported to the ionosphere via Alfvén waves. Only this transverse magnetohydrodynamic wave mode can carry field-aligned current. Launched in the magnetosphere, the Alfvén waves are reflected back and forth between the ionosphere and the current generator in the tail until a stationary equilibrium is reached.

Figure 19 shows qualitatively the development of the magnetic disturbance field and thus the field-aligned current flow after switch-on of a current generator in the magnetotail. At $t=0$, an Alfvén wave is launched which carries a current corresponding to the generator current and thus a particular magnetic disturbance field. This wave reaches the ionosphere at $t=t_A$, the Alfvén wave traveltime between magnetosphere and ionosphere, that is,

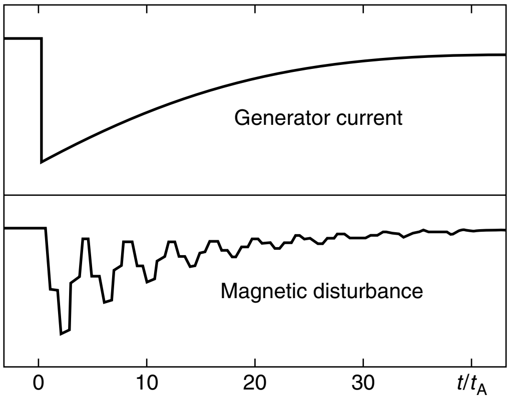

Figure 19 Magnetic disturbance due to switch-on of a current wedge. Adapted from Baumjohann W and Treumann RA (1996) *Basic Space Plasma Physics*. London: Imperial College Press, with permission from Imperial College Press.

some 30 s. Here, about 80% of its amplitude is reflected with the magnetic field of the reflected wave adding to the primary disturbance field.

At $t = 2t_A$, the reflected wave comes back to the generator and launches a third wave, whose magnetic disturbance must be of opposite polarity to decrease the total wave magnetic field such that the total disturbance matches that caused by the generator current at this time. Multiple bounces of the wave lead to magnetic field disturbances which oscillate with a period of $4t_A$ until they finally converge to match the generator current. The magnetic oscillations with periods of some 100 s are readily observable as Pi2 pulsations. They are often used as a good indicator for the onset of substorms.

5.03.7 Conclusions

This chapter gave a brief introduction into the fundamentals of magnetospheric physics. The topics and phenomena discussed were selected by their influence on the terrestrial field as measured on the Earth's surface. There are many more interesting features that can be observed in magnetospheric plasmas, let alone in other space plasmas, like solar or astrophysical plasmas.

However, all of them follow the same basic principles outlined above. If one includes the Earth's bow shock (which was not discussed here, since its physics has little influence on the terrestrial magnetic field), detailed *in situ* studies of the space plasmas in the Earth's neighborhood are an effective means to understand many solar and astrophysical phenomena, from which we have only sparse observational information transmitted by electromagnetic radiation.

Hence, geomagnetism is not only the root of magnetospheric physics (ground-based observations of magnetic variations done by Humboldt and Gauss provided the first window into what was later called magnetosphere), but in a broader sense, that is, by measuring magnetic fields in the Earth's neighborhood, it is still essential to understand the plasma universe.

A more exhaustive description of all possible external sources of geomagnetic field variations (and on their use in diagnosing magnetospheric dynamics) is presented in Nishida (1978). A full description of theory and observations of space plasmas in the Earth's neighborhood can be found in Baumjohann and Treumann (1996). For those readers who want to know more about the guiding center approach, we recommend reading the monograph by Alfvén and Fälthammar (1963) or that by Northrop (1963). More about the physics of trapped particles, the ring current, and magnetic storms can be found in Lyons and Williams (1984), Kamide *et al.* (1998), and Daglis *et al.* (1999). The physics of the ionosphere and ionospheric currents is detailed in Hargreaves (1992) and Rishbeth and Garriot (1969). A good description of solar wind–magnetosphere coupling is given in a review article by Cowley (1982). Additional material on high-latitude current systems and magnetosphere–ionosphere coupling is found in a monograph by Kamide and Baumjohann (1993) and in a review article by Untiedt and Baumjohann (1993). For a detailed account on substorms see Baker *et al.* (1996). An exhaustive elementary description of fluid plasma waves is given in Bittencourt (1986) while further information about pulsations is contained in Glassmeier (1995) and McPherron (2005).

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