3 The Magnetosphere

3-1 Formation of the Magnetosphere and Magnetospheric Plasma Regime

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The Earth's magnetosphere is formed by the plasma flow from the Sun; i.e. solar wind. This solar wind particle can enter the magnetosphere through non-MHD processes and produces specific regions of plasma. This is due to the convection motion seen in the magnetosphere. An enhancement of the magnetospheric convection causes storms and substorms in the magnetosphere. Highly energetic particles can be produced through very efficient acceleration processes during the storms. In this paper we describe the fundamental physics of the magnetosphere, aiming a transition of researches to the Space Weather forecast.

Keywords
Magnetosphere, Plasma, Magnetospheric convection, Storms and substorms, Energetic particles

1 Outline of the Formation of the Magnetosphere and the Magnetospheric Plasma Structure

The magnetosphere is a distinct region in space surrounding the Earth, and its structure has been the subject of numerous detailed satellite observations. Fig.1 shows a representation of this structure, with the upper front quarter removed to show the interior. The Earth is at the center, and the solar wind flows from left to right. The front (dayside) of the magnetosphere is compressed, while the nightside is stretched, forming the tail of the magnetosphere (magnetotail). First let us define the names of the magnetospheric components. The magnetosphere is the region inside the magnetopause. The wide structure on the north and south sides of the equatorial plane is referred to as the lobe. Here, the magnetic field lines extending from the polar regions of the Earth are stretched toward the nightside. The magnetic field lines are earthward in the northern hemisphere and tailward in the southern hemisphere.

There is an influx of solar wind plasma particles in the lobe region. The area of the lobe near the magnetopause is referred to as the mantle. The magnetic field intensity is low near the equatorial plane, where the northern and southern lobes meet. Hot plasma accumulates in this region, referred to as the plasma sheet. Characteristic plasma regimes are present near the Earth, with plasma with higher energies relative to the plasma sheet. These regimes surrounding the Earth form the ring current that causes magnetic storms; these regimes also form the Van Allen radiation belts. Near the Earth, upward diffused ionospheric plasma forms the plasmasphere. The plasmasphere has a clear external boundary referred to as the plasmapause.

The plasma regimes studied in this paper consist of: (1) the boundary layer, featuring particles resembling those in the solar wind; (2) the plasma sheet, consisting of medium-energy particles (several keV); (3) the inner magnetosphere, consisting of high-energy particles (> 10 keV); and (4) the plasmasphere, consisting of cold plasma. When grouped according to plasma origin, (1), (2), and (3) are plasmas originating in the solar wind, and generally, particles nearer the Earth have higher energies. In contrast, (4) is plasma originating from the Earth. These regimes are not completely isolated from each other; they coexist and interact.

The followings are the terms used in this paper in the explanation of magnetospheric physics. As seen from the Earth, the magnetosphere on the sunward side is referred to as the dayside magnetosphere, and the opposite side is referred to as the nightside magnetosphere. Similarly, we will use the terms "dawn" and "dusk" sectors. Fig.1 shows the magnetosphere as seen from the dusk sector. The characteristic feature of the nightside magnetosphere is the tail, which is elongated over a great distance; this structure is referred to as the magnetotail.

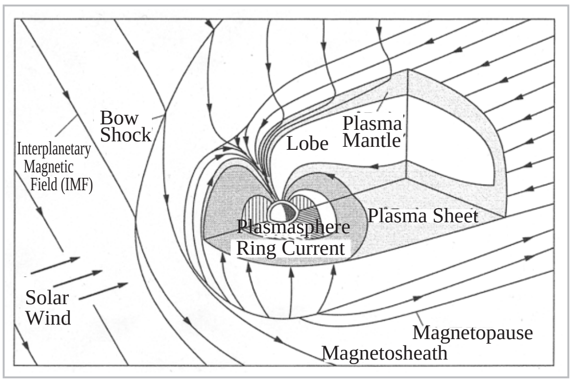

Fig.1 Structure of the Earth's magnetosphere

2 Influx of Solar Wind Particles and External Plasma Regimes

2.1 Magnetosheath Particles

The solar wind is a supersonic flow. The Earth moves through the solar wind plasma at supersonic speeds, in a system moving within the solar wind. The effects of deceleration and compression of the solar wind as it collides with the magnetosphere cannot be transmitted at sonic velocities to the upstream regions of the solar wind, and thus, a shock structure is formed. Such shocks, on the exterior of magnetopause, have been confirmed through satellite observations. These shocks are referred to as the bow shock, due to the overall structure's similarity to waves created by the bows of ships.

The magnetosheath is the region between the bow shock and the magnetopause. The plasma in this region has properties similar to those of the solar wind plasma, but in this region the plasma is heated upon crossing the bow shock. The plasma flow inside the magnetosheath is slightly slower than the solar wind velocity, and on the whole, this flow is deflected along the magnetopause surface. Simulations have been conducted on the direction of the solar wind magnetic field in the magnetosheath based on gas-dynamic theory and on MHD (magnetohydrodynamics), and the models have been found to be consistent with observations.

2.2 Magnetopause Region

When the supersonic plasma flow from the sun (solar wind) collides with the geomagnetic field, its front (dayside) region is compressed, and a clear boundary is formed. The solar wind dynamic pressure and the magnetospheric magnetic pressure are balanced at this plane, which is referred to as the magnetopause. The distance from the center of the Earth to the magnetopause is approximately 11 Re (Radius of Earth). When the solar wind dynamic pressure increases, the magnetopause comes closer to the Earth.

To conduct a 3-D simulation of the magnetopause, it is necessary to estimate the precise pressure distribution in the solar wind. The solar wind essentially circumvents the Earth. Detailed estimations were made of the stress perpendicular and parallel to the magnetopause surface, and the results of these estimations are shown in Fig.2. Two interesting structures can be observed to the north and south. All magnetic field lines converge at a single point, where the magnetic field intensity is zero. This neutral point is referred to as the cusp. The cusp is important in driving the magnetospheric convection, as will be discussed in detail in a later section.

