

**Simulation Study on
Enhancements of Energetic Heavy Ions
in the Magnetosphere**

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Abstract

One of the dynamic phenomena emerging in the geospace is the substorm. During the substorm, reconfiguration of the magnetic field takes place in the magnetosphere and the energetic charged particles are enhanced. In particular, singly charged oxygen (O^+) ion is known as the most responsible ion species for the substorm. Many observations show that energetic O^+ ions (tens of keV) rapidly increase in the inner magnetosphere and contribute significantly to the ring current during substorms. In spite of many studies, the energization process of the O^+ ion in the inner magnetosphere is still a controversial issue.

Previously, two candidates of the O^+ energization have been proposed. The first one is the non-adiabatic acceleration in the nightside tail region. Ions from the dayside polar region are transported to the lobe, then they are injected to the nightside plamasheet during substorm expansion phase. The second one is the direct supply from the auroral region. After the substorm onset, energetic O^+ ions are extracted from the ionosphere with the auroral acceleration processes, and the O^+ ions are directly supplied to the nightside plamasheet. Many studies investigate which process is the dominant energization mechanism during the substorm. For the first process, a generation mechanism of the dawn-to-dusk electric field according to a development of the magnetic reconnection and its impact in terms of flux enhancements are unclear. For the second process, the distribution function of the auroral ions and their paths to the inner magnetosphere are unclear.

In the present study, we perform test particle simulations in a global MHD electromagnetic fields. Using the test particle simulation result, we reproduce spatiotemporal variations of distribution function and flux of O^+ ion after the substorm-time acceleration based on the Liouville theorem. Through the numerical studies, the global trajectories and accelerations of O^+ ions from their source regions and their contributions to the energetic O^+ ions in the inner magnetosphere are examined.

First, we focus on an acceleration of O^+ ion around the nightside magnetic reconnection region, which can be thought as the most dynamic region during the substorm. Mechanisms of the enhancement of the dawn to dusk electric field and of subsequent accelerations of O^+ ions due to the intensive electric field are investigated in detail. In the inner magnetosphere, our simulation reproduces a realistic flux enhancement with the O^+ ion such as the dispersion-less structure, the dispersed structure and the nose structure which are often observed by in-situ observations. In addition to the dispersion structures, our simulation shows that another type of structure named void structure in the inner magnetosphere. The structure is observed by the Van Allen Probes HOPE instruments. We reveal that the generation mechanisms of the void structure consist of the formation of the strong equatorward flow in the low pressure region and tailward flow in the high pressure region and the intense non-adiabatic acceleration of O^+ ions.

Second, we examine variations of O^+ outflow during the substorm and their impacts on the enhancement of energetic O^+ in the inner magnetosphere. We reveal that, during the substorm growth phase, O^+ ions at tens of eV are extracted from the dayside polar region due to the region 1, resulting in the enhancement of the warm O^+ ions (hundreds of eV) in the lobe. This process works as a "pre-conditioning" of the O^+ ion. After the substorm onset, the enhanced warm O^+ ions are non-adiabatically accelerated to tens of keV and injected to the inner magnetosphere. A combination of the pre-conditioning and the non-adiabatic acceleration of the O^+ establishes a realistic O^+ ring current. At the same time, the initial brightening occurs in the midnight aurora region, then up to a few keV O^+ ions are extracted and directly supplied to the inner magnetosphere, developing a fraction of the O^+ ring current.

Third, a local acceleration on the azimuthally directed magnetic field lines emerging during substorm is focused. Our test particle simulation result shows that a small percentage of the O^+ ions passing through the kinks of the magnetic field lines is effectively accelerated to hundreds of keV. This process can slightly modulate the O^+ ring current.

The present study addresses important issues and contributes to understanding the big picture of the O^+ ion energization during substorms. From the results, we conclude that a combination between the pre-conditioning of the warm O^+ ion (hundreds of eV) in the lobe due to the enhancement of the region 1 field aligned current and the non-adiabatic acceleration in the near-earth plasmasheet is the dominant energization process for the ring current O^+ ion during the substorm.

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Chapter 1

General Introduction

1.1 Introduction

The global space economy is growing for the last several decades. In recent years, many communications satellites, weather satellites and the Global Positioning System (GPS) satellites were launched. These satellites provide many indispensable services for our modern society, so they are called "space infrastructure". For the space infrastructure, space plasmas is a major obstacle because they sometimes cause operational anomalies. Especially, the region of outer space near the Earth, known as "geospace", is populated by a large number of energetic charged particles known as the Van Allen radiation belts and the ring current. These groups of energetic charged particles have large impacts on the space infrastructure. For an expansion of the human activity on the space, to understand features of the energetic charged particles is an essential issue. Previously, new international projects have been started with the aim of understanding the energetic plasma environment in the geospace. The Van Allen Probes (VAPs) mission was designed and launched by the National Aeronautics and Space Administration (NASA). In addition, the Japan Aerospace Exploration Agency (JAXA) schedules a launch of a new observation satellite of the energetic plasma environment named Exploration of energization and Radiation in Geospace (ERG) satellite. For comprehensive understanding of the energetic plasma environment in the geospace, combinations of the observations and space plasma simulations and the integrated analyses are needed.

1.2 Overview of the Space Environment

1.2.1 Solar wind and the Earth's magnetosphere

Figure 1.1 shows the schematic illustration of the Earth's magnetosphere and surrounding electromagnetic environment [Kivelson and Russell,1995]. The solar wind is a plasma stream from the Sun at speeds of about ~ 400 km/s. The source of the solar wind is the Sun's hot corona and the solar wind has a weak magnetic field so-called Interplanetary Magnetic Field (IMF). In the solar magnetic field, the electrical conductivity is so high that the solar wind satisfies the frozen-in magnetic field condition. The interactions between the solar wind and the Earth's dipole magnetic field forms the electromagnetic environment called magnetosphere [Gold, 1959] around the Earth. The size of the magnetosphere is determined by the pressure balance between the earth's magnetosphere and the solar wind. The magnetosphere is compressed on the side facing the solar wind and elongated in the other direction, forming a magnetotail. Near the equatorial plane, hot plasmas are accumulated in a sheet-like region. The region is called the plasmasheet region. In addition, regions adjacent to the plasmasheet where the plasma density is reduced are called the lobe region.

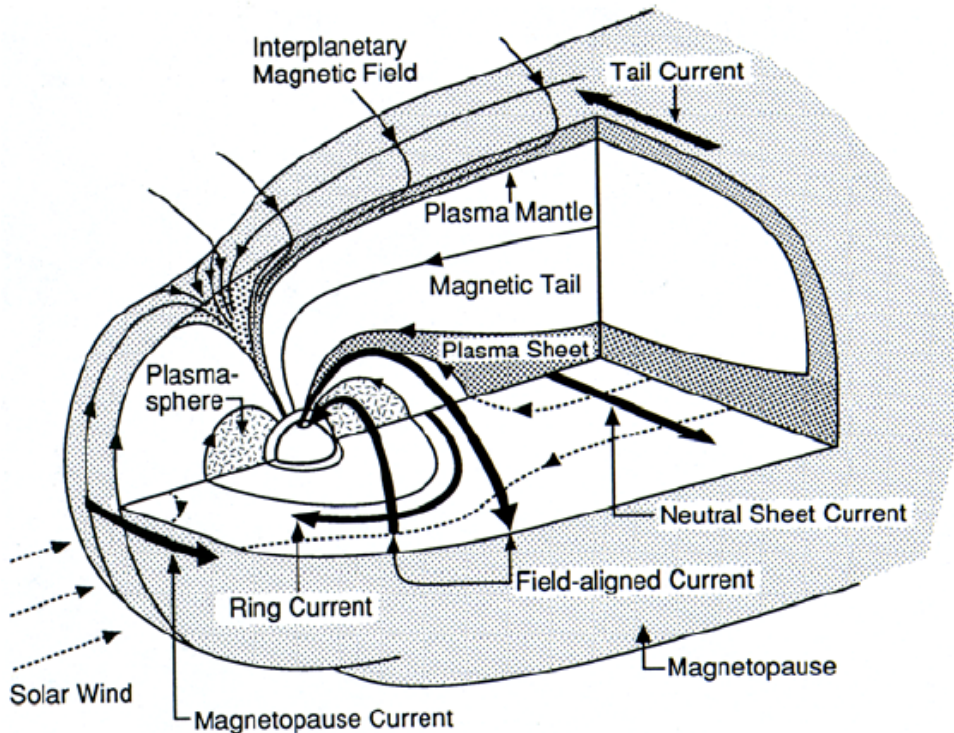


Figure 1.1: Schematic illustration of the Earth's magnetosphere [Kivelson and Russell,1995].

1.2.2 Magnetic storm and substorm

The Earth's magnetic field on the ground is sometimes largely perturbed on a long time scale (for several to tens of hours) form a class of phenomena called magnetic storm. It usually result from variations in the solar wind such as a coronal mass ejection and a high speed stream originating from a region of weak magnetic field on the Sun's surface. Under the solar wind conditions with a southward (opposite the direction of Earth's magnetic field) IMF, the solar wind energy transfers into Earth's magnetosphere, results in a global disturbance of Earth's magnetosphere. One of the important phenomena emerging during the magnetic storm is a development of a large scale strong convection electric field in the tail region. It causes a dynamic variation of the energetic plasma environment.

Another highly dynamic process in the magnetosphere is a substorm sometimes referred to as a auroral substorm. The substorm is the sequence of events (a few hours) and it is divided into three phases; the growth, expansion and recovery phase. Most of substorm events start when the IMF turns from northward to southward. Under the southward IMF, energy of the solar wind entry into the earth's magnetosphere via day-side reconnection region and is stored in the tail region, which constitutes the growth phase. The flows of the dayside reconnection and the magnetic flux are schematically shown in Figure 1.2 [Kivelson and Russell,1995]. The numbered field lines indicate the time sequence of the transport of magnetic flux into the magnetosphere. After tens of minutes to a few hours from the turning of IMF, the expansion phase begins with a sudden increase in the brightness of the part of a quiet arc, which is called Initial Brightening (IB) [Akasofu, 1964]. The arc rapidly moves the geomagnetic poleward and westward. The timing of the initial brightening is known as substorm onset. During the expansion phase, the energy stored in the tail region is released when the field lines in the inner magnetosphere relax from their stretched, tail-like configuration and back into a more dipolar configuration. This dynamic reconfiguration process is known as dipolarization. A local and intensive dawn to dusk electric field is induced in the tail region together with the dipolarization, and it impulsively accelerates charged particles in the near-earth plasma sheet and inject them into the inner magnetosphere. This process is understood by that the energy stored in the tail region converts into the kinetic energy of plasmas. The energy flows into the ionosphere guided by field-aligned currents, and it is finally consumed by the Joule heating process in the ionosphere. After the energy consumption,

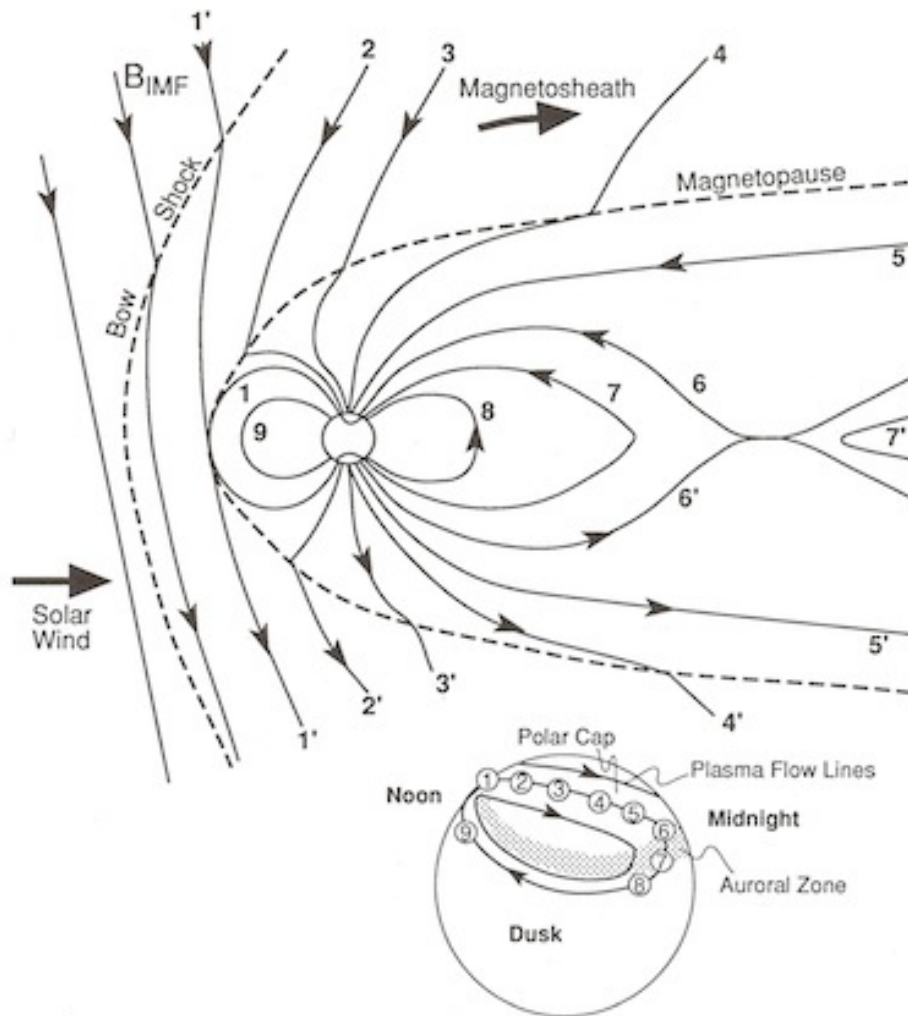


Figure 1.2: Schematic illustration of the dayside reconnection [Kivelson and Russell,1995]. The numbered field lines indicate the time sequence of the transport of magnetic flux into the magnetosphere.

the magnetosphere returns to the quiet state, which is known as the recovery phase.

1.2.3 Radiation belts and ring current

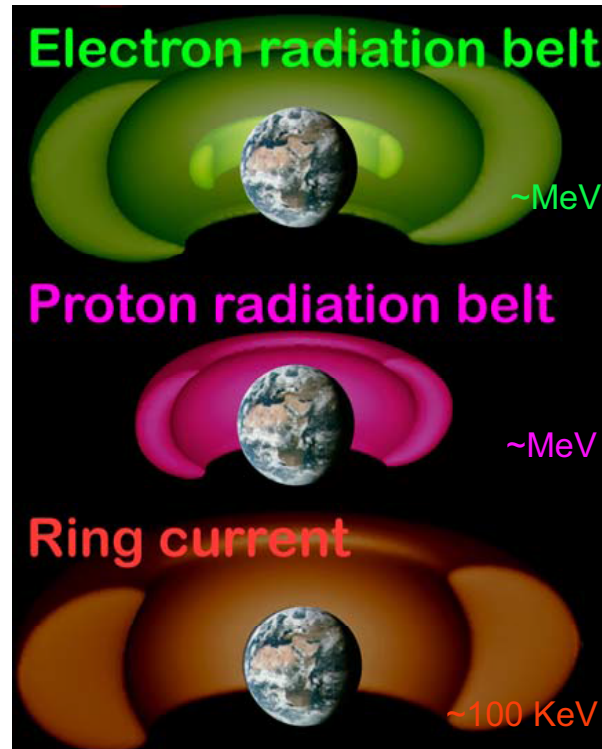


Figure 1.3: Schematic illustration of the radiation belt and ring current [After Ebihara and Miyoshi, 2011].

Charged particles (electrons and ions) with various energies are trapped in the earth's magnetosphere. The magnetospheric come from two primary sources: the solar wind and the ionosphere. In particular, energetic particles in the inner magnetosphere are called radiation belt and ring current according to their energy. Figure 1.3 shows the schematic illustration of the radiation belt and ring current [After Ebihara and Miyoshi, 2011]. The radiation belts mainly consist of electrons and ions at around millions electron volt (MeV) [Van Allen and Frank, 1959]. Especially for electrons, the radiation belts consist of the inner and outer radiation belts, which is located, respectively.

On the other hand, ring current is consist of electrons and ions at around tens to hundreds of keV [Frank, 1967; Smith and Hoffman, 1973]. The current toroidally flows westward around the Earth usually around at altitudes of 2 to 6 R_E , where R_E is Earth radius (~ 6371 km). The ring current is usually enhanced according to the geomagnetic activities, results in a long time scale magnetic perturbation (magnetic storm) which is

identified as a decrease in Dst index. One understanding of the enhancement of the ring current is a result of the energy conversion of solar wind energy during magnetic storms and substorms. Solar wind-Magnetosphere coupling during magnetic storms and substorms results in the global and long-lasting convection electric fields and local inductive electric fields which accumulate charged particles into the inner magnetosphere with adiabatic and non-adiabatic accelerations. Another important aspect of the ring current is that the ring current itself drives drastic phenomena in the magnetosphere, which may lead additional magnetospheric disturbances.

1.2.4 O^+ ion in the magnetosphere

The O^+ ion is known as one of the major ion species in the magnetosphere [e.g. Shelley et al., 1972; Lennartsson et al., 1979; Kistler et al., 1989; Daglis and Axford, 1996; Moore et al., 1997; Elliott et al. 2007; Kistler et al., 2010; Liao et al., 2010]. Observations have shown that the O^+ ions are widely distributed in the magnetosphere, such as the plasma sheet, the lobe, the mantle, and the inner magnetosphere [e.g., Young et al., 1982; Lundin et al., 1982; Krimigis et al., 1985; Hamilton et al., 1988; Moore et al., 1997; Nosé et al., 2001; Nilsson et al., 2004]. The exclusive source of the O^+ ions is thought to be the earth's ionosphere [Moore and Delcourt, 1995; Moore et al., 2001] because the O^+ ions are not observed in the solar wind. The O^+ ions outflowing from the ionosphere are grouped into four categories; polar wind, auroral bulk O^+ upflow, ion beams, and ion conics, according to energy and pitch angle distributions, as summarized in Moore et al. [1995]. The polar wind flows from the polar cap region, and is characterized by O^+ ions with thermal energy of the order of eV. Auroral bulk O^+ upflow frequently occurs in the topside auroral ionosphere (~ 500 km) at velocities of 100 - 1000 m/s or greater. Ion beams and ion conics are manifestations of acceleration processes where all or only a fraction of the ions are energized. Both ion beams and ion conics have energy in the 10 eV to few keV range. The O^+ ion is known as the most responsible ion species for the geomagnetic activities. Processes that ionospheric ions (mainly $< \sim 10$ eV) are accelerated to tens of keV and transported to the ring current region during geomagnetic activities are one of the unsolved issues of the magnetospheric study.

1.3 Overview of Previous Studies

In terms of the ring current enhancements, O^+ ion accelerations during geomagnetic activities have been researched by many studies. The ring current is populated by energetic particles such as H^+ , O^+ , He^+ ions and electrons [Gonzalez et al., 1994; Daglis et al., 1999]. During quiet times, the ion pressure in the ring current region is dominated by H^+ ions [e.g., Gloeckler et al., 1985; Krimigis et al., 1985; Hamilton et al., 1988]. However, the contribution of O^+ ions to the ring current becomes large in accordance with the geomagnetic activities [e.g., Lundin et al., 1980; Hamilton et al., 1988; Kistler et al., 1989; Roeder et al., 1996; Daglis, 1997; Daglis et al., 2000; Feldstein et al., 2000; Korth et al., 2000; Greenspan and Hamilton, 2002; Nosé et al., 2005; Kronberg et al., 2012]. Therefore, it is assumed that the O^+ ions play an important role to control configuration of the magnetosphere especially under large solar activities.

It is accepted that the O^+ energization occurs on two different time scales: the storm time scale ($>$ hours) and on the substorm time scale (< 30 min) [Ebihara and Miyoshi, 2011; Keika et al., 2013]. During magnetic storms, convective transport is caused by the potential electric field induced into the magnetosphere under southward IMF through solar wind-magnetosphere-ionosphere coupling [e.g. Ebihara and Ejiri, 2000]. Accordingly, the energy density ratio of O^+/H^+ in the ring current region is increased [e.g. Hamilton et al., 1988]. Figure 1.4 summarize the dependence of O^+/H^+ and He^+/H^+ energy density ratios on the Dst/SYM-H index [Daglis 1997; Nosé et al., 2005; Keika et al., 2013]. The horizontal arrows in Figure 1.4 represent the ratios based on Geotail observations in the plasma sheet. It have shown that the ratio has a good correlation with magnetic storm strength represented by the Dst or SYM-H index. For intense storm events, O^+ ion becomes the dominant ion species [Hamilton et al., 1988; Daglis, 1997; Roeder et al., 1996; Nosé et al., 2005].

During substorms, the energy flux of O^+ ions at tens of keV is rapidly increased in the inner magnetosphere [e.g., Daglis and Axford, 1996; Nosé et al., 2000; Fu et al., 2002]. Data from the Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE) shows that the contribution from the O^+ ion to the total ion energy density increases at geosynchronous altitude when the AE index is high [Daglis et al., 1993], and that the bulk of the ion energy density comes from the high energy component of O^+ (17-300 keV) in comparison with the low energy one (1-17 keV) after the substorm onset [Daglis and Axford, 1996]. Fu et al. [2002] identified rapid flux

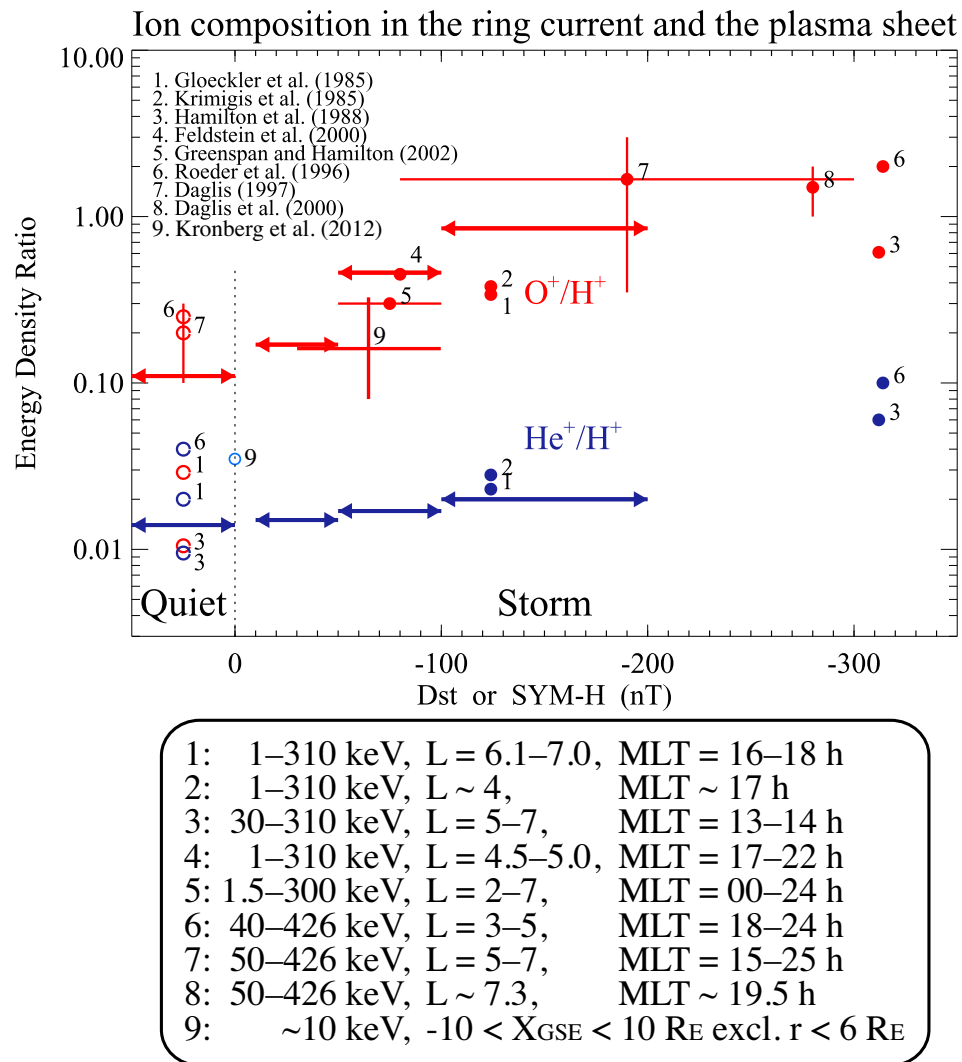


Figure 1.4: A summary of the dependence of O^+/H^+ and He^+/H^+ energy density ratios on the Dst/SYM-H index [Keika et al., 2013].

intensifications of the O^+ ions in the inner magnetosphere during substorm-associated events based on the data from the Combined Release and Radiation Effects Satellite (CRRES). One typical observation result showed that, in the pre-midnight sector, the O^+ ion flux in the energy range of > 50 keV increased within 5 minutes after a substorm expansion onset, and the increase in the flux lasted about 30 minutes. Energetic neutral oxygen with energy between ~ 50 and ~ 200 keV was observed to be rapidly enhanced in the inner magnetosphere at almost the same time as auroral substorms [Mitchell et al., 2003; Ohtani et al., 2007; Keika et al., 2010]. Snapshots of energetic neutral oxygen emitted from the energetic O^+ ions have been observed by Imager for Magnetopause-to-Aurora Global Exploration/High Energy Neutral Atom (IMAGE/HENA). Figure 1.5 shows temporal variation of the integrated ENA flux for hydrogen at 27-60 keV (dotted), hydrogen at 60-119 keV (dashed), and oxygen at 52-180 keV [Mitchell et al., 2003]. The bottom images are auroral Far Ultra Violet (FUV) images obtained by Wideband Imaging Camera (WIC) onboard IMAGE. Energetic neutral oxygen with energy between ~ 50 and ~ 200 keV was observed to be rapidly and selectively enhanced in the inner magnetosphere at almost the same time as auroral substorms [Mitchell et al., 2003; Ohtani et al., 2007; Keika et al., 2010].

To explain the enhancement of energetic O^+ ions during substorms, two processes have been proposed (Figure 1.6). First one is the "non-adiabatic acceleration" process. O^+ ions from the dayside polar region are first transported to the lobe [Vaisberg et al., 1995; Moore et al., 1997], then they are injected to the nightside plamasheet and ring current region during substorm expansion phase with a non-adiabatic acceleration [e.g., Nosé et al., 2000; Fok et al., 2006; Nakayama et al., 2015]. Second one is the "direct supply" process. Just after the substorm onset, energetic O^+ ions are extracted from the ionosphere with the auroral acceleration processes, and the O^+ ions are directly supplied to the nightside plasmasheet [e.g., Gazey et al., 1996; Sauvaud, 2004; Ohtani et al., 2011; Kistler et al., 2016]. To examine these processes, both observation and modeling studies have been conducted. From the analysis of bursts of energetic neutral oxygen observed by IMAGE/HENA, Mitchell et al. [2003] suggested that non-adiabatic acceleration of pre-existing O^+ ions in the near-earth plasmasheet is responsible for the observed O bursts because the time delay between substorm expansion onset and the O burst in the inner magnetosphere ($3-5 R_E$) is short (~ 20 minutes). Fok et al. [2006] released the oxygen ions from the polar region during a substorm and calculated the plasma pressure in the simulation. They concluded that a sudden enhancement of energetic oxygen atom

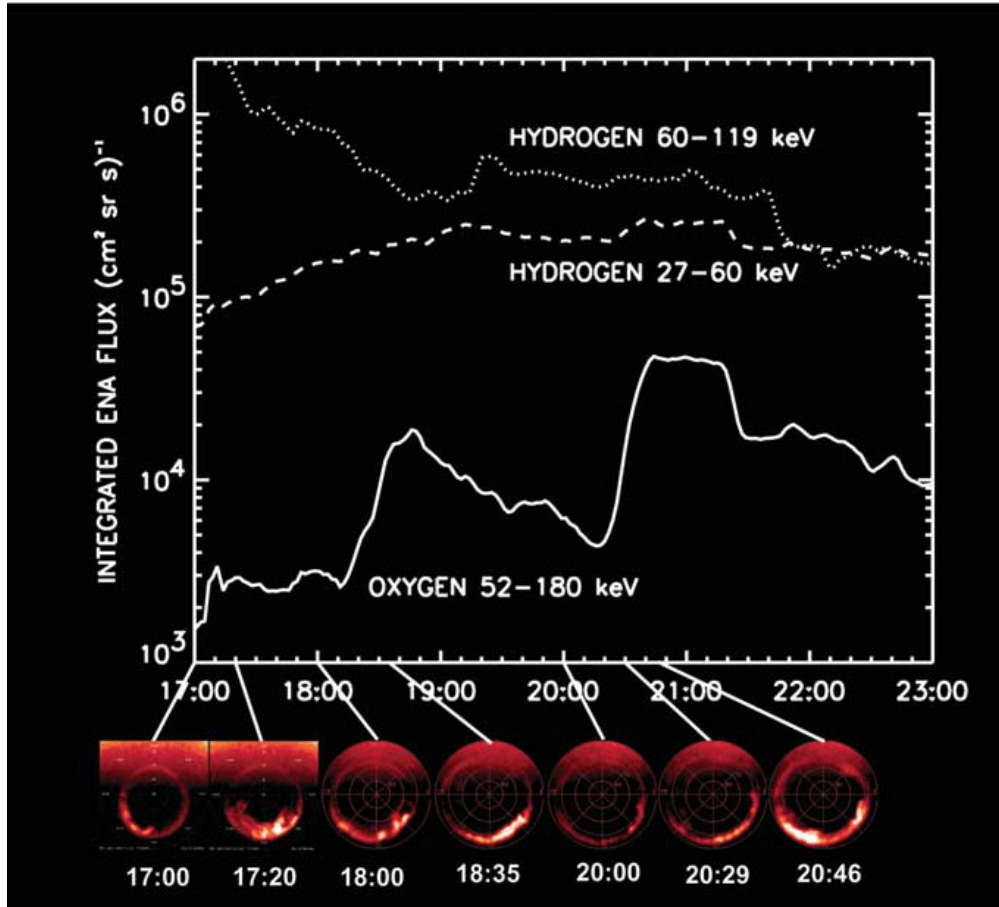


Figure 1.5: Temporal variation of the integrated ENA flux for low and high energy hydrogen, and oxygen [Mitchell et al., 2003]. The bottom images are auroral FUV images obtained by WIC onboard IMAGE.

measured by IMAGE/HENA can be explained by the nonadiabatic energization rather than the direct supply from the ionosphere. Previously, Nosé et al. [2016] and Keika et al. [2016] investigated the magnetic field dipolarization in the inner magnetosphere and its associated ion flux variations, using the magnetic field and energetic ion flux data acquired by the Van Allen Probes. They showed that O^+ ions at > 50 keV are impulsively enhanced in all pitch angle, which indicates that they are transported from the plasmasheet. However, they also showed that the field-aligned and energy-dispersed O^+ ions at 0.1-50 keV are enhanced simultaneously to the onset of the dipolarization. In spite of many studies above, general characteristics of energetic O^+ enhancements during the substorm is still unclear.

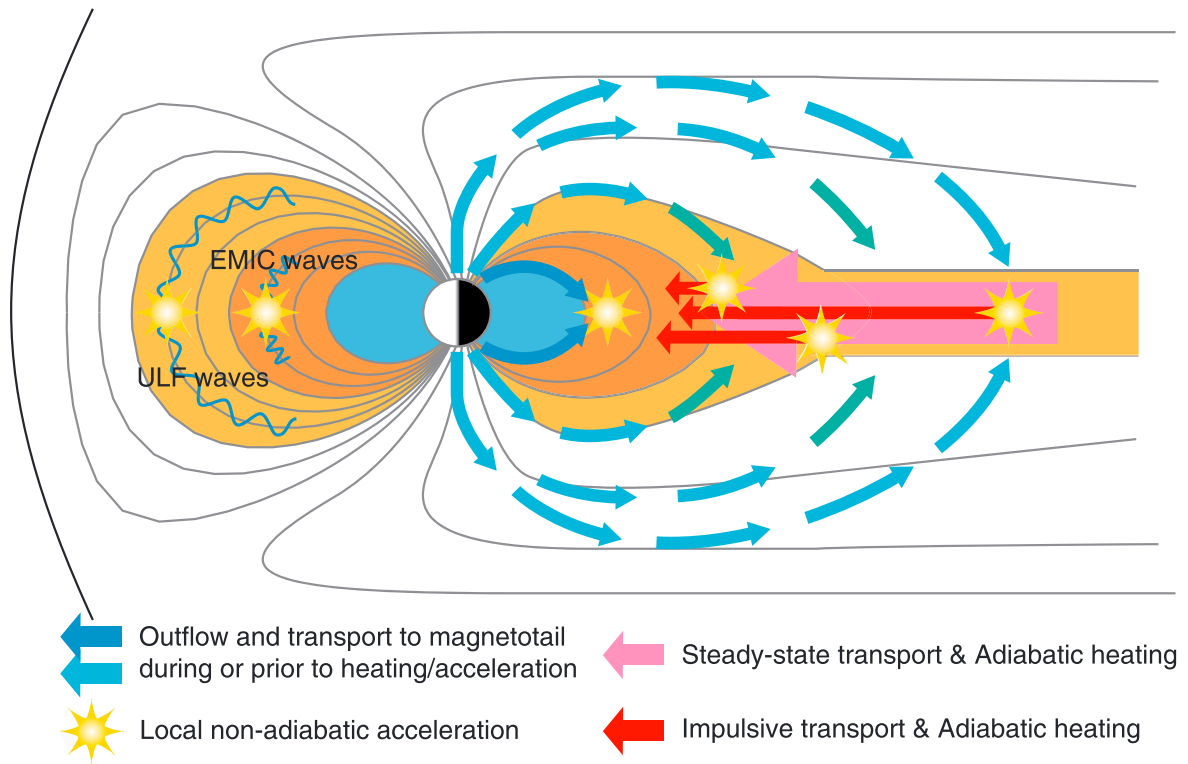


Figure 1.6: Illustration of a global overview of the possible heating/acceleration mechanisms and O^+ supply processes [Keika et al., 2013].

1.4 Outline of This Thesis

In the present study, we focus on the O^+ ion in the inner magnetosphere, which is known as the most responsible ion species for the geomagnetic activities. We investigate the global acceleration and transport processes of the O^+ ion and examine what is(are) the

dominant energization mechanism(s) during substorms. For the comprehensive understanding of the substorm-time characteristics of the O^+ ion, we develop numerical simulations which can reproduce spatiotemporal variations of the six-dimensional distribution function and the directional energy flux of the O^+ ion. Via the analysis of the simulation result, generation mechanisms of the accelerations and their impacts on the ring current build up are investigated in detail. This thesis consists of seven chapters as follows.

In Chapter 2, numerical techniques of a global MHD simulation developed by Tanaka et al. [2010] and test particle simulation used in the present study are explained. First, the basic equations, grid system and magnetosphere-ionosphere coupling method of the global MHD simulation are briefly provided. Second, a particle tracing technique which globally simulate both O^+ ions' adiabatic and non-adiabatic motion is also described.

In Chapter 3, general features of the non-adiabatic acceleration process emerging in the near-earth plasmasheet during the simulated substorms are studied. Two substorms are produced under two different solar wind conditions by using the global MHD simulation. Using the simulation result, common and different phenomena between the two cases in terms of generation mechanisms of the dawn to dusk electric field are analyzed. Test particle simulations in the electric and magnetic fields for these two cases are also conducted, and the flux of the O^+ ions in the inner magnetosphere is calculated in accordance with the Liouville theorem. It is shown by the simulation that the O^+ ions coming from the lobe are accelerated from $\sim eV$ to $>100 keV$ in ~ 10 minutes, resulting in a rapid enhancement of the flux of O^+ ion up to 200 keV.

In Chapter 4, a generation mechanism of the void structure is investigated by using the numerical simulation. Previous observations taken by the Van Allen Probes Helium Oxygen Proton Electron (HOPE) instrument show a new type of enhancement of O^+ ions in the inner magnetosphere during substorms. We call this structure as void structure. Using the observation data from the HOPE during 9 substorm events, we introduce general characteristics of the void structure. We also calculate the flux of O^+ ions in the inner magnetosphere using the same model developed in Chapter 3. The simulated spectrograms are well consistent with the ones observed by Van Allen Probes, and it is revealed that the generation mechanisms of the void structure consist of the formation of the strong equatorward and tailward plasma flow and the intensive non-adiabatic acceleration.

In Chapter 5, relative importance of the two source regions (dayside polar region and

aurora region) and the acceleration processes on their path to energetic O^+ ions in the inner magnetosphere are investigated. We perform a test particle simulation in the global MHD electromagnetic fields by the same manner introduced by Fok et al. [2006]. From the simulation result, we find that an enhancement of the warm O^+ ions (>300 eV) from the dayside polar region is a key phenomenon for the substorm-time O^+ ring current enhancements observed by in-situ observations.

In Chapter 6, an acceleration and transport process of O^+ ion around azimuthally directed (in the east-west direction) magnetic field lines is investigated. The structure of the magnetic field lines azimuthally elongated near the equatorial plane is previously reported by Saita et al. [2010] and is different from that directly associated with magnetic reconnection. Using the global MHD simulation, a generation mechanism of the azimuthally directed magnetic field lines from the global MHD simulation result is analyzed. A test particle simulation is also performed in the global MHD electromagnetic fields to understand an acceleration taking place in the field lines. Based on a test particle simulation, it is shown that the O^+ ions departing in the flux rope structure a few minutes before the onset go around in the near-earth plasma sheet twice, experience strong dawn-dusk electric field, and the ions gain kinetic energy as high as 200 keV in 10 min. This acceleration is effective for the O^+ ions with small pitch angle which may modulate the distribution function of O^+ ion.

In Chapter 7, a summary of the present study and conclusions obtained in the present computer simulations are provided. Suggestions are also presented for future studies.

Chapter 2

Numerical Simulations for Computer Experiences

2.1 Global MHD simulation

We used a global MHD simulation developed by Tanaka et al. [2010] and Tanaka [2015]. The MHD simulation can produce selfconsistent electromagnetic fields treating the solar wind-magnetosphere-ionosphere coupling. The numerical model adopts the Finite Volume (FV) Total Variation Diminishing (TVD) scheme with a unstructured grid system so as to reach the numerical calculation with a high resolution [e.g., Tanaka, 1994].

