Non-adiabatic features in magnetotail fast flows: Orbit tracing and data comparisons

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NON-ADIABATIC FEATURES IN MAGNETOTAIL FAST FLOWS:
ORBIT TRACING AND DATA COMPARISONS

BY

BRYAN MICHAEL BALL
B.S. Physics, University of New Hampshire, 1993

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirement for the Degree of

Doctor of Philosophy
in
Physics

September, 2001
This dissertation has been examined and approved.

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July 20, 2001
Date
This dissertation is dedicated to my entire family
My Mom
My Dad
My Grandmother
My sister Berdine
My brother Blaine
My nieces and nephews, Andy, Adam, Jessica, Kaiya,
Jeremy and Michael
Also Loretta and Ray,
and everyone else, cousins, aunts, uncles, etc.
for being supportive over the years.
ACKNOWLEDGEMENTS

Since I have already thanked my family in the dedication, I will concentrate on all those people at UNH that have been so helpful over the years. First I would like to thank my advisor Richard L. Kaufmann for his immense patience with what must be an amazingly frustrating job: trying to train someone to think. I hope I got it.

I would also like to thank my committee, Roger Arnoldy, Terry Forbes, Dawn Meredith and James Ryan. This thesis has benefited from their attention and time.

There are so many people that I have known here, I will never be able to thank them all. Here goes a good try. First, to Doug and Ioannis, two parts of the three magi (at least that's what the Greek priest said)! Doug has spent years developing the code that was used in the orbit tracing section here and this should not be overlooked, as well as being my partner in dueling Ross Perots for so long. Huge thanks go to Ioannis for introducing me to the Acropolis!

Special thanks also go out to the two people who had the (mis?)fortune of being my roommates for most of my graduate career, Mike and Korac. Good times, good times. Let's not forget the rest of the usual movie crowd suspects, Ben, Dean, Scott and all the others. Also, a huge steaming load of thanks to Trudy, Carrie, Alan and Maggie, the party quartet that helped to make my graduation day so incredible.

Finally, the groups! All the softball people. Also, the old Wednesday night poker crowd. And the Sunday/Friday night D&D crowd. Och, and the Highland Games! Too many I have to leave out, but you aren't forgotten.
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ABSTRACT

NON-ADIABATIC FEATURES IN MAGNETOTAIL FAST FLOWS: ORBIT TRACING AND DATA COMPARISONS

by

Bryan Michael Ball

University of New Hampshire, September, 2001

The purpose of this study is to investigate velocity space distribution functions in space plasmas. Orbit tracing methods are used to generate self-consistent models of several different magnetic and electric field configurations. Fast flows in the magnetotail are selected to be modeled using a relatively thin current sheet compared with quiet times. Four different electric fields are imposed, varying in characteristic thickness and magnitude. Using these four particle based models we were able to generate velocity distribution functions that show clear evidence of non-adiabatic features that depend on the electric field characteristic width. Several years of Geotail Comprehensive Plasma Instrumentation (CPI) data were subsequently examined to find data sets for comparison. Four events out of more than twenty are chosen for closer comparison. It is shown that the modeled distributions are very similar to the spacecraft data. Non-adiabatic orbits can be interpreted as the cause of these features, and an understanding of how they interact with the local electric fields is reached.

Research Advisor: Professor Richard L. Kaufmann
CHAPTER I

BACKGROUND

The intent of this thesis is to use particle orbit tracing techniques to create and then analyze velocity space distribution structures that are measured in the Earth’s magnetosphere. These created models will then be compared with spacecraft data. Electrons and ions can behave differently in the magnetosphere. Electrons in this region have low energies and generally follow helical orbits about the magnetic field lines. Ions have higher energies, momenta and larger radii of curvature that are often larger than the characteristic scale size of the field gradients in the local magnetic field. The orbits the ions follow in such configurations are known as non-adiabatic. One way to study these orbits is to examine plasma distribution functions. In regions where non-adiabatic effects can occur, there are certain orbit types that contribute clear features in these distribution functions. It is the focus of this work to try to model some important magnetotail structures on a computer, and subsequently identify them in spacecraft data. It is important to choose structures that have a good probability of showing distinctive features. Normally the magnetotail is much thicker than the region containing non-adiabatic orbits, and any features present would be subtle and difficult to see. We need to pick events that are more apt to show distinctive features.
Regions containing rapidly flowing plasma have been selected as good candidates for study. There are several reasons to choose fast flows. First, they commonly form during the expansion phase of a substorm, which closely follows a period of current sheet thinning in the growth phase. As we will see later in this introduction, these thin current sheet configurations have a good chance of exhibiting non-adiabatic effects. Fast flows are also obvious in the data, making them good candidates for analysis. There are two general ways to model a region containing fast flows. The perpendicular bulk flow of a plasma with an electric field present can be shown to first order in MKS units to be
\[ v_E = E \times B / B^2 \] [Northrop, 1963]. This velocity can be made to be arbitrarily large in two ways: 1) if \( E \) gets large, or 2), if \( B \) gets small, such that \(|E|/|B|\) is large.

