Space Plasma Physics

Larry Lyons
UCLA Department of Atmospheric Sciences

For
Encyclopedia of Physical Science and Technology
Third Edition

To be Published by Academic Press

GLOSSARY

Aurora Emissions emitted from the upper atmosphere by constituents that have been excited by the impact of energetic particles from the magnetosphere.

Auroral oval The prime region of visible auroral emissions, which consists of approximately circular zones surrounding each geomagnetic pole that are a few degrees in latitude wide and centered near 70° geomagnetic latitude.

Convection Flow of plasma throughout the magnetosphere that is driven by the solar wind.

Geomagnetic latitude Latitude based on the Earth's magnetic axis.

Gyroradius Radius of the circular motion of charged particles about a magnetic field.

Interplanetary magnetic field Magnetic field from the sun that is carried throughout interplanetary space by the solar wind

Ionosphere Region of enhanced ionization that surrounds the Earth at altitudes between ~75 and 500 km altitude.

Magnetopause Current layer that to a large extent separates the interplanetary magnetic field from the geomagnetic field.

Magnetosphere Region of space within the magnetopause that is dominated by the geomagnetic field.

Plasma An ionized gas in which electric forces maintain approximate charge neutrality (the excess of negatively or positively charged particles is everywhere much smaller than the total ion density)

Plasma sheet Energetic plasma region that occupies the outer portions of the magnetosphere

Precipitation Loss of magnetospheric particles to the atmosphere by collisions at the low-altitude ends of magnetic field lines

Radiation belts Region of high fluxes of very energetic electrons and ions that encircles the Earth in the inner portion of the magnetosphere

Solar wind Plasma that flows outward from the sun and fills interplanetary space

Space Plasma Physics is the study of the plasmas that originate from the sun and from the planets and moons within the solar system. These plasmas occupy interplanetary space and the magnetospheres of planets. This article gives an overall description of the plasma processes which control the large scale structure and dynamics of the near-Earth space plasma environment. This includes the formation of the solar wind and interplanetary plasma disturbances. It also includes the interaction of the solar wind plasma and magnetic field with the magnetic field of the Earth and how this interaction leads to the interesting and dynamic space plasma environment which exists in the vicinity of the Earth. Topics include energy transfer to and within the Earth's magnetosphere, formation of magnetospheric structure, and disturbances of the magnetosphere-ionosphere system which constitute what is recently been termed "space weather". Space Plasma Physics also includes the interaction of the solar plasma with other planets, the mixing of solar and planetary plasmas, and a wide range of wave modes associated with plasma oscillations in space.

I. Introduction

The sun continuously emits a stream of ionized particles, which is referred to as the solar wind and is the primary component of the plasma which fills interplanetary space. The average speed of this stream in the ecliptic plane is ~400 km/s, so that it takes about 4 days for particles to reach the Earth. Solar wind speeds, however, can be quite variable. They typically range from ~300 km/s to ~800 km/s, with speeds exceeding 1000 km/s being occasionally observed. The Earth's internal magnetic field is approximately that of a dipole. However, the interaction of the solar wind particles with the Earth's magnetic field compresses the Earth's field on the dayside and draws the field out into a long tail on the nightside. This interaction also confines most of the magnetic field of the Earth to a region referred to as the magnetosphere (See Figure 1, which is a sketch of the magnetosphere in the noon-midnight meridian plane). The outer boundary of the magnetosphere is called the magnetopause, which typically lies ~10 R_E above the noon equator and ~15 R_E away from the Earth within the dawn-dusk meridian plane. On the nightside, the magnetosphere flares outward with increasing distance away from the Earth, eventually becoming approximately cylindrical with a diameter of 40-50 R_E. Solar wind speeds are supersonic, so that a shock (called the "bow shock") lies several R_E upstream of the dayside magnetopause.

Plasma particles move in circles around magnetic field lines and thus can become trapped within the magnetosphere. Major regions of trapped energetic particles within the magnetosphere are the plasma sheet and the radiation belts. As illustrated in Figure 1, the plasma sheet on the night side is displaced from the high-latitude magnetopause by what are referred to as the tail lobes and extends along the entire magnetospheric tail inward to an equatorial radial distance from the center of the Earth r ~5-12 R_E. The plasma sheet also extends around the Earth to other local times and has an outer boundary that lies adjacent to the magnetopause on the dayside. Typical energies of plasma sheet particles are ~1-50 keV for ions and ~0.2-10 keV for electrons. Earthward of the plasma sheet lies a population of more energetic electrons and ions which encircle the Earth and are referred to as the "radiation belts". These particles form a current encircling the earth which is referred to as the "ring current".

Particles from the magnetosphere can move along magnetic field lines and strike the upper atmosphere. Those that reach an altitude of ~100-200 km undergo collisions with the neutral atmosphere resulting in a loss of their energy to the neutral atmosphere and their loss from the magnetosphere. Such loss of energetic magnetospheric particles is referred to as precipitation. The energy from precipitating particles excites constituents of the upper atmosphere, and the relaxation of the upper atmospheric constituents back to their ground state gives off emissions, which when sufficiently intense, are referred to as the aurora *(Suggested cross reference)*. Such precipitation is most intense from the plasma sheet, leading to an approximately circular region of emissions surrounding each magnetic pole that is referred to as the auroral oval. The oval is typically a few to several degrees in latitude wide and is centered near 70° geomagnetic latitude.

II. Basic Concepts

Space Plasma Physics often requires that dynamics be analyzed in terms of both the motion of individual particle and in terms of macroscopic moments such as temperature T, density n, and pressure P. Individual particle motion is based on considering the force **F** = q(**E** + **v x B**) acting on a particle of charge q, mass m, and moving with a velocity **v** in an electric field **E** and magnetic field **B**. Particle motion is generally separated into components $v_{||}$ parallel to **B** and **v** perpendicular to **B**. With **E** = 0 and a uniform, time independent magnetic field, $v_{||}$ is a constant and **v** is circular motion about **B** with a frequency |qB/m|, which is referred to as the gyrofrequency, and radius = mv /|qB|, which is referred to as the gyroradius. The direction of gyration is right (left)-handed with respect to the direction of **B** for electrons (positive ions) as illustrated in Figure 2. Except very near current sheets, particle gyroradii are generally very much less than the scale length for field and plasma variations in space plasmas. Also, particle gyroperiods are generally very much less than space plasma time scales for transport and for changes in plasma and field properties.

Figure 2 shows the motion of electrons and positive ions in uniform and constant electric and magnetic fields. The acceleration by the perpendicular component of the electric field **E** alternatively increases and decreases the particle gyroradius once each gyration, so that, in addition to the gyromotion about **B**, particles move with an average velocity $\mathbf{V}_E$ = (**E x B**)/B^2, which is referred to as the electric field drift speed. This relation can be rewritten as:

(1) $$\mathbf{E} = -\mathbf{V}_E \times \mathbf{B}$$

When $|\mathbf{V}_E| << |\mathbf{v}|$, as is the case throughout most of space, we can separate the particle motion into its gyration about **B** and a drift of the gyrating particle with velocity $\mathbf{V}_E$. Any electric field parallel to **B** simply gives constant particle acceleration along **B**.

As shown in Figure 2, electric fields perpendicular to **B** cause all charges particles to drift with the same velocity, which does not lead to currents. Spatial variations in magnetic field also give particle drifts. However, the drifts from magnetic field variations are oppositely directed for negatively and positively charged particles so that a current is formed. This current is azimuthal in the region of the radiation belts, giving rise to the ring current in this region. Such a current also flows within the tail plasma sheet and is directed across the tail from the dawn side to the dusk side.

The current formed by an individual charge particle gyrating about **B** can be represented as a magnetic dipole with magnetic moment μ = K /B, where the perpendicular energy K = (mv ^{2})/2. As long as magnetic field changes experienced by a particle are small during the course of one gyration about the magnetic field, μ is conserved for particles undergoing electric and magnetic drifts perpendicular to **B** and motion parallel to **B**. This is important because it generally means that particles' energies increase (decrease) when particles undergo a drift across magnetic field lines into regions of increasing (decreasing) B. On the other hand, motion along magnetic field lines results in a conversion of parallel energy to (from) perpendicular energy as B increases (decreases) with the total particle energy being conserved.

When we think of the plasma as whole, we deal with macroscopic variables that are defined per unit volume. We consider the forces acting on the plasma per unit volume, which we write as:

(2) $$\rho d\mathbf{V}/dt = -\nabla P + \mathbf{J} \times \mathbf{B}$$

where ρ is the total plasma mass per unit volume, **V** is the mass averaged velocity for all particles within a unit volume, P is the plasma pressure, and **J** is the current density (current per unit area normal to the current). Equation (2) assumes charge neutrality (essentially equal numbers of positive and negative charges), an assumption which is nearly always valid for space plasmas, and neglects gravity, an assumption which is valid for most space plasmas (neglect of gravity is not valid, for example, near the sun).