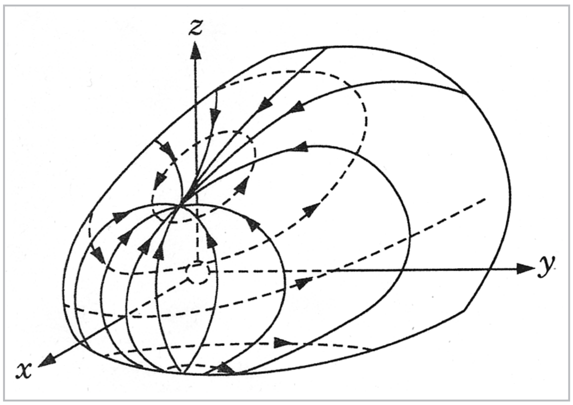

Fig.2 The 3-D structure of the magnetopause. Solid and dashed lines represent magnetic field lines and magnetopause currents, respectively. (Midgely, 1963)

The magnetosphere is a region usually shielded from solar wind particles. Most of the solar wind particles are deflected away from the Earth, but during a southward solar wind magnetic field, there is a large injection of energy into the magnetosphere. This theory met with wide attention when it was first proposed by Dungy (1963). As shown in Fig.3, when the solar wind magnetic field is oriented southward, reconnection of the magnetic field lines occurs in the dayside magnetopause. A terrestrial magnetic field line that has been connected to a solar wind magnetic field line becomes open and migrates downstream (to the nightside). The momentum of the solar wind enters the magnetosphere along with solar wind particles. In this manner, large amounts of both momentum and magnetic field flux accumulate in the nightside magnetosphere.

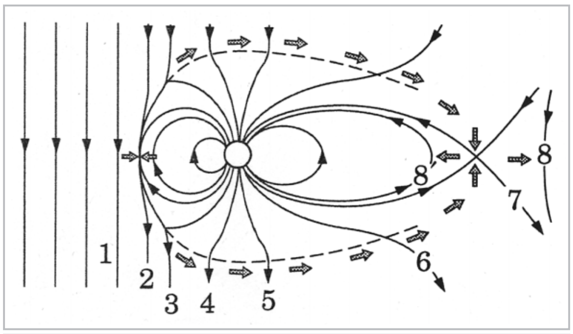

Fig.3 In the dayside magnetopause, the magnetic field lines are reconnected to interplanetary magnetic field (IMF) lines. Magnetic field lines migrate along the lines numbered 1—8

How do the reconnections of the magnetic field lines occur? Fig.4 shows a pair of magnetic field lines in the reverse directions positioned above and below a plane perpendicular to the page (a magnetic neutral plane). When they are pushed closer to each other, a current is generated at the boundary, in accordance with Ampere's law. This current is referred to as a neutral sheet current. If conductivity is assumed to be infinite, then a barrier of stronger current is created as the magnetic field lines approach each other, and the field lines remain isolated. However, if resistance is created somewhere on the neutral plane, then the energy of the magnetic field is consumed at that point. Magnetic field lines near the point migrate toward this point to compensate for the energy loss. In Fig.4(c), X repre-

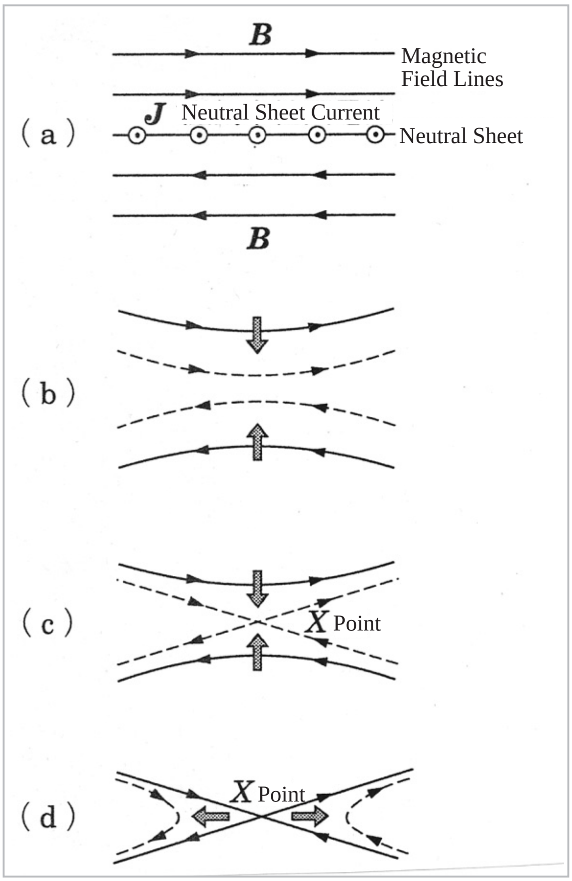

Fig.4 Schematic diagram of reconnection of magnetic field lines

sents the point at which magnetic field lines converge and are reconnected. Fig.4(d) shows the new pair of magnetic field lines resulting from the reconnection.

2.3 Cusp Particles

The high-latitude region of the dayside magnetosphere features a characteristic magnetic field configuration. This structure, called the cusp, is located at the boundary between the closed magnetic field lines on the dayside and the magnetic field lines that reconnect with the solar wind magnetic field and stream toward the tail. There is direct downward injection of solar wind plasma toward the Earth at the cusp region (solid black region in Fig.5(a)). The terrestrial end of the magnetic field line of the cusp region corresponds to the geomagnetic latitude of approximately 75° on the dayside.

Cusp particles have properties closely resembling magnetosheath particles, but they have the distinct characteristic of being accelerated downward along magnetic field lines. Satellite observations have confirmed precipitating electrons above the ionosphere experiencing an acceleration of approximately 100 V. Furthermore, results of rocket experiments have also confirmed episodic precipitation of electrons. The precipitating electrons have energy-dispersion structures (higher energy particles falling first), and detailed analysis has revealed that the region of electron injection is located near the equatorial region (reconnection region of magnetic field lines) in the dayside magnetosphere.

Satellites crossing the cusp in the south-north direction have observed ions drifting toward high-latitude regions as they precipitate. This phenomenon, where ions with lower precipitation energies drift to higher latitudes, can be explained by the presence of tailward convection in the polar cap (region surrounded by auroras).