The ideal MHD equations are written in conservative forms as below [Chen, 1984].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}_{\text{MHD}}) = 0 \quad (2.1)$$

$$\rho \frac{\partial \mathbf{V}_{\text{MHD}}}{\partial t} + \nabla \cdot (\rho \mathbf{V}_{\text{MHD}} \mathbf{V}_{\text{MHD}} - \frac{\mathbf{B}\mathbf{B}}{\mu_0} + P^* \mathbf{I}) = 0 \quad (2.2)$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{V}_{\text{MHD}} \times \mathbf{B}) = 0 \quad (2.3)$$

$$\frac{\partial U}{\partial t} + \nabla \cdot \left[(U + P^*) \mathbf{V}_{\text{MHD}} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{V}_{\text{MHD}})}{\mu_0} \right] = 0 \quad (2.4)$$

and

$$P^* = P + \frac{B^2}{2\mu_0}, \quad (2.5)$$

$$U = \frac{P}{\gamma - 1} + \rho \frac{V_{\text{MHD}}^2}{2} + \frac{B^2}{2\mu_0} \quad (2.6)$$

where $\rho, P, \mathbf{V}_{\text{MHD}}, \mathbf{B}, \gamma, \mu_0$ and U are plasma mass density, plasma pressure, plasma velocity, magnetic field, the polytropic index, the vacuum permeability and total energy density, respectively. These equations 2.1-2.4 are known as continuity equation, equation of motion, induction equation and energy equation, respectively. A vector of dependent variables $\mathbf{u}$ is defined with components in Cartesian coordinate system (x, y, z, t) as

$$\mathbf{u} = (\rho, m_x, m_y, m_z, B_x, B_y, B_z, U)^T \quad (2.7)$$

where m is momentum. Basic equations to solve the dependent variables with the unstructured grid system was introduced by Tanaka [1994 and 1995]. The ideal MHD equations in conservative forms can be written in the Cartesian coordinate system as

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \frac{\partial \mathbf{H}}{\partial z} = 0 \quad (2.8)$$

where $\mathbf{F}, \mathbf{G}$ and $\mathbf{H}$ are flux functions in the x, y and z directions. The components of $\mathbf{F}, \mathbf{G}$ and $\mathbf{H}$ are given by follows,

$$\mathbf{F} = \begin{bmatrix} \rho v_x \\ \rho v_x^2 + P + \frac{B^2}{2\mu_0} - \frac{B_x^2}{\mu_0} \\ \rho v_x v_y - \frac{B_x B_y}{\mu_0} \\ \rho v_x v_z - \frac{B_x B_z}{\mu_0} \\ 0 \\ B_y v_x - B_x v_y \\ B_z v_x - B_x v_z \\ (U + P^*)v_x - \frac{(\mathbf{B} \cdot \mathbf{V}_{\text{MHD}})B_x}{\mu_0} \end{bmatrix}, \quad (2.9)$$

$$\mathbf{G} = \begin{bmatrix} \rho v_y \\ \rho v_y v_x - B_y B_x \\ \rho v_y^2 + P + \frac{B^2}{2\mu_0} - \frac{B_y^2}{\mu_0} \\ \rho v_y v_z - \frac{B_y B_z}{\mu_0} \\ B_x v_y - B_y v_x \\ 0 \\ B_z v_y - B_y v_z \\ (U + P^*)v_y - \frac{(\mathbf{B} \cdot \mathbf{V}_{\text{MHD}})B_y}{\mu_0} \end{bmatrix}, \quad (2.10)$$

$$\mathbf{H} = \begin{bmatrix} \rho v_z \\ \rho v_z v_x - \frac{B_z B_x}{\mu_0} \\ \rho v_z v_y - \frac{B_z B_y}{\mu_0} \\ \rho v_z^2 + P + \frac{B^2}{2\mu_0} - \frac{B_z^2}{\mu_0} \\ B_x v_z - B_z v_x \\ B_y v_z - B_z v_y \\ 0 \\ (U + P^*)v_z - \frac{(\mathbf{B} \cdot \mathbf{V}_{\text{MHD}})B_z}{\mu_0} \end{bmatrix}. \quad (2.11)$$

Using Gauss's law, the integration form of equation 2.8 can be written as

$$\frac{\partial}{\partial t} \int \mathbf{u} dv + \int (\mathbf{F}n_x + \mathbf{G}n_y + \mathbf{H}n_z) dS = 0 \quad (2.12)$$

where dv is the volume element of the control volume and dS is the surface element of the control volume, and $\mathbf{n}$ is a unit vector normal to the surface of the control volume. A 8×8 matrix $\mathbf{T}$ which rotates the x axis to the direction of $\mathbf{n}$ is also introduced as

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & \mathbf{T}_1 & & \vdots \\ \vdots & & \mathbf{T}_1 & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix} \quad (2.13)$$

with

$$\mathbf{T}_1 = \begin{bmatrix} n_x & n_y & n_z \\ t_{1x} & t_{1y} & t_{1z} \\ t_{2x} & t_{2y} & t_{2z} \end{bmatrix} \quad (2.14)$$

where $\mathbf{t}_1$ and $\mathbf{t}_2$ are unit vectors tangent to the surface of the control volume and or-

thogonal to each other [Tanaka, 1995]. Using the matrix, equation 2.12 can be written as

$$\frac{\partial}{\partial t} \int \mathbf{u} dv + \int T^{-1} T(\mathbf{F}n_x + \mathbf{G}n_y + \mathbf{H}n_z) dS = 0 \quad (2.15)$$

Because the MHD equations must be unchanged for the rotation of the coordinate system, a following relation can be assumed

$$T[\mathbf{F}(\mathbf{u})n_x + \mathbf{G}(\mathbf{u})n_y + \mathbf{H}(\mathbf{u})n_z] = \mathbf{F}(T\mathbf{u}) = \mathbf{F}(\mathbf{u}_n). \quad (2.16)$$

Then we obtain

$$\frac{\partial}{\partial t} \int \mathbf{u} dv + \int T^{-1} \mathbf{F}(\mathbf{u}_n) dS = 0. \quad (2.17)$$

A new vector of variables $\mathbf{u}_1$ is also introduced as

$$\mathbf{u}_1 = \begin{bmatrix} \rho_1 \\ m_{0x} \\ m_{0y} \\ m_{0z} \\ B_{1x} \\ B_{1y} \\ B_{1z} \\ U_1 \end{bmatrix} := \begin{bmatrix} \rho/\rho_0 \\ m_x/\rho_0(RT_0)^{(1/2)} \\ m_y/\rho_0(RT_0)^{(1/2)} \\ m_z/\rho_0(RT_0)^{(1/2)} \\ B_x/B_{00} - B_{0x} \\ B_y/B_{00} - B_{0y} \\ B_z/B_{00} - B_{0z} \\ \frac{1}{\rho_0 RT_0} U - \frac{\mathbf{B}_1 \cdot \mathbf{B}_0}{\beta} - \frac{B_0^2}{2\beta} \end{bmatrix}, \quad (2.18)$$

where $\beta = \mu_0 \rho_0 R T_0 / B_{00}^2$, and R , ρ_0 , B_{00} and T_0 are the gas constant, the normalization density, the normalization magnetic field, the normalization temperature. $\mathbf{B}_0$ is assumed with the conditions $\partial \mathbf{B}_0 / \partial t = 0$, $\text{rot} \mathbf{B}_0 = 0$ and $\text{div} \mathbf{B}_0 = 0$ [Tanaka, 1993, 1994 and 1995]. Using the $\mathbf{u}_1$, the conservation law form with the resistive term is rewritten as follow [Tanaka, 2000]

$$\frac{\partial}{\partial t} \int \mathbf{u}_1 dv + \int T^{-1} [\bar{\mathbf{F}}_1(\mathbf{u}_{1n}, \mathbf{B}_{0n}) + \bar{\mathbf{F}}_2(\mathbf{B}_{1n})] dS = 0, \quad (2.19)$$

with $\mathbf{u}_{1n} = T\mathbf{u}_1$, $\mathbf{m}_{0n} = T_1 \mathbf{m}_0 = (m_{0n}, m_{0t1}, m_{0t2})^T$, $\mathbf{B}_n = T_1 \mathbf{B} = (B_n, B_{t1}, B_{t2})^T$, $\mathbf{B}_{1n} = T_1 \mathbf{B}_1 = (B_{1n}, B_{1t1}, B_{1t2})^T$, $\mathbf{B}_{0n} = T_1 \mathbf{B}_0 = (B_{0n}, B_{0t1}, B_{0t2})^T$, and

$$\bar{\mathbf{F}}_1 = \begin{bmatrix} m_{0n} \\ P_0 + \frac{m_{0n}m_{0n}}{\rho_1} + \frac{B^2}{2\beta} - \frac{B_n B_n}{\beta} - \frac{B_0^2}{2\beta} + \frac{B_{0n}B_{0n}}{\beta} \\ \frac{m_{0r1}m_{0n}}{\rho_1} - \frac{B_{r1}B_n}{\beta} + \frac{B_{0r1}B_{0n}}{\beta} \\ \frac{m_{0r2}m_{0n}}{\rho_1} - \frac{B_{r2}B_n}{\beta} + \frac{B_{0r2}B_{0n}}{\beta} \\ 0 \\ \frac{m_{0n}}{\rho_1} B_{t1} - \frac{m_{0r1}}{\rho_1} B_n \\ \frac{m_{0n}}{\rho_1} B_{t2} - \frac{m_{0r2}}{\rho_1} B_n \\ \frac{m_{0n}}{\rho_1} \left(U_1 + \frac{B_1^2}{2\beta} + P_0 \right) \\ - \frac{B_{1n}}{\beta} \left(\frac{m_{0n}}{\rho_1} B_{1n} + \frac{m_{0r1}}{\rho_1} B_{1t1} + \frac{m_{0r2}}{\rho_1} B_{1t2} \right) \\ + \frac{B_{1r1}}{\beta} \left(\frac{m_{0n}}{\rho_1} B_{0t1} + \frac{m_{0r1}}{\rho_1} B_{0n} \right) \\ + \frac{B_{1r2}}{\beta} \left(\frac{m_{0n}}{\rho_1} B_{0t2} + \frac{m_{0r2}}{\rho_1} B_{0n} \right) \end{bmatrix}, \quad (2.20)$$

$$\bar{\mathbf{F}}_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\eta J_{t2} \\ \eta J_{t1} \\ 0 \end{bmatrix}, \quad (2.21)$$

t is normalized by $L_0(RT_0)^{(1/2)}$ where L_0 is normalization length. As $\mathbf{B}_0$, a normalized dipole magnetic field is adopted.

From the equation 2.19, the variable component of U_1 , ρ_1 , m_0 and B_1 are related to normalized pressure P_0 by the equation

$$P_0 = (\gamma - 1) \left(U_1 - \frac{m_0^2}{2\rho_1} - \frac{B_1^2}{2\beta} \right). \quad (2.22)$$

The resistivity η is artificially set in this simulation, which is expressed by

$$\mathbf{J}_n = \mathbf{T}_1 \mathbf{J} = \mathbf{T}_1 \text{rot} \mathbf{B}_1, \quad (2.23)$$

$$\eta = k'_1 f_1(x) |J|^2 / |B|^2, \quad (2.24)$$

where $\mathbf{J}_n$, $f_1(x)$ and k'_1 are rotated current, a time-independent fixed function and a scaling

constant, respectively. The scaling constant is set to be small in the near-Earth region at $x > -20 R_E$ (GSM Coordinate system is utilized unless otherwise noted), it linearly increases toward downtail, and saturates at $x < -60 R_E$ [Tanaka, 2000].

The grid system is based on a dodecahedron [Moriguchi et al., 2008]. First, a spherical surface is divided into 12 pentagons and then each pentagon was divided into 5 triangles, yielding a total of 60 triangles and 32 grid points. This is called Level 1 gridding. Then each triangle is further divided into 4 triangles to yield a total of 240 triangles and 122 grid points. This is called Level 2 gridding. This grid system is shown in Figure 2.1. In this study, Level 6 gridding was used in Chapter 3, 4 and 5, and Level 5 gridding was

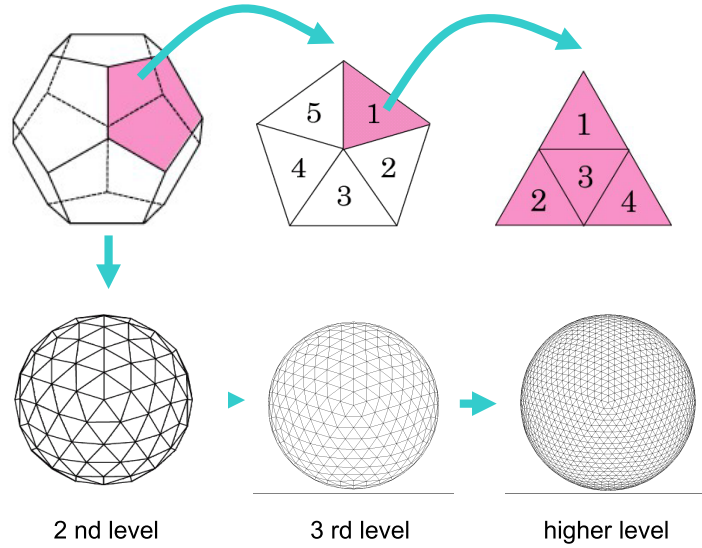


Figure 2.1: Grid system of the global MHD simulation [After Moriguchi et al., 2008].

used in Chapter 6. The grid system in the magnetosphere is basically generated by radial stacking of the spheres. The grid points in the magnetosphere is shown in Figure 2.2. In particular, dense grids are allocated at the inner boundary and in the plasmasheet. The inner boundary is located at $2.6 R_E$. Inside of the inner boundary, the dipole magnetic field is assumed.

On the ionosphere, the MHD variables are projected from the inner boundary along the dipole magnetic field lines. The electric potential at the ionospheric altitude Φ_i is calculated by

$$\nabla \cdot \Sigma \nabla \Phi_i = J_{\parallel} \quad (2.25)$$

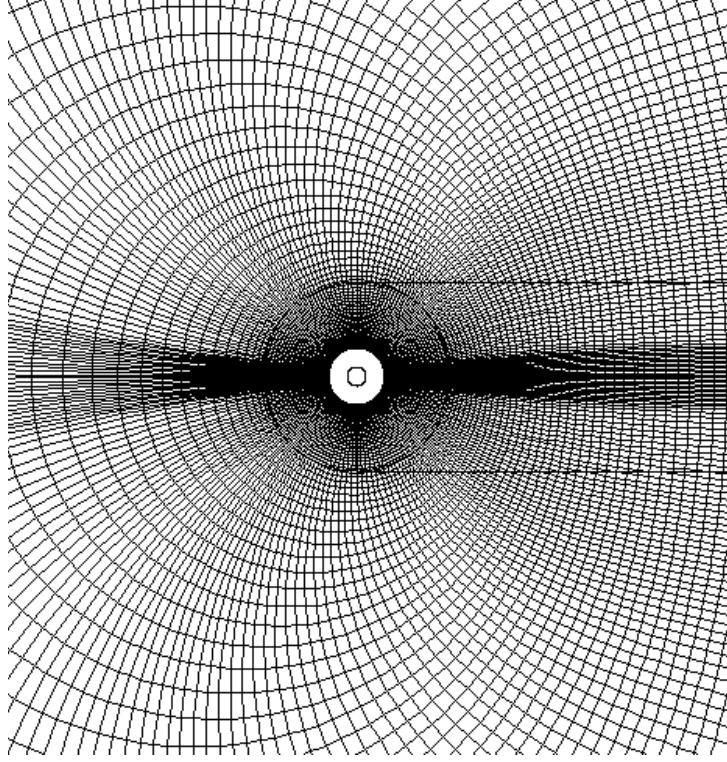


Figure 2.2: Illustration of the grid points of the MHD simulation in meridian plane [Tanaka, 2000].

where Σ is the height-integrated conductivity tensor. The ionospheric current was calculated as

$$\mathbf{J}_i = \Sigma \mathbf{E}_i = - \begin{pmatrix} \Sigma_{\theta\theta} & \Sigma_{\theta\phi} \\ \Sigma_{\theta\phi} & \Sigma_{\phi\phi} \end{pmatrix} \nabla \Phi_i \quad (2.26)$$

where $\mathbf{J}_i$ is the current density and $\mathbf{E}_i$ is electric field at the ionospheric altitude. The conductivity consists of three sources as stated in Tsunomura [1999], and the terms can be written as the following functions.

$$\Sigma_{\theta\theta} = k_{i1}(\lambda) \frac{\sigma_0 \sigma_1}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \quad (2.27)$$

$$\Sigma_{\theta\phi} = k_{i2}(\lambda) \frac{\sigma_0 \sigma_2 \sin I}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \quad (2.28)$$

$$\Sigma_{\phi\phi} = k_{i3}(\lambda) \frac{\sigma_1 \sigma_0 \sin^2 I + (\sigma_1^2 + \sigma_2^2) \cos^2 I}{\sigma_1 \cos^2 I + \sigma_0 \sin^2 I} \quad (2.29)$$

where I is the inclination of the magnetic field, σ_1 is the Pedersen conductivity, σ_2 is the Hall conductivity, and σ_0 is the parallel conductivity that is assumed to be 8 [Ebihara

et al., 2014]. The amplification factors, k_{i1} , k_{i2} , and k_{i3} , depend on latitude λ , so as to represent large height-integrated conductivities near the equator. After the calculation, the potential Φ_i is mapped to the MHD variables at the inner boundary as the potential electric field [Ebihara et al., 2015].

2.2 Test particle simulation

In the global MHD electromagnetic fields, we perform the test particle simulation, which is known as a powerful tool to investigate particles' transport and acceleration process. Normally, a motion of charged particle follows cyclotron motion under a conservation of the first adiabatic in-variant; magnetic moment μ_p given by $\mu_p = \frac{mv_\perp^2}{2B}$, where m_p and $v_\perp$ are mass and perpendicular velocity of the particle. However, for O^+ ion in the magnetosphere, because it is heavy ion, the motion often follows non-adiabatic motion and sometimes it becomes chaotic. The non-adiabatic acceleration occurs when a Larmor radius of charged particle R_L is comparable to the curvature radius of the magnetic field line R_c given by

$$R_L = \frac{m_p v_\perp}{qB}, R_c = \left| \frac{1}{(\mathbf{b} \cdot \nabla) \mathbf{b}} \right| \quad (\mathbf{b} = \frac{\mathbf{B}}{B}) \quad (2.30)$$

where q is charge of the particle. Sergeev et al. [1983] traced particle trajectories in a model magnetotail current sheet configuration and have pointed out that a charged particle undergoes non-adiabatic motion when the ratio $K_c = R_c/R_L$ is less than 8. We calculate the ratio K_c for test particles to estimate particles' motion.

If the value K_c is less than 8, we assume the particle motion follows adiabatic (cyclotron) motion. To trace the cyclotron motion of the test particles, we use the guiding center approximation with the fourth-order Runge-Kutta method. Equations of the motion of the guiding center are given by follows

$$\frac{d\mathbf{X}}{dt} = \mathbf{V}_\perp + \mathbf{b}V_\parallel \quad (2.31)$$

$$\frac{dV_\parallel}{dt} = -\mu \nabla_\parallel B + \frac{q}{m} E_\parallel \quad (2.32)$$

$$\frac{dW}{dt} = q\mathbf{V} \cdot \mathbf{E} \quad (2.33)$$

$$\mathbf{V}_\perp = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{mv_\perp^2}{2qB^3} \mathbf{B} \times \nabla \mathbf{B} + \frac{mv_\parallel^2}{qB^2} \mathbf{B} \times (\mathbf{b} \cdot \nabla) \mathbf{b} \quad (2.34)$$

where $\mathbf{V}$ is velocity of the guiding center. Three terms of the equation 2.34 are equivalent to $\mathbf{E} \times \mathbf{B}$ drift, grad B drift and curvature drift. Under the adiabatic motion, the cyclotron period T_c is given by

$$T_c = \frac{2\pi m}{qB}. \quad (2.35)$$

For this calculation, time step Δt is set to be T_c .

On the other hand, if the value of K_c is less than 8, we assume the particle motion follows non-adiabatic motion. To trace the non-adiabatic motion of the test particles, we solve the full motion of charged particles that are given by below

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (2.36)$$

where $\mathbf{v}$ is velocity of the test particle.

Under the non-adiabatic motion, the time step Δt referring the cyclotron period T_c is not appropriate because test particles do not follow the cyclotron motion. We determine the stepsize Δt using straightforward technique called "step doubling" [Abramowitz and Stegun, 1964] with the fourth-order Runge-Kutta method. We take each step twice, once as a full step, then, independently, as two half steps. We define

$$\mathbf{Y}^i = (x^i, y^i, z^i, v_x^i, v_y^i, v_z^i), \quad (2.37)$$

and the two approximate solutions for an advance from t to $t + 2\Delta t$ by $\mathbf{Y}_1$ (2 steps each of size Δt) and $\mathbf{Y}_2$ (one step $2\Delta t$). From the fourth-order Runge-Kutta method, $\mathbf{Y}_1$ is given by

$$\mathbf{Y}_1 = \mathbf{Y}'^n + \frac{1}{6}(\mathbf{k}_5 + \mathbf{k}_6 + \mathbf{k}_7 + \mathbf{k}_8)\Delta t \quad (2.38)$$

where

$$\mathbf{Y}'^n = \mathbf{Y}^n + \frac{1}{6}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4)\Delta t, \quad (2.39)$$

$$t'^n = t^n + \Delta t \quad (2.40)$$

$$\mathbf{k}_1 = f(\mathbf{Y}^n, t^n) \quad (2.41)$$

$$\mathbf{k}_2 = f(\mathbf{Y}^n + \mathbf{k}_1 \frac{\Delta t}{2}, t^n + \frac{\Delta t}{2}) \quad (2.42)$$

$$\mathbf{k}_3 = f(\mathbf{Y}^n + \mathbf{k}_2 \frac{\Delta t}{2}, t^n + \frac{\Delta t}{2}) \quad (2.43)$$

$$\mathbf{k}_4 = f(\mathbf{Y}^n + \mathbf{k}_3 \Delta t, t^n + \Delta t), \quad (2.44)$$

and

$$\mathbf{k}_5 = f(\mathbf{Y}'^n, t'^n) \quad (2.45)$$

$$\mathbf{k}_6 = f(\mathbf{Y}'^n + \mathbf{k}_5 \frac{\Delta t}{2}, t'^n + \frac{\Delta t}{2}) \quad (2.46)$$

$$\mathbf{k}_7 = f(\mathbf{Y}'^n + \mathbf{k}_6 \frac{\Delta t}{2}, t'^n + \frac{\Delta t}{2}) \quad (2.47)$$

$$\mathbf{k}_8 = f(\mathbf{Y}'^n + \mathbf{k}_7 \Delta t, t'^n + \Delta t). \quad (2.48)$$

On the other hand, $\mathbf{Y}_2$ is given by

$$\mathbf{Y}_2 = \mathbf{Y}^n + \frac{1}{6}(\mathbf{k}_1 + \mathbf{k}_9 + \mathbf{k}_{10} + \mathbf{k}_{11})2\Delta t \quad (2.49)$$

$$\mathbf{k}_9 = f(\mathbf{Y}^n + \mathbf{k}_1 \frac{(2\Delta t)}{2}, t^n + \frac{(2\Delta t)}{2}) \quad (2.50)$$

$$\mathbf{k}_{10} = f(\mathbf{Y}^n + \mathbf{k}_9 \frac{(2\Delta t)}{2}, t^n + \frac{(2\Delta t)}{2}) \quad (2.51)$$

$$\mathbf{k}_{11} = f(\mathbf{Y}^n + \mathbf{k}_{10} \frac{(4\Delta t)}{2}, t^n + \frac{(4\Delta t)}{2}). \quad (2.52)$$

In the procedure, these 11 evaluations are required for next step $2\Delta t$. The difference between the two numerical estimates with different time step is a useful indicator of truncation error which is

$$\Delta = |\mathbf{Y}_2 - \mathbf{Y}_1|. \quad (2.53)$$

We advanced the solution in time when the following equation $\Delta < \epsilon$ is satisfied. Otherwise, we recalculated the solution with a reduced step size given by the following equation.

$$\Delta t = 0.8\Delta t(\epsilon/|\mathbf{Y}_2 - \mathbf{Y}_1|)^{0.5}. \quad (2.54)$$

The parameter ϵ was set to be $63.7 \text{ m } (10^{-5} R_E)$.

Chapter 3

Oxygen Injection in the Plasmasheet during the Substorm

3.1 Introduction

As is stated in Chapter 1, a notable feature of the O^+ ions in the inner magnetosphere is their drastic enhancement in accordance with geomagnetic activities [e.g. Young et al., 1982; Hamilton et al., 1988; Roeder et al., 1996; Daglis and Axford, 1996; Daglis et al., 1997] and fast plasma flows in the near-Earth tail [Zong et al., 1997; Ohtani et al., 2015]. The rapid appearance of the O^+ ion with energy of the order of 100 keV in the inner magnetosphere can be explained by the acceleration and transport of the O^+ ions in the near-Earth plasma sheet during a dipolarization [e.g. Delcourt et al., 2002; Fok et al., 2006, Ashour-Abdalla et al., 2009; Perroomian et al., 2011; Birn et al., 2013]. Delcourt [2002] investigated the processes by using a test particle simulation. To model electric and magnetic fields associated with a dipolarization, he introduced the magnetic field given by interpolating two states of the empirically-obtained magnetic field, and the electric field obtained by the time derivative of the vector potential. The result shows that an O^+ ion with initial energy of ~ 10 eV in the equatorial plane is accelerated to ~ 100 keV as it encounters the dipolarization when it moves from $L = 9.0$ to $L = 6.8$. An O^+ ion with an initial energy of 100 eV was also launched from the auroral zone on the nightside. The kinetic energy is increased to ~ 100 keV when dipolarization is introduced, whereas the energy is increased only to ~ 10 keV for the absence of the dipolarization. Fok et al. [2006] performed a test particle simulation under the electric and magnetic fields obtained by a global magnetohydrodynamics (MHD) simulation, and concluded that direct injection of cold O^+ ions from the ionosphere will result in a significant time lag

between the onset of the O^+ outflow and the enhancement in the inner magnetosphere. This means that direct injection of cold O^+ from the ionosphere is unlikely to explain the burst of the energetic neutral oxygen measured by IMAGE/HENA. Fok et al. [2006] pointed out that nonadiabatic acceleration of preexisting O^+ ions can account for the O^+ burst without introducing direct injection of O^+ ions from the ionosphere.

It is also accepted that a non-adiabatic acceleration triggered by dipolarization significantly contributes to the rapid energization of O^+ ions [Delcourt et al., 1990; Delcourt et al., 1991; Delcourt and Moore, 1992; Delcourt et al., 2002]. The non-adiabatic acceleration occurs when a Larmor radius of charged particle is comparable to the curvature radius of the magnetic field line. This process easily happened for O^+ ions because heavy O^+ ions have a large Larmor radius as compared with light ion in the magnetosphere like H^+ and He^+ . This can explain the observations that O^+ ions are more effectively accelerated than H^+ and He^+ ions during the substorms [Fu et al., 2002; Mitchell et al., 2003; Ohtani et al., 2005].

Many studies have pointed out the importance of the dawn-to-dusk electric field in the near-Earth plasma sheet and non-adiabatic acceleration during the depolarization for the rapid generation of energetic O^+ ions associated with a substorm. However, at least two questions remain unanswered. The first question is the generation mechanism of the dawn-to-dusk electric field that rapidly accelerates the O^+ ions to the energy of the order of 100 keV. The second question is the evolution of the distribution function (or the differential flux) of the O^+ ions as a function of position, energy, and time. To answer these questions, we performed a test particle simulation in the electric and magnetic fields obtained by a global MHD simulation, and reconstructed the distribution function of the O^+ ions.

3.2 Observations of substorm-time injection

Fu et al. [2002] showed three examples of counting rates of O^+ ions observed by CRRES during substorms as a function of energy and time. At $L < 6.6$ near the equatorial plane, the counting rates of the O^+ ions increase at all energy. The increase of the counting rates has a delay depending on energy. That is, an energy-time dispersion appears. Sometimes drift echo appears in accordance with the drift period of the O^+ ions. In the near-Earth plasma sheet, the response of the O^+ ions is different from that in the inner magnetosphere.

	Solar wind speed (km/s)	IMF (nT)
Case I	372	(0, 2.5, 4.33) →(0, 4.33, -4.33)
Case II	500	(0, 2.5, 5.0) →(0, 2.5, -5.0)

Table 3.1: Solar wind parameters that are used as boundary conditions in the MHD simulation.

Figure 3.1 shows two examples of the differential flux of the O^+ ions taken by magnetospheric ion composition spectrometer (MICS) onboard the Polar satellite [Wilken et al., 1992]. The Polar satellite was launched into an elliptical orbit with an apogee of $9 R_E$, a perigee of $2 R_E$, and inclination of 86 degrees. Two examples were obtained at $L \sim 6.6-9.0$ near midnight near the equatorial plane. In both cases, the Polar satellite moved outward from the Southern Hemisphere to the Northern Hemisphere. The differential flux of the O^+ ions is kept relatively high in the entire energy range between 5 keV and 200 keV for the first one-third period. During this period, the flux sharply decreases with energy. During the second one-third period (between 07:15 UT and 08:10 UT in Figure 3.1a; between 20:13 UT and 22:00 UT in Figure 3.1b), the flux below 10 keV significantly decreases. The flux has a peak at 15-30 keV. We discuss the feature of flux decrease at low energies and its generation mechanism later.

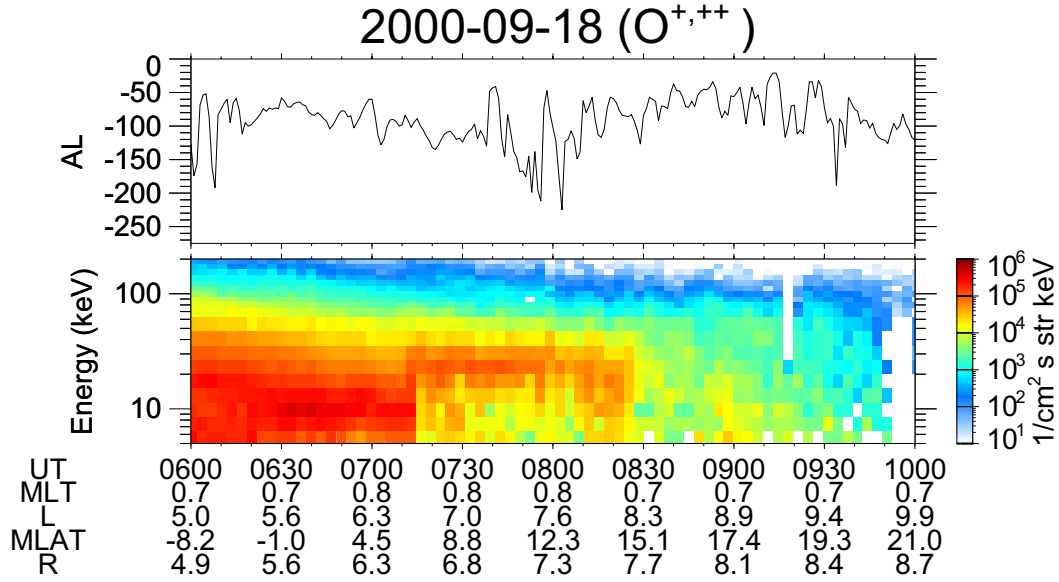
3.3 Simulation

3.3.1 Settings for the global MHD simulation

We used a global MHD simulation developed by Tanaka et al. [2010] to derive the electric and magnetic fields associated with a substorm self-consistently. Two different boundary conditions in the solar wind were used, which are summarized in Table 3.1.

In Case I, the solar wind speed was held constant to be 372 km/s, and IMF turned from (0, 2.5, 4.33) to (0, 4.33, -4.33) nT. In Case II, the solar wind speed was held constant to be 500 km/s, and IMF turned from (0, 2.5, 5.0) to (0, 2.5, -5.0) nT. The simulation settings for Case I are the same as those used by Ebihara and Tanaka [2013]. The onset of substorm expansion phase is defined as the moment at which the calculated AL index suddenly decreases, and hereinafter referred to as $t = 0$.

(a)



(b)

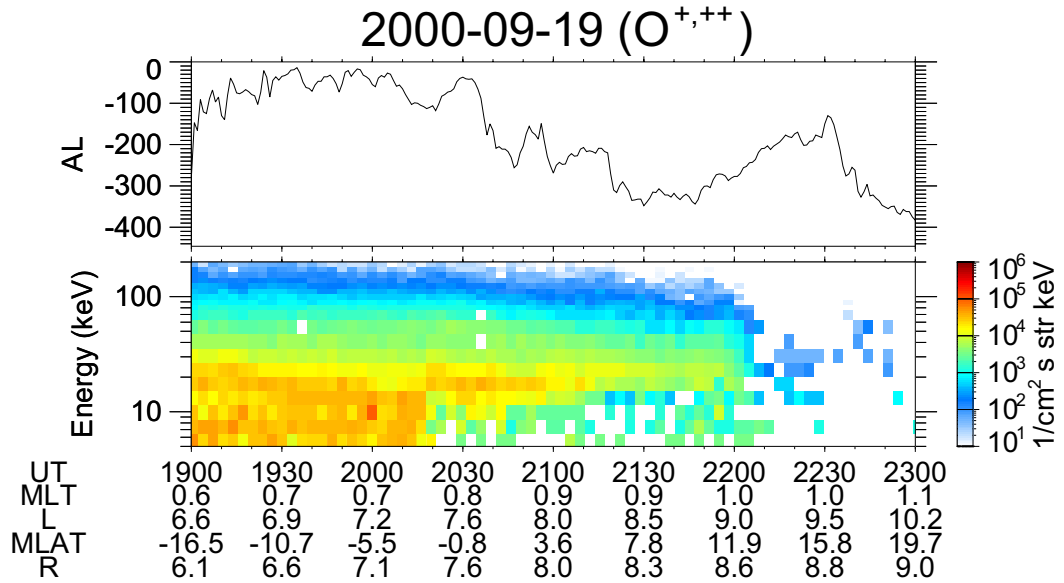


Figure 3.1: Differential flux of the O^{+} ions taken by the Polar satellite at $L \sim 6.6-9.0$ near midnight near the equatorial plane. Ephemeris information is included at the bottom of the figure. MLT represents the magnetic local time in hours, MLAT represents the magnetic latitude in degrees, and R represents the geocentric distance in R_E

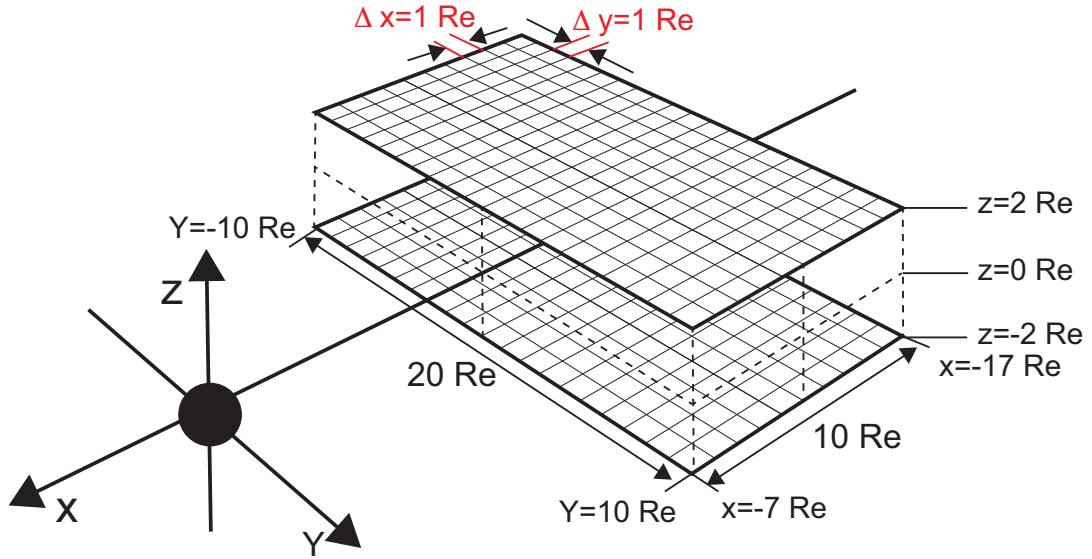


Figure 3.2: The geometry of the grid cells that are used to place test particles.

3.3.2 Settings for the test particle simulation

Since our primary focus is on the acceleration and transport processes of the O^+ ions in near-Earth tail region, we started tracing the ions at off-equator where cold O^+ stream outflowing from the ionosphere is dominant. We introduced two planes parallel to the equatorial plane $Z = \pm 2 R_E$, ranging from $X = -7$ to $-17 R_E$, and from $Y = -10$ to $10 R_E$. We divided the plane into 10×20 Cartesian grid cells, and each grid cell has $1 R_E$ width (ΔX_i) and $1 R_E$ length (ΔY_i). The geometry of the grid cells is shown in Figure 3.2. O^+ ions were placed at the grid points ($11 \times 21 \times 2$ in total) with an interval time Δt of 1 minute. In velocity space, we introduced spherical coordinates; kinetic energy, polar angle θ (the angle between the velocity vector and the Z axis), and azimuthal angle ϕ (the angle between the velocity vector and the Sun projected on the X - Y plane). Initial kinetic energy K_i is defined in the frame of the bulk velocity simulated by global MHD simulation and it is logarithmically divided as

$$K_i = 10^{0.3h_i} \text{ eV}, \quad h_i = 0 \text{ to } 10 \quad (3.1)$$

Thus, K_i ranges from 1 eV to 1 keV with a constant interval in logarithmic scale. We added the ions with $K_i = 0$ eV because these ions have the bulk velocity in the inertial frame of reference. Initial polar angle θ_i is divided linearly from 90° to 180° in the Northern Hemisphere and 0° to 90° in the Southern Hemisphere with an interval of 1° . Initial azimuth angle ϕ_i is also divided linearly from 0° to 360° with an interval of 10° . In total, a few billion test particles were traced from the planes for each case. The scheme for test particle tracing is the same as that described in chapter 2.

