Structure and Dynamics of the Plasma Sheet Boundary Layer in the Distant Magnetotail

地球磁気圏遠尾部における プラズマシート境界層の構造と力学に関する研究

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Structure and Dynamics of the Plasma Sheet Boundary Layer in the Distant Magnetotail

by

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Abstract

This thesis deals with the structure and dynamics of the plasma sheet boundary layer (PSBL) in the Earth's magnetotail.

The Earth's magnetosphere is formed by the interaction between solar wind and Earth's dipole magnetic field. Because of this interaction, the Earth's dipole magnetic field is deformed into a shape that is compressed on the dayside and stretched out into a geomagnetic tail on the nightside. The presence of the magnetotail represents excess energy imparted from the solar wind through the magnetopause and stored in the magnetosphere. The magnetotail is largely divided into two regions; plasma sheet and lobe. The plasma sheet is a sheet-shaped region of tenuous but hot plasmas in the equatorial region, while the regions on both sides of the plasma sheet are called lobe(s), where the magnetic field is relatively strong and stable and no significant hot plasma exists. One of the fundamental problems in magnetospheric physics is to determine the physical processes for the formation of the plasma sheet.

PSBL is a region between plasma sheet and lobe, which is one of the most active regions in the Earth's magnetosphere. Study of the structure and dynamics of the PSBL is essential for understanding the formation mechanism of the plasma sheet. In spite of the importance of this region, in-situ observations of the PSBL have so far been done mainly in the region of ≤ 30Re from the Earth.

It has been known that dynamics of the magnetosphere can be understood in the general frame work of the reconnection model. Southward interplanetary magnetic field can connect to the northward geomagnetic field at the dayside magnetopause. The newly-connected (reconnected) open field lines that are rooted in the polar cap are convected tailward with the solar wind flow. In the geomagnetic tail, magnetospheric field lines from the northern and southern polar caps can reconnect again at an X-type neutral line. The main purpose of this thesis is to examine the plasma data mainly observed in the magnetotail on the basis of this reconnection model.

For the above objectives, we have analyzed the data obtained by the AKEBONO and the GEOTAIL satellites. AKEBONO is a polar orbiting satellite with an apogee of $\sim 10,000$ km and an inclination of 75 degrees, while the orbit of GEOTAIL is optimized for investigation of the magnetotail up to distances of $X_{GSE} \sim -210$Re. This author has participated deeply in design, calibration, and data evaluation of the low energy particle (LEP) instrument onboard the GEOTAIL satellite. The LEP instrument is designed to measure three-dimensional velocity distributions of electrons and ions over an energy range of a few ten eV/Q to $\sim$ 40keV/Q with fine time resolution. The instrument characteristics and the method of data processing are presented in Chapter 2. The method of the numerical calculation used in designing the instrument, and the results of the calibration with detailed characteristics of the LEP instrument are presented in Appendix A.

The author has also participated in developing the onboard software of the velocity moment calculation for LEP instrument. The detailed method of this calculation and the evaluation of the obtained plasma velocity moment are presented in Appendix B.

Since the magnetic field line converges near the Earth, observations by a near-Earth polar orbiting satellite provide us with a "remote sensing" of various regions in the magnetotail. The PSBL in the magnetotail corresponds to the poleward edge of the auroral oval, which is the boundary region between polar cap and auroral oval. If there exists a magnetic field structure such as the X-type neutral line in the magnetotail, ions entering from the lobe to the plasma sheet near the X-type neutral line are accelerated by the dawn-to-dusk electric field around the weak north-south component of the magnetic field. Some of the accelerated particles flow to the Earth in the PSBL regions and precipitate into the polar ionosphere around the poleward edge of the auroral oval. The AKEBONO observations of such ions are discussed in Chapter 3.

Though we can obtain some information about the X-type neutral line from the above mentioned "remote sensing method", the most effective way to investigate the PSBL is to make observations in the magnetotail region where the X-type neutral line is expected to exist. When we make observations in the magnetotail, we can observe various regions, though the velocity of the satellite with respect to the sun-Earth fixed frame is very slow. It indicates the existence of some motions of the magnetotail in the sun-Earth fixed frame. In Chapter 4 we discuss three-dimensional variations of the plasma bulk flow direction in the plasma sheet at $X_{GSE} \sim -60$Re observed by the LEP instrument onboard the GEOTAIL satellite. The variations of the flow direction are interpreted as representing the tail flapping motion with velocity shears.

The ions observed by the near-Earth polar orbiting satellite presented in Chapter 3 are explained from the view point of the single particle motion of ions around the magnetic field structure like X-type neutral line. Plasmas also have fluid characteristics, and from this view point, slow-mode shocks are predicted to be formed at the boundary between plasma sheet and lobe bounding the X-type neutral line, if the magnetic field reconnection occurs in the magnetotail. The important role of the slow-mode shocks is to convert the magnetic field energy in the lobe to kinetic energies of particles in the plasma sheet.

Chapter 5 deals with identification of the slow-mode shocks in the PSBL with the GEOTAIL/LEP observations. We have investigated 303 PSBL crossings during about 5 months' observation. Thirty two out of the 303 PSBL crossings are identified as slow-mode shocks. This result is consistent with the existence of the X-type neutral line expected from the reconnection model of the Earth's magnetosphere. Characteristics of the ion distributions in velocity space have revealed the kinetic property of the slow shocks. In the upstream (lobe) region backstreaming ions which flow from the shock surface to the upstream are found at the same time with the ions flowing into the shock surface. These counterstreaming ions may be the source of the dissipation required by slow-mode shocks in the collisionless magnetospheric plasma. Between the upstream and downstream regions, acceleration of cold ions are also observed.

We have also found out that the accelerated cold ions, at times, show a ring-shaped velocity distribution. Chapter 6 discusses these ring-shaped ions in detail. We have found 11 examples of these ring-shaped ions during about one month's observation. One of the 11 examples is observed in the PSBL which satisfies the conditions for a one-dimensional slow-mode shock. The generation mechanism of the ring-shaped ions may reflect the kinetic property of the PSBL including the cross-shock potential in slow-mode shocks.

Chapter 1

General Introduction

1.1 Structure of the Earth's Magnetosphere

The Earth's magnetosphere is formed by the interaction between solar wind and Earth's dipole magnetic field. Before the human being obtained artificial satellites, the structure of the Earth's magnetosphere had been inferred from several geomagnetic phenomena observed on the ground. Since the first artificial satellite was launched in 1957, a number of scientific satellites have been put into orbits to investigate the plasma environment around the Earth. Figure 1.1 [adapted from Pilipp and Morfill, 1978 (slightly modified)] shows a schematic view of the magnetic and plasma structure around the Earth, which has been made clear by in-situ observations during the last three decades. The solar wind, which is a fast plasma flow from the sun, is continuously blowing against the Earth. Since the solar wind is supersonic and super-Alfvénic, a shock wave called 'bow shock' is created in front of the Earth, where the solar wind is decelerated and thermalized, and a region called 'magnetosheath' exists in the downstream. The surface which bounds the regions where geomagnetic field is dominant is called 'magnetopause', and the entire regions inside this magnetopause is called 'magnetosphere'. The Earth's dipole magnetic field is compressed on the sunward side, and contrarily elongated on the anti-sunward side, forming a tail-like magnetic field structure called 'magnetotail'. Since charged particles are difficult to move across the magnetic field, the fast high density plasma in the sheath region cannot easily enter into the magnetosphere. To elucidate the entry process of the solar wind plasma into the magnetosphere is one of the most important problems in space plasma physics. The magnetotail is largely divided into two regions; plasma sheet and lobe. The 'plasma sheet' is a sheet-shaped region of tenuous but hot plasmas in the equatorial region, while the regions on both sides of the plasma sheet are called 'lobe(s)', where the magnetic field is relatively strong and stable and no significant hot plasma exists. The boundary region between the lobe and the plasma sheet is called 'plasma sheet boundary layer (PSBL)'. There is a point where the magnetic field configuration has an X-shape in the magnetotail, called 'X-type neutral line'. However the existence of this 'X-type neutral line' is still controversial because most of the in-situ observations have been made in the relatively near-Earth regions of $X > \sim -30$Re. One of the main purposes of this thesis is to clarify whether such structure really exists in the Earth's magnetotail.

1.2 Reconnection Model of the Earth's Magnetosphere

A theoretical model which explains the formation mechanism of the Earth's magnetotail is proposed by Dungey [1961]. Figure 1.2 [adapted from Hill, 1983] shows the concept of this model schematically. He applied the concept of the magnetic merging to the magnetosphere for the first time. In the solar wind there exist magnetic fields called 'interplanetary magnetic field (IMF)', which are originated from the Sun, being convected toward the Earth with the solar wind according to the frozen-in property of infinitely conductive fluid plasma. When it has southward component, the IMF can connect to the northward magnetospheric magnetic field at the dayside magnetopause. The newly-connected open field lines are convected anti-sunward with the solar wind and stretched away in the magnetotail. In the magnetotail the magnetic field lines from the northern and southern polar caps are anti-parallel in the lobe region and hence can reconnect again, forming an X-type neutral line in the magnetotail. The convected and elongated field lines in the magnetotail and the associated cross-tail current represent the stored energy imparted from the solar wind. When the magnetic field lines reconnect, magnetic energy is converted to kinetic energies of plasma.

Energy conversion from the magnetic energy to the kinetic energies of plasma particles at times occur abruptly and violently when a substorm occurs[Akasofu, 1964]. Hones [1977] proposed a model that such an abrupt energy conversion is realized by formation of two X-type neutral lines, a distant neutral line and a near-Earth neutral line, which lead to formation of a closed-loop magnetic field structure called 'plasmoid'. Figure 1.3 [adapted from Hones, 1979] shows this concept schematically.

1.3 Fast Flowing Ions in the PSBL

1.3.1 Recent Observations of the Fast Flowing Ions in the PSBL

One of the most conspicuous phenomena in the PSBL is the existence of high-energy ion beams which have often been observed by satellites, for example by the ISEE 1 and 2 satellites [DeCoster and Frank, 1979; Takahashi and Hones, 1988], and the AMPTE satellite [Nakamura et al., 1992] at the near-tail region of $\leq$25Re. Eastman et al. [1984, 1985] found that these ion beams are almost always present under various geomagnetic conditions. Comparing the estimated total number flux and energy flux transported in the PSBL with those in the plasma sheet, they concluded that PSBL is a primary plasma transport region of the magnetotail.

The distribution functions of these ion beams change from field-aligned beams in the outer region of the boundary to a characteristic shape called "kidney bean" shape, and finally to nearly isotropic or shell-like distributions near the central plasma sheet [Eastman et al., 1986]. Recently Onsager et al. [1990] proposed a model that the "kidney bean" shape distributions can be understood in terms of the velocity filter effect due to $\mathbf{E} \times \mathbf{B}$ drift under the dawn-to-dusk electric field with a distributed source of the beam ions in the central plasma sheet (current sheet).

In the near-tail region, these high energy ion beams at times show counter-streaming characteristics. In the transition from the lobe to the plasma sheet, the ion beams are initially flowing earthward along magnetic field lines, and then tailward flowing ion beams with higher energies begin to be observed at the same time with the earthward flowing ions. This phenomenon was first noted by Forbes et al. [1981a], who explained that the tailward flowing ion beams are due to reflection near the Earth by the magnetic mirror force.

Some of the ion beams in the PSBL flowing to the Earth are not reflected but precipitate into the ionosphere. Since the magnetic field converges near the Earth, observations of these precipitating fast ion beams by a low-altitude satellite provide us with an opportunity to infer a global image of these ion beams in the magnetotail. These precipitating ions are for the first time recognized by Bosqued [1987] and Kovratzkhin et al. [1987] as velocity-dispersed ion structures (VDIS) using data obtained at altitudes of ≤ 2000km by AUREOL3 satellite. VDIS is observed in the vicinity of the poleward edge of the nightside auroral zone. Most of the VDIS show a feature that higher-energy ions precipitate into the higher latitude. Zelenyi et al [1990] investigated these precipitating ions in detail and explained the observed ion distributions in terms of the velocity filter effect caused by $\mathbf{E} \times \mathbf{B}$ drift under the dawn-dusk electric field with an assumption on the magnetic field shape in the magnetotail.

1.3.2 Current Sheet Particle Acceleration

The PSBL high-energy ions may be created near X-type neutral line by "current sheet acceleration" [Speiser, 1965, 1967; Lyons and Speiser, 1982; Speiser and Lyons, 1984]. Figure 1.4 [adapted from Speiser, 1965] shows ion and electron motions in a current sheet. The ions in the lobe, which are originated from the solar wind and/or the ionosphere, are accelerated by the cross-tail dawn-dusk electric field in a region where a small normal magnetic field component B_z exists in the current sheet. The accelerated energy is determined by the Larmor radius of the ions moving around weak B_z. Since the Larmor radius of electrons is very small, electrons are not effectively accelerated by this process. This acceleration does not necessarily require the X-type neutral line as long as the normal magnetic field component B_z is sufficiently weak in the current sheet. However, if an X-type neutral line exists, this acceleration mechanism works more effectively around the X-type neutral line.

1.4 Slow-Mode Shocks in the Earth's Magnetotail

1.4.1 PSBL Characteristics : Slow-Mode Shocks

So far we have argued about the high-energy ion beams in the PSBL which may be explained in terms of a single particle motion assuming the existence of the X-type neutral line. In the single-particle limit, plasma sheet particles can be regarded as current-sheet accelerated particles. However the real plasma shows diamagnetic effects, which requires preacceleration of the particles before the current-sheet acceleration [Hill, 1975]. Thus, in the fluid limit of plasma, the current-sheet acceleration is not required but the plasma sheet particles must be accelerated by another process, for example, slow-mode shocks bounding the X-type neutral line.

If magnetic field reconnection occurs in the geomagnetic tail, it is predicted that slow-mode shocks are formed at the boundaries between plasma sheet and lobe [Petschek, 1964; Vasyliunas, 1975 and references therein]. Figure 1.5 [adapted from Vasyliunas, 1975] shows magnetic field lines (solid lines) and plasma stream lines (dashed lines) around the X-type neutral line. There are four slow-mode shocks bounding the X-type neutral line. From the northern and southern lobes, plasma is convected toward the neutral sheet by $\mathbf{E} \times \mathbf{B}$ drift under the dawn-to-dusk electric field. The velocity of the slow mode wave approaches zero as the propagation direction becomes perpendicular to the magnetic field. Therefore the plasma flow is supersonic with respect to the slow-mode wave in the vicinity of the X-type neutral line, even when the flow velocity of the plasma is small. As a result the collision of plasmas flowing from the northern and southern lobes is expected to give rise to slow-mode shocks.