2.4 Mantle Particles

As shown in Fig.5, the magnetosheath plasma penetrates into the lobes and creates a region referred to as the mantle. From Table 1, which lists the plasma parameters in each magnetospheric region, it can be seen that mantle plasma features density of approximately 0.01/cc, ion temperature of 300 eV, and electron temperature of 50 eV. Since the magnetic field intensity of the lobe is higher than that of the sheath, the β-value (ratio of particle energy to magnetic field energy) is approximately 0.003. A portion of the mantle plasma continues to migrate, and enters the plasma sheet.

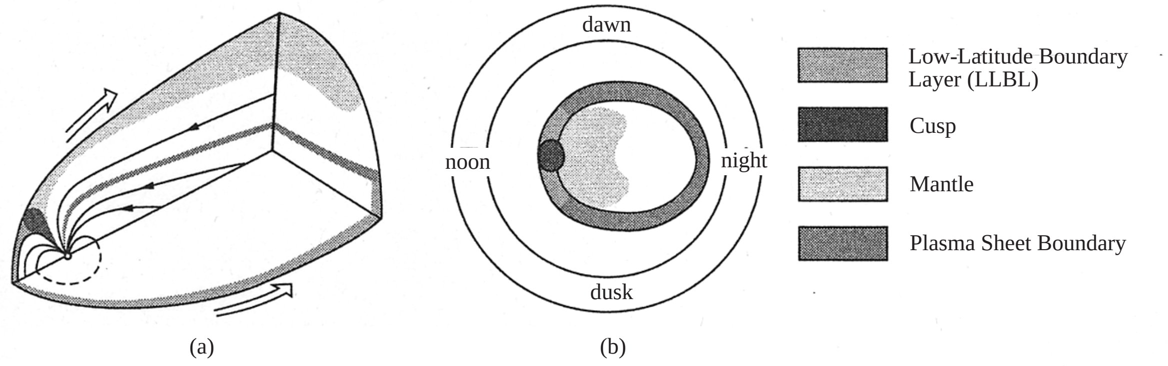

Fig.5 (a) Cross-section of the magnetosphere sliced at the meridian plane in the northern hemisphere and at the equatorial plane in the dusk sector. (b) Projection of each region onto the polar ionosphere.

Table 1 *Plasma Parameters for the Magnetospheric Regions*

	Magnetosheath	Lobe	Plasma Sheet Boundary	Central Plasma Sheet
Density [cm^{-3}]	8	0.01	0.1	0.3
Ion Temperature [eV]	150	300	1 000	4 200
Electron Temperature [eV]	25	50	150	600
β-value	2.5	0.003	0.1	6
Magnetic Field [nT]	15	20	20	10

2.5 Low-Latitude Boundary Layer (LLBL) Particles

The region labeled LLBL in Fig.5 represents the low-latitude boundary layer. A satellite crossing this region would observe an outer layer where solar wind plasma stretches the magnetic field lines tailward, and an inner layer where solar wind mixes with magnetosphere plasmas. There is virtually no flow in the inner layer, and plasma heating takes place. In contrast to the mantle, which does not have a clear boundary with the lobe, the LLBL does have a clear boundary. The LLBL projected onto the polar ionosphere is positioned at latitudes lower than the cusp, and extends over several hours both dawnward and duskward of the dayside. The ion temperature, which was approximately 100 eV at the magnetosheath, gradually increases within the LLBL and reaches 2 keV at the plasma sheet boundary.

The LLBL, with a typical radius of approximately 1 Re, is considered to arise out of the mixing of the plasma by the large wave that develops at the boundary formed by the velocity gradient between the fast flow outside this boundary and the stationary interior. This mixing process allows the influx of the solar wind plasma into the LLBL.

2.6 Polar Rain

In previous sections, magnetospheric phenomena were viewed from the perspective of the influx of solar wind plasma into the magnetosphere. Another such phenomenon is the polar rain, which is the precipitation of electrons in the polar cap (the region surrounded by auroras). Previous studies have identified the source of polar rain as the high-energy part in the solar wind (the strahl). Strahl electrons have energies of several hundred eV, and travel along the magnetic field lines propagating out from the sun. Past satellite observations have found that polar rain was present during away (or toward) IMF orientation in the northern (and in the southern) hemispheres. In terms of magnetic reconnection of the IMF and the geomagnetic field, in this case, the northern hemisphere magnetic field lines connect with field lines with sources in the Sun during away IMF orientations. This leads to the influx of strahl components, and thus to polar rain. In contrast, the magnetic field lines in the southern hemisphere are isolated from the solar field lines, and strahl components are not incorporated.

The above explanation corresponds to the state of southward IMF orientation. However, recent studies have revealed that electron precipitation in the polar cap occurs even during northward IMF. Electron precipitation in this case occurs in spike-like episodes, which is in sharp contrast to the extremely uniform precipitation of the polar rain. The precipitating electron spikes are slightly accelerated and, under closer observation, were found to generate auroras. These auroras are referred to as sun-aligned arcs (aurora lines directed toward the sun), and are believed to be precipitations of mantle particles that have entered the magnetosphere in the polar caps during northward

IMF. These precipitating electrons were previously referred to as polar showers. Their mechanism of generation has yet to be determined.

3 Magnetospheric Plasma Convection and Plasma Regime Formation

3.1 Circulation of Magnetic Field Lines

Let us return to Fig.3. The magnetic field line 2, which is completely reconnected in the dayside magnetopause, migrates tailward along with the solar wind to lines 3, 4, 5, and then to 6. As stated in the previous section, the solar wind plasma penetrates into the magnetosphere (mantle) and becomes the source of the plasma sheet particles; these will be described in a later section. An important process during the migration of the magnetic field lines occurs at line 7. The field lines approaching the equator from the northern lobe and from the southern lobe are in opposite directions, and these field lines undergo reconnection. As a result, one becomes completely closed and is directed earthwards (line 8'), while the other becomes completely open and is cut off in the tailward direction (line 8). The magnetotail field lines are stretched by the solar wind. When this force weakens or disappears, the magnetic field lines attempt to return to the original configuration. Thus, the magnetic field line 8' begins to migrate back toward the Earth due to magnetic field tension.

3.2 Plasma Sheet

The region near the equatorial plane in the magnetotail is a special region. Here, hot plasma forms a sheet referred to as the plasma sheet. The density of this region is lower than 1 /cc, but the mean ion and electron temperatures are several keV and several hundred eV, respectively. The total particle energy is approximately 3 keV/cc. This plasma sheet region has a weak magnetic field, and is almost magnetically neutral. The overall plasma pressure of the plasma sheet is in balance with the lobe magnetic pressure.