There are two obvious reasons to perform this study. First, a knowledge of the current carriers in the magnetosphere is important to predict its behavior. The individual orbit trajectories that create this current are the primary building blocks of the entire magnetospheric current system, and an understanding of how they behave in every situation can only advance our knowledge of the magnetosphere. Another reason to do this study is based on the fact that orbit trajectories necessarily incorporate information about non-local field configurations. The hope here is that we can reach an understanding about the way electromagnetic field configurations and ion particle orbits combine so that analyzing a distribution function at one point can give us information about the magnetosphere over a larger region. We can reasonably expect to be able to draw conclusions about spatial regions that are on the order of the typical Larmor radii of the local ion populations.

This project addresses the large electric field case of fast flows. The enhanced dawn-dusk electric field is broken into three main models, with three different electric
fields of varying width. The details of this model will be left to Chapter 2. The minimized magnetic field configuration can be modeled with an X-line magnetic field, which contains a null point where the magnetic field magnitude goes to zero. An example of a magnetic field of this type appears in Appendix B.

Chapter 1 is this background chapter. Chapters 2 and 3 are linked. They will explore in detail the enhanced electric field model and then compare this model with Geotail Comprehensive Plasma Instrumentation (CPI) data, respectively. Chapter 4 is a summary and discussion of the models and data, paying particular attention to the distribution functions. Appendix A provides a brief description of the code used to search through the Geotail data, as well as detailed descriptions of the search parameters and initial results of the data search. Appendix B will show an X-line field that was derived using the same techniques outlined in Chapter 2.

The remainder of this chapter explores the magnetosphere and the important physics associated with it. We need to first understand the work that has been done before we can put this project in context. First we will outline the basics of the Earth's immediate space environment, not only the quiet time configuration but also the dynamical evolution of a substorm. Thin current sheets, fast flows and X-lines in particular will be discussed. Next, the basic equations of plasma physics will be summarized. Emphasis will be placed on the regimes in which they are most and least useful. In particular, adiabatic and non-adiabatic orbits will be outlined. One major key to this thesis are the characteristics of these two regimes of particle orbits, so it is important to understand how they differ. Plasma distribution functions will then be introduced. The plasma distribution function is a powerful concept in space physics, and from the title it is obvious that I will be placing a
great deal of emphasis on it in this work. Next, the Geotail satellite will be discussed, not only the instrument itself, but the yearly and spatial coverage that were available to us in this analysis. Finally, the Consistent Orbit Tracing (COT) model technique will be presented in detail, covering the history of its development, as well as its advantages and disadvantages in the present study. MKS units will be used exclusively throughout this dissertation.

1.1 What is a Plasma?

It is impossible to discuss the Earth's magnetosphere without first defining a plasma. A plasma is often referred to as the fourth state of matter, with the first three being the familiar solids, liquids and gasses. One common configuration is a gas of particles heated to such a degree that most of its atoms are ionized into positively charged ions and negatively charged electrons. Good examples of plasmas like this are fluorescent lights and neon signs. The charge of the system over a large scale is still zero, but on small scales there are often collective effects that may result in local enhancements of either positive or negative charge. The typical scale size for collective effects in a plasma is known as the Debye length. It is defined to be the distance past which a solitary particle's potential is shielded by the surrounding charged particles, or \( \lambda_D = \left( \frac{e^2 kT_e}{n_e^2} \right)^{1/2} \). Another parameter can be defined by the sphere with the Debye length as its radius, or the Debye sphere. If the number of particles contained within the Debye sphere is significantly larger than one, that we can assume that we have a well defined plasma. For the typical parameters in the region of space we are studying (\( kT_e \sim 1 \text{ keV}, \ n_e \sim 1/\text{cm}^3 \)) we have a typical Debye length of about 200 meters. Since particle densities in this region are 1/cm³, we
have many more particles in our Debye sphere than is needed to define a reasonable plasma.