1.4.2 Theoretical Works

The large-scale structure and dynamics of the magnetotail including the PSBL have been numerically studied using MHD simulations. The existence of the slow-mode shocks in the PSBL is shown by Sato[1979], Scholer and Roth[1987], and Ugai[1993]. Birn et al. [1986] and Hesse and Birn [1991], on the other hand, reported that slow-mode shocks were not formed on the earthward side of the X-type neutral line, where the magnetic field is connected to the ionosphere.

Slow-mode shocks, which are expected to exist bounding the X-type neutral line, are generated in collisionless plasmas. Since the slow shocks convert the upstream magnetic field energy into kinetic energies of the downstream plasma, there must be some dissipation mechanisms which are not due to classical collisions.

The first theoretical work on the structure of slow shocks was made by Coroniti [1971]. His result shows that the slow shocks are associated with a dispersive wave train in the downstream region. He suggested that the energy dissipation of the slow-shock is provided by dumping of the dispersive wave train.

Several numerical simulations on kinetic properties of the slow-mode shocks have been reported as well. With a hybrid-code simulation Swift [1983] found the upstream escape of the hot plasma and a damped left-handed circularly-polarized wave on the trailing edge of the shock. Omidi and Winske [1992] also used a hybrid-code simulation to investigate the structure of slow shocks and ion heating in the low-beta regime. In particular, they studied the effects of the Alfvén/ion cyclotron waves on the structure of slow-mode shocks. The Alfvén/ion cyclotron waves are generated by the interaction between the incident and backstreaming ions via electromagnetic ion/ion cyclotron instability.

1.4.3 Previous In-Situ Observations

The existence of the slow-mode shocks in the distant-tail regions was for the first time reported by ISEE 3 deep-tail mission [Feldman et al, 1984a,b, 1985; Scarf et al., 1984; Smith et al., 1994]. Analyzing the three-dimensional magnetic field data and two-dimensional electron data, Feldman et al. [1985] identified the slow-mode shocks and concluded that the slow-mode shock is a semi-permanent structure of the plasma sheet-lobe boundaries in the distant-tail region. They also noticed the variation of the electron distribution function, which shows heat flux leakage from the shock toward the upstream region as well as thermalization in the plasma sheet. At the same time, electrons are accelerated by the shock potential and form flat-top distributions in the downstream of the shock. The electron dynamics and the variation of the distribution functions through slow-mode shocks were investigated in detail by Schwartz et al. [1987].

The existence of the slow-shock structure in the near-Earth magnetotail at X~ -20Re was also reported by Feldman et al. [1987], based on three-dimensional magnetic field data and two-dimensional electron and ion data obtained by ISEE 2 satellite. They reported that the lobeward edge of the plasma sheet-lobe boundary was identified as a slow-mode shock, which was different from the plasma sheet-lobe boundaries in the distant magnetotail where the entire boundary region had a slow-shock structure. Using the AMPTE/IRM data, Cattel et al. [1992] investigated $\sim$80 plasma sheet-lobe crossings at X~ -10 to -18Re. They concluded that the plasma sheet-lobe boundaries in the near-tail region were not well modeled by a planar MHD discontinuity with a normal component of the magnetic field, and in particular, did not contain a slow mode shock. They suggested that some factor operating earthward of the neutral line prevents the formation of slow-mode shocks in the near-Earth region. They also suggested that the plasma sheet boundary in the near-Earth region is usually a tangential discontinuity, or there are effects such as time variations, single particle effects, or three-dimensional structures, which invalidate the assumptions of planar time-stationary MHD.

In summary, the strict and detailed investigation of the characteristics of the PSBL in the mid-tail to the distant-tail region has not yet been done, since only insufficient plasma data (two-dimensional electron and no ion data) were available in the ISEE 3 deep tail observations.

1.5 Why can we Observe PSBL? – Motion of the Magnetotail –

In the distant tail, the motion of the satellite with respect to the sun-Earth fixed frame is very small compared with the scale of the magnetotail. However there exists a flapping motion of the magnetotail, for example, due to variations of the solar wind dynamic pressure. The motion of the magnetotail with respect to the sun-Earth fixed frame enables us to observe various regions of the magnetotail including the PSBL crossings. On the basis of the observations by ISEE 1 and 2 spacecrafts during substorms, Forbes et al.[1981b] reported some examples of the motion of the magnetotail which were due to both passage of the surface wave generated by Kelvin-Helmholtz type of instability and thinning and thickening of the magnetotail during substorm. Hones et al. [1984] also investigated the motion of the magnetotail statistically, and concluded that the motion was due to a thinning and thickening of the plasma sheet during substorm. However, even when the magnetic condition is moderate to weak, satellites encounters the PSBL, which suggests the existence of the tail flapping motion due to mechanism(s) other than the plasma sheet thinning/thickening.

1.6 Organization of this Thesis

The main purpose of this thesis is to examine the reconnection model of the Earth's magnetosphere through observational study of the structure and dynamics of the PSBL. This objective has been attained by analyzing the data obtained by the near-Earth polar orbiting satellite AKEBONO and the spacecraft GEOTAIL which explores the magnetotail in detail.

This thesis consists of 7 Chapters and 2 Appendixes. In Chapter 2, the instrumentation and the data evaluation of the low energy particle experiment (LEP) onboard the GEOTAIL satellite are presented. In Chapter 3, the earthward projection of the PSBL fast ion flow is examined, based on the low energy particle data obtained by a polar orbiting satellite AKEBONO. In Chapter 4, rapid variations of the plasma bulk flow direction observed in the plasma sheet at $X_{GSE} \sim -60$Re are examined. We shall suggest that these variations are caused by combination of the spatial gradient in the bulk flow and the flapping of the tail. In Chapter 5, characteristics of the PSBL in the distant geomagnetic tail are investigated. Some of the PSBL are identified as slow-mode shocks, which suggests the existence of the X-type neutral line expected from the reconnection model of the Earth's magnetosphere. In Chapter 6, a ring-shaped distribution of ions observed in the PSBL is investigated. Concluding remarks are given in Chapter 7. In Appendix A, detailed characteristics of LEP sensors (LEP-EA and LEP-SW) onboard the GEOTAIL satellite are presented. In Appendix B, the method of GEOTAIL onboard plasma velocity moment calculation and the evaluation of the observed velocity moments are presented.

Chapter 2

Low Energy Particle Experiment onboard the GEOTAIL Satellite

For the purpose of investigating the plasma environment mainly in the geomagnetic tail, low energy particle (LEP) experiment is under operation on the GEOTAIL satellite. The objective of this chapter is to describe the principle and functions of LEP-EA and LEP-SW, and to present the method of data processing on the ground. The methods of numerical calculation and experimental calibration of LEP-EA and LEP-SW with detailed characteristics of these instruments are presented in Appendix A. The method of onboard velocity moment calculation and the evaluation of the observed results are presented in Appendix B.

2.1 Overview of the GEOTAIL Satellite

Figure 2.1 shows a schematic view of the GEOTAIL spacecraft in the operational configuration on orbit. The main body has a cylindrical shape with a diameter of 2.2 meters and with a height of 1.6 meters. The spacecraft is spin-stabilized with a spin rate of $\sim$ 20rpm and the spin axis is nearly perpendicular to the ecliptic plane. Seven scientific instruments are carried onboard the GEOTAIL satellite. Table 2.1 lists these instruments. For instrumentation details, refer to J. Geomag. Geoelectr., vol. 46, No.1 and No.8.

The GEOTAIL spacecraft was launched on 24 July, 1992, by Delta II launch vehicle from Kennedy Space Flight Center in U.S.A. Figure 2.2 shows the orbit, which is optimized for the investigation of the important but unexplored regions of the magnetotail. For about two and a half years the spacecraft is placed in the distant-tail orbit using Sun-Synchronous Double Lunar Swingby, in order to make extensive observations beyond the lunar orbit up to about 210Re from the Earth. After this period, the spacecraft will be moved to a near-tail orbit with an apogee of 30Re in order to investigate the neutral sheet in the near-Earth tail region. In this thesis, the data obtained during the distant-tail orbit are analyzed.

2.2 Objectives of Low Energy Particle Experiment

The low energy particle (LEP) experiment on GEOTAIL satellite makes comprehensive observations of plasma and energetic electrons and ions with fine temporal resolution in the terrestrial magnetosphere (mainly in the geomagnetic tail) and in the interplanetary space. The major observation objectives of LEP are (1) to study the nature and the dynamics of plasmas in various regions of the magnetotail, (2) to analyze the plasma conditions under which the suprathermal particle acceleration takes place in the magnetotail, (3) to study plasma circulation in the magnetosphere and its variability in response to the formation of near-earth neutral lines and magnetospheric substorms, (4) to identify ionospheric contribution to the plasma sheet population, and (5) to study the entry processes of plasmas from the magnetosheath into the magnetosphere.

2.3 Principle and Functions of LEP Instruments

2.3.1 Overview

The LEP instrument consists of three units of sensors (LEP-EA, LEP-SW, and LEP-MS) and a common electronics (LEP-E). LEP-EA provide three-dimensional distribution functions of electrons and ions with high time resolution, while LEP-SW measures three-dimensional distribution functions of solar wind ions. LEP-MS is an energetic-ion mass-spectrometer, which provides three-dimensional determinations of the ion composition. The block diagram of LEP instrument is shown in Figure 2.3. In this Chapter, we will report the principle and functions of LEP-EA and LEP-SW. The detailed description of LEP-MS is reported by Hirahara and Mukai[1993].

2.3.2 LEP-EA

Figure 2.4 shows a schematic diagram of LEP-EA. LEP-EA consists of two nested sets of quadrispherical electrostatic analyzers that measure electrons and positive ions. The inner analyzer, LEP-EAe, measures electrons over an energy range from 8eV to 38keV, while the outer analyzer, LEP-EAi, measures positive ions over an energy range from 32eV/Q to 43keV/Q. Charged particles with selected energy/charge and incident angles can travel through the analyzers and be measured. Seven channel electron multipliers (CEMs) and seven microchannel plates (MCPs) are used as electron detectors and ion detectors, respectively. These detectors (CEMs and MCPs) are placed at the positions corresponding to the incident elevation angles of 0°, $\pm 22.5^\circ$, $\pm 45.0^\circ$, and $\pm 67.5^\circ$.

EAi has a large geometrical factor of 1.5×10^{-3} cm^2 str eV/eV (channel 4) to observe tenuous plasma in the lobe region with high time resolution. This large geometrical factor is realized by a large incident area of the instrument. The geometrical factors of seven channels of EAi and EAe sensors are nearly proportional to the cosine of the incident elevation angles. These characteristics of the geometrical factor make it easy to calculate two dimensional distribution function on the plane perpendicular to the satellite spin axis. The basic parameters of the instrument performance for the EAe and EAi sensors are shown in Table 2.2. Detailed characteristics of the spherical electrostatic analyzers (EAe and EAi) are presented in Appendix A.

The measurement is synchronized with the spin phase clock of the spacecraft. LEP-EA can measure three-dimensional energy/charge distributions of electrons and positive ions, separately and simultaneously, in one spin period (about 3 seconds). One spin period is divided into 16 azimuthal sectors, and in each sector, the electron and ion energies are scanned over the whole or selected energy range. The scanned energy range can be selected by changing the RAM table which has the information of the applied voltage level to the analyzer plates. Each instrument has two RAM tables A and B. An example of the energy sweep is shown in Figure 2.5 (EAi : RAM A mode). The scanned energy bins of EAi and EAe are shown in Tables 2.3 and 2.4, respectively.

2.3.3 LEP-SW

Since LEP-EAi has too large geometrical factors to measure the solar wind ions (especially protons), LEP-SW with a smaller geometrical factor is supplemented to measure the solar wind ions in an energy range from 0.1 to 8 keV/Q. The measurement principle and method of LEP-SW are quite similar to those of LEP- EAi, however LEP-SW uses a 270°-spherical electrostatic analyzer. Figure 2.6 shows schematically the principle of this analyzer. Since the transmission characteristics of the 270°-spherical electrostatic analyzer with respect to the incident angle and energy is compact, this instrument has sufficiently high angular and energy resolution to measure solar wind ions. The measurement of LEP-SW is carried out within spin phase of $\pm 45°$ from the direction toward the sun, which is divided into 16 sectors, and in each sector, the energies are scanned over the whole energy range. The basic parameters of the instrument performance for the SW sensor are shown in Table 2.5, and the scanned energy range is shown in Table 2.6.

2.3.4 Measured and Derived Parameters

Raw count rate data of dimension 32(E) $\times$ 16(Az) $\times$ 7(El) are generated by each instrument in one spin period. Observed count rates C_o are converted to differential flux $j(E)$ using the following equation.

$$j(E) = \frac{C_o}{\tau g E \eta(E)} \tag{2.1}$$

where τ is the sampling time, E is the observed energy, g is the geometrical factor and η is the detection efficiency. Distribution function $f(v)$ is calculated by the following equation.

$$f(v) = \frac{j(E)m^2}{2E} \tag{2.2}$$

where m is the mass of charged particles.

The geometrical factors of the analyzers are decided by experimental calibration in the laboratory (see Appendix A). When we calculate absolute plasma parameters from raw count rate data, we have to know the efficiencies of the detectors, CEMs and MCPs, as well as geometrical factors. We have decided the efficiency by comparing the plasma density calculated from LEP data with the plasma frequency observed by Plasma Wave Instrument (PWI) onboard the GEOTAIL satellite [Matsumoto et al., 1994]. The decided detection efficiency of each detector of EAe, EAi, and SW at the beginning of the observation was 0.65, 0.65, and 0.75, respectively. Since the detection efficiency is usually a slowly-varying function of detected particle energy, we can neglect the dependency on the particle energy. The efficiency varies with degradation of CEMs and MCPs, and it also varies with the level of the voltage applied to the detectors. The degradation can be monitored through scanning the discrimination level of the output pulse height of the detectors. Using both methods, comparison of the plasma density between LEP and PWI and scanning the discrimination level, we have decided the temporal variation of the detection efficiencies.

Besides the count rate data, plasma velocity moments are calculated on the spacecraft every spin period. The calculated velocity moments are density, bulk velocity, pressure tensor, and heat flux tensor of ions, electrons and solar wind ions. This calculation is executed by a digital signal processor in LEP-E. The detailed calculation method and evaluation of the obtained velocity moments are presented in Appendix B.

The measured raw count rate data and onboard calculated velocity moments are transmitted to the ground mainly by two ways. The data obtained during the real-time operation, called editor-A data are available for about 8 hours/day. Besides the editor-A data, 24-hour continuous data, called editor-B data are available. While the onboard calculated velocity moments are obtained every spin period in both editor-A and editor-B data, the complete three-dimensional velocity distributions can only be obtained in a period of four spins in editor-A data owing to the telemetry constraints; the count data are accumulated during the four-spin period. Two dimensional count rate data, which are obtained by simply adding the count rate of 7 channels of each sensor, are transmitted to the ground as editor-B data.