When plasma and field changes are small in the direction of **B**, (2) can be rewritten using the Maxwell equation

(3) $$\mathbf{J} = \nabla \times \mathbf{B}/\mu_o - \varepsilon_o \partial \mathbf{E}/\partial t$$

to obtain

(4) $$\rho d\mathbf{V}/dt = -\nabla(P + B^2/2\mu_o).$$

Here the constants $\mu_o = 4\pi \times 10^{-7}$ Henry/m and $\varepsilon_o = 8.85 \times 10^{-12}$ Farads/m, and the term $\varepsilon_o \partial \mathbf{E}/\partial t$ in (3) was been neglected in (4) because it is small for the large-scale phenomena discussed here. Assuming steady state and no changes in the direction of **V**, (4) becomes:

(5) $$P + B^2/2\mu_o = \text{constant}$$

Equation (5) is referred to as pressure balance and is usually applied to regions, such as the geomagnetic tail, where changes in the direction of **B** are small. $B^2/2\mu_o$ can be thought of as magnetic pressure, so that (5) states that the total pressure (plasma + magnetic) is constant. This tells us, for example, that the magnetic pressure in the lobes, where plasma pressure is low, is greater than the magnetic pressure in the plasma sheet, where the plasma pressure is high.

Equation (3), with $\varepsilon_o \partial \mathbf{E}/\partial t$ neglected, relates currents and magnetic field structure. For example, it tells us that a change in magnetic field strength ΔB across a plane perpendicular to **B** must be associated with a current within the plane across which **B** changes. Such a planar current is referred to as a current sheet and has a magnitude per unit distance normal to the current direction of $I = \Delta B/\mu_o$ A/m. For the magnetospheric tail, this current is directed in the dawn-to dusk direction across the tail and is referred to as the cross-tail current sheet (see Figure 1)

III. Solar Wind and Interplanetary Magnetic Field

The sun is a large ball of gas held together by its own gravity. The gases are about 90% hydrogen and 10% helium with minor amounts of other constituents. Due to the high temperature of the sun, the solar gases are mostly ionized. The sun appears to have a visible surface because the steep radial gradient in solar density gives a sharp transition between lower regions, where photons are absorbed and remitted by solar gases without traveling very far, and higher regions, where most photons move away from the sun along straight trajectories without collisions. Solar radiation appears to arise from this narrow transition region (only a few hundred km thick), which is referred to as the photosphere.

Solar gases extend outward well beyond the photosphere with very high temperatures, forming what is referred known as the solar corona. The solar corona is sufficiently hot that many coronal particles have outward directed velocities with a magnitude that exceeds the speed for gravitational escape from the sun. Such particles stream outward from the sun forming what is known as the solar wind. The solar wind escapes towards the near vacuum of interstellar space at supersonic speeds, filling the entire solar system with coronal plasma.

A. General structure

If it were not for the solar magnetic field, the escaping plasma from the solar corona would form an approximately spherically symmetric solar wind flowing radially outward from the sun at ~750 km/s. However, the escaping plasma is strongly affected by the magnetic field of the sun because of the tendency for particles to more easily move along magnetic field lines than across them. The solar magnetic field is highly variable, which makes the solar wind and the magnetic field it carries with it into interplanetary space highly variable in space and in time.

To a first approximation, the magnetic field near the visible solar surface can be regarded as a dipole like that of the Earth. This field is carried outward into interplanetary space from the sun by the solar wind, giving a solar magnetic field configuration (sketched in a plane perpendicular to the ecliptic plane in the upper panel of Figure 3) which is like a dipole near the sun, but is highly stretched away from the sun. At radial distances more than a few solar radii, the stretched solar magnetic reverses direction across a narrow region near the ecliptic plane forming a current sheet surrounding the sun. In the regions where the magnetic field lines are approximately dipolar and do not extend well away from the sun, plasma accumulates giving regions of high density coronal plasma as illustrated in Figure 3. Such regions are clearly visible in images of the solar corona. For the magnetic field configuration shown in the upper panel of Figure 3, a region of high density corona extends around the sun in the vicinity of the equator. Free escape of plasma only occurs well within the regions where magnetic field lines extent large distances into interplanetary space. There solar wind speed reach ~750 km/s. Near the boundaries between the approximately dipolar field lines and the field lines that extent out large distances, the solar wind escapes, but with a lower average speed of ~350 km/s. The Earth, which is near the ecliptic plane, is exposed more often to the this slow solar wind than to the fast solar that covers most of the region away from the ecliptic plane.

The magnetic field and solar wind flow configuration illustrated in the upper panel of Figure 3 corresponds to periods when the solar magnetic field is more dipolar than at other times. During such periods, which are referred to as solar minima, magnetic and sunspot activity on the sun is low. Solar minima occur every 11 years. After solar minimum, the dipolar magnetic field structure of the sun gradually is destroyed. This process takes a few years, leaving the solar magnetic field in a much more disorganized state as illustrated in a plane perpendicular to the ecliptic plane in the bottom panel of Figure 3. Magnetic and sunspot activity on the sun is high during these periods, which are referred as solar maxima. At solar maximum, localized regions of magnetic field lines that return to the solar surface without extending far into space and contain high coronal densities can occur over almost any portion of the sun. After solar maximum, the dipole field of the sun returns with the direction of the dipole reversed from what is was during the previous solar minimum. This gives an 11 year solar cycle from one solar minimum to the next, with the direction of the magnetic field reversing every cycle. While the solar cycle is 11 years, the total period for this magnetic field variation of the sun is 22 years.

B. Solar wind disturbances and their relation to solar magnetic structure

Both the dynamic pressure of the solar wind and the interplanetary magnetic field (IMF) are important for the interaction of the solar wind with the Earth's magnetosphere, and both of these are generally quite variable. In addition to a variety of wave phenomena, there are two types of large-scale disturbances of the solar wind plasma that are known to have large effects on the magnetosphere. The first type is related to the shape of the interplanetary current sheet. Rather than being precisely a disc within the ecliptic plane, the current sheet is generally titled somewhat with respect to the ecliptic plane and also has a wavy structure as function of azimuthal angle around the sun. Within azimuthal regions where the tilt and/or wavy structure displaces the current sheet sufficiently far from the ecliptic plane, fast solar wind can be emitted near the ecliptic plane. Due to the rotation of the sun (with an ~27 day period) locations near the ecliptic plane can thus be exposed to periods of slow solar wind followed by fast solar wind. This is illustrated in the ecliptic plane in the upper panel of Figure 4. In this plane, the solar rotation also imparts a spiral shape to magnetic field lines. Within azimuthal regions where fast solar wind follows slow wind, the fast solar wind will catch up with the slow solar wind. The interaction of the fast solar wind with the slow solar wind (referred to as "stream-stream interactions") causes a compression of the solar wind plasma and magnetic field within the interface region between the fast and slow streams. Such compressions give regions of greatly enhanced solar wind densities and magnetic field strengths which can significantly affect the magnetosphere. These stream-stream interactions are particularly important during the period after solar maximum, but before the next solar minimum, when the solar dipolar magnetic field is reforming.

The second large-scale disturbance of the solar wind plasma is associated with the localized high coronal density regions that form during solar maximum. These regions can become buoyant and break away from the sun, carrying the high density coronal plasma and associated magnetic fields radially away from the sun as illustrated in the bottom panel of Figure 4. These ejections of coronal material, referred to as "coronal mass ejections," can have dramatic affects on the Earth's magnetosphere.

As discussed later, the component of the IMF directed parallel to the Earth's magnetic dipole (which is directed from the northern polar cap to the southern polar cap), rather than the total interplanetary magnetic field magnitude, is most important for activity within the Earth's magnetosphere. This component of the magnetic field is referred to as the southward component. Thus the magnetic field enhancements associated with stream-stream interactions and coronal mass ejections most strongly affect the magnetosphere when the enhanced magnetic field happens to be directed southward.

IV Solar Wind and Interplanetary Field Interactions with the Geomagnetic Field

A. The magnetopause

The solar wind can be generally viewed as highly conducting, so that to a first approximation the interplanetary and geomagnetic fields do not mix. This requires that the solar wind be diverted around a cavity that has an outer boundary which approximately separates the geomagnetic and interplanetary fields. This boundary is referred as the magnetopause, which is a current sheet of appropriate intensity to separate the interplanetary and geomagnetic fields.