The fact that there are now clouds of charged ions and electrons interacting with each other and with external magnetic and electric fields gives rise to physical effects that are not seen in other types of matter. Examples of many of these effects can be found in any basic plasma physics book, such as Chen [1984], or a more advanced book such as Ichimaru [1992].

In space, plasmas are everywhere, from the outer layers of the sun, to the solar wind that blows out past the planets, to the plasma that drifts in the Van Allen belts. In the area we will be studying, the magnetotail, plasmas are simple in composition, but complicated in behavior. In the current sheet, the plasma is almost completely made up of protons and electrons (although there are small amounts of some other ions, such as He** and O†). Typical densities of these components are roughly 1/cm³, with a temperature of approximately 5 keV for protons, which corresponds to about 32 million degrees Fahrenheit, or 2×10⁷ Kelvin. For comparison, a neon sign typically has a temperature in the range of 6000 °F, but since the gas density of 10¹²/cm³ is much lower than its surroundings the neon tube only seems warm to the touch due to thermodynamic heat capacity effects (for comparison a cubic centimeter of water at 1 atmosphere and room temperature has about 10²³ molecules).

1.2 Magnetosphere Configuration

The Earth's magnetic field is generated by electric currents that flow deep under the ground. This field, if left alone by outside influences, would be similar to the field of a simple dipole magnet. The solar wind that impinges on the dayside of the magnetosphere
distorts the magnetic field into a shape that is different from that of a simple dipole. In the front, or at local noon, the magnetosphere is compressed by the solar wind pressure, causing an increase in flux density on the dayside. Some of the flux from the front is diverted to the nightside through convection processes, and as we move away from the front and look towards the sides and back, we see that the field is stretched anti-sunward, forming a long magnetic tail. This tail can stretch out to 200 $R_E$ (1 Earth radii = 6371 km or 3957 miles) or more behind the Earth (for comparison the Moon is at roughly 60 $R_E$).

The plasma within the magnetosphere is not homogeneous. Roughly speaking, when the magnetic field character (i.e. curvature, magnitude or topology) changes drastically, so does the plasma population contained therein. The regions we are concerned with most in this work are the region in the center and just off-center of the middle magnetotail (~10 to 30 $R_E$ tailward of the Earth). In this region there is a great deal of complex activity, and the nature of the plasma contained there can teach us much about the magnetosphere. Before we focus on this select region, we will briefly summarize the sun-Earth system, starting with the solar wind.

The solar wind that emanates from the solar corona is a source of both energy and plasma for the magnetosphere. Its configuration when it interacts with the magnetosphere is an important influence on the magnetosphere’s subsequent evolution. The solar wind generally flows between 200 to 700 km/s, and consists primarily of protons and electrons. The existence of the solar wind is the primary reason that the Earth’s magnetosphere is not dipole shaped. This shape, as seen in Figure 1.1, is a sort of tapered cylinder, flattened on the dayside, with an exaggerated tail on the nightside. The solar wind pressure on the dayside causes the flattening and compression of the Earth’s magnetosphere, while conversely
the nightside magnetosphere is stretched out to great distances tailward. Typically the
dayside magnetopause boundary is at around $10 \, R_E$ while the nightside tail can stretch out
to $200 \, R_E$ or more. The distance of this dayside boundary is directly related to the
dynamic pressure of the solar wind through pressure balance requirements with the mag­
etosphere, and can and does change periodically. For example, there was a unusual event
around May 11 and 12, 1999. At this time, there was a massive depletion of particle flux
in the solar wind. The proton density dropped to around 3% of its average. Measurements
of the bow shock distance by the WIND and IMP 8 satellites showed that the bow shock
was at 57 to 63 $R_E$ from the dayside [Szabo, et. al., 1999], indicating an exaggerated
change from an average distance of 15 to 20 $R_E$.