2.4 Method of Background Noise Subtraction

In spite of several efforts to reduce noise count rates, some of them are still inevitably included and have to be subtracted from the raw count data, especially in regions with extremely low density, such as in the lobe region. The main sources of the noise count rates are (1) solar EUV photons (2) high-energy particles (cosmic ray etc.) (3) electrical noise and (4) photoelectrons (for EAe).

When the solar EUV photons enter the CEMs or MCPs through multiple reflections by the analyzer plates, it can generate spurious count rates. We have made a serration inside the analyzer plates of EAe and EAi to prevent these spurious counts. Besides making the serration, we have coated the analyzer plates with carbon. As a result of these efforts, the solar EUV photons entering the CEMs or MCPs are reduced by order of 10^{-7} (assuming the detection efficiency of 1 % for EUV photons). However, the remaining count rate due to the solar EUV photons still have an effect when plasma density is low. We have measured the count rate profile generated by EUV photons using a deuterium lamp in the laboratory, and compared the laboratory profile with the inflight profile. An example of the result is shown in Figure 2.7 (for channel 4 of EAi). On the basis of this comparison, we have decided the noise count level generated by solar EUV photons. Table 2.7 and Table 2.8 show this result.

The noise count rates due to high-energy particles and electrical noise also have to be subtracted from EAi data in order to calculate plasma parameters correctly in the lobe region where plasma density is low. (The noise due to these sources is negligibly small in the EAe and SW data.) The noise count rates appear randomly. We have reduced the noise count rates assuming that "noise count should appear independently". The obtained count rate C can be expressed as a function of elevation angle α_i, azimuthal angle ϕ_j, scanned energy step E_k, and time t_l. We have checked all the count data obtained at (α_i, ϕ_j, E_k, t_l), where $i = 1 \sim 7$, $j = 1 \sim 16$, $k = 1 \sim 32$, and $l = 1 \sim$ 'number of data', and identified noise count rates. The procedure of this identification for three-dimensional count rate data (editor-A data) is as follows. We have calculated the sum $S(i,j,k,l)$ of all the count rates around a point in the four-dimensional space (α_i, ϕ_j, E_k, t_l).

$$S(i,j,k,l) = \sum_{i'=i-1}^{i'=i+1} \sum_{j'=j-1}^{j'=j+1} \sum_{k'=k-1}^{k'=k+1} \sum_{l'=l-1}^{l'=l+1} C(i',j',k',l') \tag{2.3}$$

When the relations

$$S(i,j,k,l) \leq S_{critical} \tag{2.4}$$

and

$$C(i,j,k,l) \leq C_{critical} \tag{2.5}$$

are satisfied, we have identified that the count data $C(i,j,k,l)$ is a noise. The values $S_{critical}$ and $C_{critical}$ are decided to be 40 and 5 by comparing the plasma density calculated from noise-reduced data and the plasma frequency observed by PWI. The procedure to identify the noise counts for two-dimensional count rate data (editor-B data) is different from the above procedure in the point that all values are function of three parameters ϕ_j, E_k, and t_l, and the summation is executed in a three-dimensional space. The values $S_{critical}$ and $C_{critical}$ for two-dimensional data are decided to be 75 and 10 by comparing the noise-reduced two-dimensional data (editor-B data) with the noise-reduced three-dimensional data (editor-A data). The noise-reduced count rate data are obtained by eliminating the noise count data identified by the procedure above, and subtracting the averaged energy-independent uniform noise count rates which are calculated from the eliminated noise count data. These energy-independent noise count rates are 0.33/4-spins for channel 2, and 0.28/4-spins for the other channels of EAi.

The photoelectrons should be removed in calculating the velocity moments of electrons. The solar EUV photons which collide with the satellite creates these photoelectrons. Since the satellite is charged positively by the photoelectron creation, the measured energy should be corrected taking account of the spacecraft potential. The method of removing photoelectrons in calculating the electron velocity moments is presented in Section 2 of Chapter 5.

Chapter 3

Signature of the Plasma Sheet Boundary Layers Observed by a Polar Orbiting Satellite AKEBONO

Using low energy ion data obtained by Akebono satellite, we have calculated distribution functions of velocity-dispersed ion beams observed at the poleward edge of the auroral electron precipitation region. The calculated distribution functions can well be fitted by one-dimensional shifted-Maxwellians, whose bulk energy and temperature are several keV and several hundreds of eV, respectively. The bulk energy and temperature show a positive correlation, which may indicate that when the ions are accelerated to higher energy, they are heated to higher temperature simultaneously. We have also found a relation between the invariant latitude width of the observed ion beams divided by the square root of the temperature and their bulk velocity, which indicates that the source region of the ion beam is compact. These ion beams are obtained with high occurrence probability, suggesting that they are supplied from a steady X-type neutral line in the earth's magnetotail.

3.1 Introduction

In the vicinity of the poleward boundary of the nightside auroral oval, precipitation of velocity-dispersed ion beams with energy of $\sim$10keV have been observed by the low-altitude AUREOL-3 satellite ($<$ 2000km) [Bosqued, 1987; Kovrazkhin et al., 1987; Zelenyi et al., 1990]. Zelenyi et al. [1990] investigated the ion beams in detail, and concluded that the velocity-dispersed ion beams corresponded to the fast ion flows which have been frequently observed in the plasma sheet boundary layer (PSBL)[Nakamura et al., 1992;Takahashi and Hones, 1989 and references therein]. Since the magnetic field converges near the earth, observations of these fast ion flows by a low altitude satellite provide us with an opportunity to infer a global image of these ion flows.

Our objective in this chapter is to investigate the distribution function of ion beams observed from the Akebono satellite at altitudes of 4,000km to 10,000km near the poleward edge of the auroral precipitation region, and search for the relation between these ion beams and the PSBL fast ion flow. We will show an example of an ion beam, first, and try to fit the distribution function with a one-dimensional shifted-Maxwellian. Next, we will investigate the fitting parameters statistically for several tens of the examples.

3.2 Observation

We have analyzed the data obtained by two sets of energy/charge(E/Q) analyzers on the Akebono satellite [Mukai et al., 1990]. We can obtain three-dimensional distribution functions of electrons and ions over the energy ranges between 10eV $\sim$ 16keV for electrons and 13eV/e $\sim$ 20keV/e for ions, respectively. The energy range is exponentially divided into 29 steps and is scanned in 0.90625s. Each set of analyzers has five channels with view directions of $0°$, $30°$, $60°$, $90°$ and $120°$ from the spacecraft spin axis which is aligned to the antisunward direction. Two sets of the analyzers are placed symmetrically with respect to the spin axis, and the entire field of view is $240°$. We used 8s time averaged data in our analysis.

Figure 3.1 shows the orbit of the satellite and the pitch-angle sorted energy-time(E-t) diagrams of electrons and ions obtained on December 12, 1989. The uppermost panel shows a polar plot of the satellite orbit in the coordinate system of invariant latitude and magnetic local time. The upper and the lower sets of three E-t diagrams provide an overview of the electron and ion energy fluxes, respectively, in three pitch angle ranges of $0°$ to $60°$(precipitating), $60°$ to $120°$(trapped) and $120°$ to $180°$(upflowing) with respect to the magnetic field. The satellite traversed the nightside region from the polar cap on the duskside to the auroral oval on the dawnside. The ion beam indicated by an arrow in the E-t diagram is observed at 23:30 UT. At this time the satellite was located at the poleward edge of the auroral oval, which can be identified as a sharp transition from weak polar rain (not visible in Figure 3.1) to the intense electron precipitation of plasma sheet origin. The ion beam shows velocity dispersion such that higher energy ions are observed at higher latitude, and can be interpreted as corresponding to the fast ion flow in the PSBL [Bosqued et al.,1987; Kovrazkhin et al.,1987; Zelenyi et al.,1990]. We assume that the distribution function of the ions at the source region is homogeneous inside the region, and that the ion beam is velocity-dispersed on the way to Earth. Then, by adding the distribution functions obtained at all the latitudes within the beam, we can construct the distribution function of the ion beam at the source region. The observed pitch angle distribution of the ion beam is isotropic except for the atmospheric loss cone. This is consistent with the model that the source is far away from the Earth, where the magnetic field is weak, and hence the calculated distribution function is the source distribution function inside a small part of the velocity space along the magnetic field line, which is mapped to the altitude of the spacecraft. Since the pitch angle distribution is isotropic, we have used the data of a fixed pitch angle between 0° and 90° in constructing the distribution function. For a similar purpose at the dayside cusp region, Hill and Reiff[1977] obtained the ion spectrum at the source by using only the peaks of the spectra. We have used all the measured spectra at a fixed pitch angle, because we intend to investigate the detailed characteristics of the source region.

Figure 3.2 is the calculated source distribution function corresponding to the ion beam shown in Figure 3.1. The abscissa is the energy of the observed ions on a linear scale, and the ordinate is the phase space density on a logarithmic scale where the ion species is assumed to be protons. We have found that the distribution function can well be fitted by a one-dimensional shifted Maxwellian

$$f = n\sqrt{\frac{m}{2\pi kT}}e^{-\frac{m}{2kT}(v-v_0)^2} \tag{3.1}$$

where n, m, v, v_0, T, k are density, proton mass, velocity, bulk velocity, temperature, and Boltzmann constant, respectively. The fitted distribution function is also shown by a dashed line in Figure 3.2. By fitting with a one-dimensional shifted Maxwellian, we can estimate the bulk velocity and temperature of the ion beam. In this case the proton energy corresponding to the obtained bulk velocity is 6.7keV, and the temperature is 460eV. As for the density, since it depends on the orbit of the satellite and the latitudinal extent of the dispersive ion beam, we cannot simply determine the number by fitting with a one-dimensional shifted-Maxwellian. Therefore we will not discuss the density in this paper.

Next, we investigate the fitted parameters of the calculated source distribution functions of the ion beams statistically. We examined 259 passes between December 1989 and January 1990, when the satellite passed the nightside auroral region between 20 MLT and 4 MLT. In these 259 passes we could find 119 events in which we could recognize dispersive ion beams at the poleward edge of the auroral electron precipitation region. In 119 events, there are some cases in which most of the ion beam is beyond the energy range of the instrument, namely, over 20keV/e. There are also some other cases in which a part of the dispersive ion beam appears to be decelerated or reflected by the electric field existing above the satellite altitude. In such cases we cannot correctly calculate the source distribution function. Thus we could execute the fitting of a shifted-Maxwellian for 50 events out of the 119 events, and examined the bulk velocity and temperature of these events.

Figure 3.3 shows the result of the fitting we have executed. The bulk energy is on the order of several keV or above, and the temperature is several hundreds of eV or more. Since there is an upper limit on the bulk velocity because of the limited range of measured energy, ion beams with higher bulk velocity may exist. The order of the bulk velocity and temperature we have obtained are consistent with the model investigated by Lyons and Speiser[1982]. In their model, the lobe ions are accelerated by the cross-tail electric field along the Speiser orbit. The bulk velocity and the temperature are positively correlated, with a correlation coefficient of 0.61. This may indicate that when ions are accelerated to higher energy, they are heated to higher temperature simultaneously.

Figure 3.4 shows a relation between the bulk energy and the width in invariant latitude (where the ion beams were observed) divided by the square root of the temperature. In the figure, a set of curves are also drawn with data points. These curves show the relation

$$\frac{\Delta I}{\sqrt{E_{th}}} \times E_0 = \text{const.} \tag{3.2}$$

where ΔI is the width of the invariant latitude where the ion beams are observed, E_{th} is the temperature, and E_0 corresponds to the bulk velocity in the energy unit. The constant on the right hand side characterizes each curve. Most of the data points are found to lie between the curves with a minimum constant of 4 (deg $\cdot$ keV$^{\frac{1}{2}}$) and a maximum constant of 16 (deg $\cdot$ keV$^{\frac{1}{2}}$), four times larger than the minimum value.

In order to explain the above relation (Eq. (3.2) and Figure 3.4), we have made a simple model as follows. We assume an adequately narrow and stable source of the ion beam in the tail region, where the distribution function of the ion beam along the magnetic field line can be fitted with a one-dimensional shifted-Maxwellian. The bulk velocity and the temperature of the distribution function are obtained by fitting the one-dimensional shifted-Maxwellian to the calculated source distribution function of the ion beam observed by the Akebono satellite. Ion beams undergo $E \times B$ drifts on the way to the Earth along the magnetic field, and this $E \times B$ drift causes the velocity dispersion of the ion beams. Then the model can be described by a simple equation

$$\Delta I \propto V_{E\times B} \times (\frac{\mathcal{L}}{v_{slow}} - \frac{\mathcal{L}}{v_{fast}}) \tag{3.3}$$

where $V_{E\times B}$ is the $E \times B$ drift velocity, v_{slow} and v_{fast} are the velocities of the slowest and the fastest ions, and $\mathcal{L}$ is the distance along the magnetic field line between the point of the observation and the source region of the ion beam. Since the distribution function of the ion beam is shifted-Maxwellian, $(1/v_{slow} - 1/v_{fast})$ is expressed by using bulk energy E_0 and temperature E_{th} as $(1/v_{slow} - 1/v_{fast}) \propto \{1/(\sqrt{E_0} - \sqrt{E_{th}}) - 1/(\sqrt{E_0} + \sqrt{E_{th}})\}$. Our observation suggests that E_{th} is much smaller than E_0. Therefore, Equation (3.3) can be simplified to

$$\frac{\Delta I}{\sqrt{E_{th}}} \times E_0 \propto \mathcal{L} \times V_{E \times B} \qquad (3.4)$$

This equation shows that the data points should lie on a set of lines expressed by Equation (3.2).

3.3 Discussion

Our results are consistent with the results of Bosqued et al.[1987], Kovrazkhin et al.[1987], and Zelenyi et al.[1990] that the observed ion beam at the poleward edge of the auroral precipitation region is identical with the PSBL fast ion flow.

We have found a relation between the bulk velocity of the ion beam and the latitudinal width divided by the square root of the temperature. In our simplified model, the observational results show that the product of the convection velocity and the source distance of the ion beam varies in a range of a factor of four. This variation is caused by the variation of the source distance, the variation of the convection velocity, and the variation of the geometry of the magnetic field, which is included in the proportional constant of Equation (3.4). Since our data were obtained under various magnetic conditions, the variation in the range of a factor of four would be reasonable.

Our model assumes that the source of the ion beam in the tail region is narrow. If the source is distributed over a wide area in the Earth's magnetotail having different bulk velocities at different areas [Takahashi and Hones, 1988;Zelenyi et al., 1990;Abdalla et al. 1991,1992], it requires more assumptions relating the width of the source region with the ion bulk velocity to explain the result in Figure 3.4. Since our simple model can well explain the results as shown in Figure 3.4, we suggest that the source of the ion beam is narrow, and the thermal distribution of the source determines the observed latitudinal width.