The location of the magnetopause can be estimated by balancing the dynamic pressure of the incoming solar wind ($n_{sw}m_pV_{sw}^2$, where n_{sw} is the solar wind density, m_p is the proton mass, and V_{sw} is the solar wind speed) with the pressure of the geomagnetic field, giving:

$$n_{sw}m_pV_{sw}^2\cos^2\psi = B_{in}^2/2\mu_o \quad (6)$$

This neglects the interplanetary magnetic pressure, which is generally a reasonable assumption. In (6), B_{in} is the magnetic field just inside the magnetopause, ψ is the angle between the solar wind velocity vector and the normal to the magnetopause, and the pressure of the IMF and of the magnetospheric plasma are neglected. For typical solar wind parameters ($n_{sw} = 5 \times 10^6$ m^{-3}; $V_{sw} = 400$ km/s), and a dipole geomagnetic field, (6) places the noon, equatorial magnetopause (a location referred to as the "nose" of the magnetosphere) at a distance $r = 10\ R_E$ from the center of the Earth, which agrees very well with its average observed position. (The Earth's dipole field strength is $3.1 \times 10^{-5}/r^3$ T. However, twice this value is typically used for B_{in} in equation (6) in order to included contributions from the magnetopause current). Equation (6) also shows that the location of the magnetopause moves further from the Earth with increasing distance from the nose. This is because $\cos^2\psi$ decreases away from the nose so that B_{in} must also decrease.

If only the Earth's dipole field and the magnetic fields of the magnetopause current sheet were included, the magnetopause would not extend significantly tailward of the Earth, and there would not be a magnetospheric tail. However, the large plasma pressures of the tail plasma sheet form the cross-tail current sheet which is identified in Figure 1, and the magnetic field of this current allows the tail magnetopause to extend up to several hundred R_E away from the Earth in the anti-sunward direction.

On the dayside, B_{in} varies as r^{-3}. With this variation, equation (6) shows that the distance to the dayside magnetopause is proportional to $(n_{sw})^{1/6}$. Solar wind densities can be quite variable, and a large solar wind disturbance can increase n_{sw} to ~50×10^6 m^{-3}. A disturbance of this magnitude compresses the magnetosphere significantly, and brings the nose of the magnetosphere to $r < 7\ R_E$, which is well earthward of its average position. Such an earthward displacement of the magnetopause corresponds to more than factor of three increase in the magnitude of the magnetopause current. This illustrates one important way in which the solar wind disturbances in the previous section can cause large dynamic changes to the Earth's magnetosphere.

B. Closed and open field lines

The above pressure calculation, with the inclusion of the Earth's dipole magnetic field and of the magnetic fields from the magnetopause and cross-tail current sheets, gives an accurate description of the shape of the magnetosphere, which is illustrated in Figure 1. Because the calculation assumes that the interplanetary and geomagnetic fields do not mix, the calculation gives geomagnetic and interplanetary magnetic fields that are parallel to the magnetopause at all locations directly adjacent to the magnetopause. However, this is not strictly valid because the magnetopause current sheet has large, but finite, conductivity, which allows a small portion (~10-20%) of the IMF to cross the magnetopause and connect with the geomagnetic field. Such penetration of the IMF into the magnetosphere connects the interplanetary and geomagnetic fields and is critical to magnetospheric dynamics, though it does not significantly affect the shape of the magnetosphere.

The connection of the interplanetary and geomagnetic fields is illustrated in Figure 1 for an IMF that is directed primarily southward (i.e., nearly parallel to the Earth's magnetic dipole). The figure shows how the penetration of a small portion of the interplanetary field into the magnetosphere modifies the geometry of magnetic field lines emanating from the polar regions of the Earth. Without a penetrating field, all magnetic field lines would leave the Earth and return to the Earth after crossing the equatorial plane. Such field lines are referred to as "closed". With a penetrating field, closed magnetic field lines do not extent all the way to the magnetic pole. Instead there is an approximately circular region centered near each magnetic pole where field lines across the magnetopause and enter interplanetary space. Such polar-cap field lines are referred to as "open". For the Earth, the boundary between open and closed field lines is at ~73° magnetic latitude. Open field lines allow for a tapping of energy directly from the flowing solar wind plasma, and such energy drives a wide variety of phenomena within the magnetosphere.

C. Mapping of interplanetary electric field into the magnetosphere

The solar wind flows radially outward from the sun carrying the IMF with it. In general the magnetic field is not parallel to the solar wind so that there is an electric field in interplanetary space that is related to the solar wind and IMF by

$$\mathbf{E} = -\mathbf{V}_{SW} \times \mathbf{B} \quad (7)$$

Since particles can move easily along magnetic field lines, it is generally appropriate to assume that magnetic field lines are so highly conducting that there can be no electric fields parallel to the magnetic field lines. This assumption implies that magnetic field lines are equipotentials so that the interplanetary electric field given by (7) maps along open polar-cap field lines through the magnetosphere down to the ionosphere. (The ionosphere is a region of ionized upper-atmospheric constituents that surrounds the Earth at altitudes between ~75 and ~500 km altitude. For the purposes here, the ionosphere is at the low-altitude ends of the magnetic field lines shown in Figure 1 and marks the lowest altitude to which the interplanetary electric field has significant effects). For the orientation of the IMF shown in Figure 1, the mapping of the interplanetary electric field into the magnetosphere gives an electric field throughout the open field line region of the magnetosphere that points from the dawn side of the magnetosphere towards the dusk. For other orientations of the IMF, the mapping into the magnetosphere is similar, but the orientation of the electric field can have some differences from that shown in the Figure.

Figure 5 shows the mapping of the interplanetary electric field into the magnetosphere along open field lines in the dawn-dusk meridian plane, where the coordinate system used has x directed from the Earth to the Sun, y directed from the dawn to the dusk side of the Earth, and z directed from the south to the north magnetic pole. This mapping gives an anti-sunward flow of plasma all along the open field region of the polar caps. At the boundary between open and close magnetic field lines, the mapped interplanetary electric field and the anti-sunward flow terminate. This boundary thus becomes charged as indicated in Figure 5, giving an electric field that extends into the closed field line region of the magnetosphere. This electric field is oriented so as to give sunward flow on closed field lines. The coordinate system used in Figure 5 has

The total electric field pattern drives a three dimensional circulation of plasma, which is illustrated in the noon-midnight meridian plane in Figure 1. This flow is referred to as magnetospheric convection. The x- component of the flow is anti-sunward across open, polar cap field lines and the flow returns in the sunward direction within the closed field line region. The flow also moves poleward on the dayside and equatorward within the tail, completing the convective circulation. This magnetospheric convection pattern is often viewed by looking at the electric field, or equivalently the plasma flow since the two are related by equation (1), as mapped to the ionosphere. Such a mapping, illustrated in Figure 6, gives a complete picture of magnetospheric convection because magnetic field lines are approximately equipotentials. Figure 6 shows electric fields and plasma flow streamlines as seen looking down onto the ionosphere from above one of the polar caps. The figure shows how the flow moves in the anti-sunward direction over the polar caps, crosses the boundary between open and closed field lines, and returns to the dayside within the closed field line region.

The strength of magnetospheric electric fields and the resulting convection depends upon the magnitude of the interplanetary electric field, which varies with the magnitude of the y and z component of the IMF and with the solar wind speed. Generally, variations in the IMF are much greater than are variations of solar wind speed, so that variations in the IMF are generally more important in modifying the strength of convection. The efficiency of the mapping of the interplanetary electric field into the magnetosphere also depends significantly on the orientation of the IMF, the efficiency increasing as the orientation becomes increasingly southward (i.e., increasing towards the negative z direction). Thus variations in the z-component of the IMF when this component is negative (and thus anti-parallel to the equatorial magnetospheric field) have the largest effects on the strength of convection, though variations in the magnitude of the y component are also important.

V. Particle access to, and transport within, the magnetosphere

A. Access

Particles within the magnetosphere come from both the solar wind and from the ionosphere. While ionospheric particles make important contributions, the solar wind source is generally dominate throughout most regions of the magnetosphere.

The entry of solar wind particles and their transport to and within the tail plasma sheet is illustrated in Figure 7. Because the geomagnetic and interplanetary magnetic fields are connected, particles with a finite $v_{||}$ are able to flow across the magnetopause. This is most effective across the dayside magnetopause. There some of the solar wind particles, which have been heated after crossing the bow shock, cross the magnetopause and enter the portion of the open field line region that is near noon. These particles initially flow primarily along magnetic field lines towards the ionosphere, but they also drift slightly poleward across magnetic field lines due to the magnetospheric electric field. As the particles flow towards the ionosphere, the magnetic field strength strongly increases, so that conservation of μ requires that parallel energy is converted into perpendicular energy. For the vast majority of particles, all parallel energy is lost before the particles reach the ionosphere. The parallel component of velocity for these particles then reverses, and the particles move along field lines in the direction away from the Earth. At the same time, the particles also continue to move poleward due to the electric field drift across field lines. The reversal of the particles parallel velocity as they flow towards increasing B is referred to as “magnetic mirroring.”

B. Transport to and within the plasma sheet

After mirroring, these solar wind particles form a magnetospheric layer that lies adjacent to the magnetopause that is referred to as the "mantle". Mantle particles flow away form the Earth along open field lines of the magnetospheric tail. As they flow down the tail, the electric field across the tail causes them to also drift towards the plasma sheet. This causes a significant fraction of the particles to cross the boundary between open and closed magnetic field lines and enter the region of the distant plasma sheet. When they reach the cross-tail current sheet, they are significantly energized by the cross-tail electric field and become an important contributor to the energetic particle population of the plasma sheet. The particles are then carried earthward by electric field drift, gaining energy as they move earthward into regions of increasing magnetic field strength. This inward motion continues until the spatial variation in magnetic field becomes sufficiently strong to deflect the particles around the Earth towards the dayside portion of the plasma sheet, which is identified in Figure 1. This deflection forms the inner edge of the nightside plasma sheet, which typically lies at r ~5-12 R_E.