Figure 1.1 shows a sketch of the magnetosphere with several important regions
labeled. The bow shock is the point at which the solar wind, which travels at a supersonic
velocity, slows abruptly when it nears the Earth's magnetic field, and forms a shock front
(a familiar shock is produced by a supersonic airplane, commonly known as a sonic
boom). Behind the bow shock is the magnetopause. This is the actual boundary of the
magnetosphere. The region between the bow shock and the magnetopause is known as the
magnetosheath. The magnetosheath is filled by solar wind plasma that has crossed the
bow shock, and in so doing been both slowed and heated by passing through the shock
front.

Within the magnetosphere, the most important region for our purposes is the
plasma sheet. This region usually coincides with the minimum $|B|$ region known as the
neutral sheet. This is where the current sheet flows. Plasma in this region usually has
Figure 1.1: Cartoon of the Earth's magnetosphere. Regions labeled are explained in further detail in the text.

Plasma densities around 0.1 to 1.0/cm³, and ion temperatures around 5 keV [Kivelson and Russell, 1995]. Plasma flows in this region are a combination of components that are both perpendicular and parallel to the local magnetic field. The perpendicular flows are what we are mostly concerned with here. They contribute most of the Earthward flow at the center of the current sheet. Other perpendicular components also self-consistently generate the current required to support the kinked magnetic field here. Kaufmann et al. [2001] have estimated the average currents based on long term averages of Geotail data. Typical current densities in the center of the average quiet time current sheet are about 3.5 nA/m² at midnight, decreasing as we move away from the center of the current sheet and out to the flanks.
As we move out of the plasma sheet, we encounter a boundary region known as the *plasma sheet boundary layer*, or PSBL. This is the boundary between the plasma sheet and the lobes. This region is typified by fast parallel flows, both Earthward and tailward, with magnitudes of hundreds of km/s. Densities here are usually around 0.1/cm³. Thermal energies are close to flow energies, meaning that if we have a flow speed of around 400 km/s we would also have a temperature of approximately 1 keV. Finally as we enter the area between the magnetopause and the PSBL, we enter the *lobe* region. The lobes are the areas where the field lines are most stretched, and the particle densities are generally less than 0.1/cm³. Another important difference between the plasma sheet and the lobes is whether the field lines are normally closed or open and therefore connected to the solar wind. A recent paper by Siscoe *et al.*, [2001] has drawn a clear dividing line between streamlines, or field lines, that originate at the *cusp* region near the Earth at the magnetic poles and field lines that are connected to the solar wind on open field lines. The conclusions reached here are that there is a clear boundary, dubbed the *fluopause*, that separates the solar wind connected field lines from those connected to the Earth at the cusp region. This seems to indicate that most lobe field lines are closed, and most of the field lines in the *mantle*, which is the region that defines the magnetopause plasma, are normally open.

The difference between open and closed field lines is best answered by briefly summarizing the process known as reconnection.

### 1.3 Reconnection and X-lines

Reconnection is a process whereby the frozen-in-flux conditions are violated, allowing plasma to diffuse across previously uncrossable flux tubes. The frozen-in-flux condition states that any amount of magnetic flux that is bounded by a volume of plasma
is a constant as that plasma volume moves and is deformed. Proofs of this theorem can be found in any standard text such as Kivelson and Russell [1995]. Reconnection can violate this requirement, allowing plasma from previously unconnected regions to mix freely. This topic is an active area of research, and far beyond the scope of this work. However, in order to understand some aspects relating to substorm processes it is necessary to present an abbreviated introduction. Several textbooks have been published recently on this topic, notably Priest and Forbes [2000].