In order to calculate the source distance $\mathcal{L}$, we have to know the proportional constant in Equation (3.4), which is determined from the geometry of the magnetic field, and from the ratio between $(1/v_{slow} - 1/v_{fast})$ and $\{1/(\sqrt{E_0} - \sqrt{E_{th}}) - 1/(\sqrt{E_0} + \sqrt{E_{th}})\}$. Using the averaged constant value of Equation (3.2) of 8.7 (deg $\cdot$ keV$^{\frac{1}{2}}$), and assuming the convection velocity as 500m/sec at the magnetic footprint, we can roughly estimate the source distance as $\sim 70 R_e$. This value of the source distance is consistent with the model that ions are accelerated by the cross-tail electric field near the X-type neutral line in the geomagnetic tail.

We have shown that the calculated source distribution function of the ion beam can be well fitted with shifted-Maxwellian of which the orders of the temperature and the bulk velocity are consistent with the result of the model calculation by Lyons and Speiser[1982]. Since the source of the ion beam is far from the earth and the mirror ratio is large, the distribution functions we have obtained are those along the magnetic field line at the source. Takahashi and Hones[1988] investigated the distribution function of fast ion flow in the x direction of the GSE coordinate system observed at $x \sim -10R_E$, and reported that it could be fitted with a shifted-Maxwellian. The orders of the temperature and the bulk velocity of their results are nearly the same as ours.

We examined 259 passes between 20 MLT and 4 MLT, and found 119 events, in which we could recognize dispersive ion beams at the poleward edge of the auroral precipitation region. Among 119 events, 50 events can be fitted with a shifted-Maxwellian. Zelenyi et al.[1990] reported that they observed velocity-dispersed ion beams at the poleward edge of the auroral precipitation region with a probability of about 10% by examining the evening-midnight-dawn sector(18 MLT - 6 MLT). In their paper, it is noted that their result is consistent with the result of Baumjohann et al.[1990] that the probability of observing high-speed flows($>$ 400km/s) is 4% $\sim$ 6% at most. Our result shows that the probability of observing dispersive ion beams is about 45%. Even when we limit the events to those that can be fitted with a shifted-Maxwellian, the probability is about 20%. Since we have examined only the orbits between 20 MLT and 4 MLT, we cannot compare our result with that of Zelenyi et al.[1990] in the strict sense. The altitudes (4,000km to 10,000km) of the Akebono observations are also higher than those of Zelenyi et al.[1990] ($<$ 2000km). Even though the two observations were under different conditions, our probability of observing the ion beam seems to be much higher than that of Zelenyi et al.[1990]. We have observed the velocity-dispersed ion beams very frequently. This is consistent with the observations that the fast ion flow in the PSBL is a steady structure.[Lui et al.,1983;Eastman et al., 1984;Takahashi and Hones, 1988]

Chapter 4

Rapid Variations of the Plasma Bulk Flow Direction Observed in the Plasma Sheet

This chapter deals with three-dimensional variations of the plasma bulk flow direction in the plasma sheet observed at $X_{GSE} \sim -60$Re by Low Energy Particle (LEP) instrument onboard the GEOTAIL satellite. These variations have two components, namely a rapidly varying component of which the period is about 8 minutes and a more slowly varying component. Separating these two components, we have found two different periods during which the motion of the bulk velocity vector had different characteristics. In both periods, the slowly varying component nearly corresponded with the direction of the magnetic field. However, the motion of the rapidly varying component was different between these two periods. In one period, the rapidly varying component showed clear rotations. We have calculated the rotation axis of this rapidly varying component and have found that the direction of the rotation axis changed by nearly 90° in a step-like motion while the vortex motion remained coherent in the plane perpendicular to the moving rotation axis. In the other period, the rapidly varying component was not a rotation but an oscillation around an axis which is nearly parallel to the magnetic field. We conclude that these variations are most likely due to tail flapping motion with velocity shears.

4.1 Introduction

In the distant tail, the motion of the satellite with respect to the sun-Earth fixed frame is very small compared with the scale of the magnetotail. However there exists a flapping motion of the magnetotail, for example, due to variations of the solar wind dynamic pressure. The motion of the magnetotail with respect to the sun-Earth fixed frame enables us to observe various regions of the magnetotail including the PSBL crossings.

On the basis of the observations by ISEE 1 and 2 spacecrafts during substorms, Forbes et al.[1981b] reported some examples of the motion of the magnetotail which were due to both passage of the surface wave generated by Kelvin-Helmholtz type of instability and thinning and thickening of the magnetotail during substorm. Hones et al. [1984] also investigated the motion of the magnetotail statistically, and concluded that the motion was due to a thinning and thickening of the plasma sheet during substorm. However, even when the magnetic condition is moderate to weak, satellites encounters the PSBL, which suggests the existence of the tail flapping motion due to mechanism(s) other than the plasma sheet thinning/thickening.

In the near-tail region around X_{GSE} ~-10Re to X_{GSE} ~-20Re, rotations of the ion bulk flow direction, the period of which is 5−20 minutes, have been observed by ISEE 1 and 2 satellites [Hones et al., 1978, 1981, 1983; Saunders et al., 1981, 1983a,b]. Hones et al. [1978] suggested that the rotations were caused by vortex like structures which convect earthward along the axis of the magnetotail. Hones et al. [1981] gathered 169 two-dimensional data, and investigated the rotations statistically. They found that the preferred sense of the rotation is clockwise in the dawn side plasma sheet and counter-clockwise in the dusk side plasma sheet. They concluded that the rotations can be explained by vortex structures on the GSE x-y plane which were produced by Kelvin-Helmholtz instability due to the shear plasma flow between the plasma sheet and the boundary layer. They also found that the occurrence of the vortex-like flow is independent of the geomagnetic activity. Saunders et al. [1981, 1983a,b] investigated similar rotating structures using the plasma data and magnetic field data simultaneously and found that the rotations of the ion bulk flow direction can be explained by MHD waves.

The rotations of plasma bulk flow direction were also observed in the distant-tail region around 200Re by the ISEE 3 low energy electron experiment [Sanderson et al. 1984]. They found 15 min period vortex-like motion both in the energetic ion data (>35keV) and in the low energy electron data, when the satellite was between the plasma sheet and south lobe.

The measurements presented here from the GEOTAIL LEP experiment have been used to investigate the full three dimensional nature of plasma vortices. We will show that the three dimensional motions of the plasma bulk flow direction can be separated into the ion flow along the magnetic field and two different motions. One is the rotations around an axis whose direction slowly changes with step-like motion keeping its direction roughly perpendicular to the magnetic field direction. This step-like motion of the rotation axis is the new feature of the vortex event we have found. The other is the oscillation around an axis whose direction is nearly parallel to the magnetic field direction.

4.2 Observation

We have analyzed the data obtained by Low Energy Particle - Energy Analyzer (LEP-EA) on the GEOTAIL satellite. This instrument provides three-dimensional distribution functions of electrons (8eV – 38keV) and ions (32eV/e – 43keV/e) every four-spin period(13.1s) during the present observation. A detailed description of the LEP-EA is given in Chapter 2, Appendix A and Mukai et al. [1994b].

On August 20, 1992, the GEOTAIL satellite was at a medium down-tail distance of X~ -60Re, Y$\sim$ 10Re, Z$\sim$ 5Re in the GSE coordinate system. Plasma observations were made for about four hours from $\sim$1300 UT to 1700

UT. During this period, the magnetogram data on the ground (not shown) was quiet (Kp$\sim$2), though there was a substorm onset around 1140 UT and magnetic conditions were considerably disturbed before 1200 UT (Kp$\sim$4). Figure 4.1(a)(b) show E-t diagrams of electrons and ions between 1300 UT and 1700 UT. The maximum count rate obtained over all the angular directions is shown by gray scale at a given energy and time. The energy range of the electron detector was changed at 1516 UT (indicated by an arrow in Figure 4.1(a)). Figure 4.1(c) – (f) show the velocity moments of the electrons (small dots) and ions (large dots; assuming protons) during the same time interval as the E-t diagram. From top to bottom, density, magnitude of the bulk velocity, elevation and azimuthal angles of the bulk velocity vector in the GSE polar coordinate system are shown. Comparing the electron data with the ion data, we can see that the electron density was much lower than ion density before 1516 UT, because we did not observe electrons below $\sim$60eV. We lowered the energy range of the electron detector at 1516 UT. The electron density and ion density nearly agreed after this time. Therefore the actual density of electrons might be nearly the same as the ion density before 1516 UT. The magnitude and the direction of the bulk flow velocity vector of electrons and ions nearly agreed throughout the whole period. Since the bulk velocity is decided from the velocity shift of the distribution function, it is less affected by the observed energy range than density.

At 1300 UT, the satellite was in the plasma sheet, and the density value was 1.5 cm^{-3}. About 5 minutes later, the density decreased to be below 0.1 cm^{-3}, indicating that the spacecraft was in the lobe region. During this period the bulk flow direction was tailward ($\phi \sim 180°$). At ~1310 UT, the satellite re-entered the plasma sheet, and the density increased to be 2.0 cm^{-3}. The bulk flow direction also changed to be earthward in the ecliptic plane. Between 1328 UT and 1345 UT, we observed earthward flowing ions with the bulk velocity of several hundred km/s, which is similar to the fast ion flow observed in the near-tail plasma sheet boundary layer (PSBL) [Nakamura et al., 1992; Takahashi and Hones, 1988 and references there in]. After that the magnitude of the bulk velocity gradually decreased to as low as 100 km/s. Around 1400 UT, rapid variation of the bulk flow direction began, and this variation continued until the end of the observation at 1700 UT. The spacecraft stayed in the plasma sheet during the interval when these rapid variations were observed in panels (e) and (f). Since the elevation angle shows large variations, we see that these variations are not confined in the ecliptic plane, but are three-dimensional. The magnitude of the bulk velocity also changed simultaneously with the variation of the bulk flow direction as we can see in panel (d).

Between 1400 UT and 1420 UT, the flow direction was nearly tailward, and the elevation angle changed from northward to southward. After 1420 UT, the flow direction changed to be mainly earthward, and the elevation angle slowly changed to be southward. Around 1420 UT, we observed intense ion flow at low energy (about 200eV). Between 1500 UT and 1540 UT the azimuthal angle oscillated between earthward direction and tailward direction, while the elevation angle was tilted southward. After 1540 UT the flow direction was mainly tailward.

Figure 4.2 (a)(b)(c) show the spectra of the variations of the angles between the ion bulk flow direction and GSE x, y, z axes (θ_x, θ_y, and θ_z, respectively) during the time interval between 1440 UT and 1632 UT. We have normalized the spectra by the highest power in each spectrum. In all of these three panels, the peaks with the most intense power have the time period longer than 20 minutes. In the spectra of θ_x and θ_y, we can see three peaks which has the time period shorter than 20 minutes. These peaks have the time period of $\sim$10 minutes, $\sim$8 minutes, and $\sim$ 5 minutes. In the spectrum of θ_z, there are also three peaks which have the time period shorter than 20 minutes. These three peaks have the period of $\sim$15 minutes, $\sim$6 minutes, and $\sim$4 minutes. Though the existence of the component with long time period can be clearly seen in the panels (a), (b), and (c), the time variation of the spectra cannot be obtained from these spectra with long time window. In order to investigate the time variation of the spectra, we have calculated the dynamic spectra with shorter time window.

Figure 4.2 (d)(e)(f)(g) show the dynamic spectra of the angles θ_x, θ_y, θ_z, and the magnitude of the ion bulk velocity during the time interval between 1428 UT and 1634 UT, nearly the same time interval as the panels (a)(b)(c).

The spectra are calculated every 2 minutes with the time window of 3354 seconds, using the data between 1400 UT and 1700 UT. We have normalized the spectra by the highest power in each spectrum as before. The dynamic spectrum of θ_x, θ_y, and θ_z varied differently, indicating that the variation of the bulk flow direction was 3-dimensional. The dynamic spectrum of the magnitude of the bulk flow velocity shows the mixed characteristics of the spectra θ_x, θ_y, and θ_z. When the variation is 3-dimensional, it is difficult to obtain the spectrum of the motion by calculating the spectra of the three angles θ_x, θ_y, and θ_z separately, because these spectra are affected by selection of the coordinate system. The magnitude of the velocity is a good indicator of the motion, because it can describe the motion by only one parameter. There are two maxima in the spectrum of the magnitude of the bulk velocity during more than a half of the time interval shown in Figure 4.2 (d)–(g). One maximum is between the period of 479 seconds and 838 seconds, and another maximum is in the period longer than 3354 seconds. The maximum of the shorter time period of these two can be found almost all the time after 1445 UT. In order to separate these two components, a rapidly varying component and a slowly varying component, we have conducted a running average over the bulk flow velocity vector. We have selected two 40-minute periods 1445 UT – 1525 UT (period 1) and 1606 UT – 1646 UT (period 2) (indicated in Figure 4.1), and have investigated the variation of the bulk flow direction in detail. These are the intervals when the variations with short time period were clearly seen in the spectrum of the magnitude of the bulk velocity (see Figure 4.2(g)).

Figure 4.3 shows the rapidly varying component of the bulk flow velocity vector projected on GSE x-y, x-z, and y-z planes during the time interval between 1400 UT and 1700 UT. We obtained this rapidly varying component by subtracting 20-minute running averaged data from 2-minute running averaged data. We can see the rotations, oscillations, and other complicated motions throughout the observed period. During the 'period 2' (indicated by an arrow in the figure), rotations were clearly seen in the x-y and x-z projection. During the 'period 1' (also indicated by an arrow in the figure), the motion was not so clear as during the 'period 2'. It was an oscillation rather than a rotation. During other periods, the motions were more complicated, and we cannot describe them by simple rotations nor by oscillations.

At first, we will investigate the 'period 2', during which clearer motion (rotation) than the motion during the 'period 1' can be seen. Figure 4.4 shows the 20 minute running averaged ion bulk flow velocity vector in the GSE polar coordinate system (solid line). Though unfortunately the magnetic field data are not available during the present observation, we have estimated the direction of the magnetic field (shown by dots in Figure 4.4) from anisotropy of the electron pressure tensor assuming that the electron distribution is gyrotropic, and either (a) of spindle shape ($P_{\parallel} > P_{\perp}$) or (b) of pancake shape ($P_{\parallel} < P_{\perp}$). We can see that the direction of the slowly varying component of the bulk flow velocity vector agreed roughly with the orientation of the magnetic field line.