We calculated the distribution function f in accordance with Liouville's theorem. Each test particle carries the real number of particles ΔN_i in the small bin in the 6-dimensional space (3 dimensions in the configuration space and 3 dimensions in the velocity space) as

$$\Delta N_i = f_i \Delta^3 r_i \Delta^3 v_i, \quad (3.2)$$

where $\Delta^3 r_i$ and $\Delta^3 v_i$ are the volumes in configuration space and velocity space, respectively, which are represented by

$$\Delta^3 r_i = v_i \cos \theta_i \Delta X_i \Delta Y_i \Delta t, \quad (3.3)$$

$$\Delta^3 v_i = v_i^2 \sin \theta_i \Delta v_i \Delta \theta_i \Delta \phi_i, \quad (3.4)$$

where v_i is the corresponding velocity of particle to K_i , that is $\sqrt{2K_i/m}$. After tracing particles, we reconstructed f by accumulating the real number of the particles falling into a small bin in configuration space and velocity space,

$$f = \sum \frac{\Delta N_i}{\Delta^3 r \Delta^3 v} \quad (3.5)$$

Reader may refer Ebihara et al. [2006] for more detailed information about the methodology. In this particular study, we assumed a drifting Kappa distribution in the source region. The drifting Kappa distribution is modified from the original Kappa distribution [Vasyliunas, 1968; Summers and Thorne, 1991] as

$$f = \frac{n}{\pi^{3/2} \theta_k^3} \frac{\Gamma(\kappa + 1)}{\kappa^{3/2} \Gamma(\kappa - 1/2)} \left(1 + \frac{|\mathbf{v}_{ini} - \mathbf{V}_{MHD}|^2}{\kappa \theta_k^2} \right)^{-(\kappa+1)} \quad (3.6)$$

and

$$\theta_k = \left(\frac{2\kappa - 3}{\kappa} \frac{kT}{m} \right)^{1/2} \quad (3.7)$$

where $n, \kappa, k, m, \mathbf{v}_{\text{ini}}, T$ and $\mathbf{V}_{\text{MHD}}$ are the density, the spectral index, the Boltzmann constant, the mass of particle, the velocity of particle, the temperature, and the bulk velocity of plasma given by the MHD simulation. We assumed that $n = 0.1 \text{ cm}^{-3}$, $\kappa = 4.5$, and $kT = 10 \text{ eV}$ unless otherwise mentioned. In order to compare with satellite observations, we calculated the directional differential flux j as

$$j = \frac{v^2}{m} f. \quad (3.8)$$

3.4 Simulation result

3.4.1 Global MHD simulation: Case I and Case II

Figure 3.3 summarizes the key quantities obtained by the MHD simulation in the equatorial plane at the onset of the substorm expansion. Our MHD simulation result showed that the formation of the near-earth neutral line (NENL) in the midtail region causes the earthward fast flow. The earthward flow corresponds to the transient electric field. The earthward flow results in the plasma squeezing and the formation of high pressure region in the inner magnetosphere. Then the AL starts to decrease [Tanaka et al., 2010]. Figure 3.3a shows the plasma pressure. The plasma pressure has a peak around 7-9 R_E near midnight. There is a sub-peak in the pressure around 10 R_E near midnight. Figure 3.3b shows the Y -component of the electric field E_y . The dawn-to-dusk electric field is significantly enhanced at $> 8 R_E$ in longitudinally narrow regions in the pre-midnight and post-midnight. The regions where the strong E_y occurs are determined by the NENL, however we don't have the answer to the question why the NENL formed in longitudinally narrow regions. The strongest E_y occurs between 8 and 9 R_E . Figure 3.3c shows the X -component of the plasma bulk flow (V_x), indicating that fast earthward flow (positive V_x) is established between 11 and 15 R_E . The region where V_x is largest is located farther away from the Earth than where E_y is the largest. Figure 3.3d shows the magnetic field strength. There is a sub-peak in the magnetic field strength between 9 and 10 R_E near midnight. The sub-peak can be explained in terms of pile-up of the magnetic flux associated with dipolarization. Figure 3.3e shows the curvature radius of a magnetic field line. Near midnight, the curvature radius is in general small ($< 1 R_E$) except around 10 R_E . The right hand side of Figure 3.3 summarizes the force density in

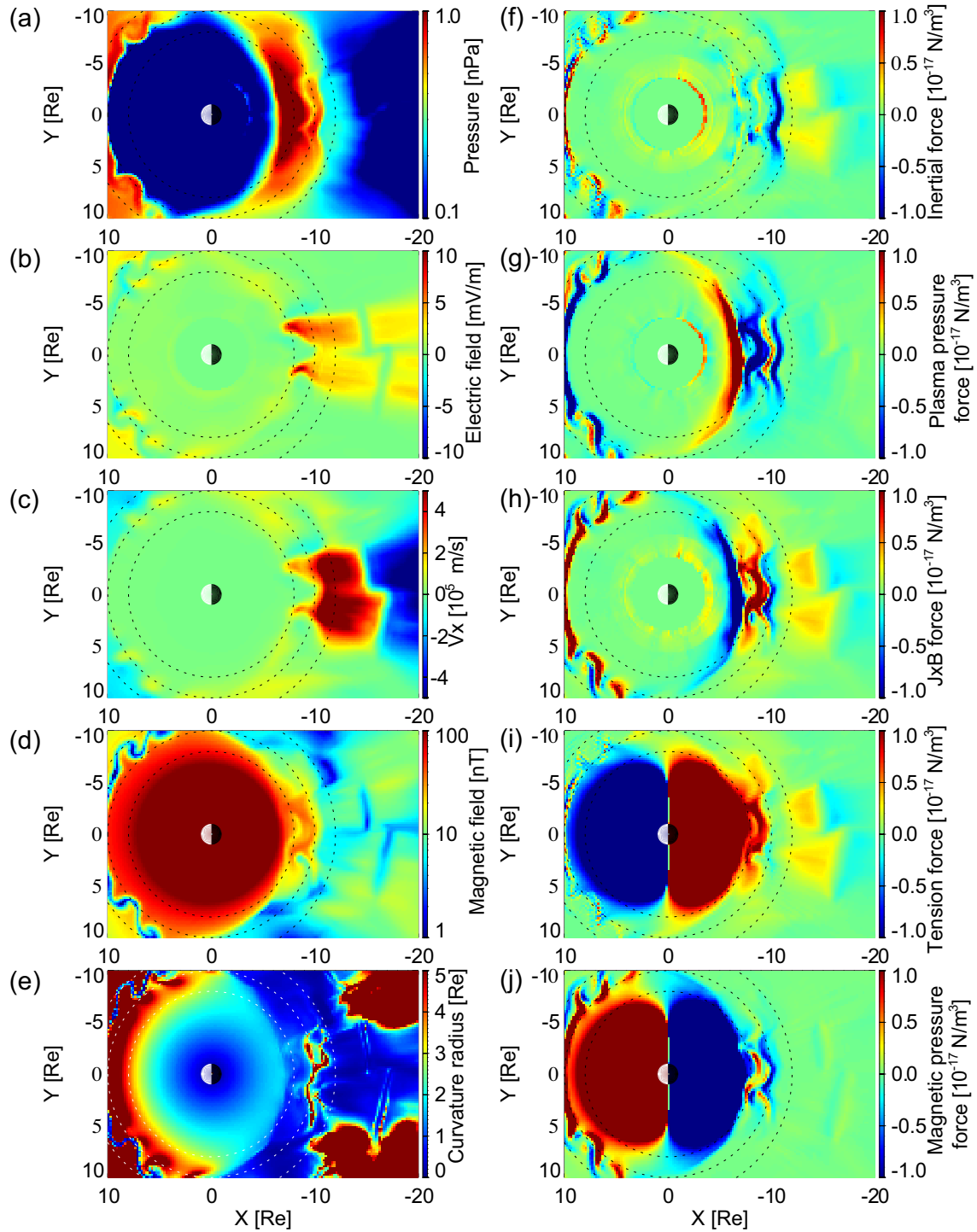


Figure 3.3: (a) The plasma pressure, (b) the Y -component of the electric field E_y , (c) X -component of the plasma bulk flow V_x , (d) the magnetic field strength, (e) the curvature radius of a magnetic field line, (f) the inertial force, (g) the plasma pressure force, (h) the Lorentz force, (i) the tension force and (j) the magnetic pressure force in the X -component in the equatorial plane at $t=0$ minutes for Case I. The sum of the Lorentz force and the plasma pressure force is equal to the inertial force.

the X -component. In the ideal MHD, the balance of the force density is given by

$$\rho \frac{d\mathbf{V}_{\text{MHD}}}{dt} = -\nabla P + \mathbf{J} \times \mathbf{B}, \quad (3.9)$$

and

$$\mathbf{J} \times \mathbf{B} = \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0} - \nabla \left(\frac{B^2}{2\mu_0} \right) \quad (3.10)$$

where ρ is the mass density, μ_0 is the magnetic constant, $\mathbf{J}$ is the current density. The left hand side of Eq. 3.9 is called inertial force, which is shown in Figure 3.3f. Two terms on the right hand side (RHS) of Eq. 3.9 are called plasma pressure force (Figure 3.3g), and Lorentz force (Figure 3.3h), respectively. The Lorentz force can be divided into two as Eq. 3.9. Two terms on the RHS of Eq. 3.9 are called tension force (Figure 3.3i), and magnetic pressure force (Figure 3.3j), respectively.

The X -component of tension force and magnetic pressure force is written as

$$\frac{\left(B_x \frac{\partial}{\partial x} + B_y \frac{\partial}{\partial y} + B_z \frac{\partial}{\partial z} \right) B_x}{\mu_0} \quad (3.11)$$

and $-\frac{\partial}{\partial x} \frac{B^2}{\mu_0}$, respectively. In Figure 3.3i and 3.3j, the sign is different between nightside and dayside because the sign of B_x and $-\frac{\partial}{\partial x} \frac{B^2}{\mu_0}$ is opposite. There are three characteristics to be noted regarding the force density. First, earthward (tailward) inertial force is established earthward (tailward) of the NENL that is located at $\sim 14 R_E$ near midnight (Figure 3.3f). The earthward inertial force is due to the dominance of the tension force that is shown in Figure 3.3i. The earthward inertial force results in the increase in V_x (Figure 3.3c), and hence the increase in E_y (Figure 3.3b). Secondly, at $\sim 10 R_E$ near midnight, tailward inertial force becomes dominant as shown by bluish color in Figure 3.3f. The tailward inertial force is caused by the plasma pressure force (Figure 3.3g) and the magnetic pressure force (Figure 3.3j). Thirdly, in a narrow region at $\sim 9 R_E$ in the midnight, the earthward inertial force becomes dominant again, which results from the earthward tension force (Figure 3.3i).

Figure 3.4 summarizes the selected quantities at $Y = -2.5 R_E$ in the equatorial plane as a function of X . The vertical black dotted lines indicate the position where the inertial force density is zero. In the region between $X = -10.8$ and $-14.5 R_E$, the inertial force density is earthward because of the dominance of the earthward tension force (Figure 3.4a), and the plasma is accelerated earthward (Figure 3.4b). In the region between $X = -8.6$ to $-10.8 R_E$, the inertial force density is tailward (Figure 3.4a), and the plasma is

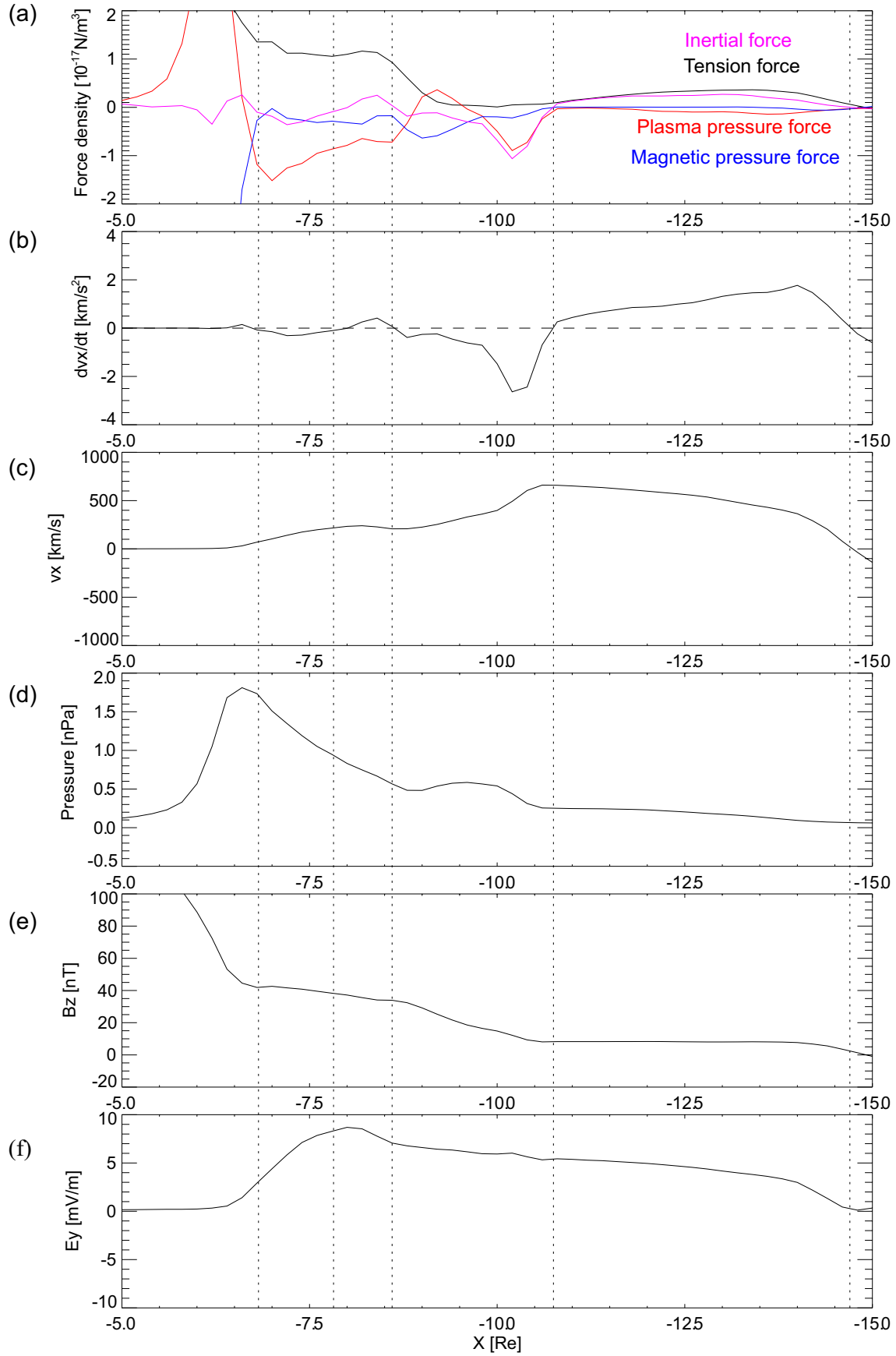


Figure 3.4: (a) The X-component of the force densities. Summation of the plasma pressure force, the tension force and the magnetic pressure force is equal to the inertial force. (b) The acceleration of the plasma bulk flow, (c) V_x , (d) the plasma pressure, (e) the Z-component of the magnetic field B_z , and (f) E_y , at $Y = -2.5 R_E$ in the equatorial plane as a function of X for Case I.

decelerated (Figure 3.4b). The deceleration of the plasma flow comes from the tailward plasma pressure force and the magnetic pressure force (Figure 3.4a). Thus, the earthward flow velocity has a peak at $X = -10.5 R_E$ (Figure 3.4c). The Z-component of the magnetic field (B_z) increases with X , which can be regarded as the pile up of the magnetic flux in association with the flow braking (Figure 3.4e). In the region between $X = -8.0$ to $-8.6 R_E$, the inertial force density is slightly positive (Figure 3.4a), and the earthward flow velocity is almost constant (Figure 3.4c). However, E_y increases with X , and has a peak at $X = -8.0 R_E$. This is simply understood to the fact that, in the ideal MHD, the electric field is given by the following equation,

$$\mathbf{E} = -\mathbf{V}_{\text{MHD}} \times \mathbf{B} \quad (3.12)$$

Thus, the peak of E_y takes place $2.5 R_E$ earthward of the peak of V_x .

Key quantities for Case II are summarized in Figure 3.5. The overall distributions of the quantities are essentially same as that for Case I. Noticeable differences between Case I and Case II are the location of the NENL and the intensity of E_y . The NENL is formed at $\sim 11.5 R_E$ near midnight, which is $2.5 R_E$ earthward of the NENL for Case I. The peak of E_y is ~ 13 mV/m for Case II (Figure 3.5b), whereas that is ~ 9 mV/m (Figure 3.3b).

Figure 3.6 is the same as Figure 3.4 except for Case II at $Y = 0 R_E$. The mechanism of the enhancement of E_y is essentially the same as that of Case I. The peak of E_y occurs $1 R_E$ earthward of the peak of V_x because of pile-up of the magnetic flux.

3.4.2 Test particle simulation: Case I and Case II

Figure 3.7 summarizes snapshots of the differential flux j of the O^+ ions at three energy intervals from 10 to 50 keV (top), 50 to 100 keV (middle), 100 to 200 keV (bottom) at $t = -5$ (left), 0 (middle), and 5 (right) minutes. A white contour line indicates the region where $|E_y|$ is 5 mV/m. At the onset and onward, there are, at least, two distinct areas where $|E_y|$ is greater than 5 mV/m in the pre-midnight and post-midnight regions. At $t = -5$ minutes (left column), the flux remains low at all energy intervals. At the substorm onset ($t = 0$; middle column), the flux at all the energy intervals is suddenly enhanced on the nightside. The region where the flux is high occupies from $7 R_E$ to, at least, $20 R_E$ in azimuthally wide area on the nightside. The significant enhancement of the flux takes place at $Y > -3 R_E$. This implies that significant acceleration of the O^+ ions

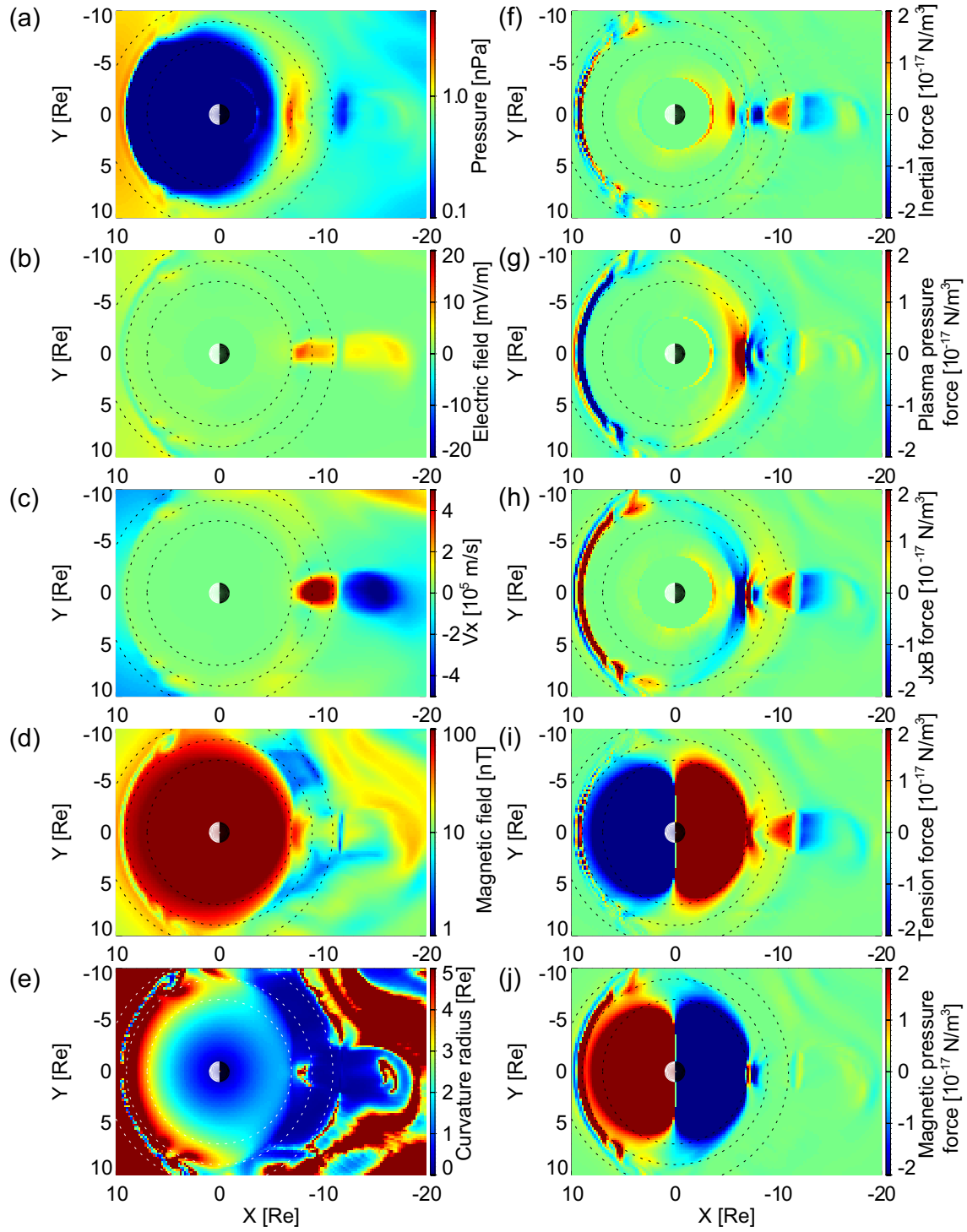


Figure 3.5: Same as Figure 3.3 except for Case II.

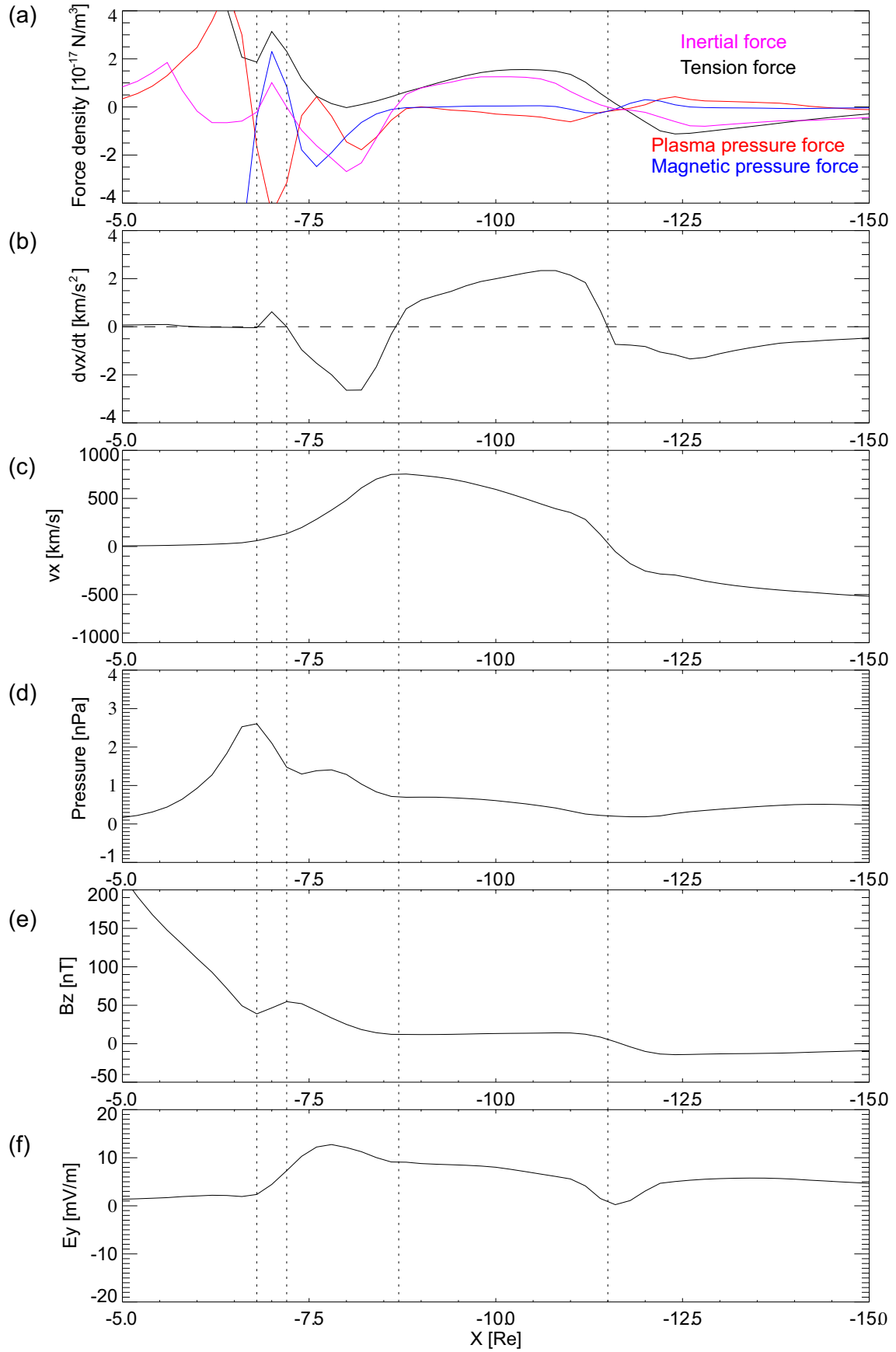


Figure 3.6: Same as Figure 3.4 except at $Y = 0 R_E$ in the equatorial plane as a function of X except for Case II.

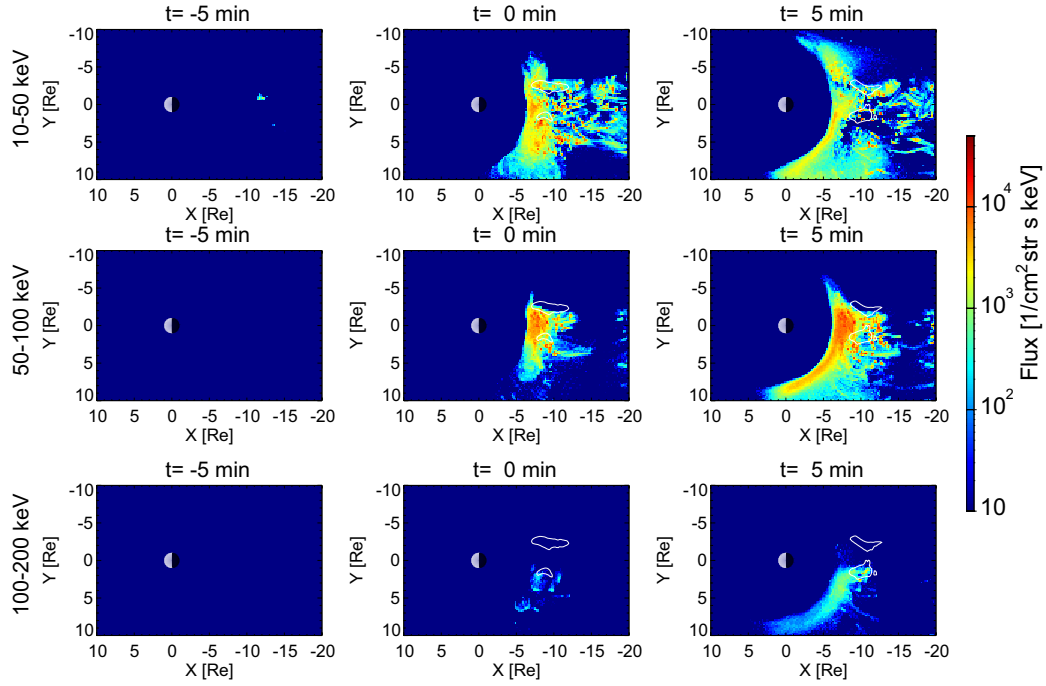


Figure 3.7: Snapshots of the differential flux j of the O^+ ions at three energy intervals from 10 to 50 keV (top), 50 to 100 keV (middle), 100 to 200 keV (bottom) at $t = -5$ (left), 0 (middle), and 5 (right) minutes. The white contour line indicates the region where $|E_y|$ is 5 mV/m.

takes place the region where $|E_y|$ is large, and that the flux at high energy increases just westward of the high E_y region. At $t = 5$ minutes (right column), the region where the flux is high propagates duskward because the ions drift westward due to the grad-B and curvature drift. After encircling the Earth, the ions came back to midnight (not shown), and contribute to the drift echo structure as mentioned later.

To understand the acceleration and transport process of the O^+ ions with energy greater than 100 keV, we focused on the 42 most significant test particles that contribute to the flux j at the energy interval from 100 to 200 keV at $X = -7.5 R_E$, and $Y = -2.0 R_E$. In total, they contribute to 5% of the flux j at that point. Figure 3.8 shows the trajectories of the 42 test particles in the X - Y and X - Z planes. The kinetic energy of the ion is indicated by color. Contour lines in Figure 3.8a indicate $|E_y|$ at $t = 0$. Black lines in Figure 3.8b indicate the magnetic field lines extending from $X = -4$ to $-16 R_E$ at $Y = -2.5 R_E$ at $Z = 0 R_E$ at $t = 0$. All the ions are found to depart at $(-13, -4, 2) R_E$ at $t = -4$ minutes with initial energy of around 5 eV. Because initial time, position and energy of the O^+ ions are same and initial polar and azimuth angle are similar, they show similar trajectories and energy increases. After the departure, the O^+ ions move tailward and toward the equatorial plane. The kinetic energy is not significantly increased. When

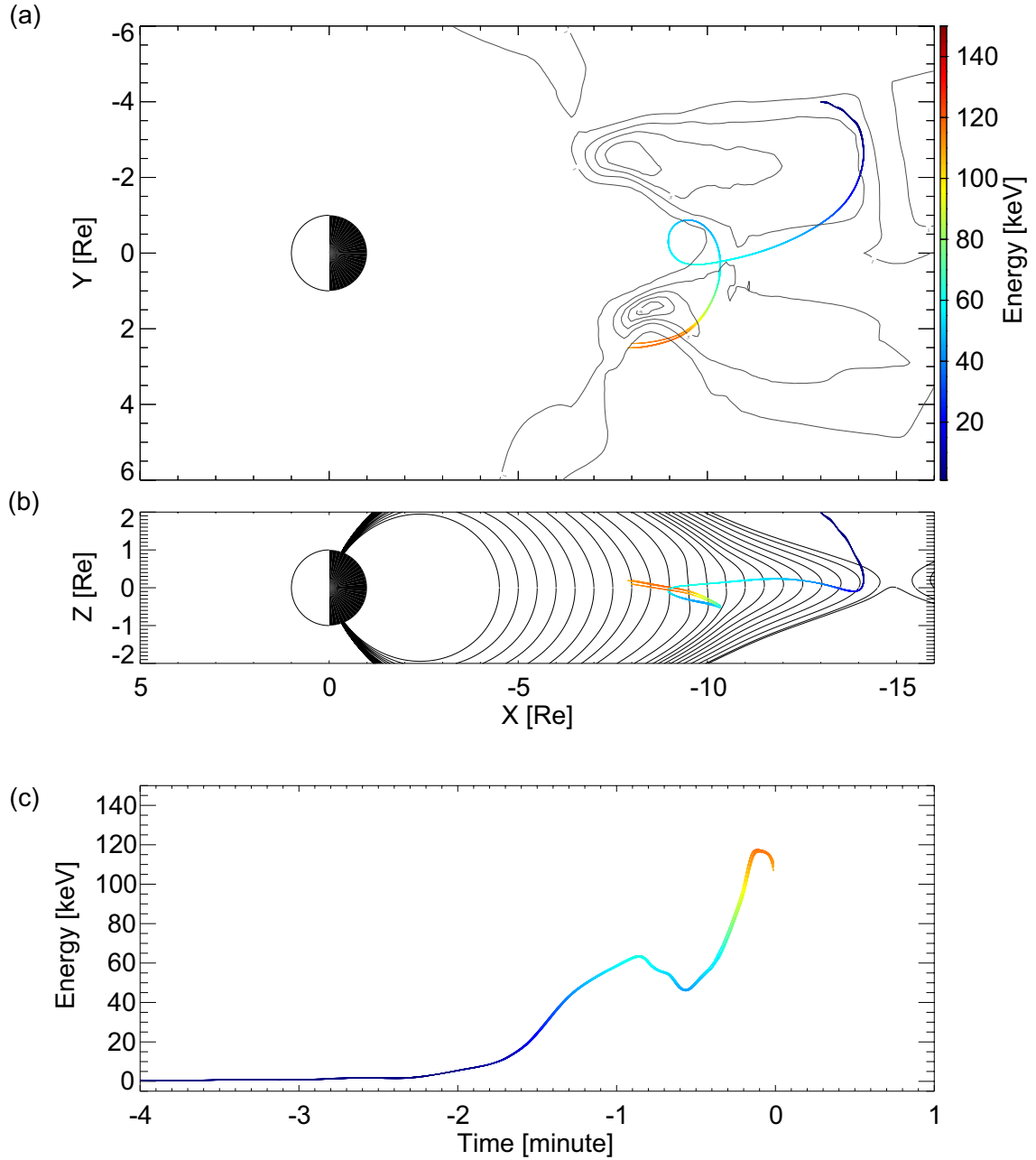


Figure 3.8: The trajectories of the 42 test particles in the (a) X-Y and (b) X-Z plane with energy color coded. The black lines in (a) and (b) represent $|E_y|$ contours and magnetic field lines, respectively. (c) The kinetic energy as a function of t .

these ions reach the earthward vicinity of the NENL ($X = \sim -14.5 R_E$) near the equatorial plane, and the direction of the ion velocity turns from tailward to earthward (Figure 3.8b). Immediately after the changing of the direction, they proceed earthward, and the kinetic energy increases. Finally, the energy reaches 120 keV. The bottom panel of Figure 3.8 shows kinetic energy as a function of time, which shows a two-step increase. The increases in energy occurs when the ions traverse the region where $|E_y|$ is large. During the first increase, the energy increases to 65 keV, and during the second increase, it increases to 120 keV.

We calculated the ratio $K_c = R_{cmin}/L_{max}$ where R_{cmin} is the minimum curvature radius of a magnetic field, and L_{max} is the maximum Larmor radius of a particle [Sergeev et al., 1983]. Sergeev et al. [1983] have pointed out that a charged particle undergoes non-adiabatic motion when $K_c < 8$. At $X = -13 R_E$, and $Y = 0 R_E$ (in which the first increase in energy takes place), the curvature radius of the magnetic field line is $0.2 R_E$, and the magnetic field strength is 8.1 nT. The Larmor radius of the O^+ ion with energy of 40 keV is $2.2 R_E$, so that $K_c = 0.09$. At $X = -10 R_E$, and $Y = 1.5 R_E$ (in which the second increase in energy takes place), K_c is calculated to be 0.7 for the O^+ ion with energy of 226 keV. Thus, it is obvious that the O^+ ions undergo non-adiabatic motion, and gain kinetic energy non-adiabatically under the influence of the strong dawn-to-dusk electric field.

Figure 3.9 summarizes snapshots of the differential flux j at the energy intervals from 10 to 50 keV (top), 50 to 150 keV (middle), and 150 to 350 keV (bottom). The flux appears to increase in and westward of the region where $|E_y|$ is large at $t = 0$. At the energy interval from 10 to 50 keV, the flux is shown to increase earthward and tailward of the NENL at $\sim 11.5 R_E$. At the energy interval from 50 to 150 keV, the flux enhancement takes place earthward of the NENL only. The pile-up of the magnetic flux occurs on the earthward side of the NENL only, so that $|E_y|$ is stronger on the earthward side of the NENL than on the tailward side. The asymmetry of the flux enhancement is obviously seen at the energy interval from 50 to 150 keV. At the energy interval from 150 to 350 keV, the flux appears to largely increase at $t = 4$ minutes.

To understand the acceleration and transport processes of the O^+ ions that reach the energy interval from 150 to 350 keV, Figure 3.10 shows trajectories of the 120 most significant test particles that contribute to the flux j at the energy interval from 150 to 350 keV at $X = -8.0 R_E$, $Y = 0.7 R_E$. In total, they contribute to 5% of the flux j at that point. The ions are found to depart at $(-8, -2, 2) R_E$ at $t = -4$ minutes with initial energy

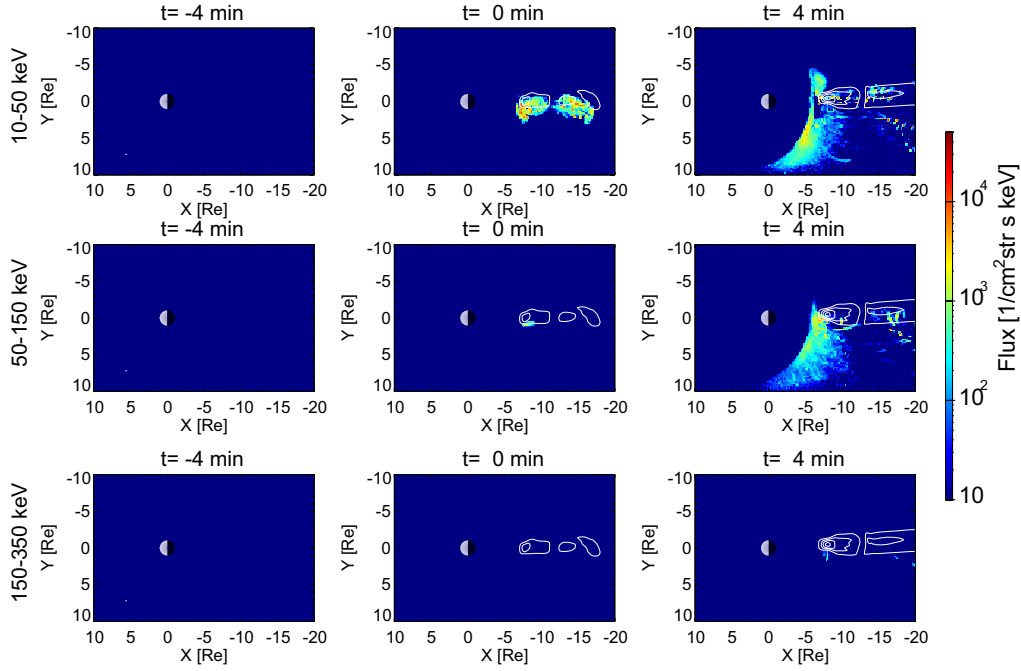


Figure 3.9: Same as Figure 3.7 except at three energy intervals from 10 to 50 keV (top), 50 to 150 keV (middle), 150 to 350 keV (bottom) at $t = -4$ (left), 0 (middle), and 4 (right) minutes for Case II.

of around 5 eV. After the departure, the O^+ ions gain kinetic energy largely when it traverses the region where $|E_y|$ is large. Finally, the energy reaches ~ 300 keV. The ions undergo non-adiabatic motion because the ratio K is 0.15 for the O^+ ions with 100 keV at $X = -10 R_E$, $Y = 0$. Obviously, the trajectories of the ions do not show regular Larmor motion.

Figure 3.11 shows energy versus time spectrograms of the differential flux of the O^+ ions at fixed positions (5.5, 6.0, and 7.0 R_E ; 21, 22, 23, and 00 MLTs; the equatorial plane) for Case II. At 5.5 R_E , the flux is enhanced at energy less than ~ 70 keV. The flux does not always increase simultaneously at all energies. At 23 MLT (Figure 3.11b), the flux between ~ 25 keV and ~ 60 keV increases first at $t = 7$, followed by the high energy and lower energy. The energy-time structure is similar to the nose dispersion that the flux increase is observed first at narrow energy range and spreads to both higher and lower energies [Smith and Hoffman, 1974; Ejiri et al., 1980]. At 22 MLT (Figure 3.11c), the energy-time dispersion becomes significant. At 21 MLT (Figure 3.11d), the flux of the ~ 10 keV ions start to increase at $t \sim 57$ minutes.