One example of this phenomenon results in an X-line configuration, which is common in the dayside magnetosphere. Dungey [1961] first proposed the existence of a region where a dipole and external field meet that could give a null point. He also showed that dayside reconnection could account for the observed two-cell convection pattern in the ionosphere. When the solar wind IMF turns southward, the fields of the solar wind and the magnetosphere can form such a null point, known as an X-line, at the dayside magnetopause. When this happens, the result is field lines whose footpoints are on the Earth and whose endpoints are suspended somewhere in the solar wind. This phenomenon results in a diversion of flux from the dayside magnetosphere to the nightside lobes, as the dangling endpoint is dragged along with the rapidly tailward flowing solar wind. These dangling field lines are dragged in such a way that their footpoints on the Earth move in the familiar convection pattern mentioned above. In situ observations have been seen at the dayside of the magnetosphere [Sonnerup et al., 1981; Paschmann et al., 1986; Gosling et al., 1990a,b] that show clear evidence of this phenomenon. The subsequent diversion of flux causes energy to be stored in the lobes of the magnetotail if the field lines that reconnect on the dayside do not reconnect in the nightside tail region at the same rate.
With the increased flux density in the magnetotail lobes, we can get an increased magnetic pressure, which can have the effect of causing the current sheet to become thinner and more intense. A classic gedanken experiment provides some physical insight into one way this phenomenon could occur, though it likely has little to do with the actual current sheet. If we have a tail-like field, and we simply double the magnetic field intensity, two major effects will occur. First, the current sheet will become thinner due to the increased pressure from the magnetic field lobes pressing inwards against the particle pressure. If the particle pressure is to balance the increased magnetic field pressure, either there has to be a dramatic increase of particle numbers in a fixed volume, which is clearly unlikely, or we simply compress our plasma volume. Second, the current required to support that field doubles, as Ampere’s law implies a linear relationship between magnetic field intensity and current density. Thus we get a thin current sheet with enhanced current density.

Regardless of whether this simple mechanism can actually explain the real magnetotail, we will still be confronted with a magnetotail in a stressed configuration when the current sheet is much thinner than normal. This unbalanced magnetic energy density has to be dissipated if the magnetotail is to ever return to its normal, quiet-time, configuration. The main mechanism for this energy dissipation is a substorm.

1.4 Substorms

A substorm is made up of three distinct phases [Aubry and McPherron, 1971]. These are the growth, expansion and recovery phases. Each phase has its own set of signatures both in the magnetosphere but also in the ionospheric polar region and auroral zones.
For a more detailed survey of these phases and the associated magnetosphere changes, see Baker, et al [1996].

**Growth Phase.** This phase is generally theorized to commence with a southward turning of the IMF. It is characterized by the eroding of magnetic flux from the dayside [Maezawa, 1975; Baker et al, 1984] to the nightside. These nightside changes can also be seen in the auroral zone as an increase in the size of the polar cap [Akasofu, 1968; Baker et al., 1994] and the equatorward movement of the auroral zone edge [Feldstein and Starkov, 1967]. One other consequence of this phase is the thinning of the cross-tail current sheet. This thinning has been directly measured [Mitchell, 1990; Sergeev et al., 1990; Sanny et al., 1994] by satellites. This thinning of the current sheet continues until the onset of the expansion phase. This phase may last for 30 minutes or longer, though there is a great deal of variability depending on the overall activity level at the time.

**Expansion Phase.** The trigger of this phase is still an open question. Proponents of the Near-Earth Neutral Line model say that the formation of a NENL, or X-line, is the cause of the energy release, and the disruption of the thinned current sheet is a consequence of that global change [Baker et al., 1996]. There are those who maintain that the disruption of the current sheet is the cause, not effect of the expansion phase [Lui, 1996]. The reason for the controversy is that the magnetosphere volume is immense. Satellites are sparsely located in such a natural laboratory. In order to clearly time events, not only do we need satellites in the right place at several areas, but they must all be on or near the same set of field lines. Finally they must be conjugate to ground data measurements, also on the same field lines. The ISTP program, which involves several satellites (WIND, Geo-
tail, POLAR, Cluster II, for instance) is part of an ongoing effort to obtain these measurements.

The current wedge that is formed also plays an important role in current disruption, and subsequent dipolarization of the field. This current structure is needed to link what happens in the magnetotail with the auroral zone. They are connected to the auroral zone by Birkeland currents, which close with ionospheric currents that close the circuit loop back to the tail. Clearly, substorms are complicated.

Causality arguments aside, the expansion phase is known to function as the energy release mechanism of the stored energy from the growth phase. The thinned current sheets are disrupted. Fast flows, both Earthward and tailward are common. The magnetic field undergoes a global change, with a separatrix layer between positive/negative $B_z$ fluctuations and Earthward/tailward fast flows seen between $x = -20$ to $-30$ $R_E$ [Baumjohann et al., 1999]. The expansion phase lasts for perhaps ten minutes.