In order to estimate the magnetic field direction, we have calculated the directions of the three principal axes, <a1>, <a2>, and <a3>, and the corresponding diagonal components, P_1, P_2, and P_3 ($P_1 > P_2 > P_3$) of the electron pressure tensor. When $1 - P_2/P_1 > 0.04$ and $P_2/P_1 - P_3/P_1 < 0.03$ the magnetic field direction is the direction of axis <a1> (category (a) : $P_{\parallel} > P_{\perp}$). When $1 - P_2/P_1 < 0.03$ and $P_2/P_1 - P_3/P_1 > 0.04$ the magnetic field direction is the direction of axis <a3> (category (b) : $P_{\parallel} < P_{\perp}$). Of the observed electron distributions, 17% fall into category (a), and 40% into category (b) during the time interval shown in Figure 4.4. We cannot decide the magnetic field direction for the remaining 43% of the observed electron distribution. This method, of course, leaves a $\pm 180°$ uncertainty. We have chosen the direction closer to the plasma flow direction in Figure 4.4. Figure 4.5 shows an example of the electron distribution function. Panel (a) shows the distribution function on the equatorial plane and Panels (b) and (c) show the distribution function on two planes perpendicular to the equatorial plane. This example falls into the category (a), and we can see that the electron distribution function is elongated along a direction which we have regarded as magnetic field direction.

Figure 4.6(a)(b)(c) shows the rapidly varying component of the bulk flow velocity vector in the GSE polar coordinate system. We have obtained this rapidly varying component by subtracting the 20-min running averaged data (as shown in Figure 4.4) from 2-min running averaged data. The azimuthal angle clearly rotated counter-clockwise three times as viewed from the positive z direction.

In order to analyze the motion of the rapidly varying component in more detail, we have calculated the direction of the instantaneous rotation axis. We have calculated the instantaneous rotation axis (n_x, n_y, n_z) of the bulk flow direction requiring that the function

$$f(n_x, n_y, n_z) = \sum_i (n_x V_{xi} + n_y V_{yi} + n_z V_{zi})^2 \tag{4.1}$$

should have the minimum value under the constraint

$$n_x^2 + n_y^2 + n_z^2 = 1, \tag{4.2}$$

where (V_{xi}, V_{yi}, V_{zi}) is the bulk flow velocity at the time indicated by i. This problem is solved by using Lagrange's method of undetermined multipliers. We have determined (n_x, n_y, n_z), which makes the following function

$$g(n_x, n_y, n_z, a) = \sum_i (n_x V_{xi} + n_y V_{yi} + n_z V_{zi})^2 - a(n_x^2 + n_y^2 + n_z^2 - 1) \tag{4.3}$$

minimum, where 'a' is the undetermined multiplier. This procedure corresponds to calculating the eigenvector of the smallest eigenvalue of the matrix

$$\begin{pmatrix} \sum_i V_{xi}^2 & \sum_i V_{xi}V_{yi} & \sum_i V_{xi}V_{zi} \\ \sum_i V_{xi}V_{yi} & \sum_i V_{yi}^2 & \sum_i V_{yi}V_{zi} \\ \sum_i V_{xi}V_{zi} & \sum_i V_{yi}V_{zi} & \sum_i V_{zi}^2 \end{pmatrix}$$

We have used successive 21 data (~ 275 seconds) in calculating the instantaneous rotation axis.

The result is also shown in Figure 4.6. Panel (d) shows $p_p \equiv n_y^2 + n_z^2$, where n_y, and n_z are GSE-y, z components of the unit vector in the direction of the rotation axis. The rotation axis is almost perpendicular to the GSE x axis, because p_p is almost at its maximum value of 1.0. Panel (e) shows the angle B_a between the estimated magnetic field direction and the rotation axis. The rotation axis remained roughly perpendicular to the magnetic field direction. Panel (f) shows the angle Z_a between the GSE z axis and the rotation axis of the rapidly varying component of the bulk flow velocity vector projected on the GSE y-z plane, $Z_a = \arctan(n_y/n_z)$. The direction of the rotation axis itself changed slowly with a step-like motion, keeping its direction perpendicular to the x direction, as can be seen from the nearly constant value of p_p around 1.0.

The variation of the bulk flow direction during 'period 1' was different from that during 'period 2'. It was an oscillation rather than a rotation. Figure 4.7 shows the 14-min running averaged ion bulk flow velocity vector in the GSE polar coordinate system (solid line). The estimated direction of the magnetic field direction is also plotted by dots in Figure 4.7. Different from the case of 'period 2', we have conducted 14-min running average, because the slowly varying component had shorter time period during 'period 1' than during 'period 2' (see Figure 4.2 (g)). We can also see that the estimated magnetic field direction roughly agrees with the direction of the 14-min running averaged ion bulk flow direction during the time interval between 1445 UT and 1525 UT.

Figure 4.8 (a)(b)(c) shows the rapidly varying component of the ion bulk flow velocity vector in the GSE polar coordinate system. We have obtained this rapidly varying component by subtracting the 14-min running averaged data from 2-min running averaged data. Figure 4.8 (d) shows the angle B_a, which is the angle between the instantaneous rotation axis and the estimated magnetic field direction. During the time interval between 1448 UT and 1514 UT, the angle B_a was nearly $0°$, which means that the instantaneous rotation axis was nearly parallel to the magnetic field direction. During 1448 UT – 1502 UT, the azimuthal angle showed about $270°$-clockwise rotation, whereas it showed about $270°$-counterclockwise rotation during 1502 UT – 1514 UT. The polar angle showed a symmetric pattern with respect to the time 1502 UT. Therefore the motion of the rapidly varying component of the bulk flow direction during 'period 1' can be described as an oscillation ($\pm 270°$) around an axis nearly parallel to the magnetic field direction.

4.3 Discussion

We have used the three-dimensional low-energy particle observations from the GEOTAIL/LEP experiment to examine the structure and evolution of the plasma bulk flows in the mid-tail plasma sheet. We have found that the plasma bulk flow consisted of a slowly varying component and a rapidly varying component. During the time interval between 1606UT and 1646UT, the direction of the slowly varying component nearly corresponded to the direction of the magnetic field. During this period the rapidly varying component was not a simple two-dimensional vortex motion, but rather a three-dimensional vortex motion whose axis was roughly perpendicular to the magnetic field and changed in a step-like way.

The sense of the rotation was counter-clockwise throughout the event when viewed from above the ecliptic plane. Since our observation was made at Y_{GSE} ~10Re, this result is consistent with the result of Hones et al. [1981] that the preferred sense of rotations of the vortex event is clockwise in the morning sector, and counter-clockwise in the evening sector when viewed from above the ecliptic plane.

Period of the rotational motion was about 8 min. Since the velocity of the slowly varying component (background flow) was $30 \sim 70$ km/s, spatial scale of the rotational motion is estimated to be $2 \sim 5$ Re if the rotation is due to passage of a spatial structure carried by the background flow. This scale size is consistent with the result obtained by Mitchell et al. [1990].

The step-like change in the rotation axis corresponds to the step-like change in the plane of the rotation. At three successive phases of the rotation the plane was inclined by nearly -45°, 0°, and 45° with respect to the ecliptic plane. In earlier publications the cases where the plane of the rotation was nearly coplanar with the ecliptic plane [Saunders et al. 1984] or highly inclined [Hones et al. 1978] were reported. The present observation shows that this plane can take various directions which change in a step-like manner.

The three-dimensional vortex motion with step-like changes in the rotation axis could be caused by flapping motion of the magnetotail if the field-aligned component of the flow velocity is sheared. When the average is subtracted from the observed velocities, the field aligned component oscillates in the presence of the shear, and the combination with the flapping motion produces a rotational motion in a plane that includes the direction of the direction of the magnetic field. The step-like change in the rotational axis means that the direction of the flapping motion changes in the step-like manner.

Alternatively the observed rotations in the flow direction could be related to MHD waves as suggested by Saunders et al. [1981, 1983a,b], Hones et al. [1983], and Southwood et al. [1985]. If this is the case the step-like changes in the rotation axis corresponds to changes in the plane of polarization. The absence of the simultaneous magnetic field observations precludes further comparison of the MHD wave model with the present observation.

We have shown that the motion of the rapidly varying component of the bulk flow direction between 1445 UT and 1525 UT can be described as an oscillation ($\pm 270°$) around an axis which is nearly parallel to the magnetic field direction. It is difficult to explain such an oscillation by MHD waves. Alternatively we explain this motion by assuming that there is a shear flow layer in the plasma sheet, and the satellite oscillated inside the shear layer as a result of the flapping motion of the magnetotail.

Figure 4.9 shows the schematic diagram of this model. The assumed shear flow layer is shown in panel (a), in which there is a layer (layer (B) in the figure) where the bulk flow direction is opposite to the flow direction outside the layer. The motion of the satellite is shown in panel (b). The numbers from (1) to (9) shows the sequence of the satellite motion. The velocity vectors are also shown in the figure. The resultant flow direction is shown in panel (c), in which the numbers from (1) to (9) correspond to the numbers shown in panel (b). The rotation angle is decided from the velocity ratio between the flow velocity in the layer (B) and the velocity of the satellite at the position (5), and it is between 270° and 360°.

Assuming this model we can calculate the average velocity of the flapping motion and its direction. The direction is shown in Figure 4.9 (d). It is a one dimensional motion on y-z plane with the average velocity of 40 km/s and with the period (the time interval from (1) to (9)) of about 19 minutes. The direction of the oscillation is inclined about 60° from the y axis in the y-z plane.

In summary, we have analyzed three-dimensional motions of the plasma bulk flow in the magnetotail, which can be separated into a slowly varying component and a rapidly varying component. The former is aligned to the magnetic field and the latter is rotations around an axis whose direction is perpendicular to the magnetic field or an oscillation around an axis whose direction is nearly parallel to the magnetic field. Combination of the spatial gradient in the bulk flow and the flapping of the tail is suggested as a possible cause of the latter component of the motion.

Chapter 5

Slow-Mode Shocks in the Magnetotail

We have identified slow-mode shocks between plasma sheet and lobe in the mid-tail to distant-tail regions by using three-dimensional magnetic field data and three-dimensional plasma data including density, velocity, temperature, and heat flux of both ions and electrons observed by the GEOTAIL satellite. Analyzing the data obtained between 14 September, 1993 and 16 February, 1994, we have found 303 plasma sheet-lobe boundary crossings. During this period the spacecraft crossed plasma sheet-lobe boundaries at distances between $X_{GSE} \sim -30$Re and $X_{GSE} \sim -210$Re. Thirty-two out of these 303 boundaries are identified as slow-mode shocks. We have found backstreaming ions on the upstream side of the slow-mode shocks, which may be important in understanding the dissipation mechanism of the slow-shocks in collisionless plasma. We have also found acceleration of cold ions between the upstream and the downstream of the slow-mode shocks. These cold ions are often observed in the lobe and they are usually flowing tailward. Upon entering the plasma sheet, they are accelerated and rotates around the magnetic field, and at times show ring-shaped velocity distributions. These ions may reflect the kinetic structure of slow-mode shocks. Slow-shocks are at times observed also on the front side of plasmoids. These slow-shocks on the front side of plasmoids have a different orientation from that of the ordinary slow-shocks observed at the plasma sheet-lobe boundaries, which suggests an existence of "heart" shaped plasmoids predicted by a numerical simulation [K. Maezawa, personal communication].

5.1 Introduction

The existence of an X-type neutral line in the magnetotail, which is expected from the reconnection model of the Earth's magnetosphere [Dungey, 1961], has long been a controversial problem. If magnetic field reconnection occurs in the magnetotail, slow-mode shocks are predicted to be formed at the boundaries between plasma sheet and lobe bounding the X-type neutral line [Vasyliunas, 1975 and references therein]. However, characteristics of the boundaries between plasma sheet and lobe, whether it is a simple discontinuity or it has a shock-like structure, has not fully been resolved from previous observations.

The existence of the slow-mode shocks in the distant-tail regions was for the first time reported by the ISEE 3 deep-tail mission [Feldman et al, 1984a,b, 1985; Scarf et al., 1984; Smith et al., 1984]. Analyzing the three-dimensional magnetic field data and two-dimensional electron data, Feldman et al. [1985] identified the slow-mode shocks and concluded that the slow-mode shock is a semi-permanent structure of the plasma sheet-lobe boundaries in the distant-tail region. They also noticed the variation of the electron distribution function, which shows heat flux leakage from the shock toward the upstream region as well as thermalization in the plasma sheet. At the same time, electrons are accelerated by the shock potential and form flat-top distributions in the downstream of the shock. The electron dynamics and the variation of the distribution functions through slow-mode shocks were investigated in detail by Schwartz et al. [1987].

The existence of the slow-shock structure in the near-Earth magnetotail at X~ -20Re was also reported by Feldman et al. [1987], based on three-dimensional magnetic field data and two-dimensional electron and ion data obtained by the ISEE 2 satellite. They reported that the lobeward edge of the plasma sheet-lobe boundary was identified as a slow-mode shock, which was different from the plasma sheet-lobe boundaries in the distant magnetotail where the entire boundary region had a slow-shock structure. Using the AMPTE/IRM data, Cattel et al. [1992] investigated $\sim$80 plasma sheet-lobe crossings at downtail distances of 10 to 18 Re. They concluded that the plasma sheet-lobe boundaries in the near-tail region were not well modeled by a planar MHD discontinuity with a normal component of the magnetic field, and in particular, did not contain a slow mode shock. They suggested that some factor operating earthward of the neutral line prevents the formation of slow-mode shocks in the near-tail region. They also suggested that the plasma sheet boundary in the near-Earth region is usually a tangential discontinuity, or there are effects such as time variations, single particle effects, or three-dimensional structures, which invalidate the assumptions of planar time-stationary magnetohydrodynamics.

The large-scale structure and dynamics of the magnetotail including the plasma sheet boundary layer (PSBL) have been numerically studied using MHD simulations. The existence of the slow-mode shocks in the PSBL is shown by Sato[1979], Scholer and Roth[1987], and Ugai[1993]. Birn et al. [1986] and Hesse and Birn [1991], on the other hand, reported that slow-mode shocks were not formed on the earthward side of the X-type neutral line, where the magnetic field is connected to the ionosphere.

The first theoretical work on the structure of slow shocks was made by Coroniti [1971], who showed that the slow shocks are associated with a dispersive wave train in the downstream region. He suggested that the energy dissipation of the slow-shock is provided by dumping of the dispersive wave train.

Several numerical simulations on kinetic properties of the slow-mode shocks have been reported as well. With a hybrid-code simulation Swift [1983] found the upstream escape of the hot plasma and a damped left-handed circularly-polarized wave on the trailing edge of the shock. Omidi and Winske [1992] also used a hybrid-code simulation to investigate the structure of slow shocks and ion heating in the low-beta regime. In particular, they studied the effects of the Alfvén/ion cyclotron waves on the structure of slow-mode shocks. The Alfvén/ion cyclotron waves are generated by the interaction between the incident and backstreaming ions via electromagnetic ion/ion cyclotron instability.

Observational study on the kinetic property of the slow-mode shocks in the distant magnetotail has not been done because of insufficient time resolution in previous observations. The low energy particle (LEP) experiment onboard the GEOTAIL satellite [Mukai et al., 1994b] has provided us with three-dimensional velocity distributions of electrons and ions with fine time resolution. The GEOTAIL satellite has crossed the plasma sheet-lobe boundaries for many times in various distances from the Earth. We have identified slow-mode shocks in a more strict way with a complete set of plasma and field data than previous observations.