The plasma sheet has a clear boundary (plasma sheet boundary) due to the presence of X point at the magnetotail at approximately 120 Re (point of magnetic reconnection; Line 7 in Fig.3). The lobe magnetic field is open, allowing the outflow of solar wind plasma. In contrast, the plasma sheet magnetic field lines are closed, and so plasma that has entered will be trapped, resulting in increased plasma density. The plasma sheet pressure is higher near the center (equatorial plane). This pressure gradient creates a current in the plasma sheet. Since the magnetic field lines in the north and south lobes are in opposite directions, the plasma sheet currents are duskward. In the distant plasma sheet, the lobe magnetic pressure and the plasma pressure of the plasma sheet are balanced. In regions near the Earth, magnetic tension acts on the magnetic field lines of the plasma sheet in the earthward direction. In the X-direction (sun-earth direction), this is balanced with the plasma pressure gradient (∇p). Therefore, the pressure of the plasma sheet is higher near the Earth.

In Fig.3, the magnetic field line 8', which has reconnected in the far tail, begins to migrate earthward. Within the plasma sheet, an earthward flow is constantly present in response to the force acting to restore the original, stable dipole field. This flow can attain a velocity of several hundred km/s. This velocity is believed to be dependent upon the reconnection efficiency and the extent of stretching of the plasma sheet (degree of magnetotail current development). In light of previous discussions, it may be concluded that the plasma sheet flow represents a flow from regions of low plasma pressure to high plasma pressure. Tension acts like a pump, and through conversion of the magnetic energy to the internal energy of the plasma, a high-pressure region is produced in the internal plasma sheet.

3.3 Plasmasphere

The discovery of the plasmapause in 1965 confirmed the existence of a large-scale convection in the magnetosphere (Fig.3). The upper atmosphere of the Earth is ionized by solar ultraviolet radiation, forming the ionosphere. The ionized plasma diffuses upward against the Earth's gravity. This diffusion occurs over an extremely wide region around the Earth, but at a distance of approximately 4 Re, there is a sharp decrease in density. This is referred to as the plasmapause, and the region below it is the plasmasphere. Particles constituting the plasmasphere originate in the ionosphere, and have extremely low energies (several eV).

There are two components to plasma motion in the plasmasphere. One is the corotation driven by the rotational motion of the Earth, and the other is the sunward magnetospheric convection. Fig.6 is the result of particle-trajectory calculation on the equatorial plane based on these two motions, and the basic components of plasmasphere formation can be understood from this figure. In regions distant from the Earth, particles flow uniformly in the sunward direction. As the particles approach the Earth, their paths are changed, and a teardrop-shaped boundary plane (line) is formed, which separates the two types of particle trajectories. Trajectories outside the boundary are open, and connect with the magnetopause. On the other hand, on the earthward side, the trajectories are closed and the particles are trapped. This boundary is the plasmapause. There is a constant supply of plasma to the interior of the plasmasphere from the ionosphere, resulting in a high-density region. The plasma outside of the boundary flows out into the magnetopause, and thus, the density outside the plasmapause is low.

The actual shape of the plasmasphere is not a complete teardrop, due to the imperfect uniformity of the magnetospheric electric field (i.e., of the convection electric field). Several electric field models have been proposed to fit the actual shape of the plasmasphere, but all have protruding structures (referred to as bulges) on the dusk sector and a plasmapause structure that extend close to the Earth in the dawn sector. When there is a rapid increase in the magnetospheric electric field, the boundary plane shifts toward the Earth and the plasmasphere shrinks.

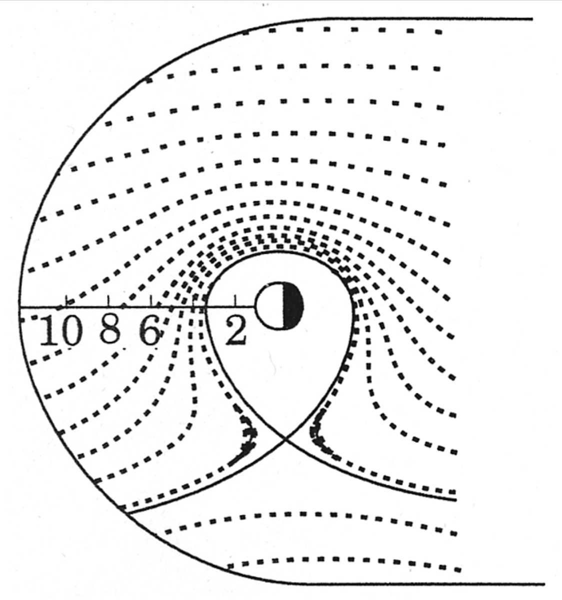

Fig.6 *Trajectories of zero-energy plasma particles on the equatorial plane of the magnetosphere.*
The magnetospheric convection electric field is assumed to be 0.3 mV/m in calculations.

4 Substorms

4.1 Variations in the Plasma Sheet

The plasma sheet sometimes experiences extreme thinning with time. During such thinning events, magnetic field lines become stretched even further on the nightside. Both the magnetic tension and plasma pressure increase, but then, at a certain point, there is a rapid relaxation, resulting in depolarization of the magnetic field and a decrease in plasma pressure. This represents a substorm triggering moment. "Substorm" is a historical term; today, it could more accurately be called an "auroral storm." When the solar wind magnetic field is oriented southward, magnetospheric convection is intensified. Expansion of the auroral oval and thinning of the plasma sheet accompany this event, resulting in an exceptional magnetotail. This is called the growth phase, and lasts for a limited time (approximately one hour) before the onset of the expansion phase. Here, there is a rapid brightening of the aurora, accompanied by a simultaneous generation of a fast, earthward flow within the plasma sheet as the magnetic field lines stretched by the plasma sheet attempt to return to their original state. After this, the plasma sheet thickens, and a cluster of plasma referred to as the plasmoid is ejected in the anti-sunward direction.

4.2 Substorm Theory

The study of substorms has a long history, but the basic issues regarding the triggering and the exact mechanism of substorms have yet to be sufficiently resolved. Recent developments in satellite observation and computer simulation have shed new light on substorm studies. Several ongoing studies are described below.