C. Formation of the radiation belts and stormtime ring current

The location of the inner edge of the plasma sheet depends on the strength of convection as well as on the strength of magnetic drift. As the strength of convection increases, particles are able to move closer to the Earth before being deflected around the Earth by magnetic drift. This lead to significant temporal variations in the location of the inner edge of the plasma sheet, a variation which is a very important component of geomagnetic activity. Occasionally, when there is a very large negative z-component of the IMF, convection becomes so strong that particles convect into the r ~2-5 R_E region of the magnetosphere before being deflected around the Earth. Particles that reach this region of high magnetic fields gain significantly more energy than normally occurs and cause significant increases in particle intensities in the region labels "radiation belts and ring current" in Figure 1. When the strength of convection reduces back to normal, particles left behind in the r ~ 2-5 R_E region begin to move in complete circles around the Earth and become part of the radiation belts. The current carried by these particles as they circle the Earth, ions in one direction and electrons in the other, increases with the number of energetic particles within this region. Periods when this ring current is sufficiently strong are referred to as magnetic "storms." The ring current during storms causes significant magnetic field changes on the surface of the Earth at low- and mid-latitudes, and these changes are the primary means by which storms are identified and monitored.

Particles also have access to the region of the ring current during periods of weaker convection as a result of fluctuations of the convection electric field. Resonant interactions between these fluctuations and the azimuthal drift of particles around the Earth gives small perturbations in the radial position of individual particles. The sum of many of these perturbations can viewed as diffusion in radial position, and the balance between this "radial diffusion" and particle losses (precipitation to the upper atmosphere and, for positive ions, charge exchange with neutral hydrogen which extends from the upper atmosphere into the region of the radiation belts) forms a permanent distribution of energetic particles within the radiation belts. The discovery of the radiation belts by James Van Allen and colleagues in 1958 using instrumentation onboard the first two successfully launched United States satellites received widespread national and international attention, and the radiation belts became popularly know as the Van Allen radiation belts.

VI. Aurora and auroral currents

Most visible aurora are formed by the precipitation of magnetospheric electrons into the atmosphere. Such aurora can be divided into two general classes. The first is diffuse aurora, which is formed primarily by the direct loss of electrons by precipitation into the atmosphere. Diffuse aurora tends to be broad in latitudinal extend and to not have strong spatial structure. Such aurora is thus generally visually unimpressive. Discrete aurora, on the other hand, results from the precipitation into the atmosphere of electrons which have been energized as they moved towards the ionosphere by electric fields aligned parallel to the magnetic field. The “field-aligned” electric fields responsible for this energization are associated with currents flowing upwards from the ionosphere to the magnetosphere. Discrete auroral displays can by intense and dynamic and are generally the most dramatic type of aurora.

Discrete aurora occurs because the magnetospheric electric field driven by the solar wind maps to the ionosphere, and the ionosphere is a good conductor of current. The relation between **E** and **V** given by (1), which would not allow for differential motion between electrons and ions within the horizontal plane of the ionosphere, only holds in the absence of collisions. In the lower regions of the ionosphere, between about ~100-150 km in altitude, collisions with atmospheric neutral constituents disrupt the electric field drift of ions but do not significantly disrupt the electric field drift of electrons. As a result, the mapping of magnetospheric electric fields to the ionosphere gives rise to currents in the horizontal plane of the ionosphere. These horizontal currents have components parallel and perpendicular to the applied electric field, which are referred to a Pedersen and Hall currents, respectively. Hall currents generally flow along closed paths within the ionosphere and are responsible for significant magnetic perturbations on the ground that are observable from within the auroral oval and the polar caps. Pedersen currents, on the other hand, generally have regions of strong convergence and divergence. Because of the requirement for current continuity, regions of convergence (divergence) of horizontal ionospheric currents are connected to currents that flow along magnetic field lines to (from) the magnetosphere from (to) the ionosphere. These field-aligned currents are an important aspect of coupling that occurs between the magnetosphere and the ionosphere, and they are important for the formation of the auroral arcs.

Large-scale coupling between the magnetosphere and ionosphere that leads to significant field-aligned currents is illustrated by the heavy filled arrows in Figure 5. The arrows parallel to the Earth’s surface indicates ionospheric Pedersen currents flowing parallel to the direction of the ionospheric mapping of the magnetospheric electric field. These currents converge on the dusk side of the polar cap regions of open field lines and diverge on the dawn side of these regions. This gives a large-scale field-aligned current system which is upward on the dusk side and downward on the dawn side. This current system extends along the boundary between open and closed magnetic field lines to all local times, as indicated by the converging and diverging electric fields along the open-closed field line boundary in Figure 6. The field-aligned currents are upward where the ionospheric electric fields converge and the open-closed field line boundary is negatively charged and downward where the ionospheric electric fields diverge and the boundary is positively charged. Another field-aligned current system lies near the inner edge of the plasma sheet. This current system is oppositely directed from the one near the open-closed field line boundary. There are also a variety of smaller-scale field-aligned currents, some of which occur within the nightside plasma sheet and are an important component of geomagnetic activity.

The field-aligned electric fields which are responsible for discrete auroras occur where the convergence of horizontal ionospheric currents gives rise to field-aligned currents flowing upwards out of the ionosphere that are too large to be carried by the precipitation of electrons that cause the diffuse aurora. The field-aligned electric fields enhance the upward field-aligned current by increasing the number of downgoing electrons which reach the upper atmosphere before mirroring. Field-aligned electric fields are generally less important in regions of downward field-aligned currents than in regions of upward field-aligned currents because downward currents can readily be carried by ionospheric electrons moving from the ionosphere to the magnetosphere. (The ionospheric ion contribution to upward field-aligned currents is generally not as large because the heavy mass of ions limits the rate at which ions can be extracted from the ionosphere.)

Most of the aurora within the auroral oval is diffuse aurora. Regions where upward field-aligned currents within the auroral become large enough for the development of discrete aurora include the large-scale upward-aligned currents that lie on the dusk side of the polar caps near the boundary between open and closed field lines. There is nearly always at least some discrete auroral activity along this boundary. Upward currents also become large enough for the formation of the discrete aurora within smaller-scale regions of the nightside plasma sheet in association with geomagnetic activity. The large-scale field aligned current system which lies near the inner edge of the plasma sheet is generally not sufficiently intense for the formation of very much discrete aurora.

VII. Geomagnetic disturbances

Transient enhancements of auroral emissions and ionospheric currents often occur within the auroral ovals and are good indicators of geomagnetic activity. These disturbances occur along magnetic field lines that extent to the plasma sheet, and they are observable at high latitudes via intense auroral activity and significant ground magnetic field perturbations associated with enhanced ionospheric currents. There are different types of such disturbances, having time scales ranging from a few minutes to an hour or so, and they occur within the ionospheric extension of the plasma sheet. Magnetic storms are a fundamentally different phenomenon from these disturbances within the auroral oval. They occur when fluxes of energetic particles within the region of the radiation belts cause a significantly enhanced ring current, leading to magnetic field depressions at the Earth's surface at latitudes equatorward of the auroral oval. Auroral oval disturbances often occur during magnetic storms, but they are not directly related to the injection of particles into the radiation belts that leads to the formation of the stormtime ring current.

Auroral oval disturbances are related to the energy and dynamics of the plasma sheet, which are highly variable and depend strongly on the solar wind dynamic pressure and the IMF. Solar wind dynamic pressure exerts control by compressing the entire magnetosphere, including the tail plasma sheet. The IMF affects the plasma sheet by controlling the strength of convection. The strength of convection strongly affects both the heating of particles within the cross-tail current sheet and the earthward penetration of the plasma sheet. When convection is enhanced, the inner edge of the plasma sheet moves earthward. This corresponds to an equatorward motion of the equatorward boundary of the plasma sheet as mapped to the ionosphere. This leads to an increase in the latitudinal width of the ionospheric mapping of then plasma sheet, and thus to an increase in the latitudinal width of the auroral oval. In addition, significant enhancement and earthward penetration of the cross-tail current occurs when convection is enhanced.

Three different types of auroral oval disturbances have now been identified that are related to large-scale disturbances of the magnetosphere-ionosphere system: poleward boundary intensifications (PBIs), substorms, and effects of solar wind dynamic pressure enhancements referred to here as “dynamic pressure disturbances”. Each of these types of disturbance has unique characteristics and reflects distinctly different physical processes occurring within the magnetosphere. The signatures of each within the auroral oval are illustrated in Figure 8. In that figure, lightly shaded regions indicate regions of undisturbed auroral emissions, darkly shaded regions indicate regions with strong discrete aurora, and regions with medium shading indicate regions of enhanced diffuse aurora which may contained some discrete auroral features.