At 6.0 R_E , the intensity of the flux is larger than at 5.5 R_E . At 00 MLT (Figure 3.11e), the flux increases almost simultaneously at energy between 10 and 120 keV at $t = 0-1$

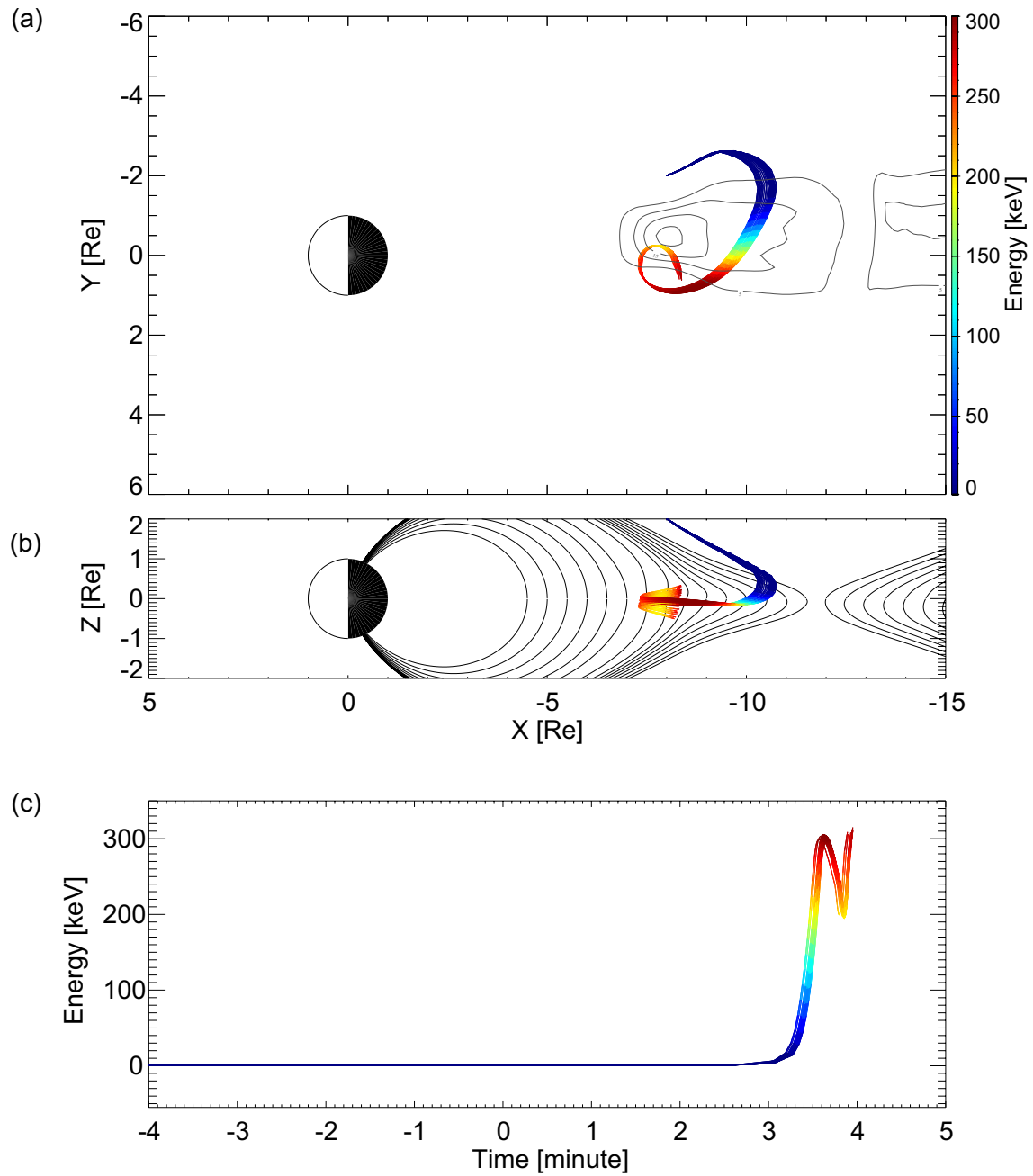


Figure 3.10: Same as Figure 3.8 except for the 120 test particles of Case II.

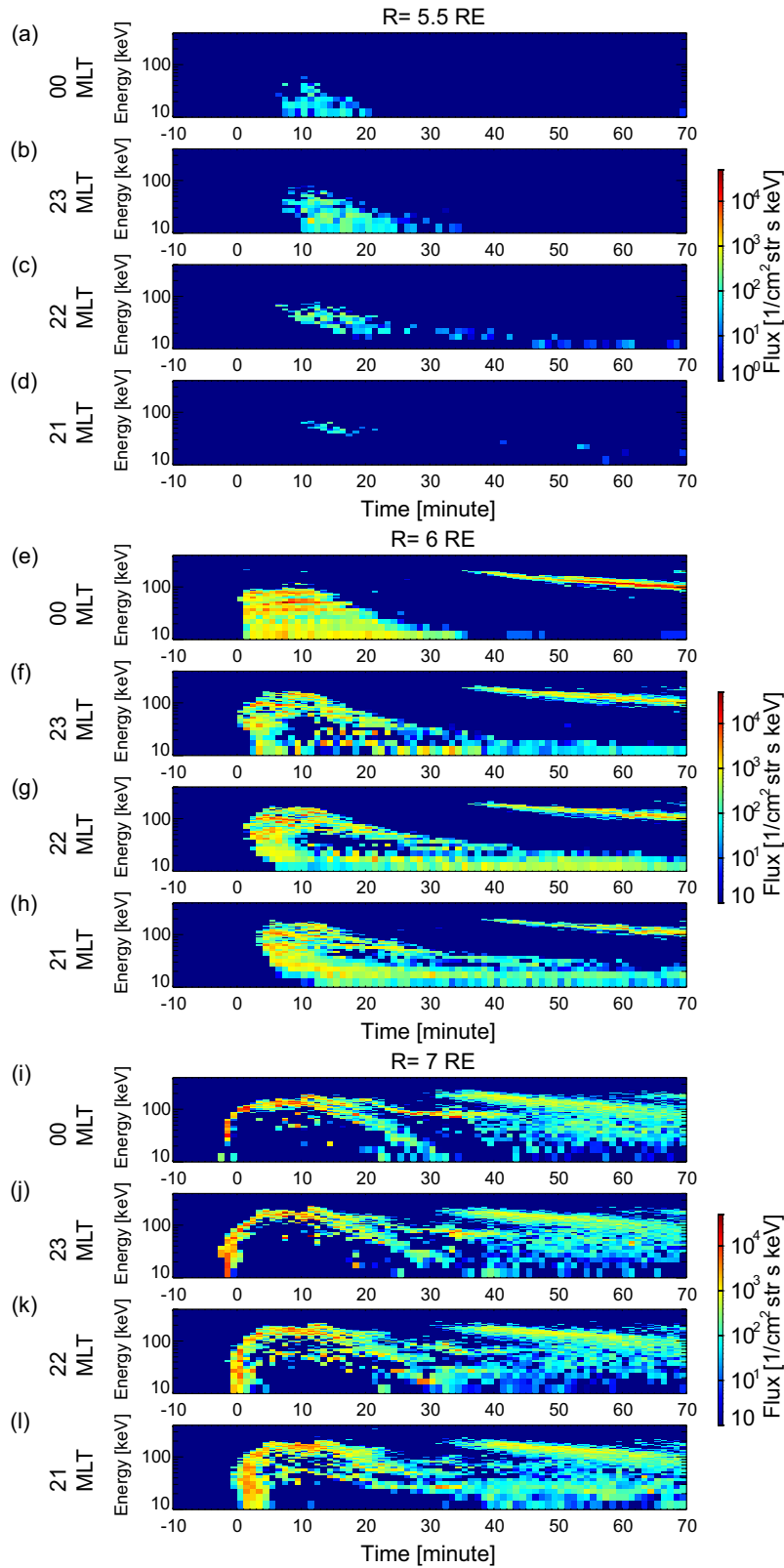


Figure 3.11: Energy versus time spectrograms of the differential flux of the O^+ ions at fixed positions (5.5, 6.0, and 7.0 R_E ; 21, 22, 23, and 00 MLTs; the equatorial plane) for Case II.

minute. High energy (> 120 keV) ion flux appears later. An isolated energy dispersion structure, energy decreasing with time, appears at $t = 35$ minutes and onward. This is called a drift echo, arising from the ions that encircle the Earth by the grad-B and curvature drift. At 23 MLT, a clear nose dispersion starts to appear at $t = 0$. At 22 and 21 MLT, the flux increases at $t = 1$ minute and $t = 3$ minutes, respectively.

At $7.0 R_E$, the flux starts to increase at $t = 3, 3, -2$, and -1 minutes at 00, 23, 22, and 21 MLT, respectively. The flux of high energy ions (> 100 keV) remains, and the flux of lower energy (< 100 keV) disappears. There is a clear discontinuity in the flux around 100 keV. As far as we know, similar energy-time spectra have not been reported in the near-Earth plasma sheet. We call this a "void" structure, and discuss it later.

Figure 3.12 shows the differential flux j of the O^+ ions as a function of energy at 00 MLT and at $6 R_E$ and at $t = 5$ minutes. Red, black, and blue lines indicate the flux with the initial temperature of 5, 10, and 20 eV. The black line is the same as a cut of Figure 3.6e. The flux shows some humps because of insufficient statistics. There is a tendency that the flux increases with the initial temperature. For example, at 2 keV, the flux is doubled when the initial temperature is increased from 5 eV to 10 eV. There is also a tendency that the spectral shape is independent of the initial temperature for this particular range of temperature.

3.5 Discussion

The O^+ ions are accelerated by the dawn-to-dusk electric field (E_y) from the order of eV to the order of tens-of-keV range and more in the near-Earth plasma sheet. This is consistent with previous simulation studies [Cladis and Francis, 1992; Delcourt et al., 2002; Fok et al., 2006; Ashour-Abdalla et al., 2009; Birn et al., 2013]. At the onset of substorm expansion, the peak of E_y takes place about $1-2 R_E$ earthward of that of the earthward plasma flow (V_x). This misalignment is a natural consequence of the MHD process in which the strength of the magnetic field is stronger in the inner region than in the outer region because of pile-up of a magnetic flux. The pile-up seems not to be simply caused by flow braking under the competition between the tension force and the magnetic pressure force. First, the plasma is accelerated earthward by the tension force near the NENL. Plasma pressure force and magnetic pressure force also participate in the action of the plasma at $\sim 8 R_E$ (in which E_y becomes large). It is emphasized that the intense acceleration of the O^+ ions occurs due to the joint action of the tension force

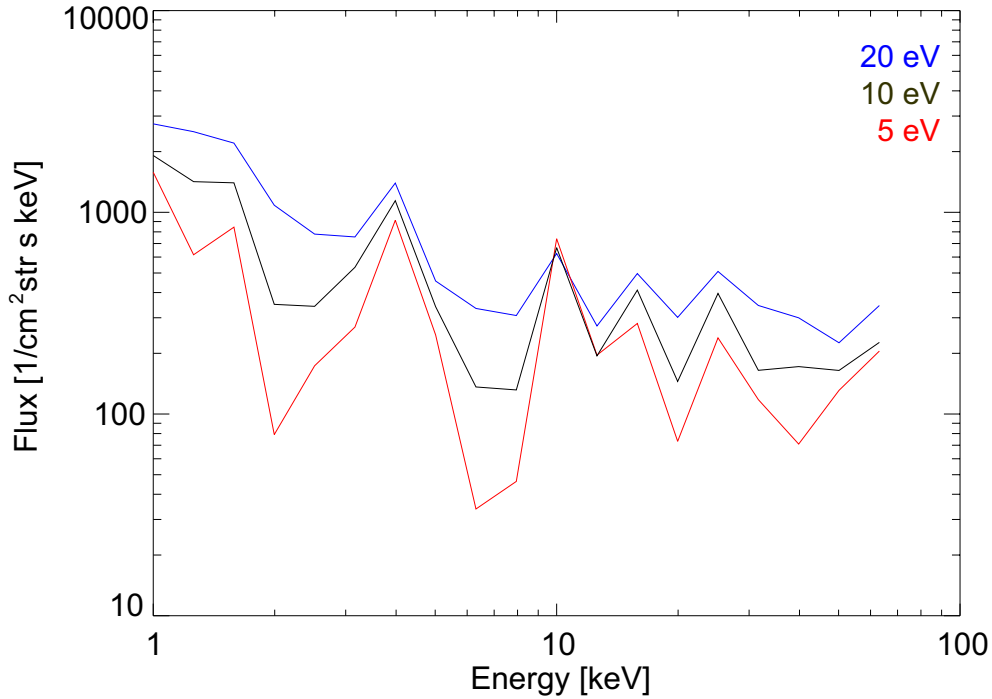


Figure 3.12: Differential flux j of the O^+ ions as a function of energy at 00 MLT and at 6 R_E and at $t = 5$ minutes. Red, black, and blue lines indicate the flux with the initial temperature of 5, 10, and 20 eV

that accelerates plasma earthward and the pressure force (including the plasma pressure force and the magnetic pressure force) that results in magnetic flux pile-up.

As shown in Figure 3.11, the energy-time spectrograms of the differential flux of the O^+ ions strongly depend on the radial distance and MLT. At 5.5 and 6.0 R_E , the flux is enhanced at or just after the onset, and remains high for at least 10 minutes. The flux enhancement starts to appear at certain energy, followed, by lower and higher energies. This structure is similar to that known as "nose" dispersion [Smith and Hoffman, 1974], and can be explained by travel time and path of newly injected ions [Ejiri et al., 1980]. That is, the ions with certain energy penetrate deeper and faster into the inner region [Ejiri, 1978]. These energy versus time spectrograms shown in Figure 3.11 are consistent with the Explorer 45 observations [Smith and Hoffman, 1974; Ejiri et al., 1980] and the CRRES observations [Fu et al., 2002]. At 7.0 R_E , the energy-time dispersion is different. After an abrupt increase in the flux, only the flux of the ions with high energy remains. A "void" region in which the flux is much lower than ambient appears in the energy-time spectrogram. The "void" structure can be caused by the quasi-electrostatic acceleration of unmagnetized ions traveling through the electric potential perpendicular to the magnetic field. If the ions are magnetized, the "void" structure will disappear

because of the following reason. When the ions undergo regular drift motion and the electric and magnetic fields are stationary, the rate of the energy change of a charged particle is given by

$$\frac{dK}{dt} = q\mathbf{V}_d \cdot \mathbf{E}, \quad (3.13)$$

where $\mathbf{V}_d$ is the grad-B and curvature drift velocity. In an extremely case, a zero-energy ion will not gain kinetic energy because the grad-B and curvature drift velocity is zero. Hence, the distribution function (and the flux) of the zero-energy ions will be unchanged according to Liouville's theorem, that is, the "void" structure will not be formed. Similar "void" structures are seen in the energy-time spectrograms observed by the Polar satellite at $L \sim 6.5-9.0$ near midnight (Figure 3.1). The flux has a peak at a 15-30 keV, and the flux of the ions with energy less than that energy is lower than ambient. The situation would be similar to that found in the auroral ionosphere where electrons are accelerated by quasi-electrostatic electric field directing upward, known as an "inverted-V" structure [e.g., Frank and Ackerson, 1971; Evans, 1974; Ergun et al., 2005]. In the simulation, the flux is absent before the "void" structure appears, whereas in the observation, the flux is relatively high before the "void" structure appears. The difference between the simulation and the observation can be explained by the existence of the preexisting hot ions near the plasma sheet. We have no such preexisting hot ions in the simulation domain. Although we need more careful diagnosis of the observed "void" structure, the "void" structure would be regarded as a new class of manifestation of the perpendicular acceleration of unmagnetized ions in the near-Earth plasma sheet.

Comparing the results of the two cases (Case I and Case II), we found that the degree of the acceleration of the O^+ ions is larger when the solar wind is fast and the southward IMF is strong. The reason would be that the intensity of E_y is large at $\sim 8 R_E$ in Case II, so that the ions are more effectively accelerated than in Case I.

3.6 Conclusion

We obtained the following major conclusions.

1. Near an onset of substorm expansion, strong dawn-to-dusk electric field E_y is produced at $\sim 7.5 - 8.0 R_E$ by a joint action of the fast earthward flow V_x (due to the tension force) and magnetic flux pile-up (due to the plasma pressure force and the magnetic pressure force). The peak of E_y is located at $\sim 7.5-8.0 R_E$, and is located $\sim 1-2 R_E$

earthward of the peak of V_x . The misalignment comes from pile-up of a magnetic flux.

2. O^+ ions with energy of the order of eV are non-adiabatically accelerated to higher than 100 keV by the strong E_y in ~ 10 minutes. As a consequence, a "void" structure appears in the energy versus time spectrogram of the ion flux. This is consistent with the Polar satellite observation. The "void" structure would be a manifestation of the perpendicular acceleration of unmagnetized ions.

3. In the inner magnetosphere (at $5.5 R_E$ and $6.0 R_E$), a nose-dispersion appears in the energy versus time spectrogram. This is consistent with satellite observations. It is shown that outflowing O^+ ions can be a direct source of the nose-dispersion seen in the inner magnetosphere.

4. The O^+ ions are more effectively accelerated when the solar wind is fast and the southward IMF is strong.

Chapter 4

Void Structure Observed by Van Allen Probes

4.1 Introduction

Sudden enhancement of the energy flux of ions is one of the common features in the inner magnetosphere during substorms [e.g. McIlwain, 1972; Konradi, 1975; Belian et al., 1978; Ejiri, 1978; Ejiri et al., 1980; Mauk and Meng, 1983; Daglis and Axford, 1996; Fu et al., 2002; Mitchell et al., 2003; Ohtani et al., 2007; Keika et al., 2010 and 2013; Gkioulidou et al., 2014 and 2015]. The flux enhancement can be explained by acceleration and transport of particles from the nightside plasma sheet [e.g. Delcourt et al., 2002; Fok et al., 2006, Ashour-Abdalla et al., 2009; Perroomian et al., 2011; Birn et al., 2013]. During the substorm expansion phase, the plasmasheet ions are accelerated and transported into the inner magnetosphere due to an intense dawn-dusk electric field [e.g. Li et al., 1998; Zaharia et al., 2000; Ashour-Abdalla et al. 2011; Birn et al., 2013; Ebihara and Tanaka, 2013]. After the transport, the energetic ions become a major constituent of the ring current [Gkioulidou et al., 2014].

Various in-situ observations of particle injections show several structures in energy-time spectrograms including the dispersionless structure [Akasohu et al., 1974; Mauk and Meng, 1983; Reeves et al., 1991; Li et al., 1998; Fu et al., 2002; Keika et al., 2010; Gkioulidou et al., 2015], the nose structure [e.g. Smith and Hoffman, 1974; Ejiri, 1978; Ejiri et al., 1980], and the wedge-like dispersion structure [Yamauchi et al., 1996; Ebihara et al., 2001; Yamauchi et al., 2006; Ebihara et al., 2008]. Recently, Zhang et al. [2015] reported a new structure using Van Allen Probes observations, termed "trunk-like structure", which is characterized by the decrease of the energy of the flux of O^+ ions as

the spacecraft moves Earthward.

Numerical simulations have been adopted in various studies as a useful tool for understanding specific structures found by the in-situ observations. Ejiri [1978] and Ejiri et al. [1980] have calculated the trajectories of ions along with their traveling times. They showed that the ions at a certain energy penetrate deeper and faster into the inner region, resulting in a characteristic of the nose structure of newly injected ions. Ebihara et al. [2001] performed particle drift simulation to investigate the generation mechanism of wedge-like dispersion structure observed by Viking. They showed that wedge-like dispersion structure can be due to the energy-dependent drift motion of ions from a short-lived plasma flow channel that exists in the near-Earth tail. Zhang et al. [2015] used a numerical simulation to trace the particle drift backward in time to understand a trunk-like structure and concluded that the trunk like structure is likely caused by a gap in the nightside ion source or greatly enhanced impulsive electric fields.

The purpose of this study is to report the characteristics of a new type of structure, which is observed by the Helium Oxygen Proton Electron (HOPE) instrument of the Van Allen Probes and understand its generation mechanisms by using the numerical simulation introduced in Chapter 3.

4.2 Van Allen Probes: HOPE Observation

The Van Allen Probes mission is designed for understanding the energetic plasma environment in the inner magnetosphere. The two Van Allen Probes spacecraft (Probe A and Probe B) are in nearly identical orbits, with a perigee altitude of ~ 600 km, an apogee geocentric distance of $5.8 R_E$, and an orbital inclination of 10° [Mauk et al., 2013]. The HOPE instrument onboard Van Allen Probes measures helium, oxygen, protons, and electrons with an energy range from a few eV to ~ 50 keV with energy resolution $< 20\%$ [Kessel et al., 2013, Funsten et al., 2013].

Figure 4.1 shows an overview of energy-time spectrograms of H^+ ions and O^+ ions observed by HOPE on the two satellites on 7 March 2013. Figure 4.1a shows the time evolution of the SML index, which is similar to the conventional AL index but is derived from the SuperMAG data set [Gjerloev, 2012]; the original data are collected by stations distributed worldwide, and therefore, the SML index tends to be a better measure of the westward electrojet if its peak intensity takes place in a longitudinally limited area or off the typical latitudinal range of the auroral oval. The SML sharply decreased to

~ -200 nT at 07:50 UT and to ~ -270 nT at 11:10 UT as shown in Figure 4.1a. It is likely that at least two substorms took place. Figure 4.1f and 4.1g show the trajectories of the satellite drawn in the SM-coordinates. During this interval, the apogees of the Van Allen Probes were located at $5.8 R_E$ and at ~ 1 hours in magnetic local time (MLT) and Probe-B was ahead of Probe-A by ~ 2.5 hours. Figures 4.1b and 4.1c (Figures 4.1d and 4.1e) show the energy-time spectrograms of the omnidirectional flux of H^+ and O^+ ions observed by HOPE-A (HOPE-B), respectively. On the outbound pass of Probe-A, at 10:40 UT, the H^+ flux started to increase first at ~ 10 keV at $L = \sim 5.3$ (at ~ 5 keV at $L = \sim 5.2$ for inbound) and the flux increase spread to both higher and lower energies with increasing L-value. The reverse pattern was seen on the inbound pass. This structure is known as the nose structure. The structure was not perfectly symmetric with respect to the apogee. This probably means that the structure depends on MLT as well as on universal time [Ejiri et al., 1980]. The O^+ flux showed a similar nose structure at $L = \sim 5.3$ on the outbound pass and at $L = \sim 5.2$ on the inbound pass. However, the observed O^+ flux was significantly low at energies below ~ 8 keV near apogee. Only the outer envelope of the nose structure is observed in the energy-time spectrogram. About 2.5 hours ahead of Probe-A, Probe-B proceeded almost the same trajectory, and observed a similar structure. Again, the O^+ flux near apogee was depleted below ~ 5 keV. The shape of the dispersion is somewhat different from that observed by Probe-A. The difference probably can be attributed to a temporal variation rather than a spatial variation. Hereinafter, we call the structure a void structure. As will be discussed later, the void structure is a different from the structures previously reported.

Figure 4.2a shows an example of the energy-L spectrogram of O^+ flux measured by Probe-A during a different event (an interval between $\sim 1:30$ UT and $\sim 6:00$ UT on 12 April 2013). During this event, the apogees of the Van Allen Probes were located at $\sim 5.9 R_E$ and at ~ 00 MLT). A substorm took place on its outbound pass as determined by the SML index. A clear nose structure was observed at $L > 4.6$ and the O^+ flux below ~ 10 keV depleted at $L > 5.6$ ($> \sim 1$ MLT). In order to specify the characteristics of the void structure quantitatively, we introduced two parameters for this study as shown in Figure 4.2b, an earthward boundary and a threshold energy of the void structure. For the observation (inbound pass of the event on 11 April 2013), the earthward boundary of the void structure was located at $L = \sim 5.6$, and the threshold energy of the void structure was ~ 10 keV at $L = \sim 5.9$.

We surveyed data from HOPE on Van Allen Probes acquired between 1 January

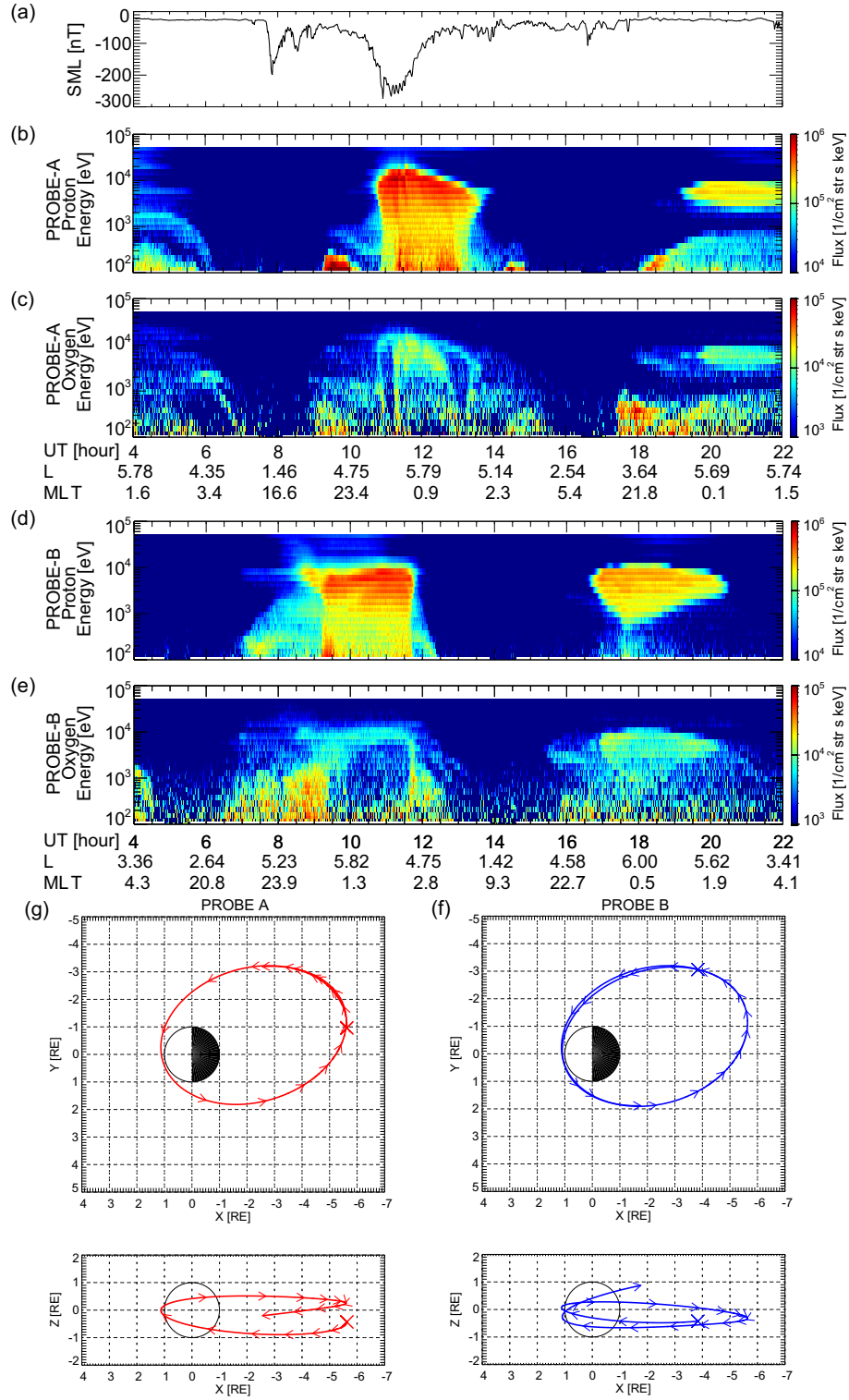


Figure 4.1: (a) SML index (similar index to AL index), (b)-(e) energy-time spectrograms of omnidirectional energy flux of H^+ and O^+ from HOPE on Probe-A and Probe-B on 3 March 2013, (f)-(g) orbits of Probe-A and Probe-B in the SM-coordinate system, X - Y plane in the upper panels, and X - Z plane in the lower ones.

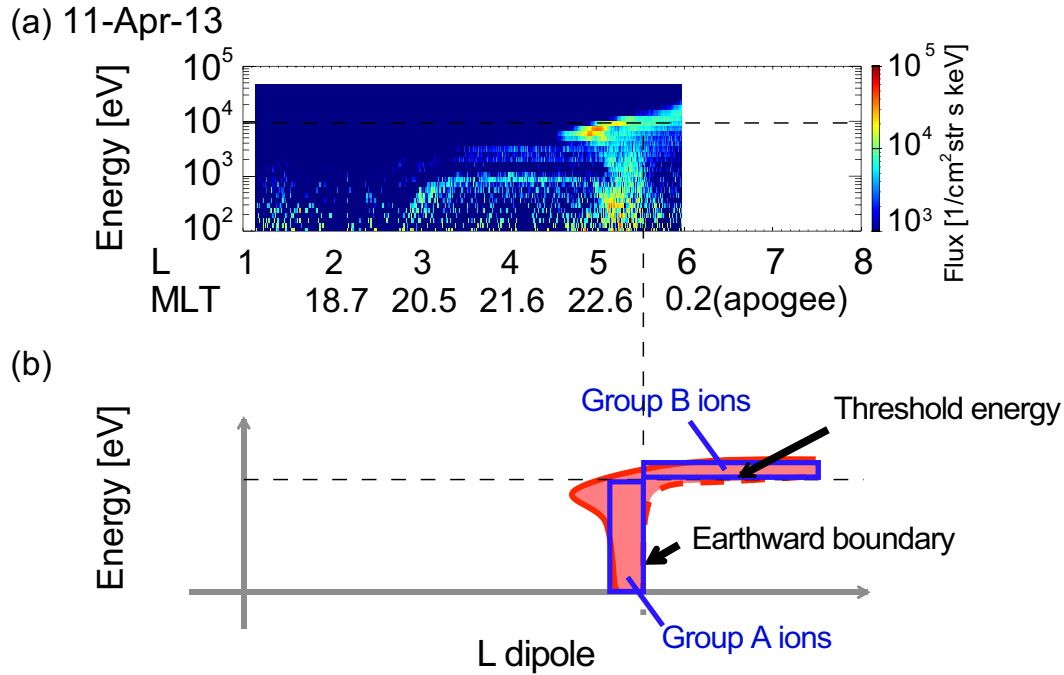


Figure 4.2: (a) Energy-L spectrogram of O^+ flux acquired by Probe-A during the interval between $\sim 21:00$ UT on 11 April 2013 and $\sim 1:30$ UT on 12 April 2013, (b) schematic drawing of the spectrogram explaining the void structure. We call ions in the earthward most edge of this spectrogram as Group A and ions in the upper edge of this spectrogram as Group B.

2013 and 30 May 2013 during which the apogees of the two spacecraft were located on the nightside. Nine void structures were identified by either one or two spacecraft, and are summarized in Table 4.1. We excluded the intervals when minimum $Dst < -30$ nT because the energy time spectrograms of the ions tended to be rather complicated during magnetic storms. The void structure was observed by at least one spacecraft within ~ 1 hour after the SML decrease for all the cases. Note that the void structure did not always appear during substorms. The reason is discussed in the discussion section.

Figure 4.3 shows the trajectories of Probe-A and Probe-B when the 9 void structures were observed. The color indicates the flux in a specific energy range. To clearly identify the earthward boundary of the void structure, we chose the energy ranging from ~ 0.7 keV to ~ 4.8 keV. The energy was kept constant through one revolution of orbit. For the H^+ ions observed on 11 April 2013, the flux sharply increased around $X = -4.4 R_E$, $Y = 2.3 R_E$ ($L = \sim 5.0$) on the outbound pass (solid arrow), and decreased around $X = -4.6 R_E$, $Y = -2.3 R_E$ ($L = \sim 5.1$) on the inbound pass (solid arrow). For the O^+ ions, however, the flux showed a sharp decrease (open arrow) soon after the sharp increase (solid arrow) on the outbound pass. The same happened on the inbound pass. These banded structures

	Date
Event 1	01-Feb-13
Event 2	05-Feb-13
Event 3	10-Feb-13
Event 4	26-Feb-13
Event 5	07-Mar-13
Event 6	09-Mar-13
Event 7	10-Apr-13
Event 8	11-Apr-13
Event 9	14-May-13

Table 4.1: Event list of the void structure.

appeared when the satellite passed through the earthward boundary of the void structure that is schematically shown in Figure 4.2b. For the observation on 11 April 2013, the earthward boundaries of the void structure are located at ~ 5.5 and ~ 5.2 on the outbound and inbound passes, respectively.

We investigated the energy that satisfies the following criterion

$$\frac{df}{d(\log_{10}K)} > 10^3, K > 10^3 \quad (4.1)$$

where f is the flux in [$1/\text{cm}^2 \text{ str s keV}$], and K is the kinetic energy in [eV]. Figure 4.4 is the same as Figure 4.3, but the colors indicate the maximum energy that satisfies Eq. 4.1. If we did not identify any energy that meets the criterion, we did not plot dots at the position. Open arrows in Figure 4.4a and b set at the same positions as in Figure 4.3e and f show the earthward boundaries of the void structure observed on 11 April 2013. Around the earthward boundaries of the void structure, the energy sharply increased to ~ 10 keV. The energy outside the earthward boundaries may be equivalent to the threshold energy of the void structure. For the observation on 11 April 2013, the threshold energy of the void structure distributed ~ 10 keV.

4.3 Reproduction of the void structure

We adopted the same simulation introduced in Chapter 3 [Nakayama et al., 2015], in which we traced the trajectories of O^+ ions by using the electric and magnetic fields reproduced by a global MHD simulation [Tanaka et al., 2010; Ebihara and Tanaka, 2013].

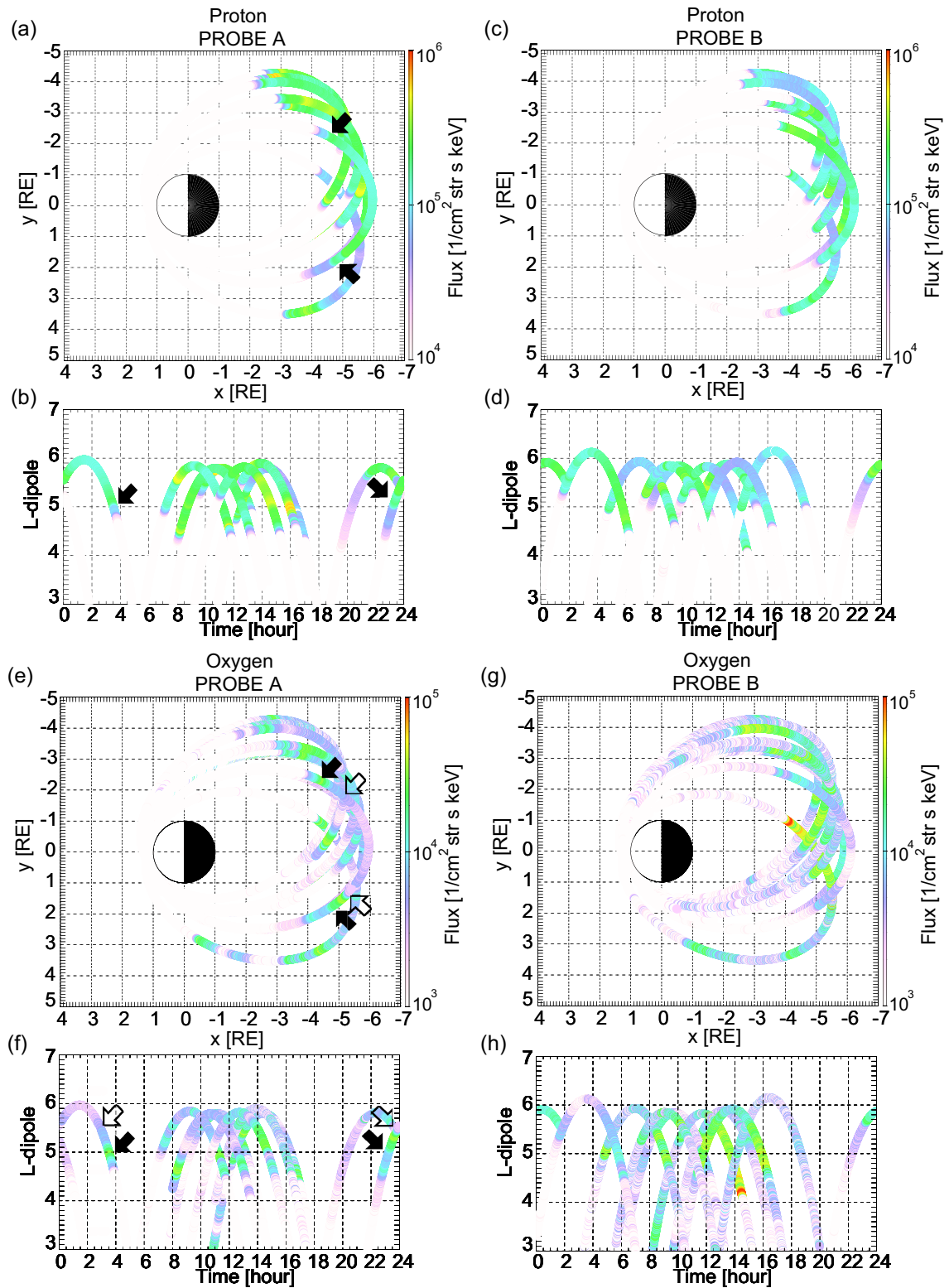


Figure 4.3: (a-d) Trajectories of Probe-A and Probe-B in X-Y plane in the SM-coordinate and L-value as a function of time during the 9 substorm events. The color indicates the flux of H^+ ions at specific energy between ~ 0.7 keV and ~ 4.8 keV. (e-h) Same as a-d but for O^+ ions.