The auroral region shows a great deal of activity associated with substorms, and much of the theoretical understanding of how they evolve is based on observations here. A general overview is provided by Kivelson and Russell [1995]. There are several points that are worth noting however, in lieu of a full explanation. The auroral substorm shows definite stages, similar to those defined in the magnetosphere. There is an onset phase, typified by auroral brightening. There is an expansion phase, in which regions of turbulent aurora expand westward and poleward. Finally there is a recovery phase, in which these turbulent and expanded aurorae relax to the normal quiet time arcs.

**Recovery Phase.** This phase commences when the expansion phase has exhausted the available free energy and the magnetosphere is no longer undergoing any growth phase.
activity. Typically, this phase commences approximately 45 minutes after growth phase onset, and may last for 2 hours. While the magnetosphere is in this phase, it is gradually relaxing to its equilibrium state from the previous disturbed substorm state.

1.5 Current Sheets in the Magnetosphere

The magnetostatic equation $\nabla p = \frac{1}{\mu_0}(\nabla \times B) \times B$ describes the steady-state equilibrium balance between plasma pressure and magnetic pressure in any time-independent field topology. In this equation we have explicitly substituted the relation $J = (\nabla \times B)/\mu_0$ on the right hand side to emphasize the field versus particle pressure aspects of this equation. In general most spatial solutions to this equation exhibit discontinuities in the magnetic fields [Parker, 1994]. A current sheet is a necessary consequence of such a discontinuity due to Ampere's law. A knowledge of the current carriers in such a configuration is essential in predicting its ultimate behavior in response to external and internal forces. Figure 1.2 illustrates the important current systems that are described below.

1. Magnetopause current. On the dayside magnetosphere at the magnetopause we have a discontinuity in the magnetic field between the outside solar wind and the interior magnetosphere [Chapman and Ferraro, 1930, 1932]. There is a current flowing in the dawn-to-dusk direction to maintain this boundary. This current structure is responsible for the dayside boundary of the magnetosphere. It flows in such a way as to give us the correct discontinuity in the magnetic field here.

We also have a current flowing along the boundary of the tail. This current is roughly cylindrical in shape, and acts to contain the magnetic field inside the magnetotail. The current sheet and dayside currents must close somewhere since the magnetosphere is locally neutral. This closure is provided by the magnetopause current, which diverts the

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Figure 1.2. Currents in the magnetosphere. a) shows an X-Z sketch of the Earth's magnetosphere, b) shows a Y-Z sketch, and c) shows a X-Y-Z sketch. Each current system is labeled as follows. 1) is the dayside magnetosheath current. 2) is the ring current. 3) is the cross-tail current. 4) is the tail magnetopause current. 5) is an example of Birkeland currents and a substorm current wedge. The circle with a dot represents current out of the page, while the circle with an x represents current into the page. See text for more details.

plasma sheet current around the outside boundary in the proper sense to close it. Some of the dayside current magnetopause current also connects to the tail magnetopause current.

2. Ring current. There are two components to the general ring current. The first part is the symmetric ring current. It cycles generally westward around the Earth between 2 and 9 $R_E$ and consists of high energy (1 to 100 keV) particles that are trapped in the
dipolar field of the Earth that are transported by gradient and curvature drift in the dipolar magnetic field. A review paper that discusses the ring currents in far more detail is *Daglis et. al.* [1999].

The other component is the asymmetric ring current, or partial ring current. This current is associated with Birkeland currents as well as the current wedge, and is briefly introduced below.

3. Cross-Tail current sheet. Inside the magnetosphere, at the point in the tail where the magnetic field is kinked the most, there is a current flowing dawn-to-dusk. This current structure is responsible for the strong curvature of the field lines near the center of the tail region.

4. Birkeland currents/Substorm Current wedges. When a thinning current sheet is disrupted, there can be enhancements in the ring current over a partial wedge shape. These current structures are known as substorm current wedges. Birkeland currents are the parallel currents formed that couple these current wedges to the ionosphere that act to close these currents back across the auroral region, back to the tail region. Birkeland currents also close the partial ring currents described above. Most of the current diversion during substorms is diverted to the ionosphere.