A. Poleward boundary intensifications

The most common type of auroral-zone disturbance is the PBI. PBIs occur repetitively with a period on the order of 10 min. They can occur independently from other types of disturbances, though their intensity and frequency of occurrence tends to increase with the strength of convection. They have an auroral signature that often can be seen to move equatorward from the poleward boundary of the auroral oval, which, on the nightside, lies very near the boundary between open and closed fields. There can be several such disturbances within the nightside auroral oval at one time, disturbances typically occurring from near dusk to a hour or two past midnight. They also extend varying distances through the auroral oval, some staying confined to very near the polar cap boundary and others extending through a large portion of the auroral oval and becoming elongated in the north-south direction. PBIs are typically associated with ground magnetic perturbations of a few tens of nT, but perturbations can be as high as ~500 nT during periods of strongly enhanced convection. The time scale for individual intensifications is typically a few minutes.

Individual PBIs are longitudinally localized and are associated with longitudinally localized bursts (~few min in duration) of enhanced plasma flow that are often observed within the tail plasma sheet. Such flow bursts transport significant mass and energy within the plasma sheet and are thus an important component of the dynamics of the plasma sheet. The flow bursts extend only a small distance across the tail. They lead to enhance auroral emissions because they are associated via equation (1) with localized enhancements in electric fields across the tail. The mapping of these electric fields to the ionosphere results in longitudinally localized regions of enhanced dawn-to-dusk directed electric fields, which on their western edge, give rise to converging Pedersen currents. These converging ionospheric currents are connected to upward field-aligned currents which are often sufficiently strong to lead to the formation of the discrete auroral forms which are observed as PBIs. Sometimes individual PBI structures observed at low altitudes traverse essentially the entire latitudinal extent of the plasma sheet, which would correspond to flow bursts that extend from the distant tail plasma sheet (~50-100 R_E) all the way to the vicinity of synchronous orbit.

B. Substorms

Substorms are a far more dramatic and large-scale, but far less common, disturbance than PBIs. The substorm occurrence rate is highly variable, but here are typically several per day. Auroral activity during substorms typically initiates within a ~1-2 hr in local time sector near the equatorward boundary of the nightside auroral oval and then expands both poleward and azimuthally. Very intense discrete aurora lies along the poleward and westward boundaries of this expanding region. The poleward expansion can bring strong aurora well into the region which is normally occupied by the polar cap, forming what is known as the auroral “bulge”. The westward expanding region of strong discrete aurora is referred as the “westward traveling surge” and can continue for up to ~30 min after the substorm onset. Ground magnetic disturbances associated with substorms are typically a few hundred nT, but can range from ~50 nT to ~2000 nT.

Substorm onsets are preceded by a $\gtrsim 30$ min growth-phase period of enhanced convection that is typically associated with a moderate to large southward directed IMF. The onsets are often associated with the impact on the magnetosphere of an IMF change, such as a reduction in the southward component of the IMF, that cause a reduction in the strength of convection. During the growth phase, the plasma sheet moves earthward and particle energization increases leading to an increase in the cross-tail current. This increase is particularly strong within the earthward portion of the plasma sheet. In addition to being associated with auroral activity, the expansion phase is associated with a reduction in strength of the cross-tail current and a displacement of the inner edge of the plasma sheet and the cross-tail current away from the Earth, and thus with a large release energy from the inner portion edge of the plasma sheet.

The reduction of cross-tail current during a substorm is initially localized and does not extend across a large distance of the tail. As with the auroral at low-altitudes, the current reduction region expands azimuthally within the plasma sheet with time after substorm onset. The edges of the current reduction region are connected to field-aligned currents extending to the ionosphere. These currents are upward and large on the dusk side of the current-reduction region. The large upward currents connect along magnetic field lines to the strong discrete aurora that forms the westward traveling surge, and their azimuthal motion within the plasma sheet corresponds to the westward motion of the surge.

While it is know that many substorms occur in response to IMF driven reductions in the strength of convection, and thus can be viewed as being triggered by appropriate IMF changes, the extent to which substorms results from such convection reductions has not yet been determined. There are currently various ideas of how substorms might result from a large-scale, internal instability of the plasma sheet during periods of steady, enhanced convection. It is known that substorm are infrequent during periods of steady enhanced convection. However, it has not yet been determined whether or not substorms are absent during such periods. If they are absent, then the idea of substorm onset by internal instability will have to be discarded. If not, then it will be necessary to determine why some substorms require appropriate IMF changes and some do not.

C. Dynamic pressure disturbances

It has recently been found that enhancements in solar wind dynamic pressure increases can cause large auroral zone disturbances during periods of strong magnetospheric convection. Dynamic pressure enhancements affect the entire auroral zone simultaneously (unlike substorms and PBIs). Within a few minutes of the time an enhancement in dynamic pressure hits the magnetopause, the poleward boundary of the auroral oval moves poleward and the intensity of auroral emissions increases throughout essentially the entire auroral oval. The equatorward boundary of the oval is not significantly affected, so that the latitudinal width of the auroral oval increases. Most of the increase in auroral intensity is in the diffuse aurora, but increases in discrete aurora most likely also occur. The enhancement in diffuse auroral emissions results from the heating of the plasma sheet plasma as the entire magnetosphere is compressed by the increase in solar wind dynamic pressure. The poleward motion of the poleward boundary of oval can be as much as 10° in latitude, which corresponds to a large broadening of the auroral oval. It also corresponds to a large reduction in the area of open, polar-cap magnetic field lines, since, except near local noon, the poleward boundary of the oval lies at the boundary between open and closed field lines.

Dynamic pressure enhancements compress the entire magnetosphere and enhance the entire magnetospheric current system. As discusses in Section IVA, increases in the current within the dayside magnetopause can be over a factor of three. It is also know that the global field-aligned current system that lies along the open-closed field-line boundary, the ionospheric current system driven by magnetospheric convection, and the cross-tail current significantly increase in response to enhancements in solar wind dynamic pressure. However, the relationship between the full magnetospheric current system and the solar wind dynamic pressure is not currently well understood. The cause of the large reduction in the area of the polar cap driven by increases in solar wind dynamic pressure is also not yet well understood, but it is likely related to the large enhancements in magnetospheric currents.

VII. Conclusions

The interaction of the interplanetary plasma with the magnetic field of the Earth has only been studied in detail since the beginning of the Space Age in the late 1950's. With the use of ground measurements of ionospheric phenomena and limited point measurements from spacecraft within the solar wind and the magnetosphere, much is now understood about how this the interaction leads to the interesting features and dynamics of the magnetosphere-ionosphere system. This is a remarkable accomplishment. However, much remains to be learned. We do not yet have a full observational description of the magnetosphere in the absence of disturbances or of the various disturbances which occur within the magnetosphere-ionosphere system. We are also far away from being able to make quantitatively accurate predictions of how the magnetosphere responds to the highly variable solar wind and IMF which impacts the magnetosphere. Only with continuing observational programs, extensive analysis of existing and future data sets, and innovative theory and modeling studies, will a far more quantitative understanding of the Space Plasma Physics of the Earth's environment become possible.

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Fig. 1. Schematic illustration of the magnetosphere in the noon-midnight meridian plane

Fig. 2 The motion of electrons and positive ions in uniform and constant electric and magnetic fields.

Fig. 3 Sketch of coronal magnetic field and plasma structure during solar minimum (upper panel) and solar maximum (solar panel).