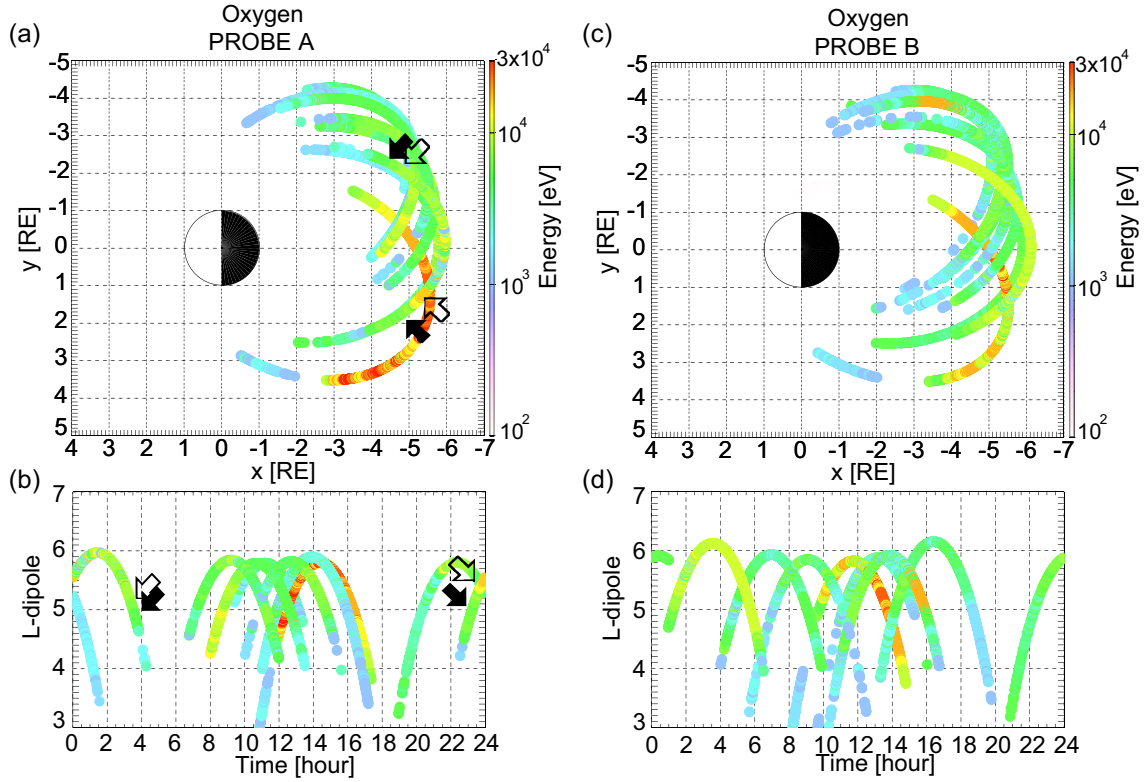


Figure 4.4: (a-d) Same as Figure 4.3e-h but the colors indicate the energy that satisfies Eq. 4.1.

As stated in Chapter 3, we assumed that cold O^+ ions (temperature is 10 eV) are continuously supplied from the ionosphere to the lobe region. This process is observed by many studies [e.g., Vaisberg et al., 1995; Moore et al., 1997] and assumed as a main source of the ring current O^+ ions [Fok et al., 2006]. On the other hand, an impulsive supply of energetic O^+ ions (a few keV) from the night side aurora region [e.g., Gazey et al., 1996; Sauvaud, 2004] was not assumed in the simulation. The global MHD simulation developed by Tanaka et al. [2010] and Tanaka [2015] successfully demonstrated several important features that emerge during a substorm such as the current system that can be observed as a current wedge [Tanaka et al., 2010], energetic particle injection [Ebihara and Tanaka, 2013], westward traveling surge [Tanaka, 2015; Ebihara and Tanaka, 2015] and the magnetic disturbance at auroral latitudes [Tanaka et al., 2010] as well as magnetic equator [Ebihara et al., 2014]. In this study, we utilized a same global MHD simulation result performed by Ebihara and Tanaka [2013] in which the solar wind speed was held constant at 500 km/s, and IMF turned from (0, 2.5, 5.0) to (0, 2.5, -5.0) nT. The result showed that the calculated AL index decreased to -800 nT [Ebihara and Tanaka, 2013]. Just after the AL decrease, the dawn to dusk electric field is enhanced to ~ 13 mV/m at $> \sim 6 R_E$ in longitudinally narrow regions in the pre-midnight and post-

midnight [Nakayama et al., 2015]. In this study, the onset of substorm expansion phase is defined as the moment at which the AL index suddenly decreases, and hereinafter referred to as $T = 0$ min.

For the test particle simulation, O^+ ions were launched from off-equatorial positions with initial energies from 1 eV to 1 keV and over an interval of 1 min. Those O^+ ions were launched at $Z = \pm 2 R_E$, ranging from $X = -7$ to $-17 R_E$ and from $Y = -10$ to $10 R_E$. The numerical simulation successfully reconstructed the O^+ flux enhancement with a dispersion-less structure in the midnight region, a dispersed structure in the dusk region and a nose structure around the inner edge of the plasmasheet at dusk region. As we showed in Chapter 3, most of the O^+ ions undergo non-adiabatic motion and that the kinetic energy of some ions increases to a level of the order of 100 keV.

Figure 4.5a is the same figure as Figure 4.2a. Figures 4.5b, c, d and e show energy- L spectrograms of the simulated O^+ ions at 00 MLT and 22 MLT in the equatorial plane. We defined that the L value and the radial distance are same in the equatorial plane. Note that the energy scale of the simulation plots is shifted by an order of magnitude from the observational plot. At 00 MLT, the energy of the ions increases with increasing L . The structure that appears in the energy- L spectrograms is consistent with that drawn in Figure 4.2, and is referred to as the void structure. That is, the structure has a clear earthward boundary of the void structure, and the threshold energy can be defined. The earthward boundary moved earthward as time progresses. The threshold energy increases between $T = 0$ min and 5 min. After $T = 5$ min, the threshold energy remains almost constant or slightly decreases. At $T = 15$ min, for example, the earthward boundary of the void structure is located at $L = 5.8$ and the threshold energy of the void structure is ~ 30 keV at $L = 6.0 R$. At 22 MLT, the ions with energy from ~ 20 keV to ~ 60 keV appears first with increasing L . The spectral shape is morphologically consistent with that shown in Figure 4.5a. Although our simulation successfully shows general features of the void structure, the energy gain of O^+ ions is a bit higher than the observed values. This is because solar wind parameters and IMF conditions are different from the observation. In the simulated substorm, the minimum AL is ~ -800 nT which is negatively much larger (~ -290 nT) than the event on 11 April 2013. During the larger substorm, the more intensive dawn to dusk electric field can be generated and results in the higher threshold energy in the calculated energy- L spectrogram as shown in Figure 4.5. Our purpose is to understand a general feature of the void structure emerging during substorms and reproducing exactly the observation is beyond the scope of this study.

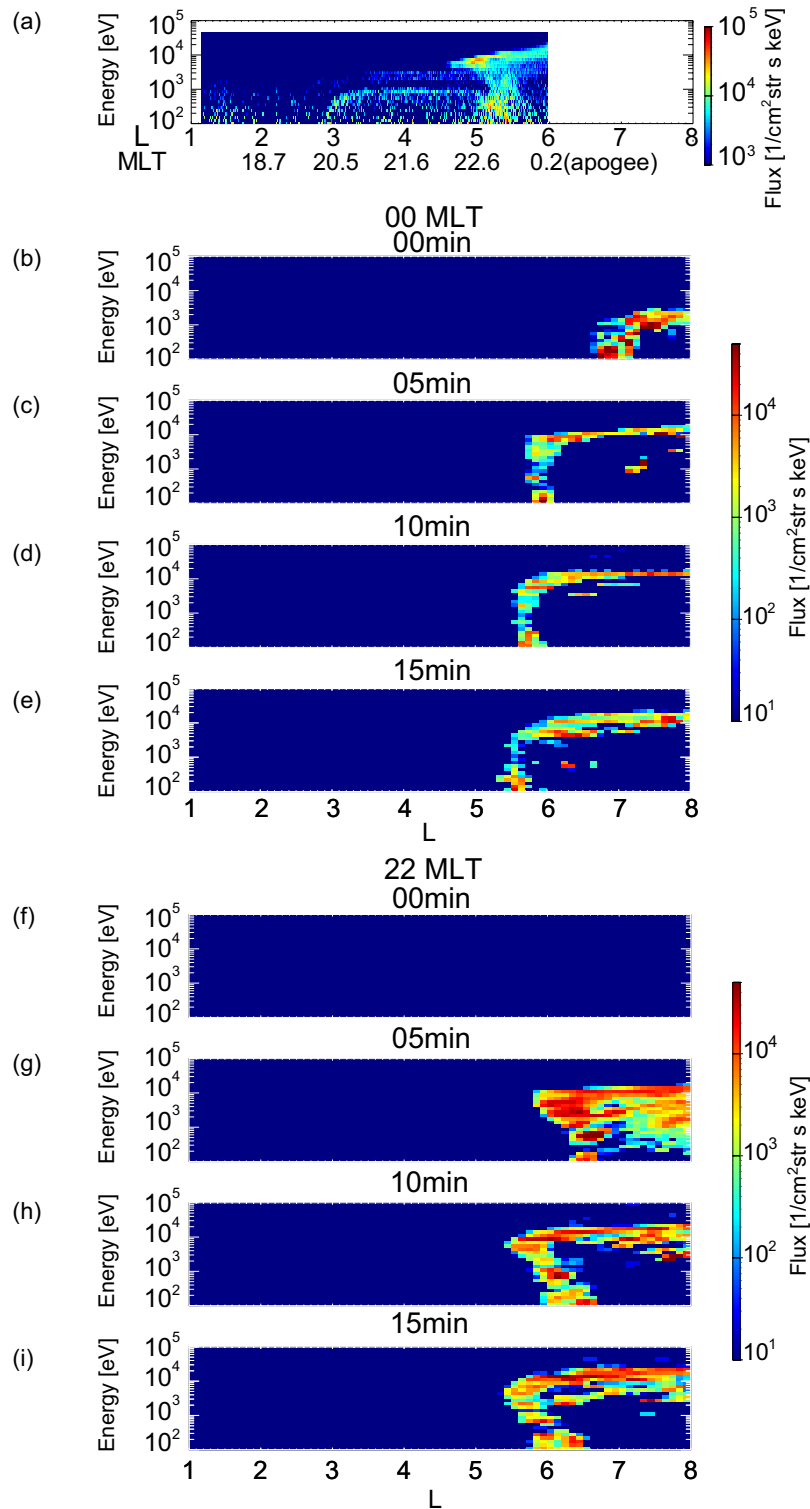


Figure 4.5: (a) Reproduction of Figure 4.2a. (b-e) Energy-L spectrograms of the simulated O^+ ions at 00 MLT in the equatorial plane. (f-g) Energy-L spectrograms of the simulated O^+ ions at 22 MLT in the equatorial plane. Min shows elapsed time after the substorm onset.

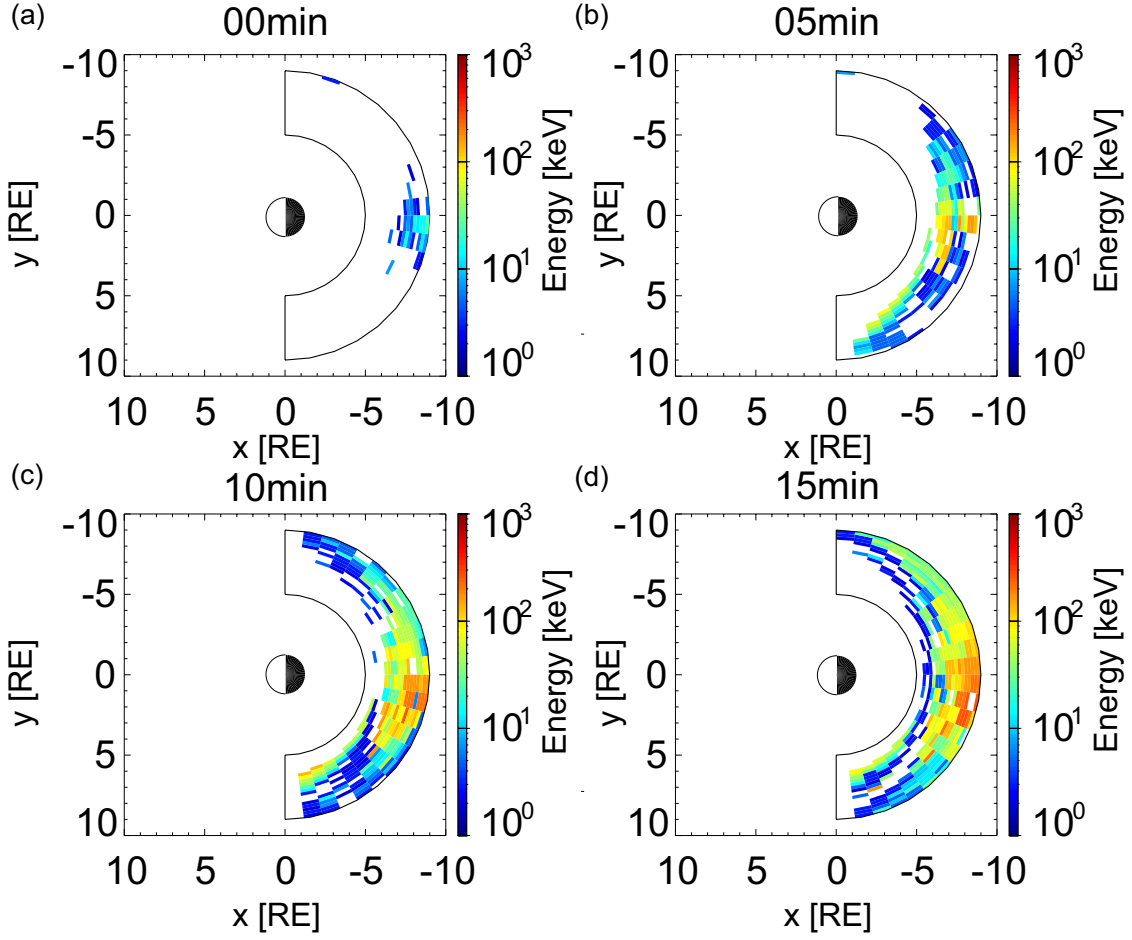


Figure 4.6: Spatial distribution in the X-Y plane of the threshold energy of the simulated void structure at $T = 0, 5, 10, 15$ min.

We also calculated the threshold energy of the simulated void structure by means of the same procedure described above. Figure 4.6 shows the spatial distribution of the threshold energy of the void structure. The region where threshold energy of the void structure is not identified is filled with white. In general, the void region is widely distributed in the nightside region. The spatial peak of the threshold energy of the void structure increases with time, and reaches ~ 200 keV at $X = -7 R_E$, $Y = 2 R_E$ at $T = 15$ min.

To investigate the generation mechanisms of the void structure, we divided the void structure into two groups. Group A consists of the earthward most edge of the envelope of the void structure. Group B consists of the upper most edge of the envelope of the void structure. The groups are schematically drawn in Figure 4.2. As a representative of Group A, we chose the ions with energies below 20 keV and located at $R = 5.6 R_E$, at 00 MLT and at $T = 15$ min. As a representative of Group B, we chose the ions with energies

between 100 keV and 200 keV and at $R = 8.0 R_E$, at 00 MLT and at $T = 15$ min as Group B ions. We did not choose ions around the earthward boundary as a representative of the Group B because generation mechanisms of the ions located around a turning point can be unclear. Figure 4.7a shows the flux as a function of the launched time of the Group A ions and Group B ions, and Figure 4.7b shows the flux as a function of the launched position of the ions in the source plane in the northern hemisphere. The vertical axis of Figure 4.7a and the color in Figure 4.7b show the flux values mapped from that of Group A and B ions. Most of the Group A ions departed the source region at ~ 10 min before the substorm onset. The initial positions are between $X = -9 R_E$ and $X = -17 R_E$ in the midnight region. Most of the Group B ions departed the source region after the substorm onset between $T = \sim -4$ min and $T = \sim 11$ min. The initial positions are distributed in the post-midnight region ($X = -8 R_E$ to $-16 R_E$, $Y = \sim -6 R_E$).

In Figure 4.8, a black arrows show the MHD plasma flow velocities in the X - Z plane (V_{xz}) at $Y = 0 R_E$ and $Y = -6 R_E$. Black and red lines indicate the magnetic field lines projected into the X - Z plane and the location of the O^+ source plane set by Nakayama et al. [2015]. As mentioned above, the initial distribution function of the O^+ ions in the source plane is given by a drifting Kappa distribution in this simulation. This means that O^+ ions are launched with the thermal velocity in the frame of the MHD plasma flow velocity. For Group A ions, from Figure 4.8a, the average of the X - Z component of V_{MHD} (V_{xz}) at the source positions ($z = \pm 2 R_E$) is ~ 10 km/s that is equivalent to ~ 10 eV for O^+ ion. On the other hand, the temperature of the launched ions (kT) is assumed as 10 eV in the simulation model. This indicates that the thermal speed is comparable to V_{xz} for Group A ions at the launched time and position.

After the substorm onset, at $Y = -6 R_E$ and $Z = \pm 2 R_E$, the flow is directed equatorward and tailward with a significant intensification (Figure 4.8d). This (1) equatorward and (2) tailward flow enhancement at the off-equatorial position is due to the following. (1) The formation of the near-earth neutral line ($X = \sim -11 R_E$ in Figure 4.8d) results in the large difference of magnetic field strength between equator ($z = \sim 0 R_E$) and off-equator ($|Z| = \sim 1 R_E$). It increases the magnetic pressure force accelerating the background plasma toward the equatorial plane. (2) After the substorm onset, the high pressure region ($X = \sim -7 R_E$) expands anti-equatorward across the magnetic field line, results in the pressure gradient force along magnetic field lines accelerating the background plasma toward the tail [Yao et al., 2015]. Another feature to be noted is the reversal of the flow direction (Figure 4.8d). This flow pattern has been investigated in Yao et al. [2015]

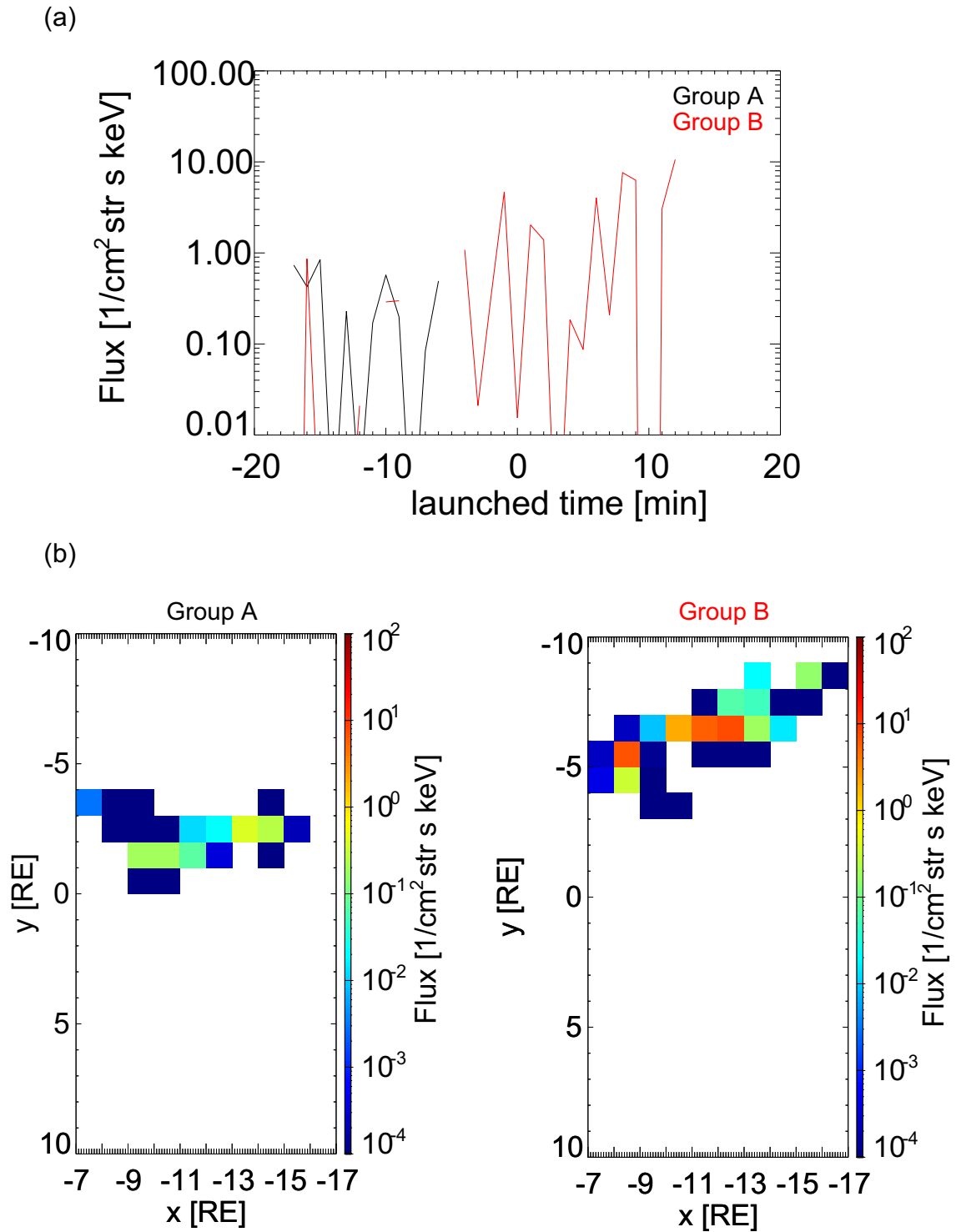


Figure 4.7: (a) Distribution of launched time of the Group A ions (black line) and Group B ions (red line), (b) distribution of launched position of the ions in the source plane in the northern hemisphere for Group A ions (left) and for Group B ions (right).

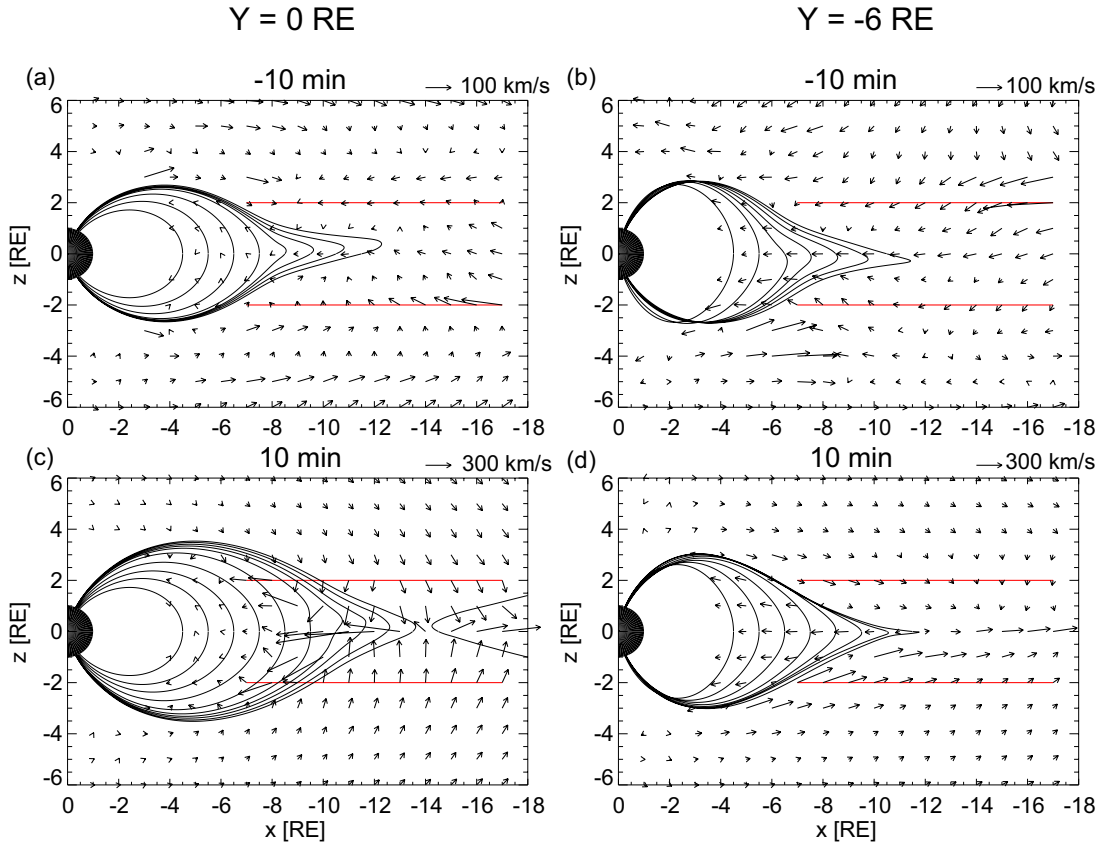


Figure 4.8: (a) MHD plasma flow velocities in the X-Z plane (V_{xz}) at $Y = 0 R_E$ and $Y = -6 R_E$ at $T = -10$ min (before the onset) and 10 min (after the onset).

using a same global MHD simulation. The show that the flow is directed earthward in the high pressure region and tailward in the low pressure region. $|V_{xz}|$ is greater than ~ 100 km/s at $Y = -6 R_E$ and $Z = \pm 2 R_E$ which is equivalent to $> \sim 1$ keV for O^+ ion. For Group B ions, because the temperature at the source position is also assumed to be $kT = 10$ eV, V_{xz} dominates thermal speed at the launched position. This strong flow brings most of the lobe O^+ ions to the plasmasheet ($X < -10 R_E$) where the curvature radius of the magnetic field line is small and dawn to dusk electric field is enhanced.

Figure 4.9 shows one typical trajectory of Group A ions. Figure 4.9a shows the trajectory of the ion in the equatorial plane together with the black contour indicating the Y-component of the electric field E_y at $T = 0$ min. Figure 9b shows the trajectory of the ion in the noon-meridian plane and black lines show the magnetic field lines. The ion departed at $(-16, -1, 2) R_E$ at $T = -10$ min, and reached $(\sim -8.5, \sim 0.5, 0) R_E$ at $T = \sim 3$ min. When the ion departed, V_{MHD} is $(26, 2, -8)$ km/s at the launched position, which

is equivalent to ~ 60 eV and the ion has the kinetic energy of ~ 30 eV in the frame of the flow. After the launch, the ion heads earthward and moves toward the equatorial plane. The ion passes through the equatorial plane just before the substorm onset. Then it is accelerated to ~ 12 keV (Figure 4.9c) and transported to inner region after a substorm onset. The magnetic moment fluctuates around 100 eV/nT during the acceleration, it suggests that the ion is adiabatically accelerated (Figure 4.9d).

Figure 4.10 shows one typical trajectory of Group B ions with a same format of Figure 4.9 except for the dawn to dusk electric field at $T = 15$ min (black contour) and the magnetic field lines at $T = 15$ min (black lines). The ion departed at $(-9, -5, 2) R_E$ where the flow velocity is $(125, 2.9, -53)$ km/s at $T = 10$ min. The V_{MHD} at the position is equivalent to ~ 1.5 keV and the ion has the kinetic energy of ~ 30 eV in the frame of the flow at the launch. After the launch, the ion moves tailward, duskward and toward the equatorial plane. The direction of the ion velocity turns from tailward to earthward when the ion reaches equatorial plane, and then the ion is immediately accelerated by the enhanced dawn to dusk electric field. Finally, the energy reaches ~ 200 keV within 2 minutes.

4.4 Generation mechanism of the void structure

We found that the ions consisting the earthward most edge of the plasma sheet (Group A ions) departed the source plane before the substorm onset (Figure 4.7a). Before the substorm onset, V_{MHD} is comparable to thermal speed (Figure 4.8a). This means that the ions do not follow the background flow, so the ions direct to various directions at the launched position before the substorm onset. Just before the substorm onset, the ions already exist around the equatorial plane. At the substorm onset, those pre-existing particles are immediately "pushed" earthward by the dawn to dusk electric field with the adiabatic acceleration. The acceleration process is adiabatic because the gyro radius of these low energy ions is small. For the adiabatic acceleration, the guiding center approximation may be valid in evaluating the change of particle energy. In such case, the gain of the kinetic energy can be described as follows

$$\frac{dK}{dt} = q\mathbf{V}_d \cdot \mathbf{E}, \quad (4.2)$$

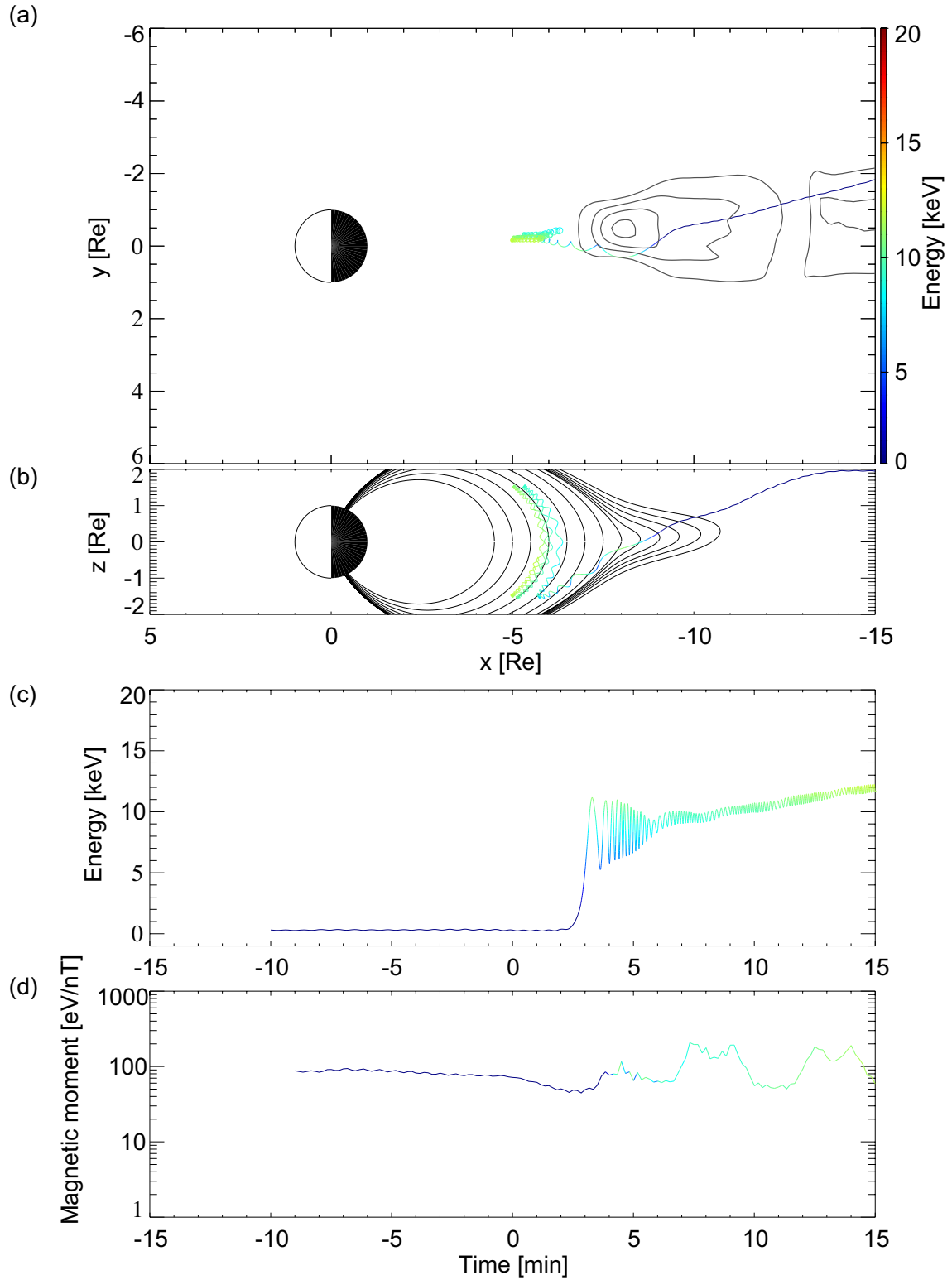


Figure 4.9: (a) Trajectory of the Group A ion in the X - Y plane with the color code and the contour lines respectively indicating instantaneous kinetic energy and $|E_y|$ at $t = 0$. (b) Same figure as (a) but in the X - Z plane and black lines indicate the magnetic field lines at $T = 0$ min. (c)-(d) The kinetic energy and the magnetic moment as a function of time.

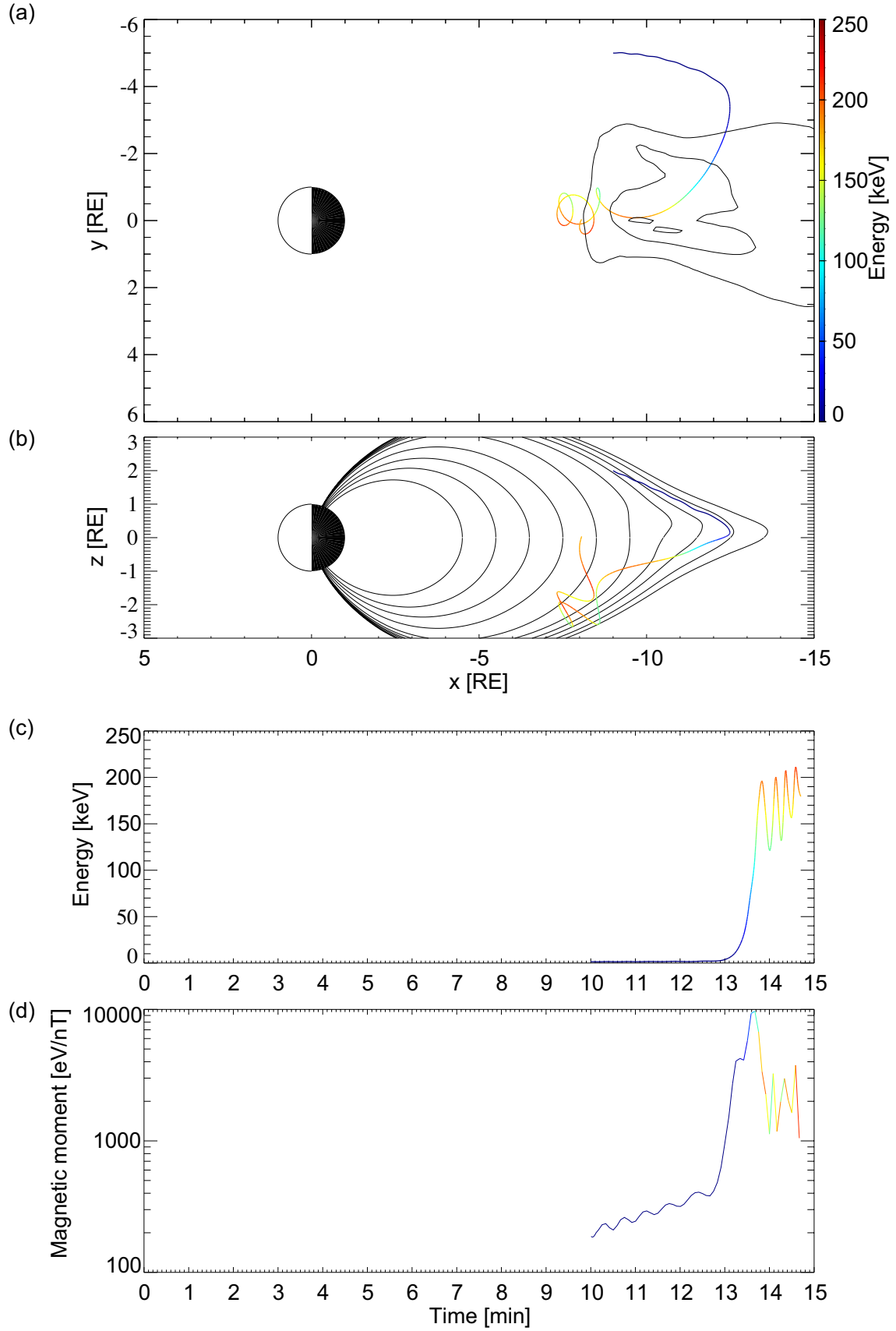


Figure 4.10: Same figure as Figure 4.9 but for Group B ion. Black lines in (b) indicate the magnetic field lines at $T=15$ min (after the onset). Depolarized magnetic configuration is observable in (b).

where $\mathbf{V}_d$ is the grad-B and curvature drift velocity. The energy gain associated with magnetic field changes is ignored. The ions get various energies depending on the drift velocity and the electric field that they experienced and develop the earthward most edge of the envelope of the void structure.

Most of Group B ions launched after the substorm onset. During the substorm expansion phase, the strong equatorward and tailward flow developed in the plasma lobe (Figure 8d). The group B ions follow the background plasma flow because V_{MHD} dominates thermal speed. According to the flow pattern, most of them reach at $X < \sim -10 R_E$ in the equatorial region. When they reach the equatorial region, the dawn to dusk electric field is already enhanced. The motion of the Group B ions is basically non-adiabatic. In such case, the energy gain of the ion can be described by the equation

$$\frac{dK}{dt} = q\mathbf{v} \cdot \mathbf{E}, \quad (4.3)$$

where $\mathbf{v}$ is the velocity of the ion. The ions are non-adiabatically accelerated within one gyro motion, so the acceleration process can be treated as quasi-electrostatic acceleration traveling through the electric potential. As we stated above, the reversed plasma flow pattern bring the plasma lobe O^+ ions to outer region in the equatorial plane ($x < \sim -10 R_E$) where the intensive dawn to dusk electric field is enhanced. Therefore, most of them experience the dawn to dusk electric field and get the similar kinetic energy that is equivalent to the electric potential. The energetic ions drift westward due to the grad-B and curvature drift, which has the energy dependence. This develops a decrease of the threshold energy with decreasing L , and the value of the threshold energy at $< \sim 10$ keV at $L < \sim 5.8$.

In order to investigate the dependence on the initial temperature, we increased the initial temperature of the O^+ ions from 10 eV to 10 keV. In this case, the thermal speed is comparable to V_{MHD} even during the substorm expansion phase. Figure 4.11 shows the energy- L spectrograms of the O^+ ions with initial temperature of $kT = 10$ keV. In Figure 4.11, the gap of the void structure appears to be filled. The ion, which has a large kinetic energy in the frame of MHD flow, can directly reach the inner region in the equatorial plane ($x > \sim -10 R_E$). In the inner region, the dawn to dusk electric field is small, thus the potential drop between the position and at $6 R_E$ at 00 MLT is small. Because of this, the ions are observed in the inner region without the significant energy increase and the void structure appears to be unclear.