Current Disruption Model

There is an extreme stretching of the magnetic field in the nightside equatorial region of the magnetosphere. This distortion of the magnetic field is due to the duskward plasma sheet current on the equatorial plane, also called the magnetotail current. During substorms, the magnetotail current is disrupted and flows into the polar region of the Earth, and after circling the polar region and entering the dusk sector as a westward auroral current, returns back to the magnetic equatorial plane (Fig.7). This 3-dimensional current structure is referred to as the current wedge, and is approximately 70° wide with a radius of approximately 6 Re. The total current exceeds 1 million A. This model is known as the current disruption model, and attributes to the initiation of auroral explosion.

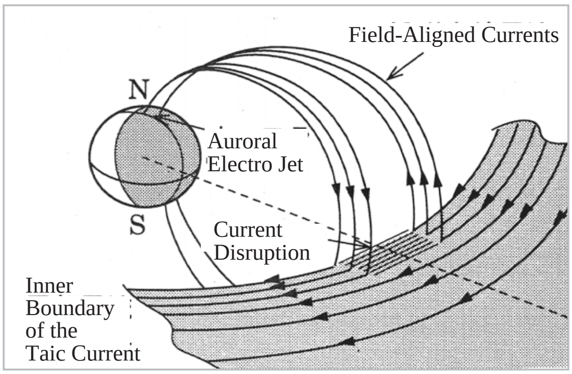

Fig.7 The magnetotail current structure during the substorm.
The duskward current in the equatorial region is disrupted and flows into the polar region (Clauer, 1974).

This explanation focuses on the observation that auroral explosions occur from the arc nearest to the equator, and is the model most consistent with observation results. However, it fails to provide a clear reason for the circumvention of the equatorial current. In this model, an abnormal increase in electrical resistance within the equatorial plasma sheet is thought to prevent current flow in the equatorial region and divert the current to the low resistance polar ionosphere. During current disruption, large oscillations of the magnetic field are observed, suggesting the existence of a process that cannot account for ideal MHD.

NENL Model

This model takes a different approach from the current disruption model. In this model, magnetic reconnection occurs near the Earth and creates a new X point, which then triggers a substorm. This X point is called the near-Earth neutral line (NENL), and has been confirmed by satellite observation to form on the nightside at distances exceeding 20 Re. The NENL not only ejects the plasmoid anti-earthward, but also generates a fast, earthward plasma flow. An auroral explosion is produced when this fast flow reaches the vicinity of the Earth. A magnetic field is carried along by this fast flow, causing depolarization of the magnetic field.

The sudden development of NENL is also a phenomenon that cannot account for ideal MHD. The NENL is an important basic element for triggering substorms, as the braking of the fast earthward plasma flow is thought to trigger substorms. The generation of velocity shear or vortices due to the deceleration near X = −10 Re may be the cause of current disruption in the magnetotail, although a theoretical explanation for this has yet to be provided.

State Transition Model

The stretched magnetotail is in a state of extreme tension, and attempts to return to the ground state; i.e., to the depolarized magnetic field. A change in topology (state transition) at a certain point in time corresponds to the substorm onset, and transition from the stretched state to the depolarized state takes place in the magnetosphere (Tanaka, 2000). This is known as the state transition model. Significantly, this model involves not only topological changes but also incorporates a change in convection structure. In this theory, the substorm onset is characterized by increased pressure and depolarization of the inner magnetosphere, induction of a fast, earthward flow in the plasma sheet near Earth, and the formation of NENL. In the substorm recovery phase, there is a thickening of the plasma sheet.

Other theories have suggested that substorms are triggered by deceleration of convection due to the northward turning of the solar wind magnetic field or that instabilities in the magnetosphere-ionosphere coupling trigger substorms. Recent theories of substorms are beginning to combine to form a unified scenario, but a comprehensive explanation has yet to be provided for the formation of NENL and the magnetotail current disruption.

4.3 Auroral Particles

The beginning of the space age in 1957 inaugurated significant progress in the studies of aurora-generating particles. Auroras can largely be divided into relatively bright auroras (corresponding to the curtain auroras seen from the ground) and diffuse auroras. The former is referred to as a discrete aurora, and the latter is known as a diffuse aurora. Fig.8 is a schematic diagram of the two types of aurora. On the dayside, there is a discrete aurora extending in the radial direction. On the nightside, curtain auroras are distributed straddling the pre-midnight sector. The diffuse auroras are characteristically bright on the midnight-dawn sector, but pale in the dusk sector.

Discrete auroras glow extremely brightly in regions of upward field-aligned current