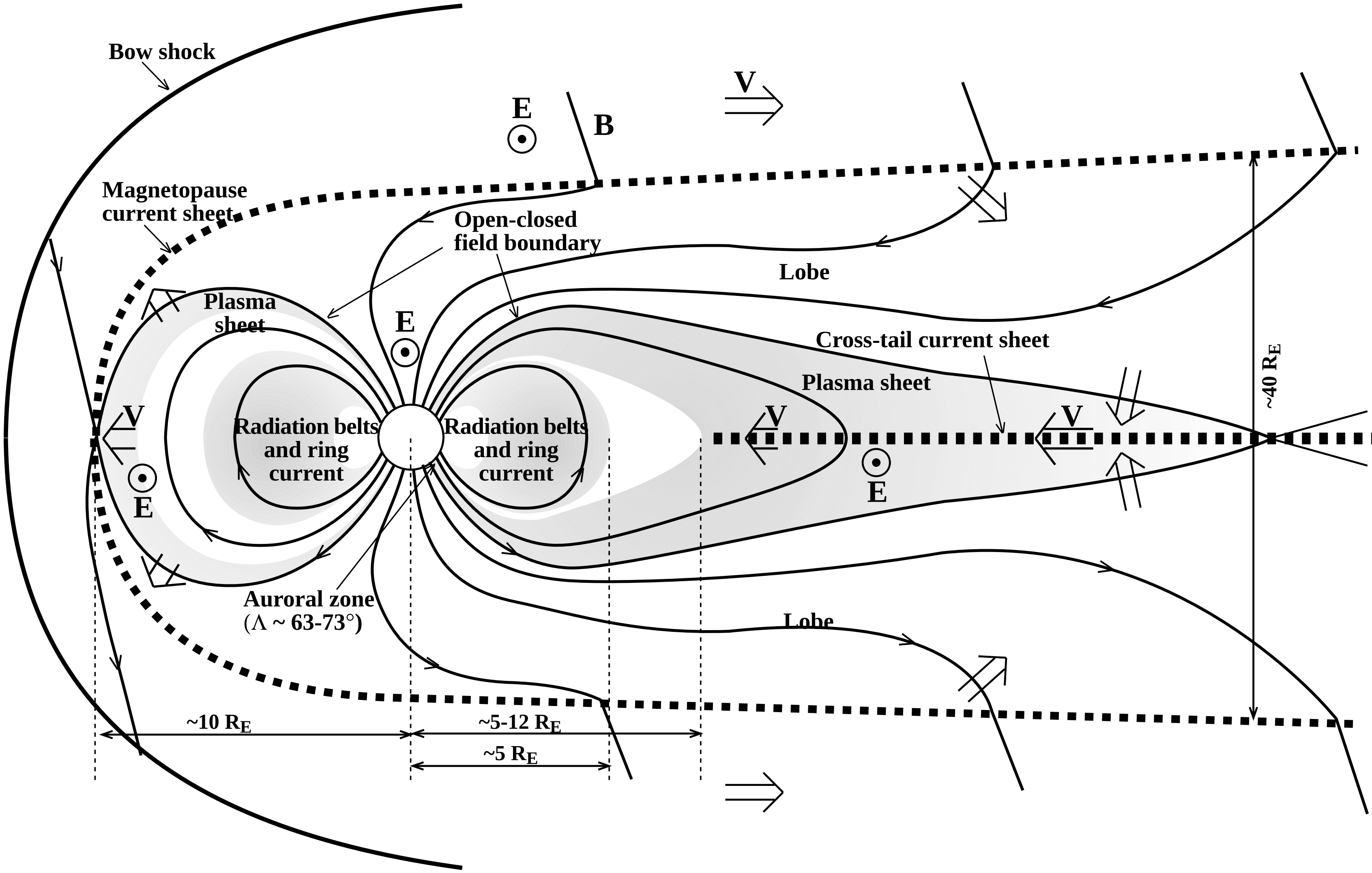
Fig. 4 Sketch of two important large-scale disturbances of the solar wind plasma, stream-stream interactions (upper panel) and coronal mass ejections (lower panel).

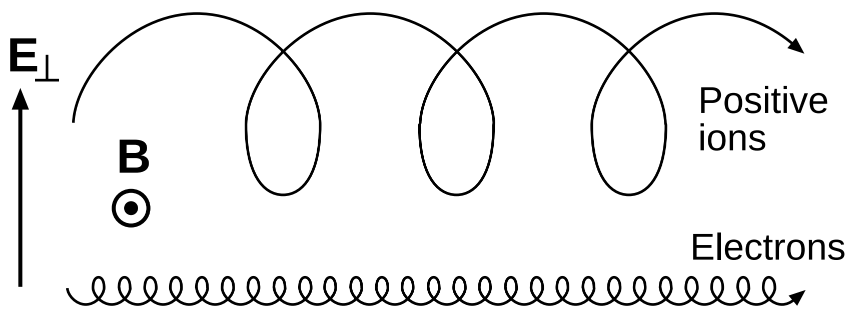
Fig. 5. Schematic illustration of the magnetosphere in the dawn-dusk meridian plane. Plus and minus signs indicate charges along the boundary between open and closed magnetic field lines, and shading identifies the region of open, polar-cap field lines.

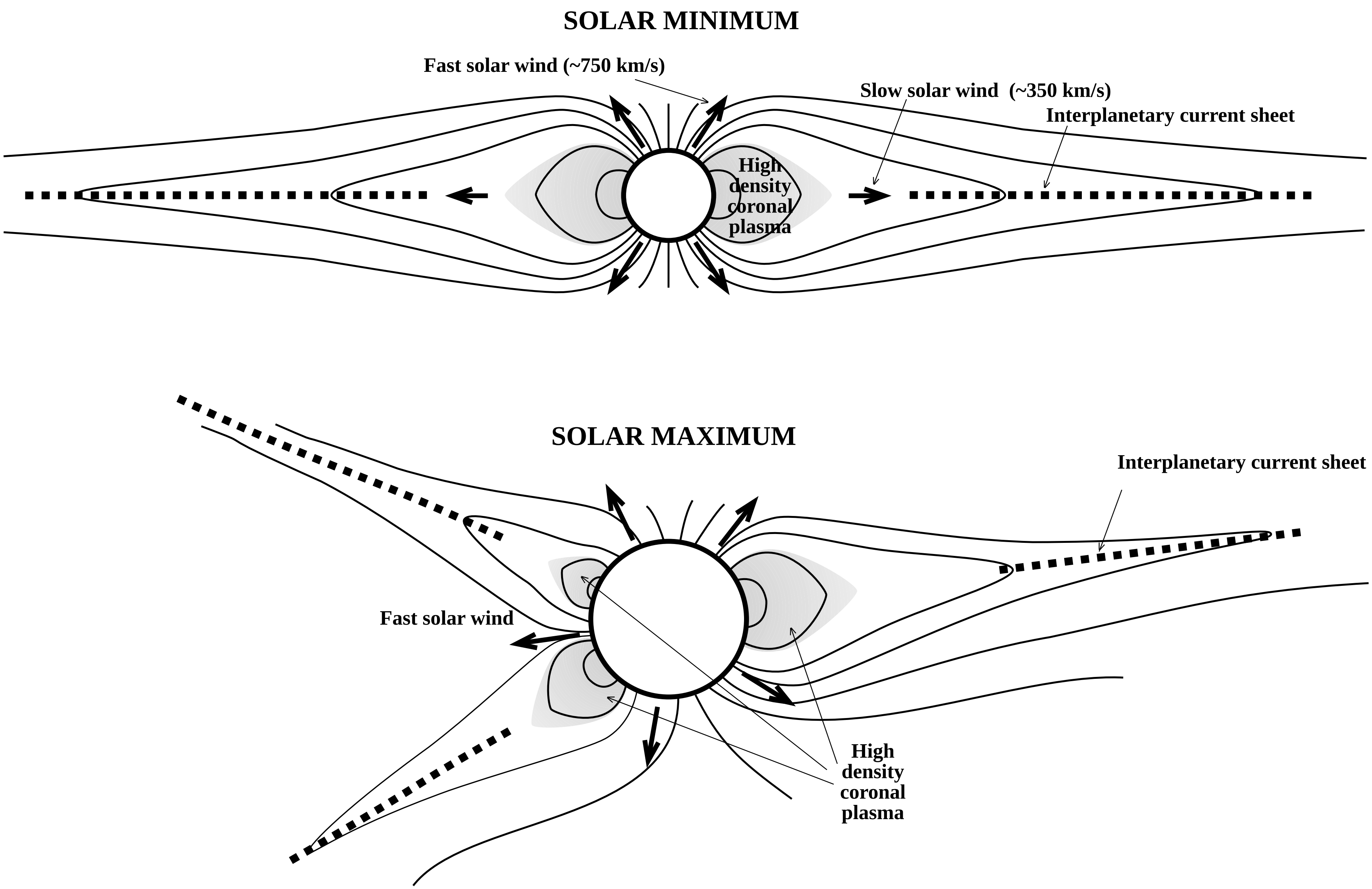
Fig. 6. Electric fields and plasma flows driven by the mapping of the interplanetary electric field into the magnetosphere as seen looking down onto the ionosphere from above one of the polar caps.

Fig. 7. Illustration of the entry of solar wind particles into the magnetosphere and their transport to and within the tail plasma sheet .