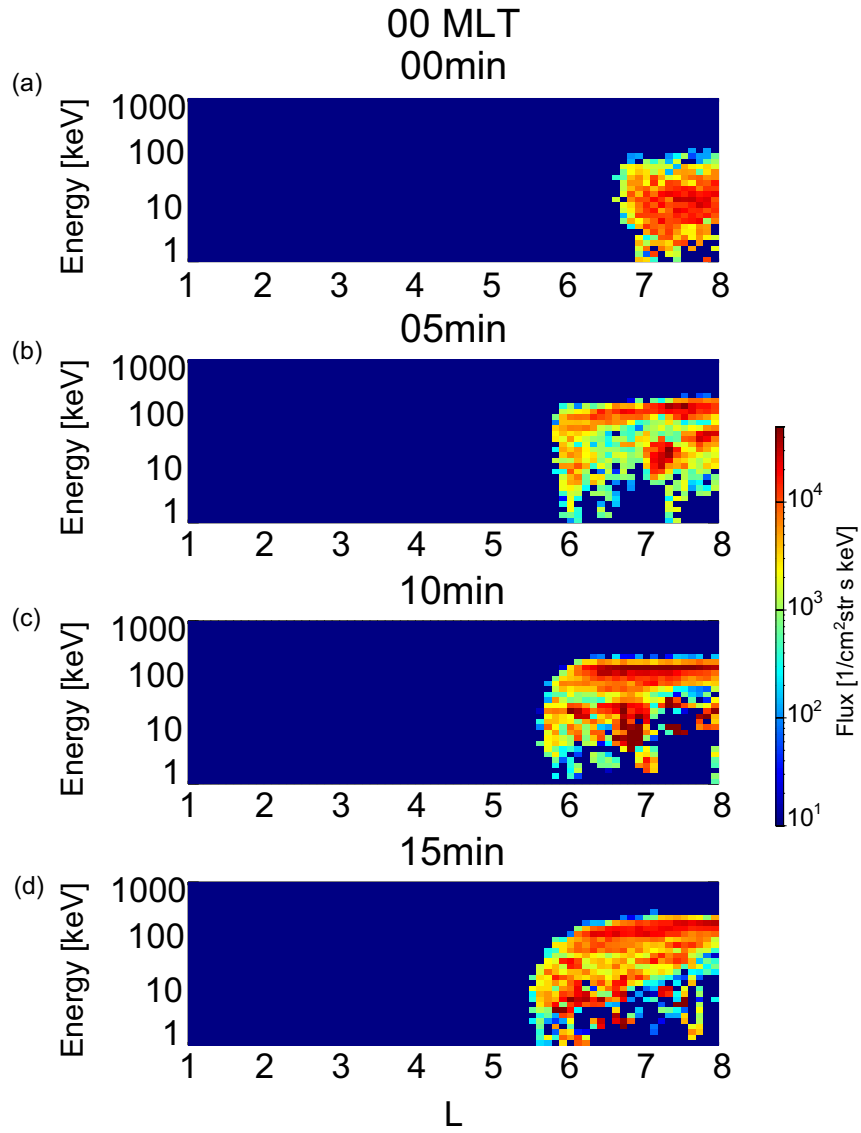


Figure 4.11: Energy-L spectrograms of the simulated O^+ ions at 00 MLT in the equatorial plane with the initial temperature of $kT = 10$ keV. Increase of initial temperature makes the void structure unclear.

4.5 Discussion

We reported the void structure and investigated its generation mechanisms. The HOPE observation shows that the void structure is seen in the energy-L spectrogram near apogee. The void structure is clearly identified in the O^+ ions, but not in the H^+ ions. Because the void structure was observed by at least one spacecraft within ~ 1 hour after the SML decreases for all the cases, we speculated that the void structure is associated with ion injection. We focused on the void structure identified in the substorms when $Dst > -30$ nT, because the void structure was sometimes unclear during storms ($Dst < -30$ nT). This can be understood by the increase in the temperature of O^+ ion in the plasma lobe region during storms as we tested.

We performed the same numerical simulation as Nakayama et al. [2015] to investigate the void structure. Our simulation reproduced the void structure well, and revealed that the generation mechanisms of the void structure consist of (1) the formation of the strong equatorward and tailward plasma flow and (2) the intensive non-adiabatic acceleration. (1) Yao et al. [2015] reported that the Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations also showed a formation of the reversed plasma flow pattern (tail ward flow in the high pressure region and earthward flow in the low pressure region). This may suggest that the formation of the intensive plasma flow pattern is a realistic phenomenon. (2) The non-adiabatic acceleration of O^+ ions during substorms has been reported [e.g. Delcourt et al., 2002; Ashour-Abdalla et al., 2009; Perroomian et al., 2011; Nosé et al., 2012; Birn et al., 2013; Nakayama et al., 2015]. Therefore, we assume that the two mechanisms are commonly occurring during substorms. One possible question is whether the void structure can be developed only with (1) the formation of the strong equatorward and tailward plasma flow or (2) the intensive non-adiabatic acceleration. (1) The strong plasma flow brings most of the plasma lobe O^+ ions to the plasmasheet where the curvature radius of the magnetic field line is small and the dawn to dusk electric field is strong. If it is not developed, the plasma lobe O^+ ions can flow into various regions, including the position where the dawn to dusk electric field is not strong. Consequently, the ions are observed in the inner region without a significant energy increase and the void structure will not be formed. (2) If O^+ ions are adiabatically accelerated, the energy increase follows the equation 4.2. This indicates that low energy ions (especially zero energy ions) cannot gain sufficient kinetic energy because the grad-B and curvature drift velocity is small. In an extremely case, the

distribution function (and the flux) of the zero-energy ions will be unchanged according to Liouville's theorem, and so the void structure will not be formed. From these points of view, we concluded that both mechanisms are essential for a development of the void structure. As we stated above, the void structure does not always appear during substorms. This may be because the O^+ temperature in the plasmashet region is high even before the substorm or the substorm is not strong enough to trigger the non-adiabatic acceleration for O^+ ions.

One notable feature of the void structure is that it is more clearly seen in the O^+ spectrum than the H^+ spectrum. This can be explained by the following reason. Our result showed that non-adiabatic acceleration contributes to the formation of the void structure. It is widely known that non-adiabatic acceleration is triggered when the Larmor radius of the charged particle is comparable to the curvature radius of the magnetic field line [Sergeev et al., 1983]. Because the mass of the H^+ ion is one sixteenth of that of the O^+ ion, it is plausible that the non-adiabatic acceleration process is less effective for H^+ ions than for O^+ ions.

The wedge-like structure has been observed primarily in the dayside region at low-energies (less than a few keV) [Yamauchi et al., 1996; Ebihara et al., 2001; Yamauchi et al., 2006; Ebihara et al., 2008]. In Ebihara et al. [2001], they expected that the temporal variation of the ion source or the development of longitudinally narrow flow channels of ion injections can explain the wedge-like structures observed by the Viking spacecraft. Our simulation results may be consistent with these expectations. We showed that the source region of the injected ions is dynamically changing around the substorm onset due to the variation of background plasma flow pattern [Yao et al., 2014]. Further investigations are needed to understand the possible fate of the injected ions in the course of their drift motion.

The trunk-like structure is observed on the dayside during the recovery phase of magnetic storms [Zhang et al., 2015]. Zhang et al. [2015] concluded that the generation mechanism is a gap in the nightside ion source or a greatly enhanced impulsive electric field associated with an elevated geomagnetic activity. The trunk-like structure is likely the same as the wedge-like one because of the reasons listed below. (1) Both the trunk-like and the wedge-like structures are primarily observed on the dayside. (2) The ions that constitute the trunk-like and the wedge-like structures probably originate from the nightside plasma sheet. As the ions drift from the nightside to the dayside, they undergo the grad-B and curvature drifts that depend on energy. When the source popula-

tion is longitudinally and/or radially confined in the plasma sheet, the trunk-like and the wedge-like structures appear, according to the simulation studies. A normal distribution function of ions, which decreases with energy in the nightside plasma sheet, is sufficient to explain the trunk-like and the wedge-like structures that are observed on the dayside. On the other hand, the void structure is observed on the nightside, and an unusual distribution function, which increases with energy in the nightside plasma sheet, is necessary. The unusual distribution function can be generated by non-adiabatic acceleration under the presence of the strong dawn to dusk electric field.

4.6 Conclusion

We obtained the following major conclusions.

1. During substorms, a new type of O^+ ion spectral feature "void structure" was observed by the Van Allen Probes. In total, the void structure was identified at 9 substorm events between 1 January 2013 and 30 May 2013. The inner edge and the threshold energy of the void structure, are usually located at $L = \sim 5.5$ and ~ 10 keV.
2. We simulated a substorm-time O^+ ion injection in the global MHD electromagnetic fields. Our simulation well reproduced the void structure observed by the Van Allen Probes. The simulation result revealed that the generation mechanisms of the void structure consist of (1) the formation of the strong equatorward flow in the low pressure region and tailward flow in the high pressure region and (2) the intense non-adiabatic acceleration of O^+ ions.

Chapter 5

Substorm-time O^+ outflow from the ionosphere

5.1 Introduction

As we stated in Chapter 1, two source regions of the energetic O^+ ions have been proposed. The first one is the dayside polar region. Ions from the dayside polar region are transported to the lobe, then they are injected to the nightside plamasheet during substorm expansion phase. The second one is the nightside aurora region. After the substorm onset, energetic O^+ ions are extracted from the ionosphere with the auroral acceleration processes, and the O^+ ions are directly supplied to the nightside plasmashet. The purpose of this study is to investigate relative importance of these two regions on the energetic O^+ ions in the inner magnetosphere.

Previously, a global MHD simulation developed by Tanaka et al., [2010] and Tanaka [2015] succeeded to demonstrate several important features that emerge during a substorm such as the current system that can be observable as a current wedge [Tanaka et al., 2010], energetic particle injection [Ebihara and Tanaka, 2013], westward traveling surge [Tanaka, 2015; Ebihara and Tanaka, 2015] and the magnetic disturbance at auroral latitudes [Tanaka et al., 2010] as well as magnetic equator [Ebihara et al., 2014]. In this study, we traced guiding centers of test particles in the electromagnetic fields provided by the global MHD simulation, and investigated impacts of the two processes (non-adiabatic acceleration and direct supply) to the O^+ ring current enhancement in a short time scale ($< \sim 30$ min). To simulate a substorm-time variation of O^+ outflow, we launched O^+ ions from the topside ionosphere with initial parameters calculated by the same method introduced by Fok et al. [2006]. For O^+ ions which transported to the inner

magnetosphere by way of the lobe, we extended a study of Chapter 3 [Nakayama et al., 2015]. In Chapter 3, we calculated the full motion of O^+ ions from the lobe region to the inner magnetosphere. The distribution function in the lobe was assumed to be a kappa distribution with constant parameters during the substorm. In this study, we calculated a subsequent change of the O^+ distribution in the lobe and simulated the flux enhancement in the inner magnetosphere using the result as the initial condition of the simulation.

5.2 Simulation settings

We used a global MHD simulation developed by Tanaka et al. [2010] and Tanaka [2015] to derive the electric and magnetic fields associated with a substorm, and to determine initial parameters of test particles. In this study, the IMF is turned from (0, 2.5, 5.0) to (0, 2.5, -5.0) nT to trigger a substorm. At the same time, the solar wind speed was increased from 372 to 500 km/s. The solar wind density was set to a constant value of 5 cm^{-3} . All simulation settings, grid system, and ionospheric conductivities are the same as those used by Ebihara et al. [2014, 2015] and Nakayama et al. [2015]. The simulation result showed that the calculated AL index is rapidly decreased after 57 minutes from an arrival of the southward IMF at the bow shock. The minimum AL reaches -800 nT [Ebihara et al., 2014] for this settings. When the AL is decreased, the dawn to dusk electric field is enhanced to $\sim 13 \text{ mV/m}$ at between $\sim 6.5 R_E$ and $\sim 11.5 R_E$ in longitudinally narrow regions in the pre-midnight and post-midnight [Nakayama et al., 2015]. In this study, the onset of substorm expansion phase is defined as the moment at which the AL index suddenly decreases, and hereinafter referred to as $T = 0 \text{ min}$.

We traced O^+ ions' trajectories from the ionosphere in the time-varying global MHD electromagnetic fields by using the guiding center approximation. We released the O^+ ions by the same manner introduced by Fok et al. [2006].

Source region was set as the topside ionosphere at 1000 km altitude and between 60° and 90° latitude in both hemispheres. O^+ ions were launched from the source region every 1 minute. Initial velocity was randomly given in the thermal energy ranges between 0-1 keV, pitch angle ranges between 0° - 90° and gyro-phase angle ranges between 0° - 360° . In total, around 100 billion test particles were traced from the source region. The thermal energy and parallel potential drop at their source positions were calculated

by using the results from the MHD simulation as follows:

$$E_{\text{th}} \text{ (eV)} = 0.1 \text{ eV} + 1.6S_{1K}^{1.26} \quad (5.1)$$

$$\Phi_{\parallel} \text{ (V)} = 1500(J_{\parallel} - 0.2)^2 \quad \text{if } J_{\parallel} \geq 0.2\mu\text{A/m}^2 \quad (5.2)$$

$$\Phi_{\parallel} \text{ (V)} = 10 \quad \text{if } J_{\parallel} < 0.2\mu\text{A/m}^2 \quad (5.3)$$

where S_{1K} is the global Joule heating in the ionosphere provided in mW/m^2 mapped to 1000 km altitude and $\Phi_{\parallel}$ is the upward potential drop along the magnetic field line. The description of the ion heating shown in equation (1) is based on observational studies of Strangeway et al. [2005] and Zheng et al. [2005]. Following these studies, we took the two primary energy sources of ion outflow, soft electron precipitation and dissipation of downward Poynting flux, into consideration. A relationship between the upward field aligned current at the ionosphere and the parallel potential drop in equations (2) and (3) are estimated from the Knight-like relation introduced in Lyons [1981]. We used a smaller threshold current density of $0.2 \mu\text{A/m}^2$ than the value of $0.33 \mu\text{A/m}^2$ which used in Fok et al. [2006].

Figure 5.1 shows the MHD parameters and the corresponding O^+ outflow parameters at 1000 km altitude at $T = -15 \text{ min}$, 0 min and 15 min . Large-scale FACs, which are consistent with those known as region 1 and 2 current systems [Iijima and Potemra, 1976], are clearly shown. During the growth phase (left column), the intensity of the upward FAC and downward FAC is increased to $0.2 \mu\text{A/m}^2$ in the region 1 and 2. E_{th} is large in the dayside polar region where midday part of region 1 FAC is increased and in the dawn-midnight sector at $\sim 70 \text{ MLAT}$. Due to the upward region 1 FAC, potential drop is increased to 10 V at $\sim 75 \text{ MLAT}$ and at $\sim 13\text{-}15 \text{ MLT}$. At the substorm onset (middle column), sudden intensification of upward FAC, which may be regarded as the initial brightening of the aurora emerges at $\sim 67 \text{ MLAT}$ and at $\sim 23 \text{ MLT}$. The potential drop is increased to $\sim 3 \text{ eV}$ by primarily the initial brightening. E_{th} is increased in the broad region in the dawn-midnight sector at $\sim 65\text{-}\sim 70 \text{ MLAT}$. After the substorm onset (right column), high E_{th} and potential drop is established in the dusk-midnight at $\sim 65\text{-}70 \text{ MLT}$ and dawn-midnight sector at $\sim 70 \text{ MLT}$, respectively.

We used same method to reproduce the distribution function as Chapter 4, although

we assumed a slightly different kappa distribution in the ionosphere as

$$f = \frac{n}{\pi^{3/2}\theta_k^3} \frac{\Gamma(\kappa + 1)}{\kappa^{3/2}\Gamma(\kappa - 1/2)} \left(1 + \frac{|\mathbf{v}_{ini} - \frac{\mathbf{B}}{B}\sqrt{2\Phi_{||}/m}|^2}{\kappa\theta_k^2} \right)^{-(\kappa+1)} \quad (5.4)$$

and

$$\theta_k = \left(\frac{2\kappa - 3}{\kappa} \frac{E_{th}}{m} \right)^{1/2} \quad (5.5)$$

We assumed that $n = 0.1 \text{ cm}^{-3}$, $\kappa = 4.5$. Detailed calculations of the phase space mapping are explained in Ebihara et al. [2006] and Nakayama et al. [2015].

5.3 Simulation result

5.3.1 Substorm-time variation of the O^+ outflow

Figure 5.2 shows temporal variations of the distribution function at $(-6, 0, 2) R_E$, $(-8, 0, 2) R_E$, and $(-10, 0, 2) R_E$, which are located in the plasmasheet, near the plasmasheet-lobe boundary and in the lobe, respectively. Black dashed line shows a kappa distribution which is used as a distribution function of the O^+ ion flowing into the lobe region in Nakayama et al. [2015]. Before the substorm onset, for all the three positions, the distribution function is almost flat at $< 100 \text{ eV}$, but the value abruptly decreases at $> 100 \text{ eV}$. The feature does not change before the substorm onset (before $T = -5 \text{ min}$). After the substorm onset, the distribution function is increased at all energy. In particular, the increase at $> 100 \text{ eV}$ is notable, and the value exceeds that of the kappa distribution (black dashed line). For example, at $(-10, 0, 2) R_E$, the distribution function is lower than 10^{-18} at 400 eV at $T = 0 \text{ min}$, and the value increases by 6 orders ($\sim 10^{-12}$) at $T = 20 \text{ min}$.

We focused on the enhancement of the warm ($> \sim 300 \text{ eV}$) ions emerging at $(-10, 0, 2) R_E$ and $(-6, 0, 2) R_E$ after the substorm onset at $T = 20 \text{ min}$. Figure 3a-b shows launched positions of the warm ions. For the lobe ions, the main source is restricted in the dayside polar region (between 83 and 87 MLAT , and 12 MLT and 18 MLT). For the plasmasheet ions, there are two main source regions. The first one is found in a broad region in noon-dusk sector (between 70 and 90 MLAT , and 12 MLT and 18 MLT) and the second one is found in the nightside aurora region (between 65 and 70 MLAT , and 00 MLT and 01 MLT). Figure 3c-d and Figure 3e-f shows the time of departure from

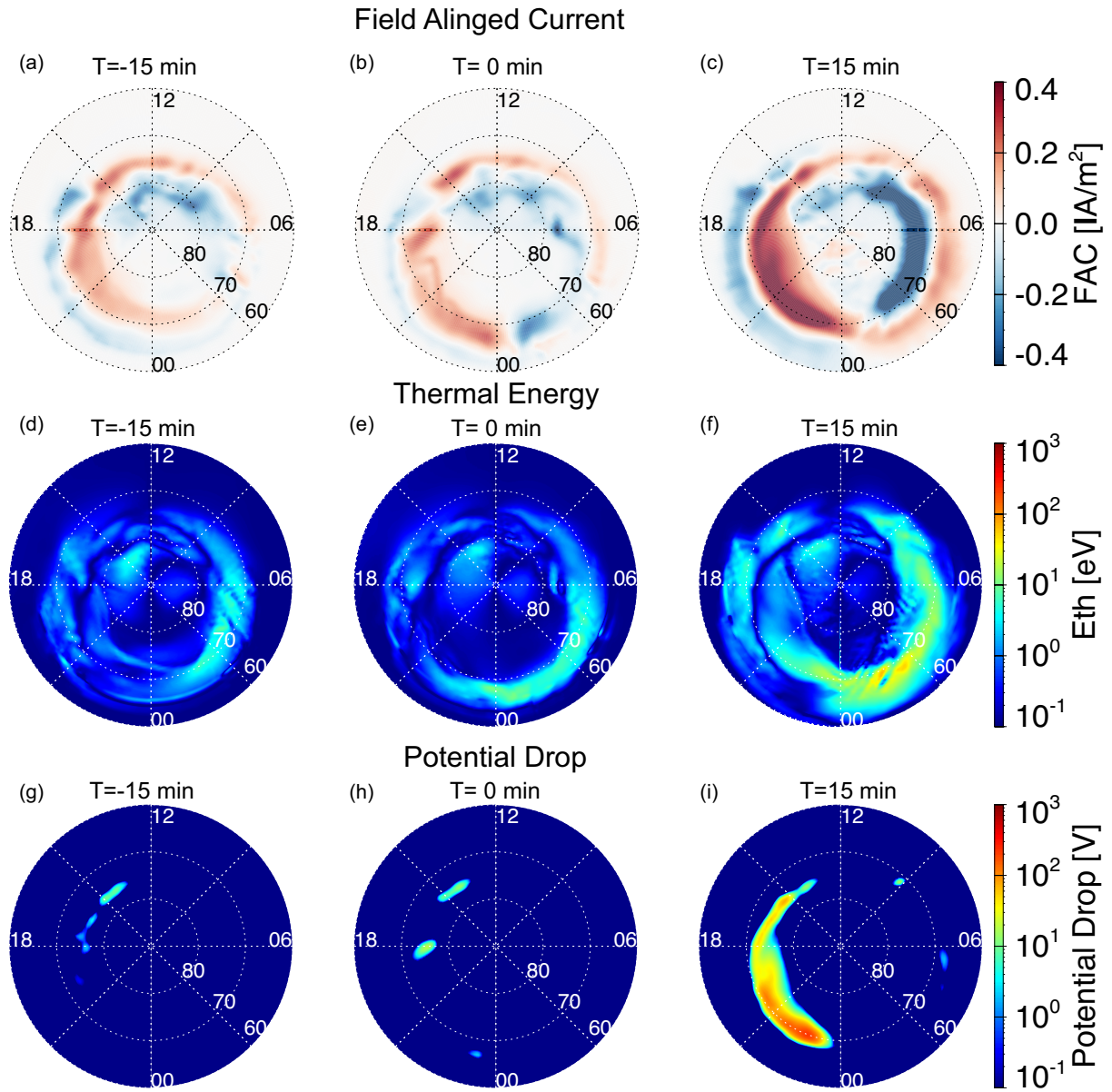


Figure 5.1: MHD conditions and auroral outflow parameters at 1000 km altitude at $T = -15, 0$ and 15 min.

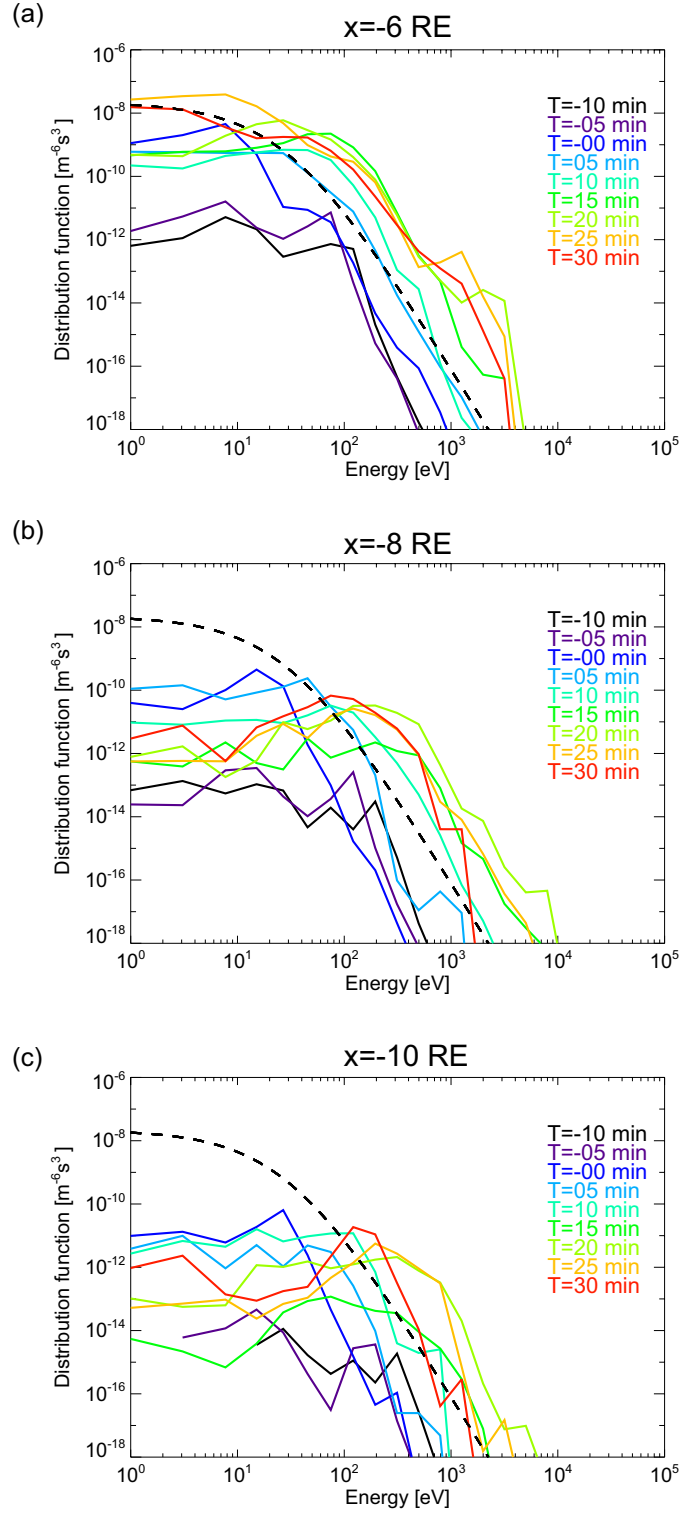


Figure 5.2: Temporal variations of the distribution function at $(-6, 0, 2) R_E$, $(-8, 0, 2) R_E$, and $(-10, 0, 2) R_E$, which located at plasmasheet, plasmasheet-lobe boundary and plasma lobe, respectively. Black dashed line shows a kappa distribution, which is used as a distribution function of the O^+ ion flowing into the lobe region in Nakayama et al. [2015].

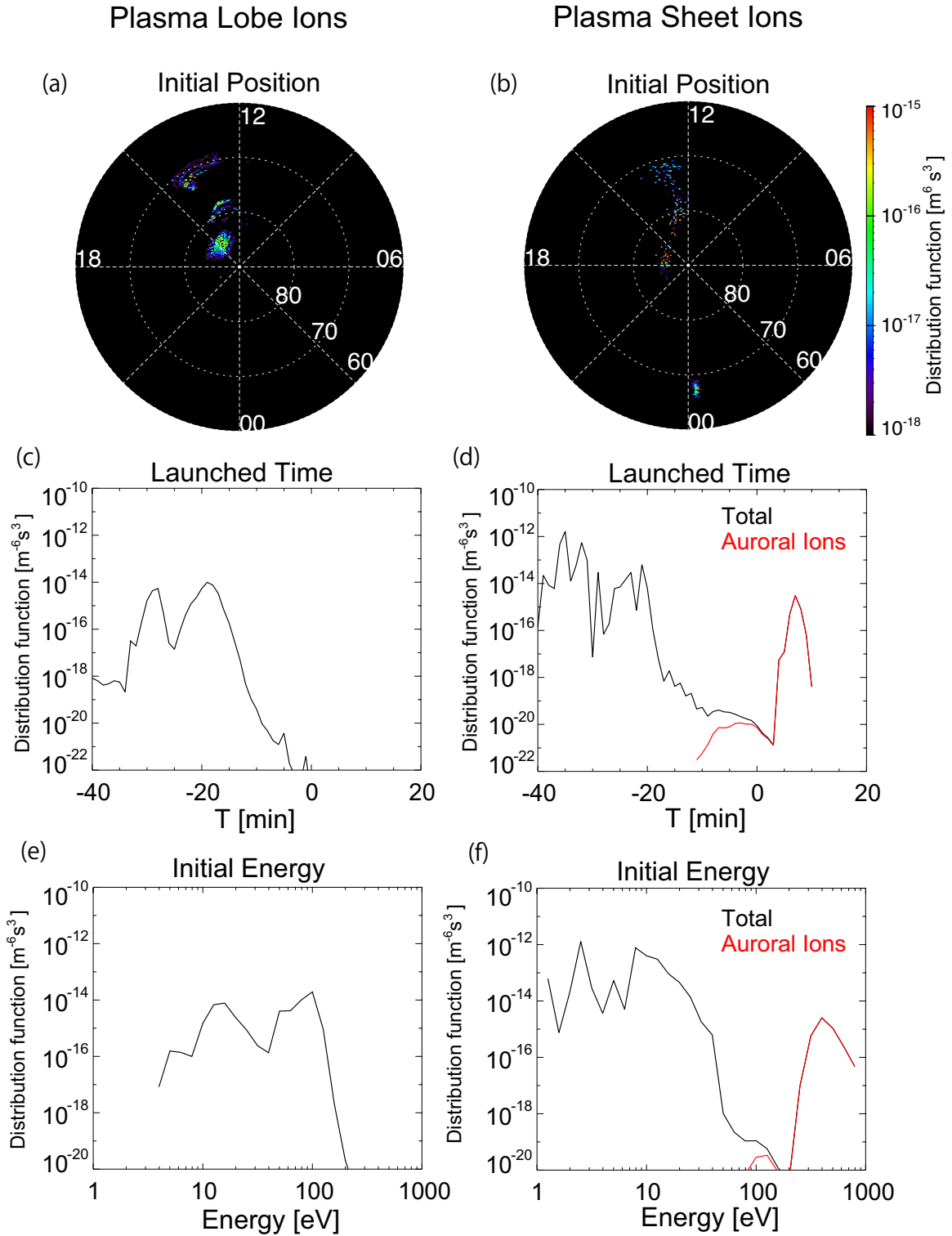


Figure 5.3: (a-b) Initial positions of the ions which flow into the lobe (at $(-10, 0, 2) R_E$) and the plasma sheet (at $(-6, 0, 2) R_E$) with > 300 eV at $T = 20$ min. The distribution function as a function of (c-d) the time of departure from the source and (e-f) the initial energy.

the source and the initial energy of the lobe and plasmasheet ions. Black lines show the total value and red lines show the value for the O^+ ion launched from the nightside aurora region. The lobe ions depart the dayside polar region with tens of eV (Figure 3e) during the substorm growth phase mainly between at $T = -35$ min and $T = -10$ min (Figure 3c). As shown in Figure 1d, O^+ ions from the dayside polar region are thermalized to ~ 10 eV due to the midday part of region 1 field-aligned current during the substorm growth phase. Therefore, a significant amount of O^+ ions at tens of eV is extracted from the region, results in the enhancement of the warm O^+ ions in the plasma lobe. The plasmasheet O^+ ions originated in the dayside region are launched during the substorm growth phase mainly between at $T = -40$ min and $T = -20$ min (Figure 3d). Their initial energy is between 1 eV and 40 eV. Plasmasheet O^+ ions originated in the nightside aurora region are launched after the substorm onset (red line in Figure 3d). The initial energy is between 200 eV and 600 eV and it has a peak around at 400 eV. As shown in Figure 2e-f, the thermal energy in the nightside aurora region is increased (tens of eV) after the substorm onset due to the initial brightening of aurora. Although the thermal energy is increased only to tens of eV, the result indicates that a substantial amount of O^+ ions at hundreds of eV are directly supplied from the aurora region to the plasmasheet. In particular, the enhancement of plasmasheet O^+ ions at > 1 keV is contributed only by the auroral O^+ ions (not shown).

Figure 5.4 shows trajectories and kinetic energy of the 20 typical test particles that flow from the dayside polar region into the vicinity of the point of $(-10, 0, 2) R_E$. The kinetic energy of the ions is indicated by color. Black lines in Figure 5.4a-b indicate the inner boundary of the global MHD simulation. Inside of the inner boundary, dipole magnetic field and no electric field are assumed. The O^+ ions depart at $T = -18$ to -17 min with initial energy of around 200 eV. After the departure, the O^+ ions move tailward and toward the equatorial plane. The kinetic energy is gradually increased from ~ 200 eV to ~ 400 eV. Figure 5.4d shows energy gain rate of one typical O^+ ion of them. The red color indicates the energy gain rate due to the drift betatron, and the blue one indicates the energy gain rate due to the gyro betatron. During the transport, the drift betatron contributes to the energy increase. This indicates that the O^+ ions are transported to the lobe region with the adiabatic acceleration under the influence of the large-scale convection electric field.

Figure 5.5 shows trajectories of the 20 typical test particles that contribute to the O^+ ions near the point of $(-6, 0, 2) R_E$. The O^+ ions are launched at $T = 7-9$ min with initial

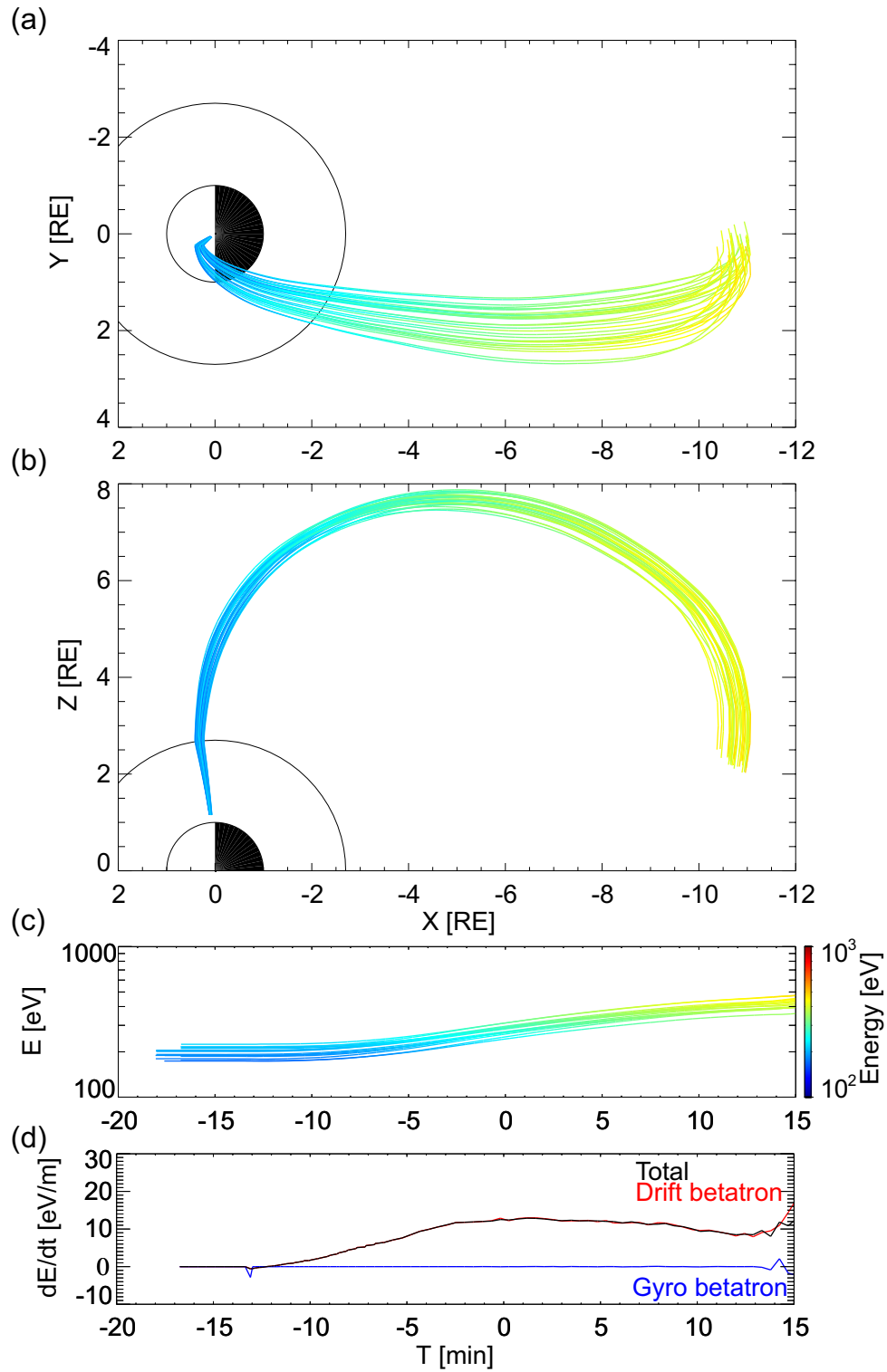


Figure 5.4: (a-b) Trajectories of the ions which flow into the lobe region from the dayside polar region, projected on the X-Y and X-Z plane. The kinetic energy of the ions is indicated by color. Black line indicates the inner boundary of the global MHD simulation. (c) Kinetic energy of the ions as a function of time. (d) Energy gain rate of one typical O^+ ion of them. The red color indicates the energy gain rate due to the drift betatron, and the blue one indicates the energy gain rate due to the gyro betatron.

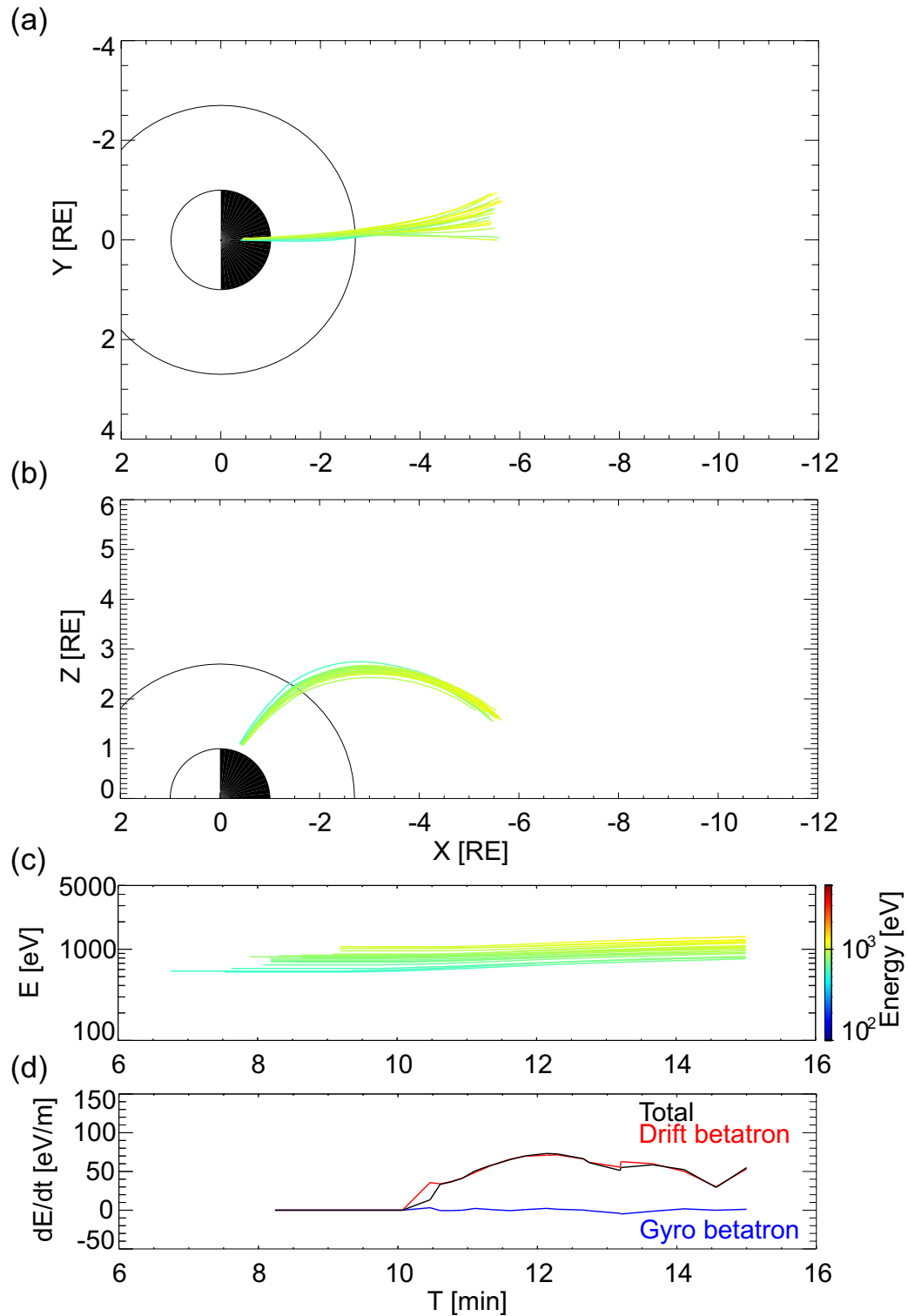


Figure 5.5: Same figure as Figure 5.4 for the O^+ ions, which are directly supplied to the plasma sheet from the night side aurora region.

energy of at $\sim 500\text{--}\sim 1000$ eV. After the departure, the O^+ ions move along the field line and flow into the vicinity of the point of $(-6, 0, 2) R_E$. During the transport, the kinetic energy is gradually increased and they gain ~ 200 eV. The ion acceleration is also due to the drift betatron. The gyro betatron contributes little to it.