5.2 Instrumentation and Velocity Moment Calculation

We have used the data obtained by the Low Energy Particle - Energy Analyzer (LEP-EA) and the Magnetic Field (MGF) experiment onboard the GEOTAIL satellite. LEP-EA provides three-dimensional distribution functions of electrons (8eV – 38keV) and ions (32eV/e – 43keV/e) every four spin periods (about 12 seconds). A detailed description of LEP-EA is given in Chapter 2, Appendix A, and Mukai et al. [1994b]. MGF measures vector magnetic fields with a time resolution of 1/16 seconds. We have used spin-averaged vector magnetic field data. A detailed description of MGF is given in Kokubun et al. [1994].

We have calculated the three-dimensional ion and electron velocity moments up to the third order (density, velocity vector, pressure tensor and heat flux tensor) using the count rate data obtained by LEP-EA. Since the spacecraft is positively charged with respect to the ambient plasma potential, the observed ions are decelerated and the observed electrons are accelerated by the spacecraft potential. The measured energy, therefore, must be corrected in calculating the velocity moments from the count rate data. The spacecraft potential can be estimated from an inflection point of the electron distribution function which separates the low-energy photoelectron distribution and the incoming accelerated plasma electron distribution. However, applying this method of estimating the spacecraft potential to the automatic calculation of the velocity moments is difficult because the spacecraft potential varies in accordance with the plasma density around the spacecraft. We have used an alternative way to estimate this spacecraft potential using single-probe potential data obtained by the Electric Field Detector (EFD) experiment onboard the GEOTAIL satellite [Tsuruda et al., 1994].

The measured count rate data at several lowest energy steps are contaminated by the spacecraft photoelectrons. When we calculate the electron velocity moments, we have to remove these contaminated counts. We have removed the photoelectron-contaminated data and replaced them by Gaussian extrapolation using the data in three to five energy steps above the spacecraft potential, which are free from the photoelectron contamination.

The corrected count rates and corrected energy levels are used to calculate the electron and ion velocity moments.

5.3 Method of Identification

We have used spin-averaged three-dimensional magnetic field data $\mathbf{B}$ and three-dimensional plasma velocity moments obtained during a four-spin period. Density ρ, bulk velocity vector $\mathbf{V}$, temperature T, and heat flux vector $\mathbf{h}$ of electrons and ions are derived from the velocity moments. With requirement that the normal component of the magnetic field is kept constant throughout the shock, we have determined the shock normal direction $\mathbf{n}$ as follows.

$$\mathbf{n} = \frac{(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_2 - \mathbf{B}_1)}{|(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_2 - \mathbf{B}_1)|}, \tag{5.1}$$

where the subscripts '1' and '2' represent upstream and downstream, respectively.

In order to identify slow-mode shocks, we have checked if one-dimensional Rankine-Hugoniot relation is satisfied between the upstream (lobe) and the downstream (plasma sheet) MHD parameters. The one-dimensional Rankine-Hugoniot relation is applied in the normal incidence frame (NIF). From the conservation of mass flux, we have determined the shock rest frame and the shock velocity $\mathbf{V}_s$, as follows.

$$\mathbf{V}_s = \frac{(\rho_1 \mathbf{V}_1 - \rho_2 \mathbf{V}_2)\cdot\mathbf{n}}{\rho_1 - \rho_2}\mathbf{n} \tag{5.2}$$

We have calculated the downstream parameters ρ_{rh2}, $\mathbf{V}_{rh2}$, and $\mathbf{B}_{rh2}$ from the upstream parameters $\rho_1 = \rho_{i1} = \rho_{e1}$, $\mathbf{V}_1 = \mathbf{V}_{i1} = \mathbf{V}_{e1}$, and $\mathbf{B}_1$, using the mass conservation and momentum conservation equations with upstream and downstream temperatures, $T_1 = T_{i1} + T_{e1}$ and $T_2 = T_{i2} + T_{e2}$, where the subscripts 'e' and 'i' represent electrons and ions, respectively, and the subscript 'rh' represents calculated parameters using R-H relation. We have compared the calculated downstream values with the observed downstream values shown in Figure 5.1. We have checked if the total energy flux E_{tot} is conserved using observed upstream and downstream values. In calculating the total energy flux, we have assumed the polytrope index γ as 5/3. The coplanarity of the plane of the magnetic field variation and the plane of the plasma velocity variation is also checked by calculating the angle between the normal of these two planes,

$$\Delta\phi_{bv} = \arccos\left(\frac{\mathbf{B}_1 \times \mathbf{B}_2}{|\mathbf{B}_1 \times \mathbf{B}_2|} \cdot \frac{\mathbf{V}_{NIF1} \times \mathbf{V}_{NIF2}}{|\mathbf{V}_{NIF1} \times \mathbf{V}_{NIF2}|}\right). \tag{5.3}$$

Our criterion for the R-H relation to be satisfied is that the difference between the calculated and observed values (ρ, B, V) is within 30%, the difference between upstream and downstream total energy fluxes is within 30%, the difference between the calculated and observed angles (θ_B, θ_V) is within 10°, and the angle $\Delta\phi_{bv}$ is within 30°. The boundary is identified as a slow-mode shock if the upstream normal incident velocity V_{1n} and the downstream normal velocity V_{2n} satisfy the relations, $V_{imd1} \geq V_{1n} > V_{sl1}$ and $V_{sl2} > V_{2n}$, where V_{imd} and V_{sl} represent intermediate and slow-mode velocities, respectively.

Besides the R-H relations, we have checked the electron heat flux leakage from the shock to the upstream region, and the flat-top distribution of electrons in the downstream region of the shock [Feldman et al., 1984, 1985].

We could have calculated all the downstream parameters from the upstream parameters using mass flux conservation, momentum flux conservation, and energy flux conservation equations, assuming that the upstream and downstream heat fluxes are zero. However, the measured plasma data show that upstream heat flux is not negligible because there is heat flux leakage from the shock to the upstream region. There may be an alternative way to calculate the downstream parameters from the upstream parameters giving the upstream and downstream heat fluxes in the energy conservation equation. We tried this method, but it turned out that about 5 % error in the estimation of the heat flux makes a significant effect on the identification of slow-mode shocks. Since the observational error in the heat flux is estimated to be $\sim$ 15%, we have abandoned this method.

In the present analysis, the existence of the slow-mode shocks is examined by searching for the upstream and downstream regions where the criteria of the slow-mode shock described above are satisfied. In order to suppress the statistical error and the wavy structure included in the observed parameters, we have made some average on the observed parameters. Varying the averaging period between 30 seconds and 6 minutes, we have searched for the upstream and downstream regions where the criteria of the slow-mode shock are most properly satisfied.

5.4 Examples of Slow-Mode Shocks

Figure 5.2 shows vector magnetic field data and plasma parameters obtained on 14 January, 1994, when the GEOTAIL satellite was at $X_{GSE} \sim$ -96.1 Re, $Y_{GSE} \sim$ 8.4 Re, and $Z_{GSE} \sim$ -4.5 Re. We have found a slow-mode shock in the transition from lobe to plasma sheet around 1540UT. Before 1540UT the spacecraft was in the lobe, where the magnetic field was about 10 nT and plasma density was about 0.02 $/cm^3$. The azimuthal angle ϕ_b of the magnetic field was $\pm 180°$, which means that the satellite was in the southern lobe. The plasma bulk velocity was about 150 km/s and its direction was tailward. At about 1540UT the satellite entered the plasma sheet, where the magnetic field decreased to be about 5 nT. It became stable to be about 8 nT at about 1545UT. The plasma density increased to be about twice the density in the lobe, and the ion and electron temperature increased simultaneously. The plasma bulk flow velocity increased to be about 800km/s and the direction changed to be earthward.

We have checked if the upstream and downstream magnetic field and plasma data satisfy the one-dimensional Rankine-Hugoniot relation. We have selected the upstream and downstream regions to get the best agreement between the calculated downstream values and the observed values. The selected upstream and downstream periods are shown in Figure 5.2.

Table 5.1 shows a summary of the upstream and downstream parameters of four examples of slow-mode shocks observed at $X_{GSE} \sim -100$Re. The locations of the four shocks are different with respect to the expected X-type neutral line. The example No.1 in Table 5.1 corresponds to the slow-mode shock observed on 14 January, 1994. Since we have calculated the downstream values by giving the upstream and downstream temperature, we can compare five parameters: density, bulk velocity (2 parameters), and magnetic field (2 parameters). The calculated downstream values and the observed downstream values show a reasonable agreement. The variation in the ion temperature is much larger than the electron temperature variation, which suggests that the observation of the ion temperature is very important in identification of the slow-mode shocks. We have checked the energy flux conservation by calculating the total energy flux E_{tot}. Table 5.1 also shows the upstream Alfvén Mach number $M_A = V_{1n}/V_A$, where V_A is Alfvén velocity, and the intermediate and slow Mach numbers $M_i = V_n/V_{imd}, M_s = V_n/V_{sl}$

in both the upstream and downstream regions of the shock. The result of the coplanarity check, the shock normal direction, and the shock velocity are also shown in Table 5.1.

The satellite position in the GSE coordinate system is also shown in Table 5.1. A schematic configuration of the satellite position with respect to the expected X-type neutral line is shown at the bottom. The example (No. 1) shown in Figure 5.2 was observed in the southern lobe. Since the flow direction of the downstream plasma was earthward, the shock was expected to be on the earthward side of the X-type neutral line.

Figure 5.3 shows examples of electron distribution functions parallel to the magnetic field in the upstream (lobe) region, downstream (plasma sheet) region and between these two regions, corresponding to the slow-mode shock shown in Figure 5.2. The direction of the positive velocity is the magnetic field direction. Electron heat flux towards the upstream direction (opposite to the magnetic field direction) can be clearly seen in the upstream region. As the spacecraft moves into the plasma sheet, the electron distribution is thermalized, and then a flat-top distribution can be seen in the downstream region.

Figure 5.4(a) shows the E-t diagram of ions obtained on 14 January, 1994 (including the shock No. 1 in Table 5.1). The maximum count rate obtained over all the angular directions of elevation and azimuth is shown by color-coded intensity at a given energy and time. The upstream and downstream regions are indicated in the figure. It should be noted that acceleration of cold ions [Hirahara et al., 1994] is observed between these two periods. We have separated this E-t diagram into four directions, tailward, dawnward, earthward, and duskward in Figures 5.4(b) - (e). The accelerated cold ions are mainly flowing dawnward, nearly perpendicularly to the magnetic field direction.

Figure 5.5(a) shows an E-t diagram of ions obtained on 17 January, 1994 (including the shock No. 3 in Table 5.1) in the same format as Figure 5.4(a). Figure 5.5(b) shows pitch angle distribution of ions in the de-Hoffmann Teller frame determined from the shock parameters. In Figure 5.5(b), the phase space density integrated over the whole energy range is shown by color-coded intensity for every 18 degrees with respect to the magnetic field direction. In the downstream region, the ion temperature is high and the pitch angle distribution is broad in the opposite direction to the magnetic field. The direction of the broader pitch angle distribution corresponds to the direction toward the deeper inside the plasma sheet, since the satellite position was tailward of the X-type neutral line in the southern lobe (see Table 5.1). On the other hand, in the upstream region, the ion temperature is cold and the pitch angle distribution is collimated in the direction toward the plasma sheet, which is opposite to the magnetic field. Around the edge of the plasma sheet-lobe boundary ($\sim$ 1537UT), we can find the region where particles are streaming toward two opposite directions, namely along and against the magnetic field direction. The ions which have an pitch angle along the magnetic field direction corresponds to the high-energy ions seen in Panel (a). These ions may be back streaming ions predicted by numerical simulations [Swift, 1983; Omidi and Winske, 1992].

5.5 Slow-Mode Shocks around Plasmoids

Figure 5.6 shows magnetic field and plasma velocity moments between 1030 UT and 1100 UT obtained on 18 September, 1993. About 1035 UT, the spacecraft entered the plasma sheet with a plasmoid encounter. The polar angle of the magnetic field direction shows two successive bipolar signatures, which means the arrival of two successive plasmoids, though the latter bipolar signature is very oscillative. Figure 5.7 shows the omnidirectional E-t diagram of ions during the same time interval as shown in Figure 5.6.

We have checked if the plasma-sheet lobe boundaries bounding a plasmoid satisfy the slow-shock conditions. The slow-shock conditions are examined for the two plasma sheet-lobe crossings when the spacecraft entered the plasmoid at $\sim$1035UT and exited the plasmoid at $\sim$ 1050UT. The result in the former time period (the front side of the plasmoid) is shown in Table 5.2. The result in the latter period (at the plasmoid exit) has already been shown in Table 5.1 (No. 4). The observed downstream values and calculated downstream values show good coincidence in both cases.

We have confirmed that in both cases of the plasmoid entry and exit, the electron distribution function parallel to the magnetic field (not shown) shows heat flux leakage in the upstream region consistent with the shock normal direction, while the flat-top electron distributions are observed in the downstream region. A remarkable difference between the plasmoid entry and exit is found in the shock normal direction. When the satellite exited the plasmoid, the Z_{GSE} component of the shock normal direction was positive, which means that the downstream region with hot plasma was in the southward of the upstream region (northern lobe with cold ions). This is an ordinary arrangement seen in the plasma sheet boundary layer. However, when the spacecraft entered the plasmoid, the Z_{GSE} component of the shock normal direction was negative, which means that the downstream region with hot plasma was in the northward of the upstream region, notwithstanding that the spacecraft was in the northern lobe. This arrangement is reverse to the arrangement of the slow-mode shock observed at the plasmoid exit. The slow-mode shocks with such "reverse" arrangement are, at times, observed on the front side of plasmoids.

It is also noted that the shock velocity on entering the plasmoid is faster than the upstream plasma velocity flowing into the shock. The shock surface on the front side of the plasmoid is expanding or flowing tailward, and it absorbs the upstream plasma flowing tailward with slower speeds than the shock velocity. The upstream plasma absorbed by the plasmoid is thermalized and accelerated tailward at the slow-mode shock in front of the plasmoid.

5.6 Statistical Study of Slow-Mode Shocks

5.6.1 Classification of the Plasma Sheet-Lobe Boundaries

We have checked if the slow-mode shock conditions are satisfied for all the plasma sheet-lobe boundary crossings when three-dimensional plasma (LEP) data and magnetic field (MGF) data are both available between 14 September, 1993 and 16 February, 1994. Some of the plasma-sheet lobe crossings are too rapid to be identified as slow-mode shocks. We have selected the crossings which have at least 5 minutes continuous upstream (lobe) and downstream (plasma sheet) regions, which totally amount 308 crossings.

The orbit of the GEOTAIL satellite in the GSE coordinate system during this period is shown in Figure 5.8. The dots in the figure show the position of the satellite at 0000UT every day. The large dots show the first day in each month. The periods when plasma sheet-lobe crossings are observed are indicated by thick lines in the orbit projected on the GSE X-Y plane. GEOTAIL satellite crossed the plasma sheet-lobe boundaries in the magnetotail of $X_{GSE} \sim -30$Re to ~ -210Re during this period.