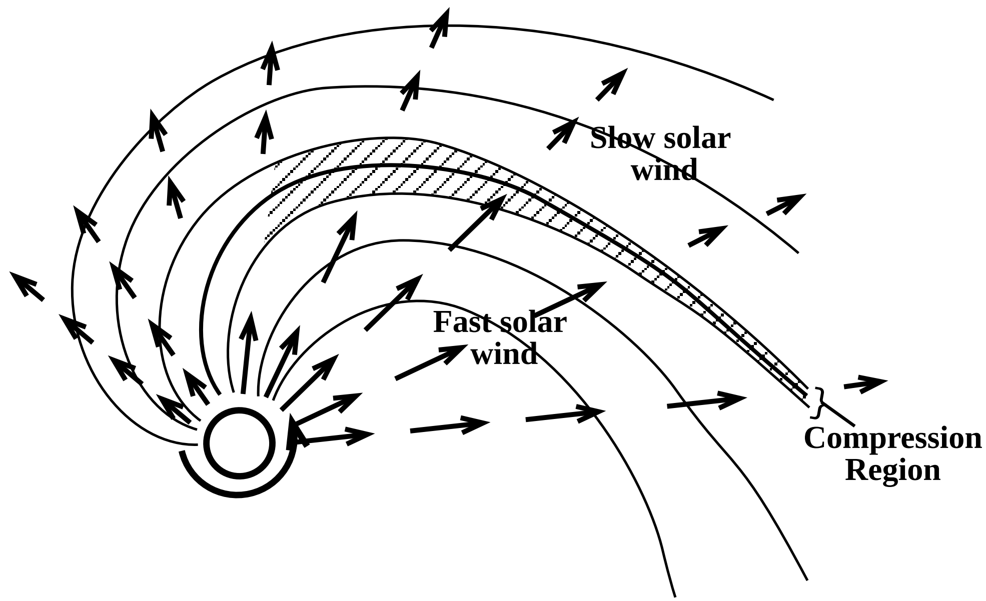
Fig. 8. Illustration of the auroral oval signatures of the three different types of auroral oval disturbance discussed in the text.


Bow shock
Magnetopause current sheet
Plasma sheet
Open-closed field boundary
E
B
V
Lobe
Cross-tail current sheet
Plasma sheet
Radiation belts and ring current
Radiation belts and ring current
Auroral zone
(Λ ~ 63-73°)
~40 R_E
~10 R_E
~5-12 R_E
~5 R_E

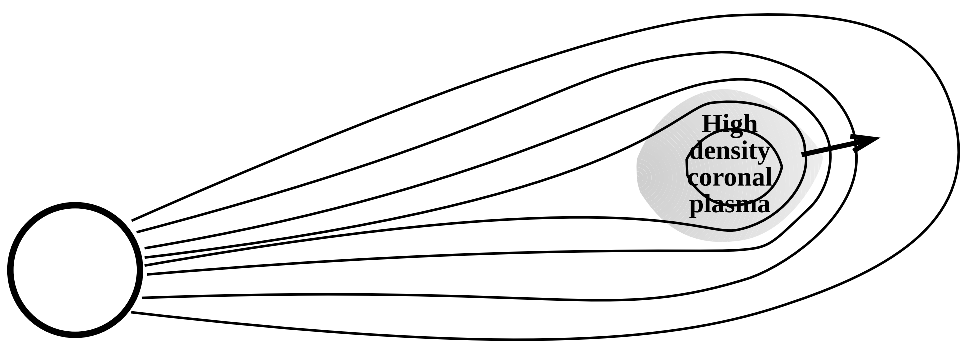

$E_\perp$
B
Positive ions
Electrons

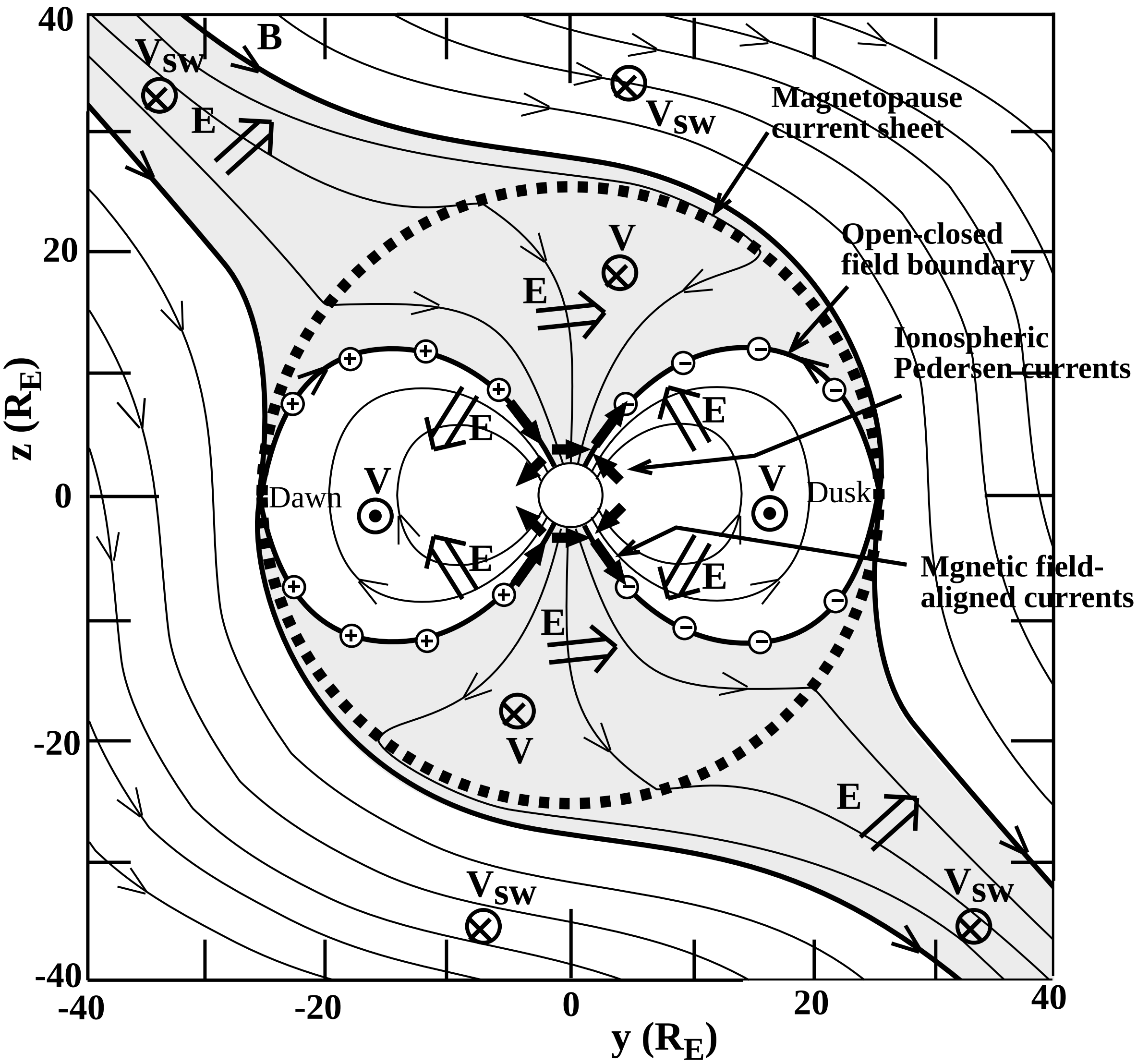

SOLAR MINIMUM
Fast solar wind (~750 km/s)
Slow solar wind (~350 km/s)
Interplanetary current sheet
High density coronal plasma
SOLAR MAXIMUM
Interplanetary current sheet
Fast solar wind
High density coronal plasma