5.3.2 Flux enhancement in the inner magnetosphere

The O^+ ions flow into the lobe region (Figure 5.2c) will be transported to the plasmasheet and ring current region with a significant acceleration due to the dawn to dusk electric field. The injection process is simulated by Nakayama et al. [2015], in which the same global MHD simulation result is used. In the simulation, O^+ ions were launched at $Z = \pm 2 R_E$, ranging from $X = -7$ to $-17 R_E$ and from $Y = -10$ to $10 R_E$. The distribution of the O^+ was assumed as a kappa distribution with constant parameters. In this study, we used the result of the O^+ outflow simulation above (Figure 5.2) to specify the distribution function at the source plane of the injection simulation.

Figure 5.6 shows energy versus time spectrogram of the differential flux of the O^+ ions at fixed positions (at $6.0 R_E$ and at 00, 23 and 22 MLTs and in the equatorial plane). At 00 MLT, the flux increase almost simultaneously at all energies below 80 keV at $T = 0$ min, which is known as dispersion-less structure [e.g., Fu et al., 2002; Keika et al., 2010; Gkioulidou et al., 2015]. A lack of the energetic O^+ at < 30 keV starting at $T = \sim 10$ min is called as a void structure [Nakayama et al., 2016]. An isolated energy dispersion structure, energy decreasing with time, appears at $T = 34$ min and onward. This is attributed to a drift echo, arising from the ions that encircle the Earth by the grad-B and curvature drift. At 23 MLT, the flux between ~ 80 keV and ~ 100 keV increases first at $T = 1$ min, followed by the high energy and lower energy. The energy-time structure is similar to the nose structure in which the flux increase is observed first at narrow energy range and spreads to both higher and lower energies [Smith and Hoffman, 1974; Ejiri et al., 1980]. At 22 MLT, the flux enhancement shows the similar structure at 23 MLT, but the energy-time dispersion becomes more significant.

5.3.3 Contribution to the ring current

We calculated a magnetic perturbation on the earth driven by the energetic O^+ ions enhanced in the inner magnetosphere. For the O^+ ions at the radial distance $r < 10 R_E$,

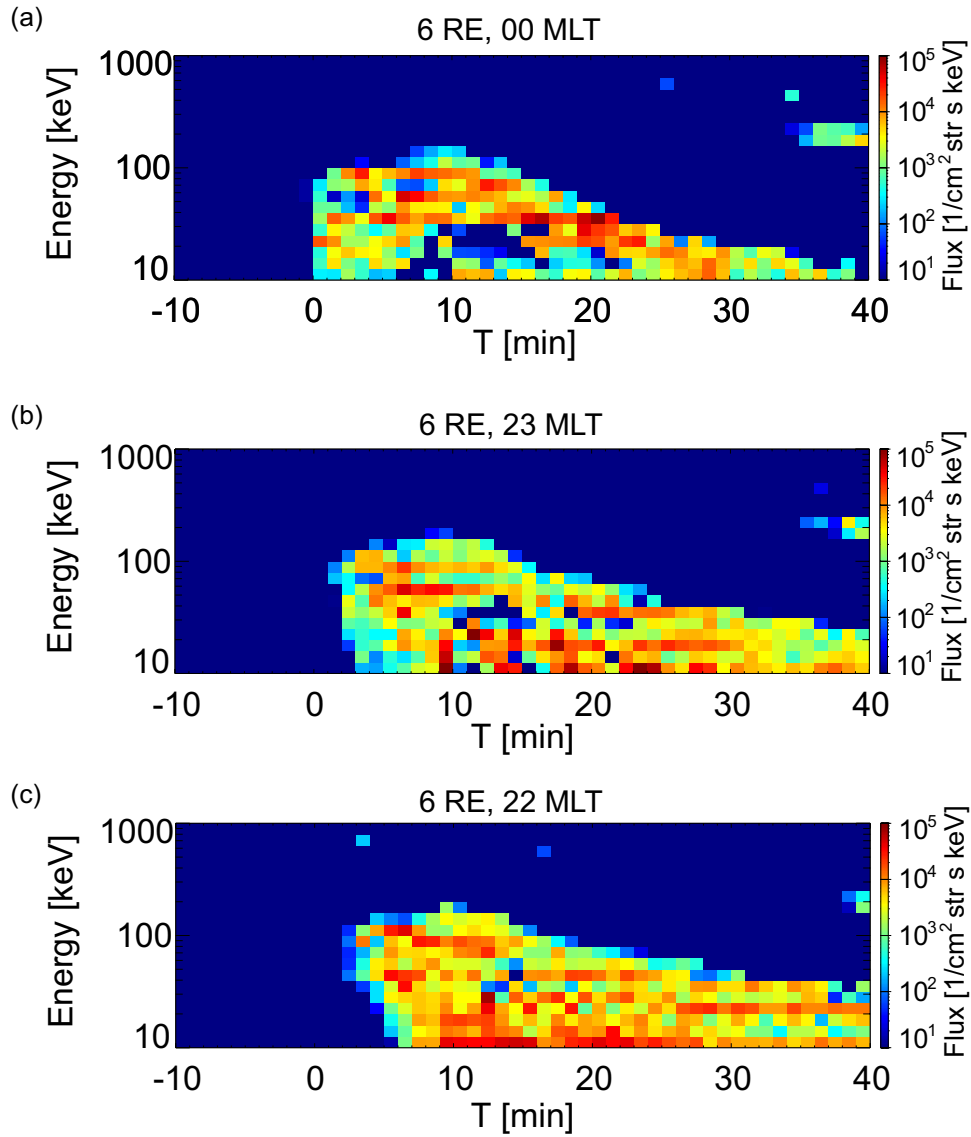


Figure 5.6: Energy versus time spectrograms of the differential flux of the O^+ ions at fixed positions (6.0 R_E ; 00, 23 and 22 MLTs; the equatorial plane) simulated by the coupled simulation. The simulated flux shows rapid increase after substorm onset with a realistic dispersion.

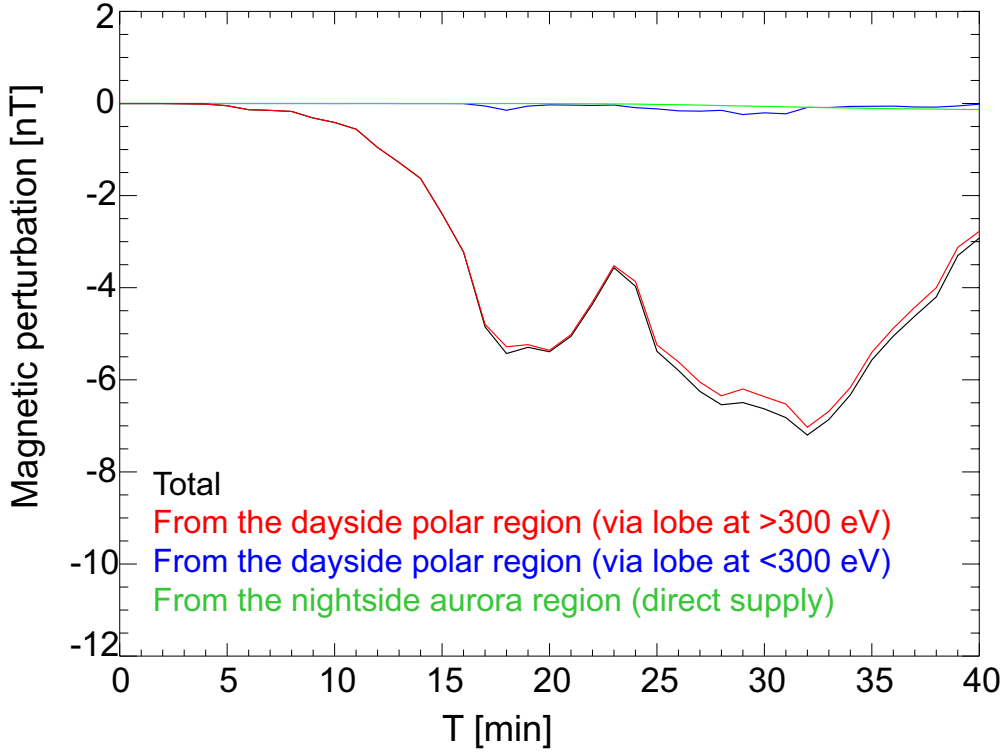


Figure 5.7: Magnetic perturbation on the ground due to the several groups of O^+ ion. The magnetic perturbation is induced after the substorm onset and reaches ~ -7.2 nT at $T=32$ min.

we calculated the Z component of $\Delta \mathbf{B}$ which is written by below,

$$\Delta \mathbf{B} = - \sum \Delta N_i \frac{\mu_0 e \mathbf{v}}{4\pi} \times \frac{\mathbf{r}}{r^3} \quad (5.6)$$

where μ_0 is the magnetic permeability and r is radial distance of the test particle. Figure 5.7 shows the magnetic perturbation on the ground as a function of time. To clarify their source regions, we divided the O^+ ions to 3 groups. First group (Group A) consists of O^+ ions passed through the lobe region with > 300 eV (red line) and second one (Group B) consists of those with < 300 eV (blue line). Third group (Group C) consists of O^+ ions directly supplied from the nightside aurora region (green line). The total value (black line) starts to show a sharp decrease at $T = \sim 10$ min and has two peaks at $T = 18$ and 32 min. The minimum value is -7.2 nT at $T = 32$ min. Group A ions contribute most of the magnetic perturbation. For example, at $T = 32$ min, they decrease the earth's magnetic field to -7.0 nT and the value reaches $\sim 97\%$ of total. Contributions of Group B and C at the time are $\sim 2\%$ and $\sim 1\%$, respectively. The result indicates that the enhancement of warm O^+ ions (> 300 eV) in the lobe during substorm has a large impact on the ring current intensity.

5.4 Discussion

Observation studies reported an enhancement of the O^+ outflow during substorm growth phase. A statistical study by Daglis and Axford [1996] suggested that the enhancement of O^+ outflow during the growth phase of substorm based on the O^+ measurements by AMPTE/CCE/CHEM. Some studies suggested that the enhancement takes place in the dayside polar region [e.g. Moore et al., 1999; Perroomian et al., 2006; Zhang et al., 2011]. Our simulation result identified a specific region and a process of the enhancement. During the substorm growth phase, the midday part of region 1 FAC is increased (Figure 5.1a), resulting in the increase in the convection and Joule heating in the ionosphere. Consequently, the outflow of thermal O^+ ions (tens of eV) from this region is increased. On the other hand, some studies reported that O^+ ions at few hundreds of eV are extracted from the aurora region during substorms [Sauvaud, 2004; Andersson, 2005; Moore et al., 2005; Perroomian et al., 2006]. Our simulation result showed that, after the substorm onset, the thermal energy in the nightside aurora region is increased due to the initial brightening of aurora. The thermal O^+ ions at hundreds of eV are extracted from the region and directly supplied to the plasmasheet (Figure 5.4b).

We also showed that the thermal O^+ ions from the dayside polar region are transported to the plasma lobe region in ~ 30 min (Figure 5.4). During the transport, the O^+ ions gain a few hundreds of eV due to the drift betatron acceleration. Accordingly, warm O^+ ions (> 300 eV) are enhanced in the lobe region. This process works as a "pre-conditioning" of the O^+ ions transported to the inner magnetosphere with the non-adiabatic acceleration in the near-earth neutral region. Some studies reported the pre-conditioning process on a storm time scale (a few hours). Kistler et al. [2010, 2016] showed that thermal O^+ ions originated in the cusp region are significantly enhanced in the near-earth plasmasheet and the lobe on a storm-time scale, and the O^+ ions enter the plasma sheet with the acceleration when reconnection occurs in the nightside region. Our simulation result suggests that the process can take places even in a short time scale.

For auroral O^+ ions, a time delay between a substorm onset and an O^+ enhancement in the inner magnetosphere is known as an important factor. Many studies pointed out that the time delay is too short (< 30 min) so that auroral O^+ ions extracted after the substorm onset cannot contribute the enhancement [e.g. Fu et al., 2002; Mitchell et al., 2003]. However, previous Van Allen Probes observation revealed that O^+ ions at 0.1-10 keV in magnetic field-aligned directions are enhanced in a short time scale [Keika et al.,

2016; Nosé et al., 2016]. Nosé et al. [2016] investigated their traveling time by a simple numerical calculation. They assumed the dipole magnetic field with no electric field and computed the transit time of O^+ ions from the ionosphere to the inner magnetosphere. The result showed that the auroral O^+ ion at ~ 1 keV reaches at $L = 6 R_E$ and GMLAT = 15 deg. in ~ 5 min. Our test particle simulation in the global MHD fields showed a similar result. The auroral O^+ ions with hundreds of eV can flow into the plasmasheet region in ~ 10 min (Figure 5). It suggests the auroral O^+ ion is observable in the inner magnetosphere even in a short time scale. However, as we stated, their contribution to the ring current is small. This may be because their energy is low ($< \text{few keVs}$) compare with the O^+ ions accelerated by the dawn to dusk electric field.

We have calculated the magnetic perturbation triggered by the O^+ ions from two different sources using numerical simulations. Our simulation result showed that, in a short time scale ($< \sim 30$ min), the ring current is dominated by the O^+ ions originated in the dayside polar region. Particularly, the O^+ ions pass through the lobe region at > 300 eV contributes most of the total ring current intensity. It indicates that an enhancement of the warm O^+ ions in the lobe is a key phenomenon for observed ring current enhancements. On the other hand, the contribution of the auroral O^+ ion to ring current is small in the short time scale. However, it should be noted that these ions (0.1-10 keV) can be further transported into the inner magnetosphere more easily than the injected high-energy O^+ ions ($> \sim 10$ keV) with an adiabatic-acceleration due to the convection electric field on a long time scale. This is because the earthward drift can be higher than the westward gradient and curvature drifts even in the deep inner magnetosphere. After the penetration due to the storm-time convection electric field, the auroral O^+ ions may be a non-negligible population to O^+ pressure.

5.5 Conclusion

We obtained the following results.

1. During the substorm growth phase, O^+ ions at tens of eV are extracted from the dayside polar region. The O^+ ions convect to the lobe with the adiabatic acceleration, results in the enhancement of the warm O^+ ions (few hundreds of eV). After the substorm onset, the warm O^+ ions are non-adiabatically accelerated to tens of keV by the dawn to dusk electric field and injected to the inner magnetosphere. Finally, the ions contribute most of the ring current enhancement.

2. After the substorm onset, O^+ ions at hundreds of eV are extracted from the night-side aurora region, and they are directly supplied to the plasmasheet in a short time scale. However, their contribution to the ring current remains to be small.

Chapter 6

Acceleration on Azimuthally Directed Magnetic Field Lines

6.1 Introduction

Observations have shown that energetic O^+ ions are enhanced in the inner magnetosphere during substorm. Some studies suggest that the energization can be explained by acceleration and transport of particles from the nightside plasma sheet [e.g. Delcourt et al., 2002; Fok et al., 2006, Ashour-Abdalla et al., 2009; Perroomian et al., 2011; Birn et al., 2013]. During the substorm expansion phase, the plasmasheet ions are accelerated and transported into the inner magnetosphere due to the intensive dawn-dusk electric field associated with the dipolarization [e.g. Li et al., 1998; Zaharia et al., 2000; Ashour-Abdalla et al. 2011; Birn et al., 2013; Ebihara and Tanaka, 2013]. For O^+ ions, because they are heavy ions, non-adiabatic acceleration is often triggered during the energization in the plasmasheet region. The non-adiabatic acceleration results in the impulsive injection of energetic O^+ ions to the inner magnetosphere and the mass dependence of the energization during substorms.

Previously, by using the global MHD simulation developed by Tanaka et al. [2010], Saita et al. [2011] pointed out that the Z -component of the magnetic field (B_z) decreases whereas the Y -component of the magnetic field (B_y) persists in the near-Earth plasma sheet about 10 min prior to a substorm onset. They also showed that the magnetic field lines are highly distorted toward the azimuthal direction (east-west direction) near the equatorial plane near midnight. The structure of the magnetic field lines is similar to a flux rope. However, the structure is different from a flux rope two reasons below. First, the formation of the flux rope structure is not directly associated with magnetic

reconnection. Second, the position is more close to the earth ($\sim 8 R_E$) compare with one usually reported and the anomalous resistivity is not large in the flux rope region.

This flux rope structure is different from the one generated in the region where anomalous resistivity is high as was previously demonstrated by Tanaka et al. [2010] and is located earthward of the reconnection-associated flux rope structure. Thus, it is most probable that there is no parallel electric field.

Although, there are many studies which investigated O^+ ion acceleration around a flux rope region, and they showed a abrupt acceleration of O^+ ions. It is not reported the acceleration process in the flux rope region before. The purpose of this study is to understand motion and acceleration mechanism of the O^+ ions that preexist in the flux rope structure by using the electric and magnetic fields provided by the global MHD simulation.

6.2 Generation of the azimuthally directed magnetic field lines

We used the global MHD simulation developed by Tanaka et al. [2010]. Solar wind density and velocity were held constant to be 10 cm^{-3} and 372.4 km/s , respectively. Interplanetary magnetic field (IMF) turned from $(0, 2.5, 4.33)$ to $(0, 4.33, -4.33)$ nT (in Coordinate system) to stimulate the magnetosphere so as to trigger a substorm. The simulation settings are the same as those of Ebihara and Tanaka [2013].

Figure 6.1 shows the calculated H -component of the ground magnetic field at 12 different magnetic local times (MLTs) at a magnetic latitude of 67° . The upper and lower envelopes of the plots correspond to the AU and AL indices [Davis and Sugiura, 1966], respectively. Epoch time zero ($T = 0 \text{ min}$) is defined as the time when the southward IMF reaches the bow shock at the sub-solar point in this study. At $T = 51 \text{ min}$, the AL index starts to decrease abruptly, which is referred to the substorm onset.

Figure 6.2 shows (a) plasma pressure (P) and (b) angle between current density ($\mathbf{J}$) and magnetic field ($\mathbf{B}$) in the meridional plane at $8.5 R_E$ near the equatorial plane at midnight at $T = 48 \text{ min}$ (just before the onset determined by the AL index). Black arrows in Figure 6.2(a) show the MHD plasma flow velocities in the meridional plane. White dots in Figure 6.2(a) and (b) indicate the position of $(-8.5, 0, 0) R_E$. In Figure 6.2(a), plasma pressure P is highly enhanced near the night side equatorial region. The high pressure region is located between $X = -7 R_E$ and $-11 R_E$. Based on a result from the same global MHD simulation model, Tanaka et al. [2010] pointed out that the high

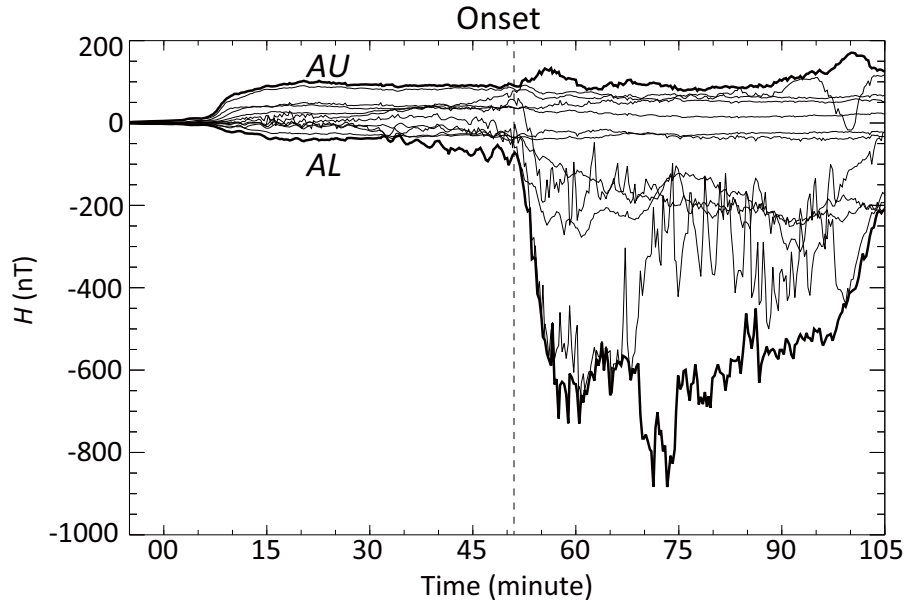


Figure 6.1: H -component of the magnetic field disturbance on the ground at 0, 2, 4, ..., and 22 MLTs at magnetic latitude of 6° . The upper and lower envelopes of the superposed plots, as indicated by thick lines, correspond to the AU and AL indices, respectively, by definition.

pressure region is substantially developed by the force imbalance in the plasma sheet. During the substorm expansion phase, the midtail region is always in the over tension state because of reduction of the $\text{grad } P$ force. The reduction of the $\text{grad } P$ force is caused by the force imbalance that is initiated in association with the formation of the near-earth neutral line in the midtail region. The over tension state results in the earthward fast flow, but the fast flow is impeded in the near-earth midtail region where the inertial force of the fast flow is balanced with the $\text{grad } P$ and $\mathbf{J} \times \mathbf{B}$ force. As a consequence of convergence of thermal energy flow, high plasma pressure region is established in the near-earth magnetotail. In Figure 6.2(b), $\mathbf{J}$ is antiparallel to $\mathbf{B}$ near $(-8.5, 0, 0) R_E$ (blue colors). However, $\mathbf{J}$ is almost perpendicular to $\mathbf{B}$ at the off-equator between $x = 7 R_E$ and $-11 R_E$ (green colors), for example, $(-8.5, 0, \pm 0.5) R_E$. This perpendicular $\mathbf{J}$ at the off-equator is dominated by the diamagnetic current, result from the establishment of the high pressure region. The diamagnetic current significantly decreases B_z around $(-8.5, 0, 0) R_E$ as mentioned below.

Figure 6.3 shows temporal variation of the magnetic field at $(-8.5, 0, 0) R_E$. The B_y remained almost constant around -5 nT before the substorm onset. But, it decreases to ~ -10 nT around the substorm onset. The decrease in B_y around the substorm onset is understood by below. Under the IMF B_y , eastward (westward) round cell is formed in the northern (southern) polar ionosphere. The magnetic field lines connecting the

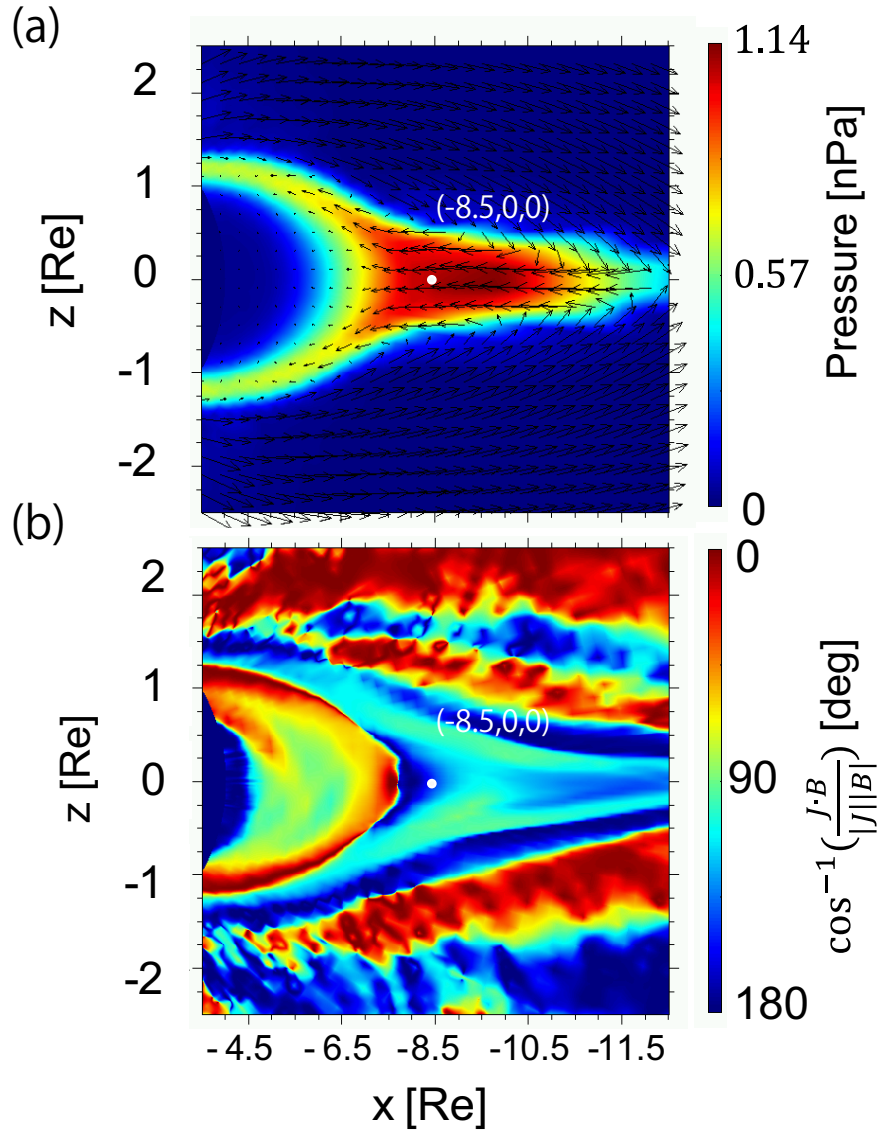


Figure 6.2: (a) The plasma pressure and (b) the angle between the current density ($\mathbf{J}$) and the magnetic field ($\mathbf{B}$) in the meridional plane at midnight at $T = 48$ min. Black arrows show the MHD plasma flow velocities in the meridional plane. White dots indicate the position of $(-8.5, 0, 0) R_E$.

round cells are twisted eastward (westward) in the northern (southern) hemisphere. As a consequence, the negative B_y emerges in the magnetosphere on the nightside [Tanaka, 1999]. On the other hand, B_z gradually decreased during the substorm growth phase. At $T = \sim 41$ min (about 10 min before the onset), B_z becomes less than $|B_y|$. When $|B_y|$ dominates B_z , the magnetic field line is directed downward near the equatorial plane near $(-8.5, 0, 0) R_E$ since B_y is negative. Figures 6.3(b) and 6.3(c) show the magnetic field lines that pass through $(-5$ to $-15, 0, 0) R_E$ in the 3-dimensional coordinates and in the X - Z plane. A magnetic field line passing through $(-8.5, 0, 0) R_E$ is shown as red lines in Figures 6.3(b) and 6.3(c). The magnetic field line passing through $(-8.5, 0, 0) R_E$ is strongly elongated to dawn-dusk direction around the equatorial region and it has two kinks located at $(-7.2, -3.3, 0.56) R_E$ and at $(-7.1, 3.8, -0.82) R_E$. Since the current flows along a field line near $(-8.5, 0, 0) R_E$, the azimuthally directed magnetic field line may be regarded as a flux rope structure. The magnetic field lines that pass through both inside and outside of $(-8.5, 0, 0) R_E$ are not azimuthally elongated as much as those passing through near $(-8.5, 0, 0) R_E$ as shown in Figure 6.3.

There are two pieces of indirect evidence of the formation of the azimuthally elongated magnetic field line. First, Saita et al. [2011] show that the longitudinal displacement of the initial brightening of aurora observed by Ostgaard et al. [2005] may be reasonably explained by the existence of the azimuthally elongated magnetic field line. Second, in situ observation performed by Time History of Events and Macroscale Interactions during Substorms observation shows that $|B_y|$ dominates B_z in the near-Earth plasma sheet near the equatorial plane just before the substorm onset [Panov et al., 2010]. Thus, the emergence of the azimuthally directed magnetic field lines may be a phenomenon which occurs in the real magnetosphere.

6.3 Acceleration of O^+ on the magnetic field lines

We performed a test particle simulation in the global MHD electromagnetic fields to investigate the acceleration process of the preexisting O^+ ions on the azimuthally directed magnetic field lines.

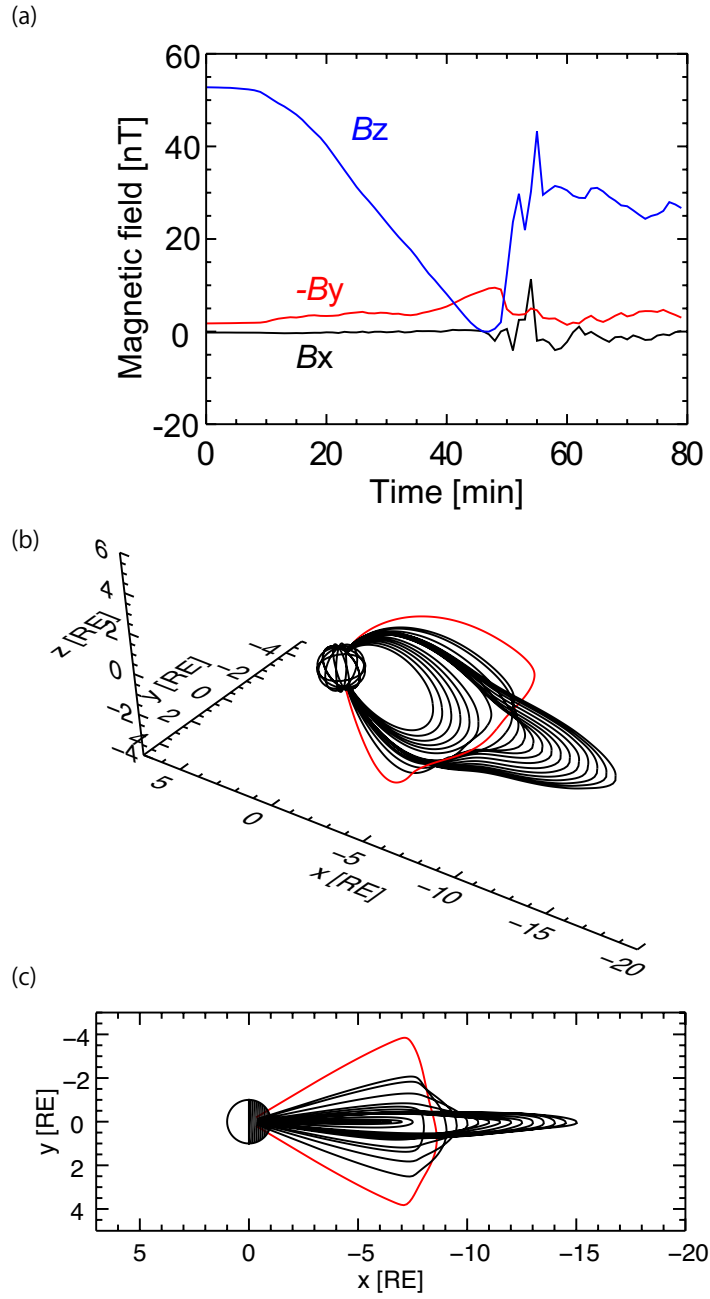


Figure 6.3: (a) Time variation of the magnetic field at $(-8.5, 0, 0) R_E$ and (b,c) configuration of magnetic field lines that pass through -5 to $-15 R_E$ in the midnight.

6.3.1 Simulation settings

In this particular study, we chose three start times and three initial locations. We started the particle tracing at $(-5.5, 0, 0) R_E$, $(-7.0, 0, 0) R_E$ and $(-8.5, 0, 0) R_E$, which referred to $P_{5.5}$, $P_{7.0}$, and $P_{8.5}$, respectively. Start times of the calculation are at $T = 44, 48$, and 52 min, which correspond to the growth phase, just before the onset and just after the onset, respectively. We repeated the same simulation for nine parameters, that is, three different times and three locations. We traced the trajectory for 10 min. The tracing was terminated when it reached the inner or outer shells located at a radial distance of $4.0 R_E$ and $25 R_E$, respectively. The inner boundary of the global MHD simulation is set at $3 R_E$, but some unwanted fluctuations of electric fields appear inside $4 R_E$. So we chose the inner boundary for the test particle simulation as a $4 R_E$ sphere. In phase space, test particles were initially distributed in the v_y - v_z plane. Initial kinetic energy ranges from 1 keV to 100 keV at an interval of 1 keV, and initial polar angle θ ranges from -180° to 180° at an interval of 1° . The polar angle θ is defined by $\theta = \tan^{-1}(v_x/v_y)$. The positive (negative) θ means that the initial velocity looks duskward (dawnward).

In this particular study, v_x is set to be zero because the results are essentially unchanged regardless of v_x (After launching particles in all directions, we confirmed that the results are essentially unchanged regardless of the particles launched in the x direction. This most likely means that the assumption of symmetric distribution with respect to the local magnetic field line is valid for the purpose of investigating acceleration processes of the O^+ ions starting at these positions). In total, 36,000 particles (100 in energy times 360 in angle) were traced in each simulation run.

Figure 6.4 shows an example of differential number flux of the oxygen ions taken by the Magnetospheric Ion Composition Sensor of the Charge and Mass Magnetospheric Ion Composition Experiment (Cammice) instrument on board the Polar satellite [Wilken et al., 1992] at $\sim 8.5 R_E$ at ~ 2.8 magnetic latitude at 22.8 MLT on 21 October 2000. The AL index ranges -57 and -34 nT, the Kp index was 1+, and the Dst index ranges -1 and 1 nT, that is, the spectrum was obtained in the magnetically quiet time. Even though the magnetospheric activities were quite low, the oxygen ions certainly existed within the energy range between 1 and 100 keV near $P_{8.5}$. The oxygen ions may be a remnant of previous substorm activities, or continuously supplied ones from the ionosphere, but we cannot distinguish them.

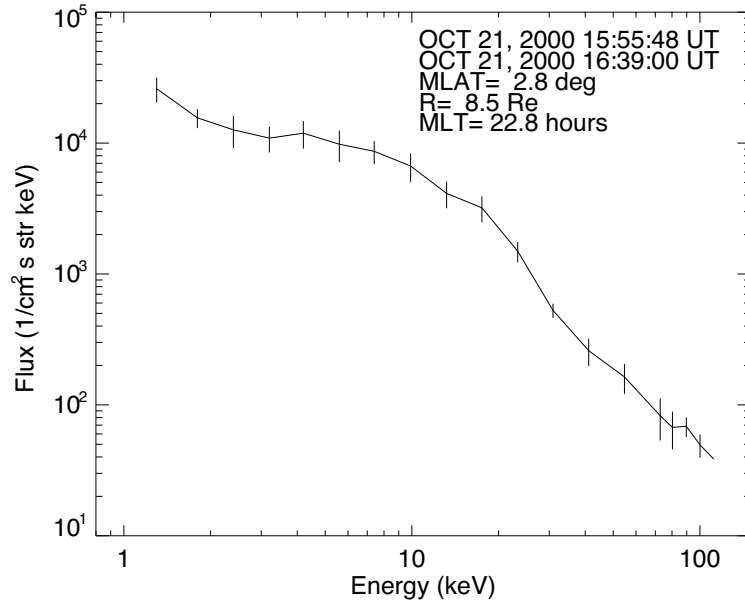


Figure 6.4: An example of differential number flux of oxygen ions observed by Polar satellite at $\sim 8.5 R_E$ near the equatorial plane near midnight on 21 October 2000.

6.3.2 Simulation result

Figure 6.5 shows the maximum energy gain (ΔK) of the traced O^+ ions in 10 min as a function of initial velocity (energy and polar angle) for the three initial locations at $P_{5.5}$, $P_{7.0}$ and $P_{8.5}$ (columns) and three starting times at $T = 44, 48$, and 52 min (rows). The O^+ ions that started at $P_{5.5}$ and at $T = 44$ min gain kinetic energy almost equally regardless of initial velocity. ΔK is about 10 keV on average as they undergo bounce motion and drift motion. For the ions started at the same position at $T = 48$ min and 52 min, the ΔK increases with the initial energy. Under the adiabatic acceleration, the higher energy ions can gain higher energy. The ΔK reaches ~ 25 keV for the simulation run. For all cases at $P_{5.5}$, ΔK is almost zero at the polar angle θ ranging between $\sim -60^\circ$ and $\sim 60^\circ$ and between $\sim 120^\circ$ and $\sim 60^\circ$. The ions were in the loss cone at the start position, and therefore, they reached the inner boundary of $4 R_E$ immediately if they did not experience the pitch angle scattering triggered by the non-adiabatic acceleration. For the ions started at $P_{7.0}$, ΔK is larger when they departed later. ΔK reaches as high as ~ 50 , ~ 80 , and ~ 100 keV for start time at 44, 48, and 52 min, respectively. For the ions started at $P_{8.5}$ (where the magnetic field directs toward the azimuthal direction), they gain kinetic energy effectively in comparison with those started at the other two positions. In particular, the ions that started at 48 min with θ ranging between $\sim -100^\circ$ and $\sim -60^\circ$ (mostly downward) are highly accelerated and the maximum ΔK reaches 201 keV. The

white line in Figure 6.5(f) denotes the direction of magnetic field projected onto the Y - Z plane, indicating that, in general, almost field-aligned ions are highly accelerated.

Figure 6.6 shows a histogram of the maximum energy gain ΔK for three starting points at elapsed time of 10 min. When the ions started at $P_{5.5}$, they gain the kinetic energy as high as about 20 keV in 10 min. When they started at $P_{7.0}$, they gain the kinetic energy as high as about 50 keV, 70 keV and 100 keV, respectively, for the starting time of 44, 48, and 52 min. When they started at $P_{8.5}$, ΔK reaches 190 keV, 201 keV and 110 keV for the starting time of 44, 48, and 52 min, respectively. At a glance, the maximum ΔK increases and the spectrum becomes "Hard" with increasing the radial distance from the Earth.