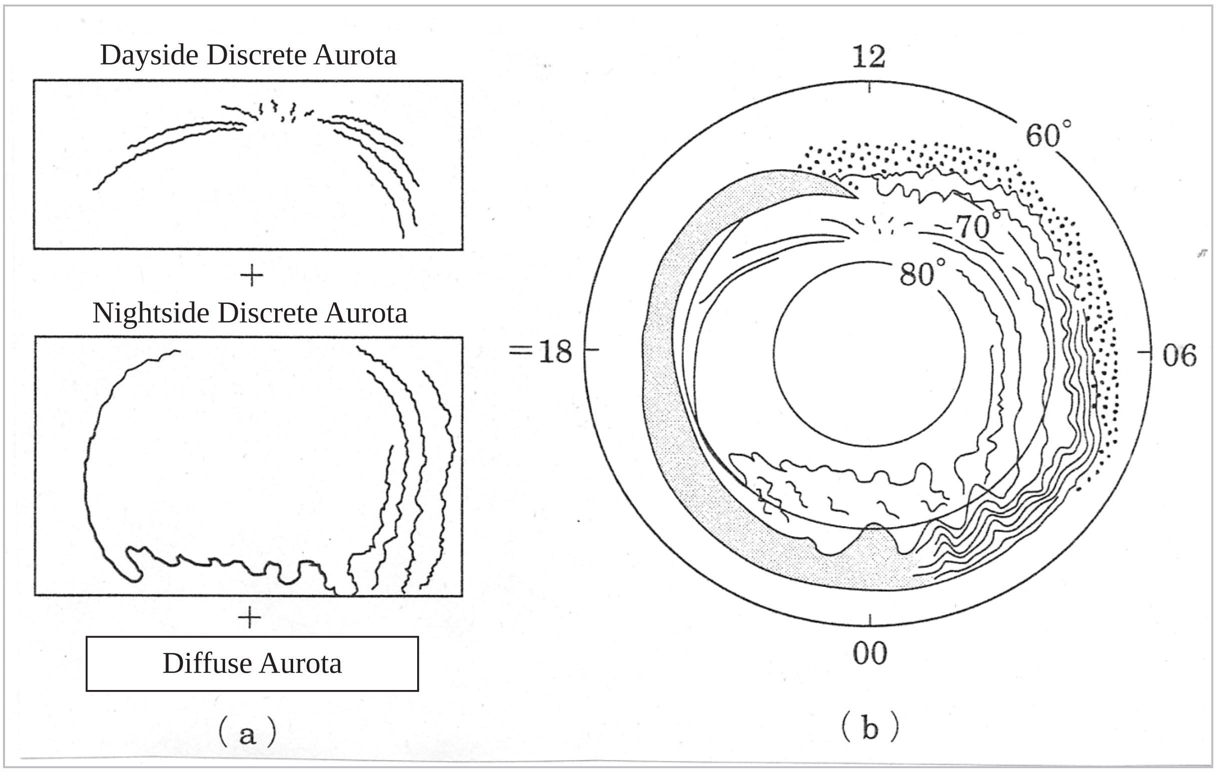

Fig.8 Discrete and diffuse auroras constituting the auroral oval

(FAC). In the upward FAC region, the magnetospheric electrons are the carriers of current, but due to low electron density, the current is maintained by electron acceleration. The acceleration may, in some cases, attain 10 kV. Detailed satellite observation studies have found that this acceleration occurs in an extremely limited area, referred to as the acceleration region. Fig.9 is a schematic diagram of this region. The vertical expanse of the acceleration region is approximately 100 km, and normally spans an altitude of 6,000 km, anywhere between 3,000 km and 12,000 km. This region is normally moving downward at 5-10 km/s. Strong radio waves are emitted from this strongly accelerated region, which are observed as Auroral Kilometric Radiation (AKR). In the right panel in Fig.9, the electric field in this region is represented by potential. As this region approaches the Earth, the potential increases, which in turn greatly accelerates the electrons on the magnetosphere side. These accelerated electrons penetrate the Earth's atmosphere and produce discrete auroras. The abnormal resistance model below has been proposed as the mechanism for the generation of electric fields aligned with the magnetic field lines. When the FAC exceeds a certain threshold value, instability is created and abnormal resistance is produced. This resistance then creates a field-aligned electric field, which accelerates the electrons. Some evidence for this mechanism of auroral electron acceleration has been provided by observation, but it has yet to be completely resolved.

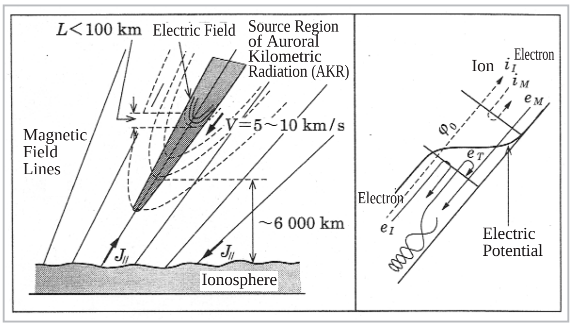

Fig.9 *State of the acceleration region of auroral particles (Left and right panels show the spatial distribution and potential of the electric field, respectively.) (Oya, 1984)*

In contrast, particles producing diffuse auroras have properties closely resembling plasma sheet particles (with Maxwell distribution with temperatures of several keV), and experience virtually no acceleration. Another characteristic of the diffuse aurora is the frequent presence of precipitating protons. The energy spectrum of the precipitating protons also follows the Maxwell distribution, with average energy around several keV, and the protons resemble plasma sheet particles observed near the Earth. This leads to the conclusion that the diffuse auroras, including proton auroras, precipitate from the central part of the plasma sheet. Pitch-angle scattering has been proposed as the mechanism of particle precipitation. A strong wave may cause large variations in the magnetic field intensity, causing the pitch angle change. Particles that enter the loss cone are precipitated along the magnetic field lines. Observation has provided some evidence to support this pitch-angle scattering.

5 Generation of High-Energy Particles

5.1 Geomagnetic Storms

A decrease in magnetic field intensity on a near-global scale was reported as early as the beginning of the 19th century by Humboldt. Fig.10 presents the Dst index calculated by averaging the data at four near-equatorial stations, along with data of the solar wind electric field and dynamic pressure. A negative Dst indicates decreased magnetic field intensity, and the onset of the main phase of the geomagnetic storm can be seen at 9:30 UT. The periods of decreasing and recovering magnetic field intensities are referred to as the main phase and the recovery phase of the geomagnetic storm, respectively. The main phase may last from several hours to a day, and the recovery phase may last as long as a few days. Geomagnetic storms are caused by an abnormal increase in the solar wind dynamic pressure and electric field. At 0:00 UT, there is an increase in the intensity of the geomagnetic field, corresponding to a state in which the magnetosphere is compressed by the dynamic pressure of the increased solar wind. This rapid increase in magnetic field intensity is referred to as a sudden commencement (SC), and the period between the start of SC and the main phase is known as the initial phase. The main phase is initiated by a sudden increase in the duskward (Ey) component of the solar wind electric field. The period of initial phase may vary from 0-24 hours or longer. This is dependent upon the timing of the southward turning of the solar wind magnetic field.

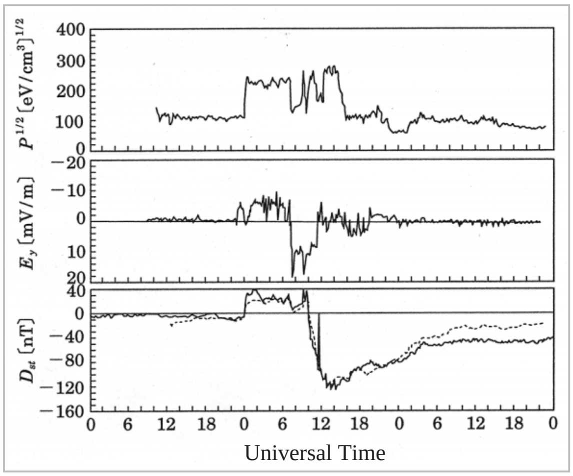

Fig.10 Example of a geomagnetic storm. From top to bottom, the panels represent solar wind dynamic pressure, solar wind electric field, and Dst index (Burton, 1975).