STREAM-STREAM INTERACTION

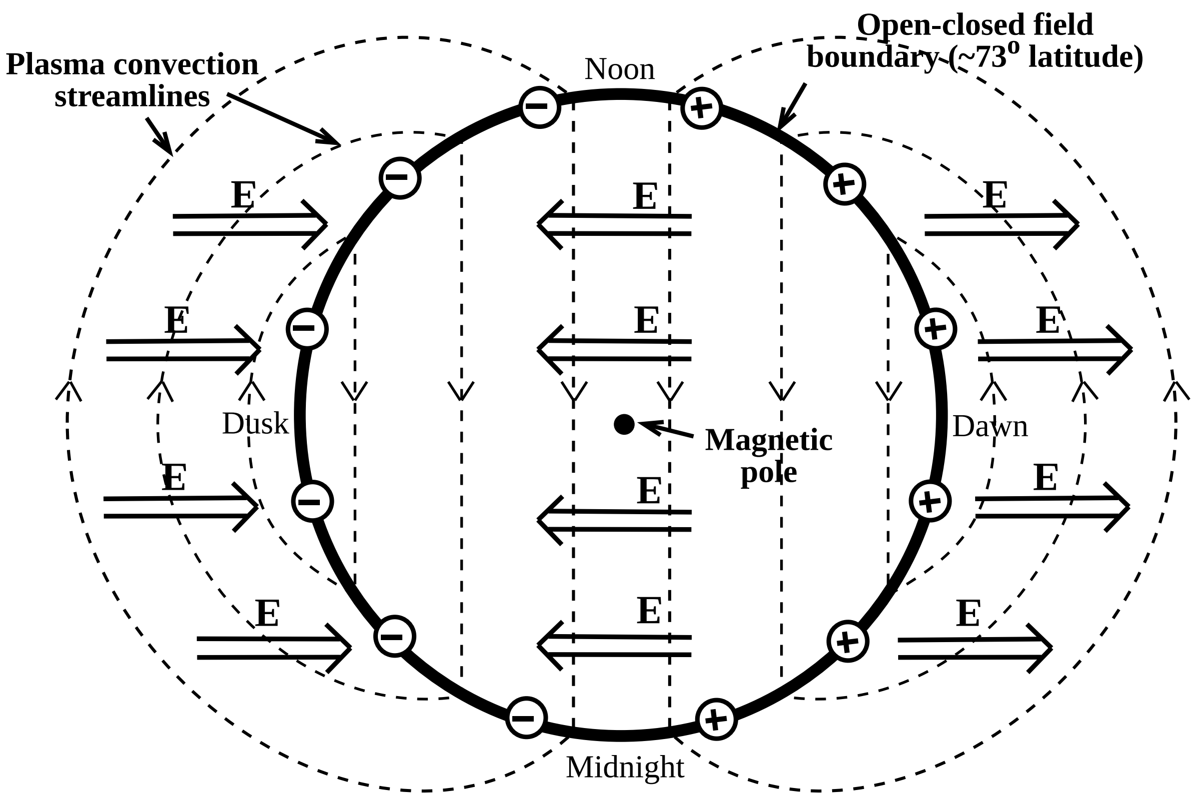


CORONAL MASS INJECTION

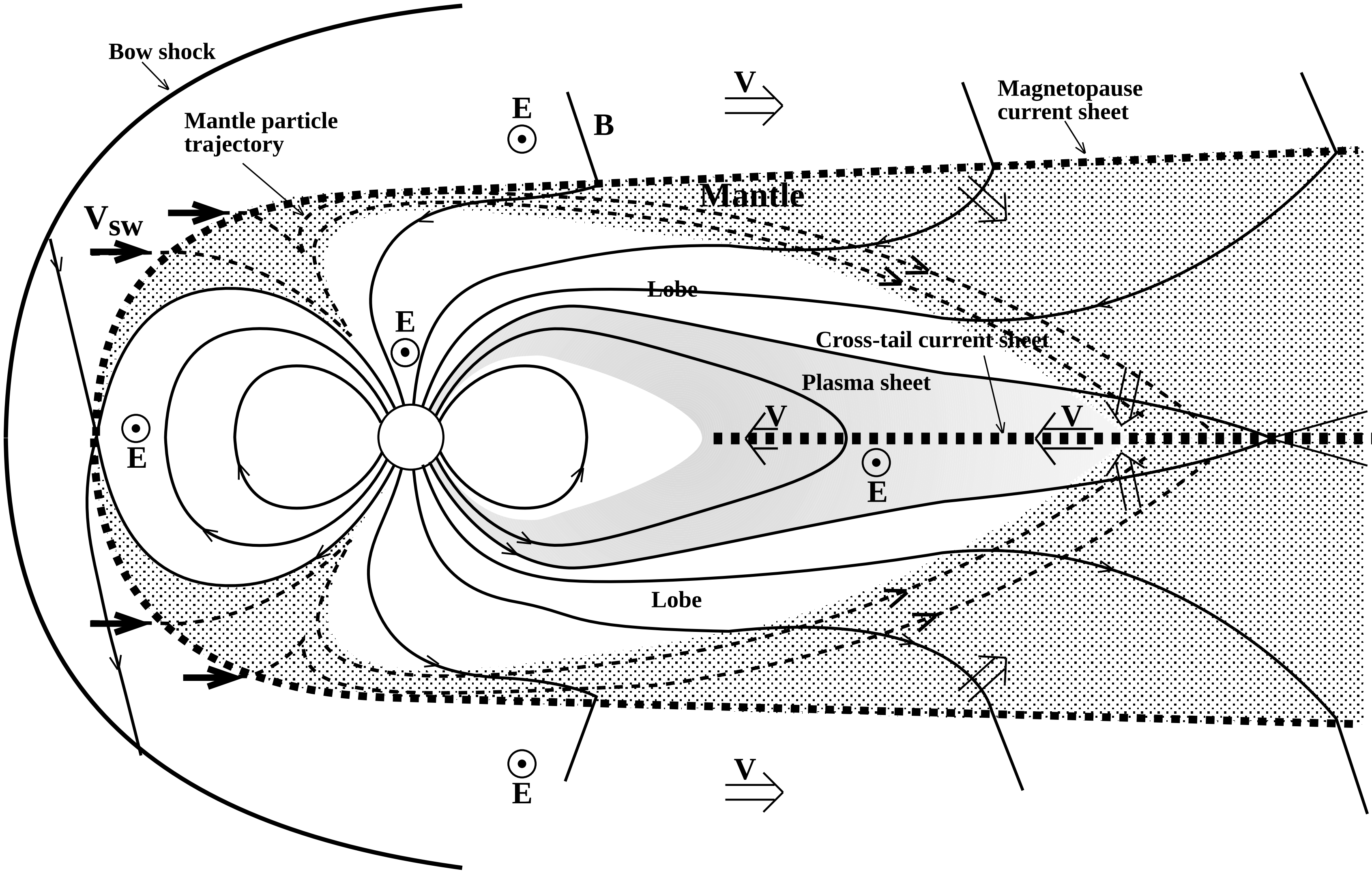




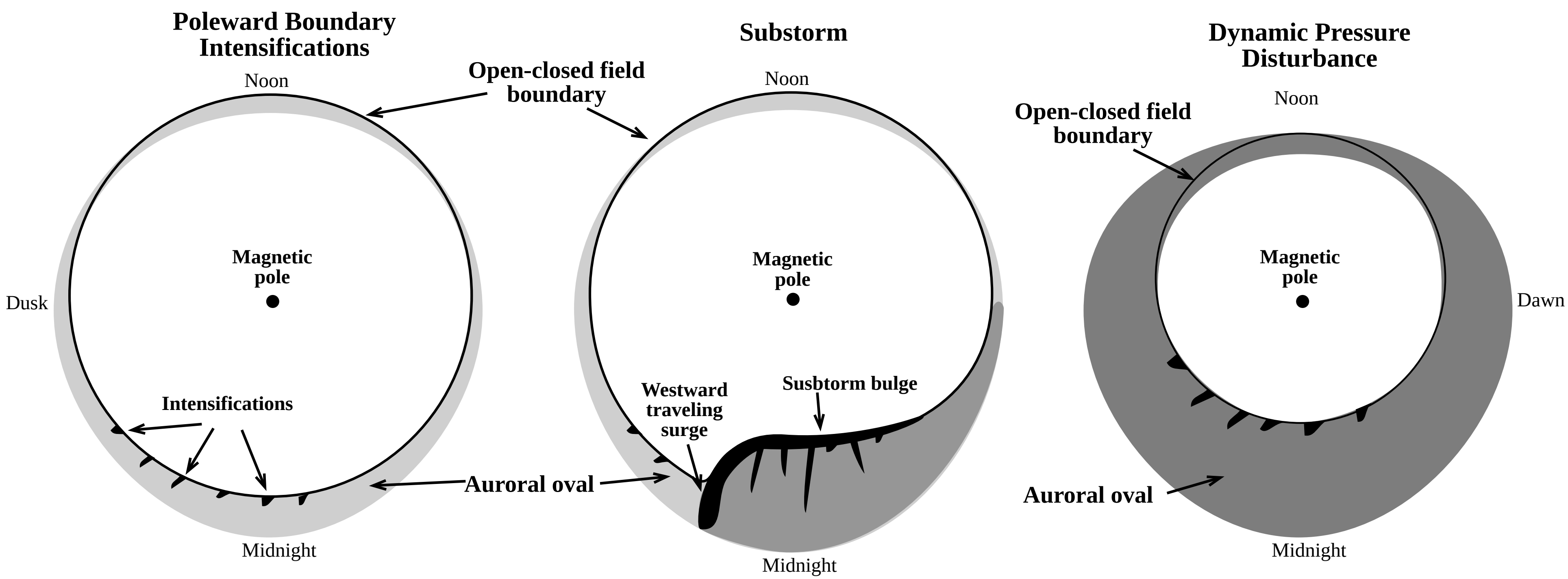
40
20
0
-20
-40
-40
-20
0
20
40
z (R_E)
y (R_E)
B
Vsw
E
Vsw
Magnetopause
current sheet
V
E
Open-closed
field boundary
Ionospheric
Pedersen currents
E
E
V
Dawn
Dusk
V
E
E
E
Mgnetic field-
aligned currents
E
V
E
Vsw
Vsw



Plasma convection
streamlines
Open-closed field
boundary (~73^0 latitude)
Noon
E
E
E
E
E
E
E
E
E
E
E
E
Dusk
Dawn
Magnetic
pole
Midnight



Bow shock
Mantle particle
trajectory
E
B
V
Magnetopause
current sheet
Mantle
V_{sw}
Lobe
E
Cross-tail current sheet
Plasma sheet
V
V
E
E
Lobe
E
V


Poleward Boundary
Intensifications
Noon
Open-closed field
boundary
Magnetic
pole
Dusk
Intensifications
Auroral oval
Midnight
Substorm
Noon
Magnetic
pole
Westward
traveling
surge
Susbtorm bulge
Midnight
Dynamic Pressure
Disturbance
Open-closed field
boundary
Noon
Magnetic
pole
Dawn
Auroral oval
Midnight