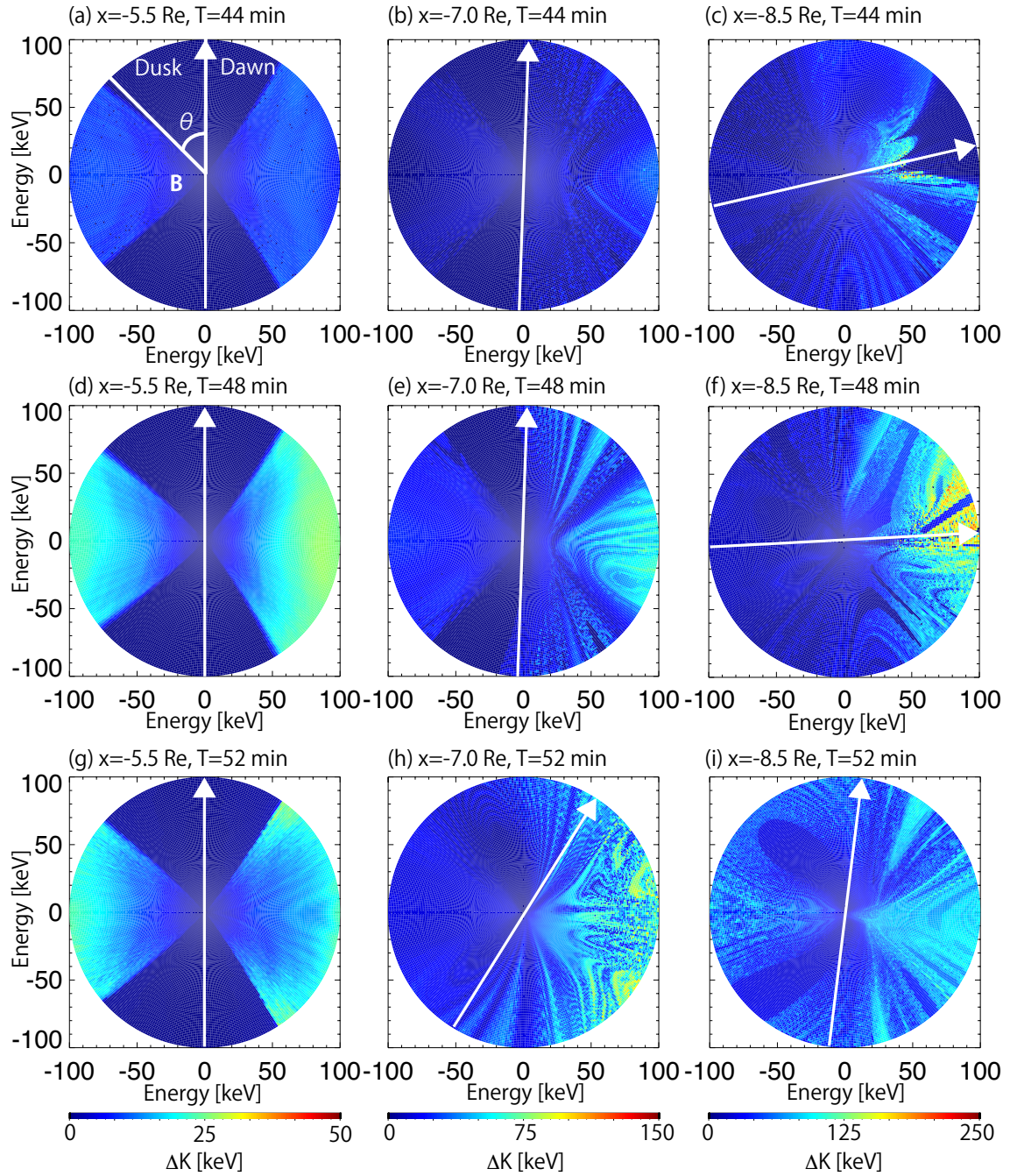


Figure 6.5: (a-i) Maximum energy gain in 10 min of O^+ ions as a function of initial velocity for the three initial locations (columns) and three starting times (lines). The radial distance from the center point indicates their initial energy. White lines indicate the direction of magnetic field line projected to Y-Z plane at the start position.

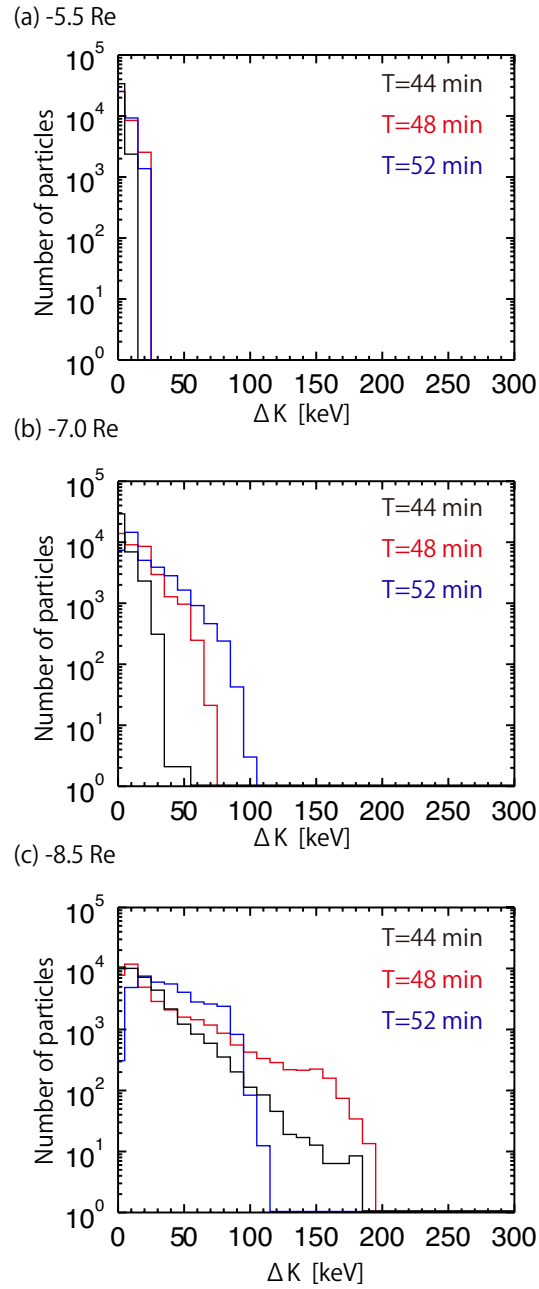


Figure 6.6: A histogram of the maximum energy gain ΔK for three starting points. The black, red, and blue color lines indicate the initial time at 44, 48, and 52 min, respectively.

Figure 6.7 shows the number of oxygen ions as a function of maximum energy (in 10 min) and initial energy of the oxygen ions that started at $P_{8.5}$ at $T = 48$ min. At a glance, the oxygen ions appear to be well "Heated". For example, some oxygen ions with initial energy of 10 keV are accelerated to 60 keV (ΔK of 50 keV), and some of them with initial energy of 85 keV are accelerated to 286 keV (ΔK of 201 keV).

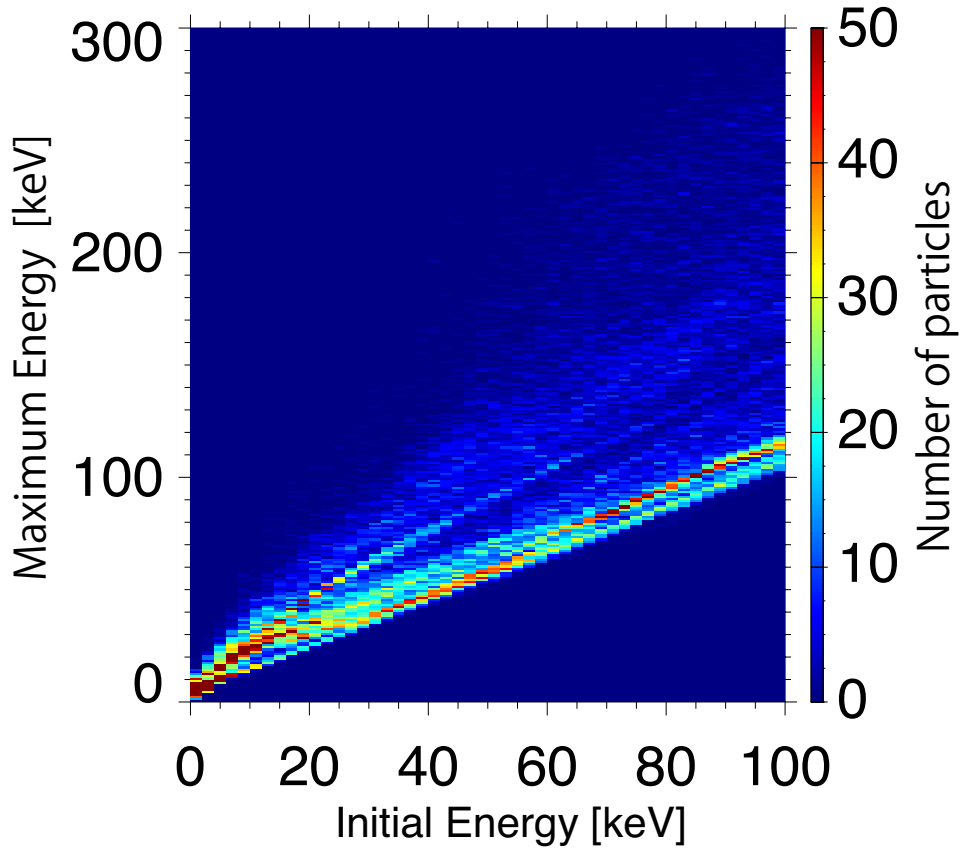


Figure 6.7: The number of oxygen ions as a function of maximum energy (in 10 min) and initial energy of the oxygen ions that started at $P_{8.5}$ at $T = 48$ min.

As demonstrated in Figure 6.5, the ions that started at $P_{8.5}$ at $T = 48$ min with θ ranging between $\sim -100^\circ$ and $\sim -60^\circ$ (mostly downward) gain the highest energy (ΔK of 201 keV) in the all ions that we traced. Here, we focus on one of the ions with initial kinetic energy of 85 keV, and θ of -86° (the pitch angle of 26°) to understand the acceleration process of the ion that gains the highest energy in this simulation.

Figure 6.8(a) shows the trajectory of this ion with color code indicating instantaneous kinetic energy. The trajectory is totally different from cyclotron motion. The kinetic energy is not increased immediately after the launch. Figures 6.8(b) shows the kinetic energy as a function of elapsed time. The kinetic energy shows a two-step increase. At

first, the kinetic energy increases from ~ 85 keV to ~ 125 keV during the period from 70 to 120 sec. After a while, it increases from ~ 100 keV to ~ 265 keV during the period from 170 to 250 sec. Figure 6.8(c) shows the magnetic moment of the ion, indicating that the magnetic moment is highly variable during the entire period. This means that the first adiabatic invariant is not conserved. Figure 6.8(d) shows the trajectory projected onto the x-y plane with the color code indicating the value of μ . The yellow-to-red (bluish) color means positive (negative) value of it. The black line indicates the magnetic field line passing through $P_{8.5}$ at 48 min. As shown in Figures 6.8(a) and 6.8(d), the magnetic field line is kinked at $X = \sim -7.5$ and $Y = \sim 3 R_E$ as pointed by arrows. This field line lies almost on the equatorial plane in between the kinks, and connects with the Earth, that is, a closed field line. Just after the launch of the ion at $P_{8.5}$ at $T = 48$ min (elapsed time of 0), the ion proceeds dawnward because the initial velocity looks almost dawnward. After a while, the ion seems to be deflected anti-sunward near the kink of the magnetic field line ($X = \sim -7.5$ and $Y = \sim 3 R_E$). The deflection may occur because of the short curvature radius of the magnetic field line. After the deflection, the ion starts to move duskward at the elapsed time of ~ 70 sec ($T = \sim 49$ min), and reached near $P_{8.5}$. In the course of duskward movement, the kinetic energy increased from ~ 85 keV to ~ 125 keV because of the presence of the dawn-dusk electric field. Again, the ion starts to go around at $T = 50$ min, and gains the kinetic energy of ~ 165 keV in the course of the duskward movement. The electric field during the second go-around is larger than that during the first one because of the significant force imbalance during the substorm expansion [Ebihara and Tanaka, 2013].

In order to demonstrate the role of the kink in the acceleration, we first divided the particles launched at $P_{8.5}$ and at $T = 48$ min into two groups. One group (5.10% of total) includes the particles passing through a sphere of radius $1 R_E$ from the center of the kink that is located at $(7.2, 3.3, 0.56) R_E$. The radius of $1 R_E$ corresponds to the gyro radius of the O^+ ion with energy of 38 keV. 18.2% of them were accelerated more than 150 keV within 10 minutes. The other group (94.9% of total) includes the particles not passing through the sphere. Only 0.40% of them were accelerated more than 150 keV. This feature is summarized in Figure 6.9, which may have the following implication: The acceleration process (passing through or near the kink and energization by cross-tail electric field) is not common. However, most of the particles that are accelerated more than 150 keV passed through or near the kink.

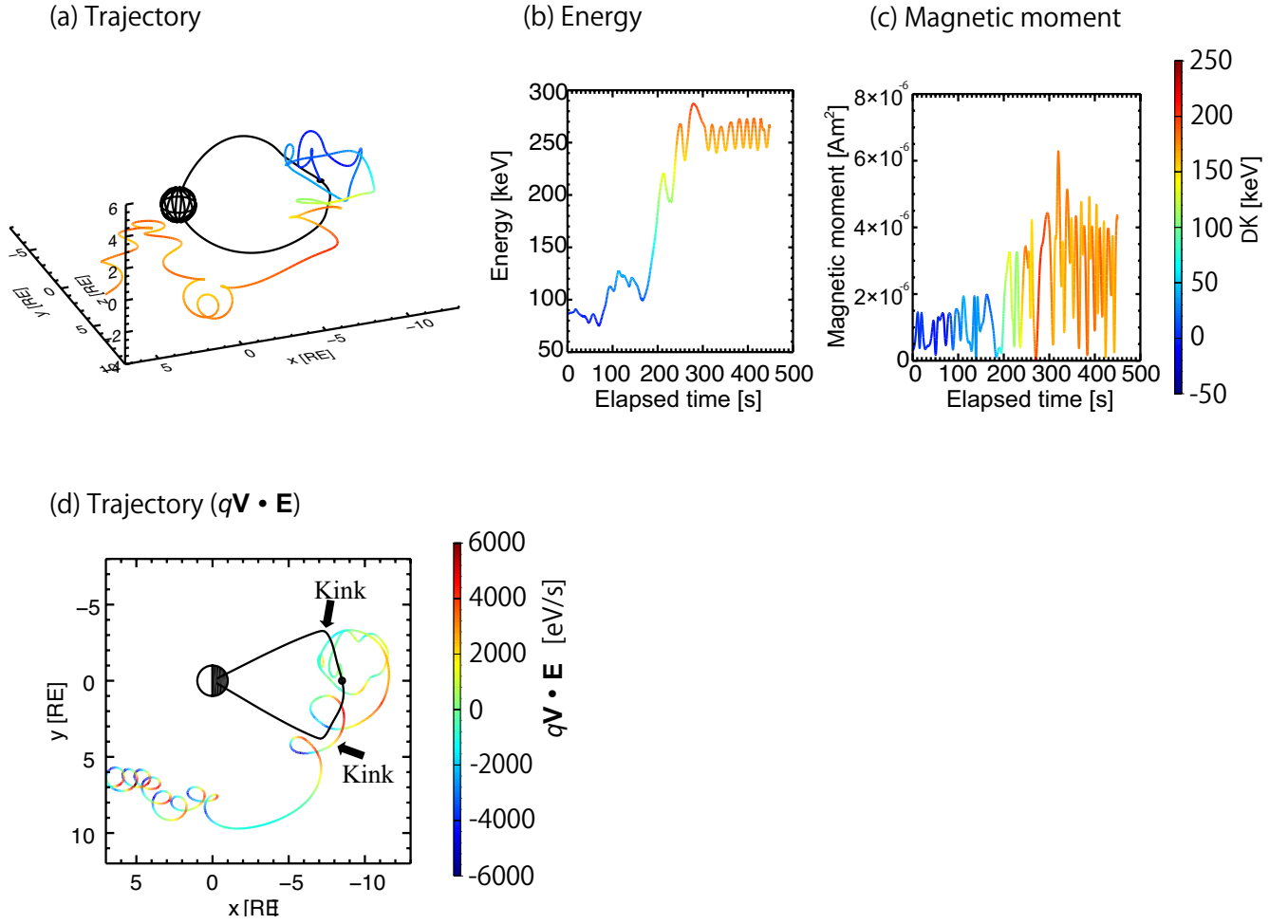


Figure 6.8: (a) The trajectory of the ion initial kinetic energy of 85 keV, initial θ of -86° , and initial pitch angle of 26° with the color code indicating instantaneous kinetic energy. (b) The kinetic energy as a function of elapsed time and (c) the magnetic moment of the ion. (d) The trajectory projected to the X - Y plane with the color code indicating the value of $q\mathbf{V} \cdot \mathbf{E}$.

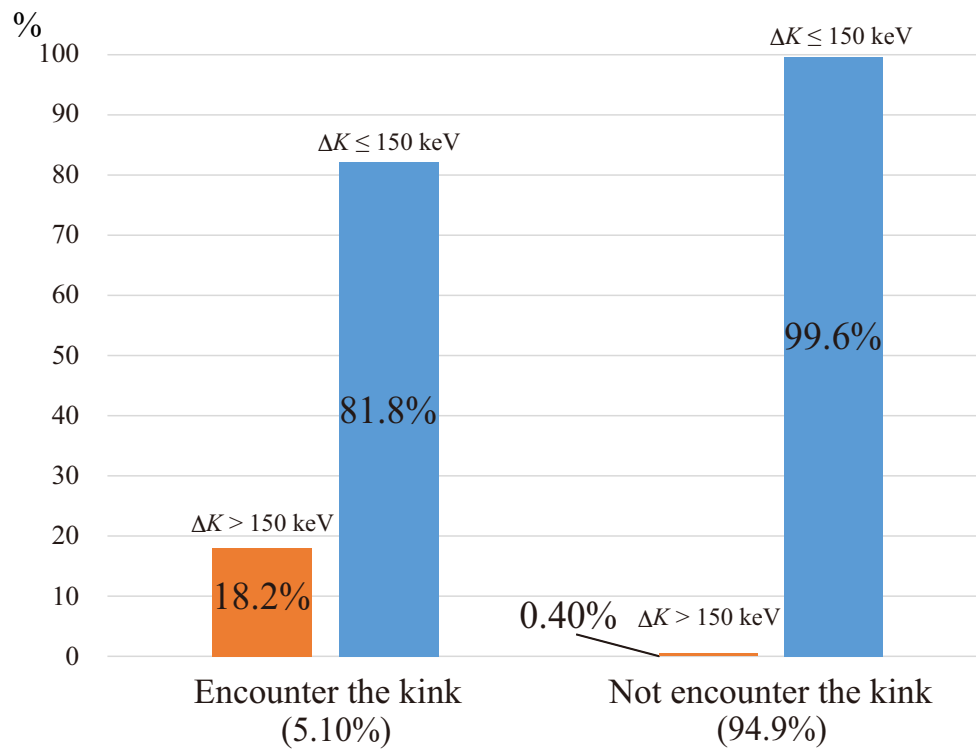


Figure 6.9: A bar graph showing the percentage of the ions being accelerated > 150 keV (orange color) and ≤ 150 keV (blue color). The left (right) bars are for the ions that pass (do not pass) through or near the kink of magnetic field line.

6.4 Discussion

The O^+ ions gain kinetic energy as they go around in the near-Earth plasma sheet twice (Figure 6.8(d)). The trajectory is, in part, similar to that demonstrated by Kim et al. [2000] who have shown that some of energetic electrons encircle a local maximum in the equatorial magnetic field strength and gain the kinetic energy of ~ 200 keV in the MHD simulation of substorm dipolarization. This acceleration process is different from that we have shown here because, in our case, the acceleration is essentially non-adiabatic, and the circular motion results from non-adiabatic motion together with the azimuthally elongated field line. Our test particle simulations have shown that the accelerated ions (larger than 100 keV) move duskward in the near-Earth plasma sheet and encounter the magnetopause. Therefore, it is still unclear whether the O^+ ions with high energy contribute to the enhancement of the energy density of ring current or not. The test particle simulations in the global MHD simulation with high solar wind speed and largely negative B_z of IMF are currently performing to understand the overall acceleration of O^+ ions in the course of the state transition of the magnetosphere and to understand the enhancement of the energy density of the ring current as observed by Krimigis et al. [1985], Hamilton et al. [1988], and Daglis et al. [1993].

6.5 Conclusion

The global MHD simulation shows that a flux rope structure appears in the near-Earth plasma sheet for about 10 min before the onset (Figure 6.3(a)). The efficiency of the acceleration depends on the departure time. We have shown that when the O^+ ions depart earlier ($T = 44$ min), the ions with high energy (> 50 keV) encounter the duskside magnetopause before being accelerated efficiently (Figure 6.5(c)). On the other hand, when O^+ ions depart in the flux rope structure a few minutes before the onset ($T = 48$ min), they go around the near-Earth plasma sheet and some of them gain the kinetic energy more than 200 keV. The go-around motion may result from the non-adiabatic motion together with the geometry of the magnetic field line having a kink. The acceleration process (passing through or near the kink and energization by dawn-dusk electric field) is not common. However, most of the particles that are accelerated more than 150 keV passed through or near the kink.

Chapter 7

Concluding Remarks

7.1 Summary and Conclusion

We have investigated the O^+ acceleration and transport processes in the magnetosphere with the aim of understanding general features of O^+ ion during the substorm. Although many studies have been conducted, a "big picture" of enhancements of energetic O^+ ion during the substorm is still unclear. In particular, fundamental issues of how the ionospheric O^+ is energized from around a few eVs to hundreds of keV and how these accelerations are connected to magnetospheric dynamics remain to be unsolved. In the present thesis, we have performed numerical studies to simulate global reconfigurations of magnetosphere during the substorm and spatiotemporal variations of distribution function and flux of O^+ ion. The simulation results have shown fairly good agreements with in-situ observations. Major acceleration processes have been studied comprehensively by using the simulation results in Chapters 3, 4, 5, and 6.

In Chapter 1, the overview of the space plasma environment in the geospace has been explained. We have also discussed previous studies of O^+ ion in the magnetosphere in terms of reactions to geomagnetic activities.

In Chapter 2, the numerical techniques of the global MHD simulation and test particle simulation have been explained. We have shown the basic equations, grid system and magnetosphere-ionosphere coupling model utilized in the global MHD simulation, and the method of particle tracings.

In Chapter 3, the non-adiabatic acceleration due to the nightside reconnection which is known as the most dynamic phenomenon during the substorm has been focused. A detailed description of the build-up of strong dawn-dusk electric fields as well as of the prominent energization of heavy ions during substorms are provided in this chapter. We

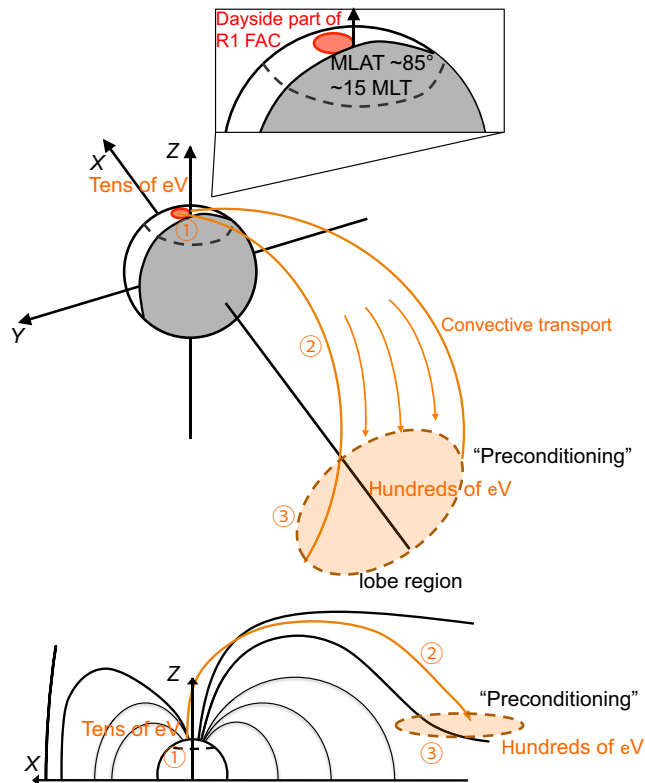
revealed that the dawn to dusk electric field is generated by a joint action of the fast earthward flow V_x and magnetic flux pile-up. The fast earthward flow and the magnetic flux pile-up contribute the dawn to dusk electric field in the inner region and outer region, respectively. Due to the intensive dawn to dusk electric field, the O^+ ions are non-adiabatically accelerated to tens of keV and transported to the ring current region. Especially, the dawn to dusk electric field in the inner region is important to energized up the O^+ ions to more than 100 keV range. In the inner magnetosphere, our simulation successfully reproduced a realistic flux enhancement of the O^+ ion.

In Chapter 4, a new type of energy dispersion of O^+ flux named void structure is firstly reported. We have analyzed general features of the void structure using 9 events observed by the Van Allen Probes HOPE observation. From the event study, it has been indicated that the void structure has a good correlation with substorm onsets. Our simulation has reproduced a structure that is well consistent with the void structure observed by the Van Allen Probes. We have revealed that the generation mechanisms of the void structure consist of the formation of the strong equatorward flow in the low pressure region and tailward flow in the high pressure region and the intense non-adiabatic acceleration of O^+ ions.

In Chapter 5, the substorm-time outflow of O^+ ion and its impact on the ring current enhancement have been investigated. We have calculated the variations of O^+ outflow by the same manner introduced by Fok et al. [2006], but with more realistic ionospheric currents. From the global simulation, we have revealed following processes. During the substorm growth phase, the region 1 and 2 current systems are enhanced in the ionosphere, and in particular, the ionospheric O^+ ions are thermalized to tens of eV in the dayside polar region due to the midday part of region 1 FAC. This results in a preconditioning state that warm O^+ ions (tens to a few hundreds of eV) are rich in the lobe region. Just after the substorm onset, the warm O^+ ions flow into the nightside equatorial region, then they are injected into the inner magnetosphere with the nonadiabatic acceleration as shown in Chapter 3, developing the most part ($> \sim 95\%$) of the O^+ ring current. At the same time, the initial brightening occurs in the midnight aurora region, then upto a few keV O^+ ions are extracted and directly supplied to the inner magnetosphere, developing a fraction ($\sim$ a few %) of the O^+ ring current.

In Chapter 6, a local acceleration on the azimuthally directed magnetic field lines emerging during substorm has been focused. The configuration have been reported from the result of the global MHD simulation [Saita et al., 2010]. We have released O^+ ions

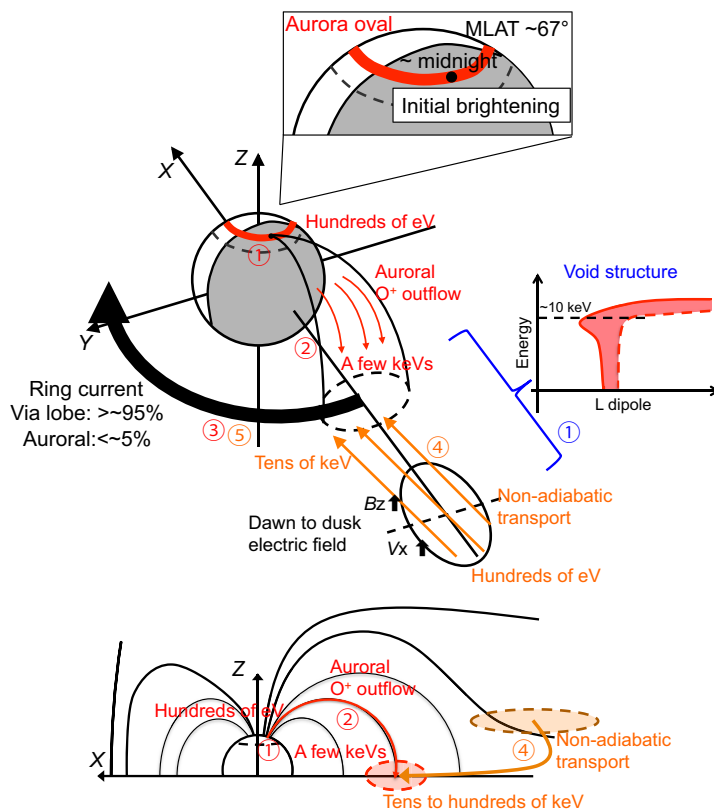
Substorm growth phase



Substorm growth phase

- ① Extraction of O+ at tens of eV due to the enhancement region 1 FAC
- ② Convective transport to the lobe region
- ③ Enhancement of O+ at hundreds of eV : "Preconditioning"

After substorm onset



After substorm onset

- ④ Non-adiabatic transport to the inner magnetosphere (tens to hundreds keV)
- ⑤ Significantly contributes the O⁺ ring current

After substorm onset

- ① Extraction of auroral O+ at hundreds eV
- ② Direct supply to the inner magnetosphere (a few keVs)
- ③ Slightly contributes the O+ ring current

After substorm onset

- ① Development of the void structure

Figure 7.1: Schematical illustration of the substorm-time O^+ acceleration and transport processes revealed by the present study.

on the azimuthally directed magnetic field lines and investigated the energy increases. Our test particle simulation result has shown that O^+ passing through the kinks of the magnetic field lines are effectively accelerated to a few hundreds keV. The percentage of the O^+ ions is small ($\sim 5\%$) that the acceleration will not have a large impact on the total O^+ ring current, though it can slightly modulate distribution function.

The present thesis addresses important issues and contributes to understand the big picture of the O^+ ion energization during substorms. Global paths of O^+ ions from the ionosphere to the inner magnetosphere have been tracked, and the realistic spatiotemporal flux has been reproduced by the large-scale computer simulations. Main results of the present study are schematically summarized in Figure 7.1. During the growth phase of the substorm, the large scale region 1 FAC results in the extraction of warm O^+ ions from the dayside polar region (number 1 in orange color). The O^+ ions transported to the lobe region with the adiabatic heating due to the convection electric field (number 2 in orange color). The warm (hundreds of eV) O^+ ions are directed to the acceleration region in near-earth plasma sheet via the lobe region which is work as the "preconditioning" (number 3 in orange color). After the onset substorm expansion phase, the rich and warm O^+ ions are rapidly (within minutes) energized up to $\sim$ tens of keV under the effect of the large dawn-to-dusk electric field (number 4 in orange color). This acceleration that occurs in the non-adiabatic manner, leading to the formation of the void structure in energy-L spectrograms (number 1 in blue color). This is consistent with in-situ observations. The energetic O^+ ions via lobe significantly contribute to the O^+ ring current build up. At the same time, the auroral acceleration process thermalizes the ionospheric O^+ ions to hundreds of eV (number 1 in red color). Consequently, they are supplied to the inner magnetosphere and contributes to a fraction of the O^+ ring current (number 2 and 3 in red color). From the results, we have concluded that a combination between the pre-conditioning of the warm O^+ ion (hundreds of eV) in the lobe due to the enhancement of the midday part of the region 1 FAC and the non-adiabatic acceleration in the near-earth plasmasheet is the dominant energization process for the ring current O^+ ion during the substorm.

7.2 Suggestions for Future Studies

For the future investigations on the energetic O^+ environment in the inner magnetosphere, some improvements are needed. A connection between the substorm-time im-

pulsive transport due to the local and intensive electric field and storm-time gradual transport due to the global and long-lasting convective electric field is still unclear. Connection between the substorm-time scale simulation developed by the present study and 4-D kinetic simulations [e.g., Fok et al., 2006; Ebihara et al., 2006] may provide clearer perspectives with the ring current study. In addition, a two way coupling (ring current-ionospheric coupling) model on storm and substorm time scale leads to further understanding of the O^+ energization. The enhanced ring current causes a perturbation of earth's magnetic field (magnetic storm) and magnetospheric reconfigurations. However, the magnetospheric disturbances may also cause additional O^+ preconditionings. For example, the enhanced partial ring current results in the ionospheric current across the aurora and sub-aurora region, which may leads more O^+ rich states. A good correlation with the O^+ enhancement and magnetic storm strength suggests that the feed back process is more significant for O^+ ion.

Collaboration of Van Allen Probes and ERG missions may contribute to the O^+ ion study. The orbit of the ERG satellite is scheduled to outward of that of Van Allen Probes. This is suitable for investigating spatiotemporal evolutions of the flux in the near-Earth plasma sheet and it will provide fundamental properties of the impulsive radial transport during substorms.

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Publication List

Major Publications

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2. Nakayama, Y., Y. Ebihara, and T. Tanaka (2015), Generation of large-amplitude electric field and subsequent enhancement of O^+ ion flux in the inner magnetosphere during substorms, *J. Geophys. Res. Space Physics*, 120, doi:10.1002/2015JA021240.
3. Nakayama, Y., Y. Ebihara, S. Ohtani, M. Gkioulidou, K. Takahashi, L. M. Kistler, and T. Tanaka (2016), Void structure of O^+ ions in the inner magnetosphere observed by the Van Allen Probes, *J. Geophys. Res. Space Physics*, 121, doi:10.1002/2016JA023013.
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Appendix A

Programing Techniques for the Test Particle Simulation

Search Algorithm for the unstructured grid system

In the present study, we trace trajectories of the test particles using the electromagnetic data on the unstructured grids. For the simulation code, a search algorithm to identify the grid number of the test particles is significant for reducing the calculation cost. The most simple search algorithm is the full-search algorithm. However, for the 3-dimensional grid system (200×160×320 grids for level 6), the full-search algorithm increases the calculation time. In the present study, another approach have been adopted to improve the calculation speed. Figure A.1 shows the grid points with one test particle. Because the grid system is based on the radial stacking of the spheres covered by triangles as stated in Chapter 2, the grid system consists of triangular prisms. With a consideration that the spheres are covered by small triangles, we can assume that the grid consists of $P_1(nx, ny, nz)$, $P_2(nx+1, ny, nz)$, $P_3(nx+1, ny+1, nz)$, $P_4(nx, ny+1, nz)$, $P_5(nx, ny, nz+1)$, $P_6(nx+1, ny, nz+1)$, $P_7(nx+1, ny+1, nz+1)$ and $P_8(nx, ny+1, nz+1)$ is a parallelepiped. We develop a simulation code which detects transfers of the test particles between the parallelepipeds. Only at the initiation of the test particle simulation, the full-search algorithm is utilized to identify the grid numbers of the particles. During the particle tracking, we determine whether the particle exits the grid calculating the following equation for the 6 surfaces of the parallelepiped

$$\mathbf{V}_1 = [(\mathbf{P}_2 - \mathbf{P}_1) \times (\mathbf{P}_3 - \mathbf{P}_1)] \cdot (\mathbf{P}_4 - \mathbf{P}_1). \quad (\text{A.1})$$

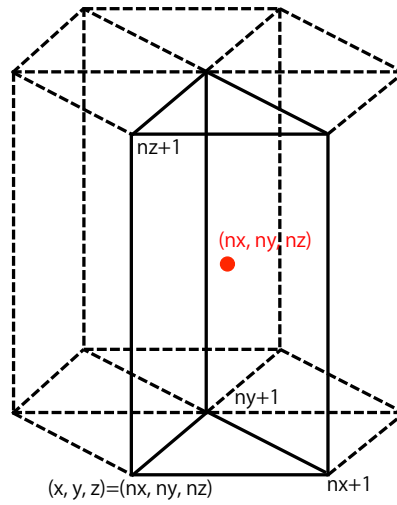


Figure A.1: Schematic illustration of the unstructured grid points. Red sphere shows a particle position.

Referring the signs of the $\mathbf{V}_{1-8}$, we can determine whether the particle exists inside the parallelepiped or not. In addition, even in the case the particle exits the grid, we can assume which parallelepipeds adjoining the previous parallelepiped the particle enters.

In order to improve the calculation speed, the sorting technique is also utilized for the n_z (radial direction) in the present study. We adopt the merge sort algorithm which requires $O(N \log N)$ calculation. By the sorting, CPU can access the field data almost continuously.

Load Balancing Technique

In the present study, the test particle simulation code is parallelized by using MPI. Not like the Particle In Cell (PIC) simulation, the test particle simulation is runnable without the interprocessor communication. The each processor traces the test particles until the finish time of the simulation domain, independently. Because time steps of tracing depends on the energy of the particles and strength of the magnetic field (for cyclotron motion), the loads become different between the processors. Therefore, the load balancing is a very important technique to optimize the calculation. In the present study, we have develop a load balancing technique using the asynchronous communication. We set one master processor which does not trace particles but manages loads of the other processors. Slave processors trace particles and send a message if they finish the test particle simulation for given test particles with the asynchronous communication. The

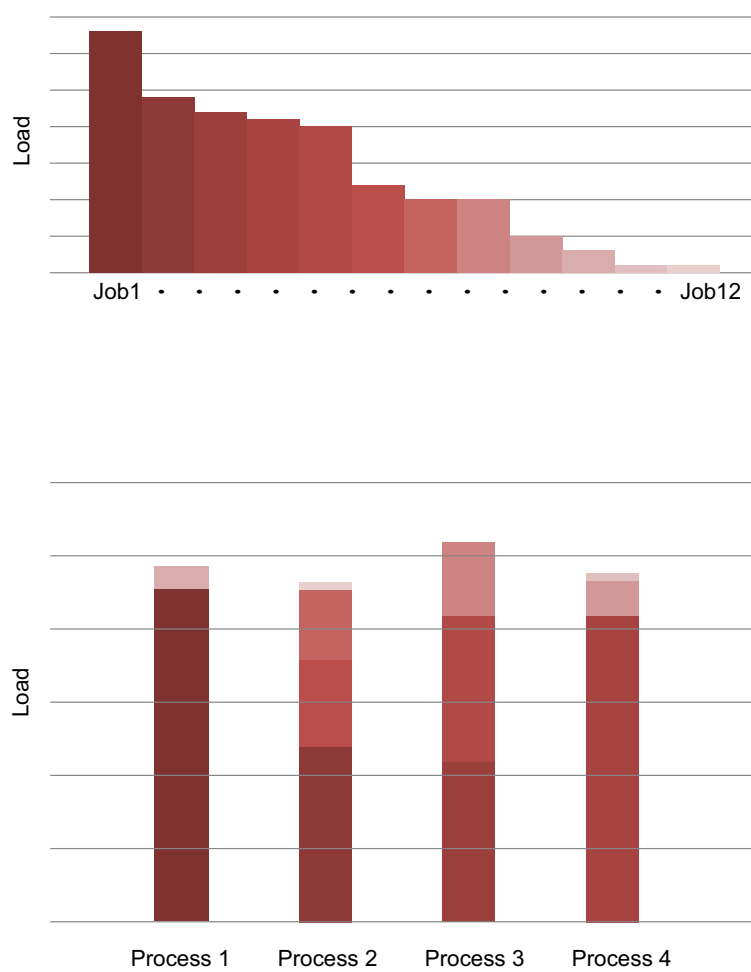


Figure A.2: Schematic illustration of the load balancing technique.

master slave detects the message and gives a new job to the slave processor dynamically. The load balance is achieved with the job load reducing gradually. A example of this load balancing technique is schematically shown in Figure A.2.

12 jobs with different load are assumed as shown in Figure A.2(a). These jobs are sequentially given to 4 processors in the order of magnitude of the loads. The 4 processors finish the calculation almost at the same time as shown in Figure A.2(b). For test particle simulations, to give jobs to processors in the order of their initial time is the most simple code. Another approach is to assume the magnitude of loads referring their initial positions.