5.2 Ring Current

An increase of the electric current, circling the equatorial plane in the magnetosphere (referred to as ring current) causes geomagnetic storms. Particles carrying the current mainly consist of ions with energy of several tens of keV and, to a lesser degree, electrons with energy of around 10 keV. Many agree that the mechanism triggering geomagnetic storms is the enhancement of earthward plasma sheet convection by the large westward electric field, which injects high-energy particles into the near Earth regions. Fig.11 schematically shows how ions and electrons are transported to near-Earth regions from the plasma sheet. Trajectories of hot particles in the plasma sheet are significantly deflected by the magnetic field gradient as they approach the Earth, and positively-charged ions drift westward, while negatively-charged electious drift eastward. Both ions and electrons exist along the boundary plane (line) that separates the two types of trajectories; the plasma sheet plasma cannot penetrate the boundary. This penetration boundary is the Earthside plasma sheet boundary. The trajectories in the region within the boundary are closed (Fig.11). The particles with these closed trajectories generate the ring current that causes geomagnetic storms. Here, a mechanism is needed to push the plasma sheet particles across the boundary plane. Many researchers attribute this to temporal changes in the convection electric field. Results of simulations are beginning to reveal how particles are affected by the strong fluctuations of the electric field and are transported into the ring current region.

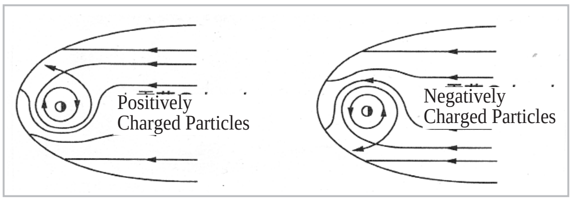

Fig.11 Drifting of positively and negatively charged particles in the magnetosphere. Positively charged ions approach the Earth in the dusk sector, and the electrons approach in the dawn sector.

Fig.12 shows the spatial distribution of high-energy particles that generate ring currents. The horizontal and vertical axes represent L-values and particle energy densities for 30-310 keV/q, respectively. The plotted points are grouped according to the scale of geomagnetic storms, and during large storms, particles feature energies approximately one order of magnitude higher than those in normal states. Observations have revealed that particles are distributed closer to the Earth in larger geomagnetic storms. The plasma motion is considered to be temporally moderate. In such cases, the pressure gradient is in balance with the J × B (electric current × magnetic field) force. As is evident from Fig.11, plasma pressure in the L > 3 region decreases with increased distance from the Earth. The generated ring current is westward since the geomagnetic field is northward. This is the current that causes the geomagnetic field intensity to decrease at the equator during geomagnetic storms. In regions of smaller L-values (L < 3), the pressure gradient is reversed, resulting in eastward currents. However, the overall scale of this current is much smaller than that of the above westward current, which dominates. As a result, the Dst index takes a negative value.

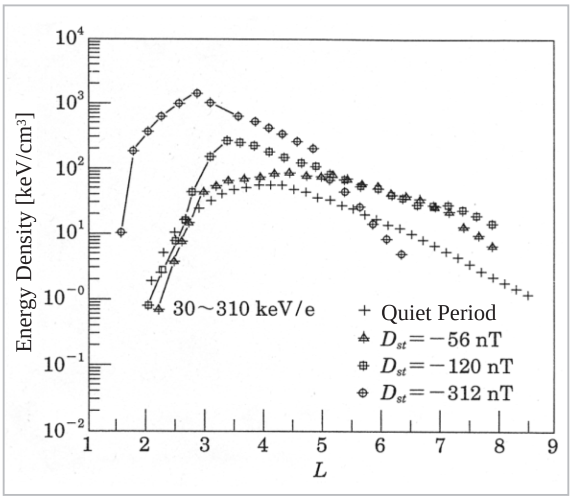

Fig.12 *Radial distribution of ions with energies of 30–300 keV/q. It is apparent that ions are distributed closer to Earth in larger geomagnetic storms (Chen et al., 1997).*

The particles (especially ions) injected into this region are unstable. They become rapidly extinct through charge exchange with neutral particles and electrons, and the geomagnetic storm ends (See Chapter 5).

5.3 Radiation Belt Particles

The Explorer III satellite, launched in 1958, revealed the double-peaked structure of the radiation belt. The region near the Earth, called the inner radiation belt, is mainly composed of high-energy (>50 MeV) protons. In contrast, the outer radiation belt, located further away from the Earth, is composed mainly of electrons with energy of > 1 MeV. Such electrons are also present in the inner belt, although there is a clear division in the electron distribution between the inner and outer belts. Large temporal variations are observed in the outer belt, and it is not rare to see variations of a few orders of magnitude. In particular, during geomagnetic storms, the flux of the outer belt electrons increases. Fig.12 shows an example for a period with several occurrences of geomagnetic storms. In each of these geomagnetic storms we note an increase in flux. In particular, at an L-value of 3-3.5, there is a remarkable increase during the April geomagnetic storm. The flux increases within 1-2 days, and then gradually decreases over the following two weeks at a moderate time constant.

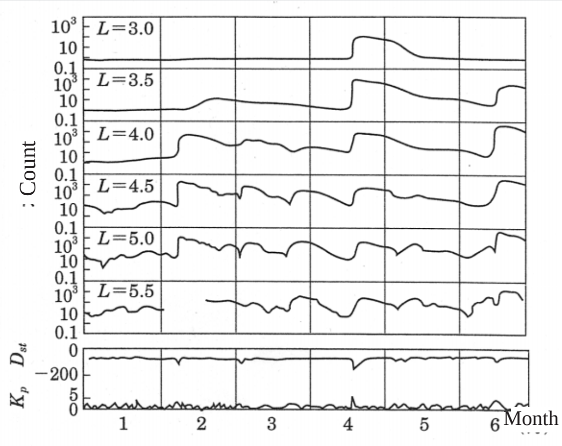

Fig.13 *Effect of geomagnetic storms on radiation belt electrons (> 1 MeV). Temporal variations in flux are presented at different distances from the Earth (Walt, 1994).*

Recent satellite observations have revealed some details of variations in the outer radiation belt. Fig.14 shows the temporal variations in the radiation belt electrons observed by the Akebono satellite. The horizontal and vertical axes represent time and L-value, respectively. The radiation electron fluxes are shown using color codes. The onset of the geomagnetic storm is at 23:00 UT on Nov.3, and the activity peaks at 12:00 UT on Nov.4, with a Dst index of −120 nT. The Akebono observation reveals some interesting facts. With the initiation of the main phase, the outer radiation belt disappears. At the final stages of the transition from the main phase to the recovery phase, the outer belt electron flux recovers, and by 12:00 UT on Nov.5, the outer radiation belt has been restored to a state equivalent to that prior to the geomagnetic storm. After that, it continues to increase, eventually reaching a level exceeding that of the pre-storm state.