Table 5.3 shows the result of the slow-shock identification. We have found totally 32 slow-shock boundaries in the 303 plasma sheet-lobe crossings. Nine of the 32 slow-shock boundaries are observed on the front side of plasmoids discussed in the previous section. The other cases which cannot satisfy our criterion for the slow shock conditions are classified into 8 types:

1. The calculated downstream value of either tangential plasma velocity or tangential magnetic field is greater or less than the observed one. We have assumed a one-dimensional slow-mode shock in the identification. If this assumption is not valid and there is a pressure gradient in the tangential direction, the calculated and observed tangential values may be different.

2. The upstream density is higher than downstream density. In this case, cold dense plasma is observed in the upstream (lobe) region. The occurrence of this case is notably high in the distant-tail region farther than X~ -140Re.

3. The ratio of the downstream plasma density to the upstream density is too large to satisfy the jump condition across the shock. In calculating the total energy flux, we have assumed the polytrope index γ as $5/3$. Therefore the permitted density jump across the shock should be less than 4.

4. Variations of the electron and ion distribution functions do not indicate the connection of magnetic field lines between the upstream and downstream regions. If magnetic field is connected between the upstream and downstream regions, electron heat flux leakage and/or backstream-

ing ions may be observed in the upstream region, electron flat-top distribution may be observed in the downstream region, and/or acceleration of cold ions may be observed between upstream and downstream regions. In this category, none of the above features are observed in the plasma sheet-lobe boundary crossings.

5. The shock velocity is much faster than the plasma velocity flowing into the shock on the shock rest frame. This situation is difficult to understand except for the case of the front side of plasmoids discussed in the previous section.

6. When the spacecraft is in the northern(southern) lobe, the downstream region with hot plasma is in the northward(southward) of the spacecraft. This is difficult to understand except for the case of the front side of plasmoids discussed in the previous section.

7. The plasma velocity flowing into and out of the shock on the shock rest frame do not satisfy slow-shock condition that $V_{1n} < V_{1imd}, V_{1n} > V_{1sl}$, and $V_{2n} < V_{2sl}$.

8. Types which are not included in other types. The cases when plasma velocity moment is not correctly calculated are included in this category.

5.6.2 Spatial Distribution

Figure 5.9 shows the spatial distribution of slow-mode shocks and the other 8 categories with respect to the GSE-X coordinate. The number of the boundaries are shown every 20Re in Panel (a), while the normalized occurrence of each category is shown in Panel (b). Plasma sheet-lobe crossings are concentrated between X~ -60Re and X~ -100Re and around X~ -200Re. Slow-mode shocks including the case on the front side of plasmoids are observed mainly in the relatively near-tail region of X> -100Re. Though the number of the plasma sheet-lobe crossings were small around X~ -160Re and X~ -180Re, we found some boundaries which satisfied the slow-shock conditions. We did not find slow-mode shocks in the region further downtail of X$\leq\sim -200$Re. However, this may be caused by the observation locations biased in the GSE-Y coordinate, which was highly negative (see Figure 5.8). When the solar-wind aberration of the magnetotail is taken into account, the deviation of the GSE-Y component of the satellite position was furthermore deviated from the tail axis. No slow-shock boundaries were observed also around the region of X~ -140Re. The GSE-Y component of the satellite position was again highly negative or positive in this region. This result suggests that the distribution of slow-shock boundaries are affected by the GSE-Y position.

The ratio of the slow-shock boundaries to all the boundaries in each GSE-X bin does not show a clear dependence on the distance from the Earth. Since the total number of the slow shocks is still small, it may be difficult to find a clear dependence. In the region further downtail of X $\leq\sim -140$Re, the ratio of the Type-2 boundaries in which the upstream density is higher than the downstream density is notably high, since the cold dense plasma is frequently observed in the lobe as mentioned earlier.

5.6.3 Dependence on Geomagnetic Activity

Here we use Kp indices for a measure of the magnetospheric activity, because the AE/AL/AU indices have not been available, and the interplanetary magnetic field data are also unavailable in many periods of time during the present observations.

Figure 5.10 shows the distribution of plasma sheet-lobe boundaries with respect to the Kp index. The number of the boundaries are shown in Panel (a) and the normalized occurrence of each category is shown in Panel (b). The occurrence number of the plasma-sheet lobe crossings increases with increasing Kp values up to Kp=4, but abruptly decreases between Kp=5 and Kp=7. Since the number of the boundary crossings is very small when Kp=6 and Kp=7, the statistical accuracy may be bad for these large Kp values. Panel (c) shows the number of the boundary crossings normalized by the occurrence rate of each Kp values during observation. The normalized number of the boundary crossings increases with increasing Kp values except for Kp $\geq$ 6. This increase may indicate that the motion of the tail including the passage of plasmoids is active when the geomagnetic activity is high.

The ratio of the slow-mode shocks in each Kp index does not show a clear dependence on Kp values. However, the sum of the number of slow-mode shocks and the number of 'Type 1' increases with increasing Kp values.

5.6.4 Location of the X-type neutral line

Figure 5.11 shows the location of the expected X-type neutral line with respect to the satellite, whether it is in the earthward or tailward of the spacecraft for the 32 slow-shock boundaries. The direction is shown every 20Re in GSE-X distance. The number of the shocks are shown in Panel (a) and the normalized occurrence of each category is shown in Panel (b). In the distant-tail region, the X-type neutral line is earthward for all the 5 slow-shock boundaries. In the region between X~ -60Re and X~ -100Re, X-type neutral lines can be located both earthward and tailward of the satellite. Though only one slow-shock boundary was observed in the X~ -40Re bin, the expected X-type neutral line was tailward in this case.

5.7 Discussion

We have identified slow-mode shocks at the mid-tail to distant-tail regions using three-dimensional magnetic field and plasma data obtained by the GEOTAIL satellite. We have checked the one-dimensional Rankine-Hugoniot relation between the upstream and downstream parameters in NIF. In order to find the shock rest frame, we have calculated the shock velocity along the shock normal, V_s. In the four cases of the identified shocks presented in Section 5.4, this value ranges from 63km/s to 133 km/s, and the direction is downstream to upstream. This shock normal velocity may include the motion of the tail with respect to the satellite and the motion of the shock structure with respect to the tail.

The determined shock normal direction is not always restricted to in the GSE X-Z plane. Especially in the case of No.3 and No.4 (see Table 5.1), the shock normal has a large GSE-Y component. Magnetotail may be twisted in such cases.

The features of ion distribution functions around the slow-mode shocks are new findings. It is noted that backstreaming ions are detected in the upstream region, and cold ion acceleration is observed between the upstream and downstream regions. We have found backstreaming ions for all the four shocks presented in Section 5.4. For the time being, the generation mechanism of these backstreaming ions is not clarified. Current-sheet accelerated particles may be included in these backstreaming ions [Speiser, 1965, 1967; Lyons and Speiser, 1982; Speiser and Lyons, 1984], but we have not distinguished such particles from locally reflected particles or leaking particles from the shock surface whose existence is predicted by several numerical simulations [Swift, 1983; Omidi and Winske, 1992]. Anyway the existence of such counterstreaming ions may be the source of the dissipation required for generation of slow-mode shocks in a collisionless plasma. The energy of the backstreaming particles shown in Figure 5.5(a) is about 16keV, whose velocity is about 1800km/s assuming protons. This velocity is comparable to the upstream Alfvén velocity. Detailed statistical investigation on these backstreaming ions will be pursued in the future.

The cold ion acceleration is not always found. We have found the acceleration of cold ions in two cases (No. 1 and 4) out of four cases in Table 5.1. Figure 5.4(b) $\sim$ (e) shows that the cold ions are rotating around magnetic field as they are accelerated. This acceleration of cold ions may be identical to the phenomena investigated by Hirahara et al [1994]. They suggested that the source of such ions are the cold ion streams which are often observed in the lobe[Mukai et al., 1994a]. They explained the acceleration by assuming the existence of an electric-field structure. The accelerated cold ions, at times, show ring-shaped distributions [Saito et al., 1994]. A ring-shaped ion distribution is found in the transition region between the upstream and downstream in the example No.4 of Table 5.1. As will be discussed in the following chapter, such ring-shaped ion distribution function can be generated from the cold ion stream in the lobe by thermoelectric field in the plasma sheet-lobe boundary. These acceleration of cold ions may reflect the kinetic structure of the slow-mode shocks.

It should be noted that the structure of slow-shocks on the front side of a plasmoid has the direction opposite to the slow shock directions observed in the ordinary plasma sheet-lobe boundaries. This characteristic structure is predicted by a numerical simulation of K. Maezawa (personal communication, 1994). The predicted structure of a plasmoid is shown in Figure 5.12. Since the Alfvén velocity near the neutral sheet is lower than in the outer plasma sheet, the front of a plasmoid is predicted to have a "heart" shape. The observed slow-shock configuration can be explained by assuming that the spacecraft crossed the front of this "heart" shaped plasmoid.

During the period between 14 September, 1993 and 16 February, 1994, GEOTAIL satellite crossed the plasma sheet-lobe boundary in the tail region of $X_{GSE} \sim -30$Re to ~ -210Re. We have examined 303 plasma sheet-lobe boundary crossings, in which 32 plasma sheet-lobe boundaries could be identified as slow-mode shocks. We have assumed that the slow-mode shock is steady and one-dimensional. This assumption may not be satisfied for some of the plasma sheet-lobe boundaries which cannot be identified as slow-mode shocks. The plasma-sheet lobe boundaries which cannot be identified as slow-mode shocks have been categorized into 8 types. The assumption of one-dimensional shock may be broken for 'Type 1' which occupies the largest number. The Kp dependence of the occurrence ratio of slow-mode shocks plus 'Type 1' suggests that when the geomagnetic activity is high, plasma sheet-lobe boundaries show a shock-like structure instead of a simple discontinuity, even though the shock-like structure may not have a simple one-dimensional property.

If the plasma sheet-lobe boundaries are tangential discontinuities, there might be none of the signatures, such as electron heat flux leakage and/or backstream ions in the upstream region, electron flat-top distributions in the downstream region and/or acceleration of cold ions around the boundaries. Such boundaries are categorized to 'Type 4'. No dependence of the occurrence ratio of this type on the GSE-X distance or on the Kp index is found. Since the total number of this type is small during the time interval we have investigated, more data may be needed to find such a dependence, if any.

When the spacecraft is located in the distant tail region further downtail of $X \leq -140Re$, the occurrence ratio of the 'Type 2' boundaries, where the density in the upstream region is higher than the density in the downstream region, becomes significantly high. Even in this case, there are some boundaries that electron heat flux leakage and/or backstreaming ions in the upstream region, electron flat-top distributions in the downstream region, and/or cold ion accelerations around the boundaries are observed, which shows that the magnetic field is connected between these two regions. These boundaries, however, cannot be identified as slow-mode shocks, because the sense of the density variation is completely opposite.

The density of the upstream (lobe) region is, at times, too small to be measured exactly by our plasma instrument. This case is categorized into 'Type 3'. We cannot argue if the boundary is a slow-mode shock in this case.

Two categories 'Type 5' and 'Type 6' cannot be explained by a simple configuration of the plasma sheet-lobe boundaries. Though we cannot deny that these configurations of the boundaries really exist, there is a possibility that these cases are generated artificially from some noise or wavy structures which cannot be smoothed out by making a simple average of the data. There is another possibility that the upstream and downstream regions we have examined are not on the same streamline for these cases.

The boundaries categorized to 'Type 7' are boundaries where the magnetic field seems to be connected between the upstream and downstream regions, and there is plasma flow into the determined shock surface, but the flowing velocity does not satisfy the slow-shock conditions. There is a possibility that these boundaries are not in a steady state and the flowing velocity of the plasma into the shock is changing. There is still another possibility that these cases are generated artificially in a similar way to 'Type 5' and 'Type 6'.

We have shown that when slow-shock boundaries are observed between X~ -60Re and X~ -100Re, the expected X-type neutral line can exist both earthward and tailward of the spacecraft position. According to the results of the numerical simulations of Birn et al. [1986] and Hesse and Birn [1991], slow-mode shocks are not formed on the earthward side of the X-type neutral line, where magnetic field is connected to the Earth. Since the slow-shock boundaries include plasma sheet-lobe boundaries in plasmoids, the positions of the expected X-type neutral line may either be the position of the distant neutral line or the position of the near-Earth neutral line. Therefore we cannot deny the results of Birn et al. [1986] and Hesse and Birn [1991].

In summary, we have found that some of the plasma sheet-lobe boundaries in the mid-tail to distant-tail region can be identified as slow-mode shocks, which provides an evidence for the existence of the X-type neutral line expected from the reconnection model of the Earth's magnetosphere. However, in many cases, plasma sheet-lobe boundaries are not identified as slow-mode shocks. In these cases, the structure of plasma sheet-lobe boundaries may be two-dimensional or three-dimensional, or it may not be in a steady state. There are also some cases that the magnetic field seems to be not connected between plasma sheet and lobe, which suggest the plasma sheet-lobe boundaries are discontinuities. More detailed studies on the kinetic structure of the slow-mode shocks and on the statistical characteristics of the slow-mode shocks will be pursued in the future.

Chapter 6

Observation of Ring-Shaped Ion Distribution Function in the Plasma Sheet-Lobe Boundary

The ring-shaped velocity distribution of ions with energies of a few keV of the gyrating motion has at times been detected in the boundary region between the plasma sheet and the lobe in the distant tail at $X_{GSM} \sim -70$ and -170Re. The normal direction of the ring-shaped distribution is almost parallel to the magnetic field, and the distribution moves tailward. In many cases the fast flowing ions of the Plasma Sheet Boundary Layer (PSBL) are observed simultaneously. The density of the ring is comparable to the density of the cold ion stream observed in the lobe. We discuss the possibility that these ring ions are generated from cold proton streams by the thermoelectric field that exists at the plasma sheet-lobe boundary.

6.1 Introduction

The boundary region between the plasma sheet and the lobe in the near tail has so far been investigated by several spacecraft, and various phenomena have been found in this region. However only a few observations have been made in the mid-tail or distant-tail plasma sheet-lobe boundaries. The GEOTAIL satellite has crossed the plasma sheet-lobe boundary many times at various distances from the Earth. During these crossings we have found ring-shaped velocity distributions of ions.

Ring-shaped ion distribution functions are observed both in the mid-tail region about X_{GSM} ~-70Re and the deep-tail region about X_{GSM} ~-170Re. Most of these ring-shaped ion distributions are observed simultaneously with the fast flowing ions in the PSBL [Takahashi and Hones, 1988, and references therein]. According to the ISEE 3 deep-tail observations, the plasma sheet-lobe boundary in the deep geomagnetic tail can often be identified as slow-mode shocks [Feldman et al., 1984, 1985]. The thermoelectric field that exists in the slow-mode shocks may generate these ring-shaped ion distributions.