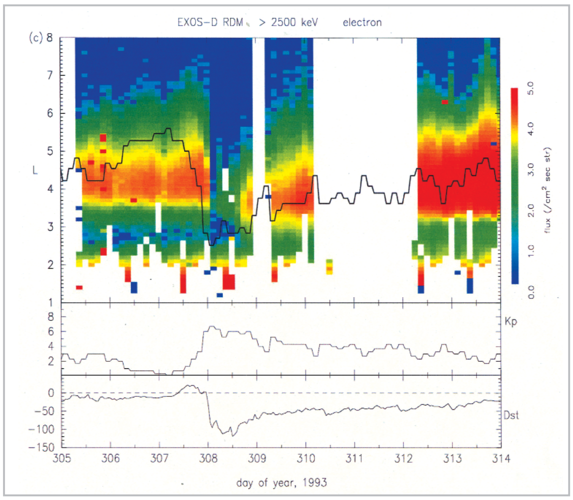

Fig.14 *Variations in the distribution of MeV electrons observed by the Akebono satellite.*
The top, middle, and bottom panels show the L-t diagram of electrons, magnetic activity, and Dst indexes, respectively (Obara, 2001).

Presently, aggressive studies are underway relating to the mechanisms behind the loss and reappearance of outer radiation belt electrons, as part of efforts to understand variations in electron content. The giant convection electric field present at the onset of geomagnetic storms may be responsible for electron loss. The development of this electric field may drive the outer radiation belt particles to the sunward magnetosphere, where they are lost. Estimations have been made of the effects of the developed ring current in reducing the local magnetic field intensity and energy. In this case, the electron velocity distribution function as a whole shifts to the zero energy side, and the high-energy component in the flux is reduced. If the electron velocity distribution can be approximated to the Maxwell distribution, then there will be significant reduction of the high-energy component (for example, of the ≧ 1 MeV component). Furthermore, it has been pointed out that plasma waves generated in the outer radiation belt during geomagnetic storms cause pitch-angle scattering of radiation electrons, which then precipitate into the atmosphere. Overall, the results of recent studies suggest that in the outer radiation belt region near the Earth ($L < 4$), adiabatic energy loss is the main cause of flux decrease, while in the other outer belt regions ($L > 4$), the stripping of radiation belt electrons by the developed magnetospheric convection is the main cause of flux decrease. Precipitation into the atmosphere is observed in regions around $L = 4$ at the onset of the main phase. There is also significant precipitation during the recovery phase. During the recovery phase of geomagnetic storms, strong wave-particle interactions cause an abnormal increase in relativistic electrons (details of this increase will be presented later). The resulting pitch-angle scattering is believed to cause the precipitation of high-energy electrons into the atmosphere.

There are two basic theories concerning the reappearance of the outer radiation belt. One may be referred to as the "external source" theory, in which the reappearance is explained by the diffusion of electrons with high energy (more than a few hundred keV) into the outer belt from the plasma sheet. In this case, the betatron acceleration (acceleration due to increased magnetic field intensity) produces the MeV electrons. The other theory, recently proposed, attributes the reappearance to internal acceleration (the "internal acceleration" theory). In this case, the ring current electrons, which generate geomagnetic storms, are accelerated into MeV electrons. Below, we will examine and compare these two theories.

For the plasma sheet particles to be able to penetrate into the outer radiation belt region solely by diffusion processes, the diffusion coefficient must have an extremely large value. With current theories, it is difficult to produce such large diffusion coefficients. The distance between the positions of the regenerated outer belts for large and small geomagnetic storms is nearly equal to the diameter of the Earth, and it is uncertain how the information concerning the extent to which the plasma sheet particle may approach the Earth may be stored during the recovery phase. There is also the issue of the mechanism generating electrons with energies of hundreds of keV in the plasma sheet region, in addition to a number of other complex points that remain unexplained.

The essential problem facing the internal acceleration theory is the resolution of the mechanism by which the ring current electron acquires the MeV energy. Several acceleration mechanisms have been proposed, and all have proposed some form of wave acceleration. Through relativistic simulations on existing wave-particle interaction theories, it has been confirmed that acceleration does indeed occur. The acceleration efficiency was found to be dependent upon wave intensity. If substorms occur frequently during the recovery phase of geomagnetic storms, electrons with energies of several keV are supplied, and the high wave intensity can be sustained. It has also been discovered that the degree of regeneration of the outer radiation belt electrons is controlled by the degree of magnetic activity during the recovery phase. The position of the regenerated outer radiation belt has been found to coincide with that of the ring current. These findings favor the internal acceleration theory over the external supply theory.

Conclusions

Solar wind supplies particles and energy to the magnetosphere. The energy injected into the magnetosphere is accumulated in the magnetotail and released periodically. When large southward solar wind magnetic fields, those accompanied by the coronal mass ejection (CME), hit the Earth, the magnetosphere becomes severely disrupted, resulting in a geomagnetic storm.

In this chapter, auroral and substorm phenomena were described as the release of energy accumulated in the magnetotail, from the perspective of particle flux. Then, the geomagnetic storm, the highest-energy phenomenon in the magnetosphere, was described, together with the resulting generation of radiation belt electrons. The region discussed in this chapter will be visited by numerous satellites and space vehicles in the future, and will be actively developed and utilized. Progress in the physics related to this region is expected not only to serve academic interests but also to contribute to safer practical use.

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