GEOTAIL Low Energy Plasma observations have revealed that "cold ion streams" exist in the lobe region [Mukai et al., 1994a], and they are heated and accelerated in the PSBL [Hirahara et al., 1994]. These cold ions consist of protons and oxygen ions, which may have originated from the ionosphere. These cold ions may be the source of the ring ions.

In the following sections, we will first show an example of the ring-shaped ion distribution function. We will then investigate the characteristics of 11 examples of these ring distributions in detail and discuss the possible mechanisms that generate these distributions.

6.2 Observation

We have used the data obtained by the Low Energy Particle - Energy Analyzer (LEP-EA) and the Magnetic Field (MGF) experiment on the GEOTAIL satellite. LEP-EA provides three-dimensional distribution functions of electrons (8ev – 38keV) and ions (32eV/e – 43keV/e) every four spin periods (about 12 seconds). A detailed description of LEP-EA is given in Chapter 2 and Appendix A or in Mukai et al. [1994b]. MGF measures vector magnetic fields with a time resolution of 1/16 seconds. We have used spin-averaged vector magnetic field data. A detailed description of MGF is given in Kokubun et al. [1994].

Figure 6.1 shows an example of the ring-shaped ion distribution function observed at 1603:48 UT on September 14, 1993, when the satellite position was X~ -71Re, Y~ 22Re, Z~ -4Re in the GSM coordinate system. Panels (a), (b) and (c) are projections in three different directions of the contour of the three-dimensional ion distribution function. We have selected the three orthogonal directions of projection that show the ring shape most clearly. The point of the intersection of these orthogonal planes is not the origin of the velocity space in the spacecraft frame because the center of the ring has a finite velocity. The ion distribution function has two components, namely the ring-shaped distribution and the high-energy beam distribution. Schematic figures of these distributions are drawn above each panel, and the look direction is shown by a short arrow. In Panels (a) and (c), the ring component can be seen as two separated contours at nearly symmetric points with respect to the origin. The high-energy beam component can also be seen in these panels on the right-hand side. The ring shape can be seen clearly in Panel (b).

Figure 6.2 compares the plasma and the magnetic field data for the interval covering the ring observation. Panels (a) and (b) show energy-time (E-t) diagrams of electrons and ions during the time interval between 1520UT and 1640UT on September 14, 1993. The maximum count rate obtained over all the elevational and azimuthal directions is shown by color code at a given energy and time. The period when the ring-shaped distribution function (see Figure 6.1) was observed is marked by an arrow. Panels (c), (d), and (e) show the total magnetic field and the direction of the magnetic field in the GSM coordinate system. Velocity moments during the same time interval as in Figure 6.2 are shown in Figure 6.3. From top to bottom, (a) ion density, (b) magnitude of the ion bulk velocity, (c)(d) direction of the ion bulk velocity in the GSM coordinate system, and (e) ion (solid line) and electron (dotted line) temperatures deduced from the velocity distributions in the GSE y direction are shown.

Before we observed ring-shaped ion distribution functions, the satellite was in the plasma sheet between 1520UT and ~1540UT. The spacecraft moved to the position nearer to the lobe between ~1540UT and 1556UT. During this period, the magnetic field direction was mostly tailward ($\phi = \pm 180^\circ$), which means that the satellite was in the southern part of the magnetotail.

The satellite was in the transition layer between lobe and plasma sheet when we observed ring-shaped distribution functions at 1603:48UT (see an arrow in Figure 6.2, 6.3). During the time interval shown in Figures 6.2 and 6.3, we observed a ring-shaped distribution function only at this time. Between 1556UT and 1615UT, the total magnetic field oscillated between about 10nT and about 2nT, while the ion temperature also oscillated between about 1keV and 8keV. High-energy tailward flowing ions were observed in phase with the oscillation, which can be seen in Figure 6.3(b)(c)(d). These high-energy ions may be identical to the fast flowing ions that are frequently observed in the PSBL. During this time interval the satellite was moving between a position deeper inside the plasma sheet and a position nearer to the lobe. The elevation angle of the magnetic field showed bi-polar signatures that corresponded to each oscillation, which may suggest that these oscillations are due to plasmoids. After 1615UT, the satellite gradually moved to the lobe, where the magnetic field shows high and stable values of about 10nT.

During an interval of one month between September 14, 1993 and October 15, 1993, we have found 25 examples of the ring-shaped ion distribution function. We have searched for the ring-shaped ion distributions from three-dimensional ion data obtained during the total period of about 80 hours when the spacecraft repeatedly crossed the plasma sheet-lobe boundary at $X_{GSM} \sim -70$Re, and at $X_{GSM} \sim -170$Re. Some of these 25 rings are partial, and some others are split to two or three fragments which are in the same plane. We have selected 11 examples which have comparatively complete ring shapes, and have investigated their common features in detail. The results are summarized in Table 6.1.

The ring distribution and the high-energy beam distribution are observed together for 10 examples, while only the ring distribution is observed in one case (No.2 in Table 6.1). The high-energy beam ions flow tailward roughly along the magnetic field for 8 examples. The earthward flowing high-energy ions are observed in two cases (No.3 and No.9 in Table 6.1). These high-energy beam ions may be identical to the fast ion flows that have been frequently observed in the PSBL at distances much nearer to the earth. It has been reported that the fast ion flows do not always exist in crossing the plasma sheet-lobe boundary [Angelopoulos et al., 1993]. We regard that all the 11 ring ions are observed in the plasma sheet-lobe boundary even if high-energy beam ions are not observed in one case out of 11 examples.

The normal to the plane of the ring distribution and the magnetic field direction agrees within 10 degrees except for one example obtained on September 18 (No.8 in Table 6.1). In this example the spacecraft crossed the plasma sheet-lobe boundary very rapidly so that the direction of the magnetic field changed by about 30 degrees during the sampling time (about 12 seconds) of the distribution function. This rapid variation of the magnetic field may be the cause for the disagreement between the normal direction of the ring and the magnetic field direction in this case.

The center of the ring moves nearly along the magnetic field in 9 cases. For the remaining 2 cases the center of the ring coincides with the origin of velocity space (No.3 and No. 10 in Table 6.1). The flow direction of the center of the ring is tailward for all these 9 cases. Even when the flow direction of the high-energy beam is earthward, the flow direction of the center of the ring is tailward. (see No.9 in Table 6.1) In some cases, the center of the ring has appreciable velocity perpendicular to the magnetic field. This perpendicular velocity can be regarded as $\mathbf{E} \times \mathbf{B}$ drift velocity, since the high-energy beam ions also have a perpendicular velocity in nearly the same direction as the perpendicular velocity of the center of the ring in such cases.

The gyrating velocity of the ring ions, which corresponds to the radius of the ring in the velocity space, is larger than the parallel velocity of the ring for all the 11 cases. The ratio of the parallel to perpendicular velocity varies from 0 to 0.95. The total velocity of the ring ions is from 291km/s to 1088km/s.

The density of the ring (assuming protons) is from $0.009/cm^3$ to $0.048/cm^3$. In some cases, part of the ring cannot be observed because of the limitation of the field of view of our plasma instrument. Since only 8% of the whole solid angle is not covered [Mukai et al., 1994b], this density value would not be very different from the true density of the ring.

The density and the velocity of the high-energy beam ions observed simultaneously with the ring ions are also shown in Table 6.1. The density of the high-energy beam ions (assuming protons) varies from 0.001 $/cm^3$ to 0.114 $/cm^3$. The energy of the beam ions of the No.1 in Table 6.1 was so high that we could observe the beam ions only partially, and the density is underestimated in this case. The density of the beam ions is much higher than the density of the ring ions for 4 cases (No.4, 5, 6, and 7), and much lower for 3 cases (No.3, 8, and 9). For the remaining 2 cases (No.10 and 11), the density of the beam ions is roughly the same as the density of the ring ions.

6.3 Discussion

We regard the cold proton stream frequently observed in the lobe [Mukai et al., 1994a] as the source of the ring-shaped ion distributions. When we observe ring-shaped ion distributions, we often observe accelerated cold ion streams [Hirahara et al., 1994] before or after we observe the ring ions. We have calculated the density of the ring with the assumption of protons for the ion species. The density is nearly the same as the density of the cold streaming ions observed in the lobe. If we assume oxygen, the density becomes four times larger than the value calculated assuming protons. Cold oxygen streams are also observed simultaneously with the cold proton streams in the lobe [Mukai et al., 1994a]. However, the density of the cold oxygen ions is generally much smaller than the density of the cold proton streams. Therefore, we may regard the cold proton streams in the lobe as the source of the ring ions.

These cold proton streams are thought to originate from the ionosphere, from which it flows tailward in the lobe [Mukai et al., 1994a]. We have shown that the flow direction of the center of the ring distribution is always tailward along the magnetic field except when the velocity of the center of the ring is very small. This is another reason why the cold proton streams seem to be the source of the ring ions. The parallel velocity of the cold proton streams in the lobe is usually less than about 100 km/s, but the parallel velocity of the center of the ring is from 0 km/s to about 600 km/s. This difference would be due to the acceleration mechanism of the cold streaming protons to the ring ions.

The ring-shaped ion distributions are not always observed in crossing the plasma sheet-lobe boundary while the accelerated cold ion streams are usually observed during these crossings [Hirahara et al., 1994]. The occurrence probability of the ring-shaped ion distributions in crossing the plasma sheet-lobe boundary is several percent.

When the plasma sheet-lobe boundary, where we have observed ring ions, is a slow-mode shock, the spatial scale of the electron temperature gradient that exists at the slow-mode shock is expected to be about the ion inertial length [Coroniti, 1971]. This electron temperature gradient with the spatial scale of the ion inertial length generates a thermoelectric field with a spatial scale of the same order [Schwartz et al., 1987]. If the layer where the thermoelectric field exists is appropriately thin, or the electric field varies with a spatial scale smaller than ion Larmor radius of the cold proton stream ions, cold ions may be deflected by the thermoelectric field and begin to show a ring-shaped distribution [M. Fujimoto, personal communication]. Figure 6.3(e) shows the electron temperature observed on September 14. The ring ions are observed in the region where the electron temperature has a gradient. The scale of ion Larmor radius and ion inertial length are comparable in this case.

We have checked if the slow-mode shock condition (see Chapter 5) is satisfied between plasma-sheet to lobe boundary region where the ring distributions are found. We have found that one of the plasma sheet-lobe transitions (No.6 in Table 6.1) satisfies the slow-mode shock condition. This result suggests that the ring-shaped ion distribution functions may be generated by the thermoelectric field in the plasma sheet-lobe boundary. Unless the crossing of the plasma sheet-lobe boundary is appropriately stable so as to determine the upstream and the downstream correctly, we cannot show that the transition satisfies the slow-shock condition. Therefore, our result that only one case out of 11 examples can be shown to satisfy the slow-mode shock condition does not necessarily deny that the transitions in other cases are also the slow-mode shocks.

The geomagnetic condition when the ring-shaped ion distributions were observed was rather quiet (Kp 1$\sim$2) except one case obtained on 14 September (No. 1 : Kp $\sim$4). According to the result in Chapter 5, slow-mode shocks exist even when geomagnetic condition is quiet. Therefore it may be possible that we have observed ring-shaped ion distributions under quiet geomagnetic condition.

Chapter 7

Concluding Remarks

Analyzing the plasma data obtained by in-situ observations, we have found several phenomena which shows the existence of the X-type neutral line expected from the reconnection model of the Earth's magnetosphere.

Using low energy particle data obtained by a polar orbiting satellite AKEBONO, we have found velocity dispersed ion beams at the poleward edge of the auroral oval. We have calculated the distribution function of these ions, and have estimated the temperature and bulk flow velocity of the ions at their source region assuming one-dimensional shifted-Maxwellians. A relation between the estimated parameters and the latitudinal distribution of the observed ions are found. This relation can be explained by a simple model that there is a compact source region of the ions in the magnetotail of X$\sim -70 \pm 30$Re, and the ions are velocity-dispersed by the velocity filter effect due to the $\mathbf{E} \times \mathbf{B}$ drift under dawn-to-dusk electric field. The source region of the ions may be the X-type neutral line expected from the reconnection model of the Earth's magnetosphere.

In order to investigate the source regions of the above mentioned velocity dispersed ions, we have made an in-situ plasma observation in the magnetotail up to $X_{GSE} \sim -210$Re, with the GEOTAIL satellite.

When we make observations in the magnetotail, we can observe various regions of the magnetotail including the PSBL. There must be a motion of the magnetotail with respect to the sun-Earth fixed frame because the motion of the satellite in this frame is very slow. We have observed an evidence of the existence of such motions of the magnetotail. We have observed rapid variations of the plasma bulk flow direction in the plasma sheet at $X_{GSE} \sim -60$Re. These variations can be explained by assuming a combination of the spatial gradient in the bulk flow and the flapping motion of the magnetotail. We have estimated the velocity of the flapping motion to be about 40km/s.

The existence of the magnetic field reconnection and the X-type neutral line can be shown indirectly by identification of slow-mode shocks in the plasma sheet boundary layers. Using the low energy particle data obtained by GEOTAIL satellite in the tail regions, between $X \sim -30$Re and $X \sim -210$Re, we have found that about 10 % of the PSBL can be identified as slow mode shocks. As for the rest (90 %) of the PSBL, there are several reasons why we cannot identify them as slow-mode shocks: the lobe density is higher than that of the plasma sheet for about 20 %, the assumption of the one-dimensional shock is not valid for about 30 %, and the density jump is too large for about 10 %. There are also some cases when the PSBL seems to be a tangential discontinuity.

The role of slow-mode shocks is to convert the upstream magnetic field energy into downstream kinetic plasma energy. Since the observed slow-mode shocks are generated in collisionless plasmas, there must be some dissipation mechanism which is not due to simple Coulomb collisions. We have found an ion distribution which can be the source of this dissipation. In the upstream region of slow-mode shocks, counter-streaming ions are often observed. One component is the low energy ions flowing into the shock from the lobe and the other component is the higher-energy backstreaming ions flowing from the shock toward the upstream (lobe) region.

Between the upstream and the downstream of slow-mode shocks, we have also observed acceleration of cold ions. These accelerated ions, at times, show a ring-shaped velocity distribution. We have found 11 examples of the ring shaped ion distributions at PSBL in the mid-tail region of $X \sim -70Re$ and in the distant-tail region of $X \sim -170Re$, during about one month's observation. The slow shock condition is satisfied for one case out of the 11 cases. The generation mechanism of these ring-shaped ion distributions may reflect the kinetic property of the PSBL, for example, the cross-shock potential in the slow-mode shock. The detailed kinetic property of slow-mode shocks may be solved in the future by examining the acceleration process of these cold ions across the slow-mode shocks in detail.