Even though there are several main current regions in the magnetosphere that contribute significant magnetic field changes, only one of these currents is dealt with in this project, the tail current. There are several reasons for this. One, we are not interested in the near Earth behavior of the particles. We only require that they can mirror in a realistic dipole field. For this reason, the ring current is not used in this study. The magnetopause currents are far outside the region of interest, and act in a global way to provide a bound-
ary to the internal fields. We do not need to trace particles out to this region, so these fields are not needed either. Finally the Birkeland current and the associated current wedges are highly time-dependent in nature. As we shall see later, the model that is used to trace particles is inherently static, so these time dependent fields cannot be accurately portrayed. It only remains to find a tail field that has a realistic current profile. This subject will be dealt with in more detail in the respective model chapters.

1.6 Non-Adiabatic Orbits in Magnetotail Configurations

A charged particle in a electromagnetic field has the following equation of motion:

\[ m \frac{d^2 x}{dt^2} = q \left( E + \frac{dx}{dt} \times B \right) \]  

(1.1)

This equation describes the force exerted on a charged particle at position \( x \) by the influence of external electric and magnetic fields, \( E \) and \( B \). For particles in non-idealized magnetic fields, it is usually impossible to solve this equation analytically to get the full path it will follow. A useful simplification is to recognize that this motion can frequently be separated into two distinct parts: (1) The cyclic, or gyro, motion around the magnetic field and (2) the remaining drift motions. When we do this we get the familiar drifts of adiabatic particle motion [Northrop, 1963]. These approximations are common in plasma physics, and are useful in describing the orbits of many particles in space environments, such as the high energy ring current particles that move in the strong near-Earth dipole field. Their adiabatic nature lies in the assumption that the magnetic moment of these particles is constant over their entire orbit. However there are regions where this assumption is not valid, and the magnetic moment is not conserved over the entire particle orbit. This is where non-adiabatic orbit theory becomes important.
One crucial place where adiabatic theory breaks down is near the vicinity of a sharp bend in a magnetic field line. Such kinks occur in the cross-tail current sheet. We define a distance parameter $z_0$:

$$z_0 = \frac{mv}{qB_{XY}(z_0)}$$  \hspace{1cm} (1.2)

This is the region where the radius of curvature around $B_{XY}(z) = (B_X(z) + B_Y(z))^0.5$ of a particle is equal to its distance from the center of the current sheet. Particles that lie within this range frequently have non-adiabatic orbit behavior. In other words, the guiding center assumption that the orbit is separable is not valid here.

One way of characterizing the degree of non-adiabicity in an orbit is the kappa parameter [Buchner and Zelenyi, 1986; 1989]:

$$\kappa = \sqrt{\frac{R_{\text{min}}}{\rho_{\text{max}}}}$$  \hspace{1cm} (1.3)

Although this parameter was originally defined only for a specific tail model, it is still a useful parameter in other models. It is defined to be the square root of the ratio of minimum curvature of a magnetic field line to the maximum gyration radius of a particle. Keep in mind that $\rho = (mv/)(q|B|)$. It depends on both the energy and mass of a particle, as well as the magnetic field magnitude. Adiabatic orbits have values of $\kappa \geq 2$. When $\kappa$ is between 2 and around 0.5, we have particle orbits that are chaotic.

Chaotic orbits generally do not conserve the magnetic moment after a current sheet interaction. They often magnetically mirror close to the current sheet, bouncing in and out several times with small parallel velocities until they either stay trapped or exit the current sheet with a large parallel velocity. The exception to this rule lies at several individual values of $\kappa$ that give what are known as resonant orbits.
Figure 1.3. Nonadiabatic orbit examples. Figure 1.3a) shows an example of a Trapped orbit. Note that it contributes current in the negative direction near the center of the current sheet, and positive current in the outer regions. 1.3b) shows a Speiser orbit. It contributes a great deal of current at the center, and virtually none outside the meandering region. Speiser orbits usually bounce more than once in the current sheet before exiting, unlike this example.

Resonant orbits do conserve the magnetic moment upon a current sheet interaction, and will leave the current sheet either on the same side, for an even resonance, or on the opposite side for an odd one. They are similar to the low $\kappa$ Speiser orbits discussed below. These resonances occur at $\kappa$ values that can be parameterized by the relation $N = 0.80/\kappa - 0.5$, $N =$ integer [Chen, 1992; Ashour-Abdalla et al., 1993; Kaufmann and Lu, 1993] used in a specific magnetotail like field.
Finally, when \( \kappa \) is less than about \( \kappa_r = B_{z o}/B_{x o} \) \cite{Burkhardt and Chen, 1991}, we start seeing what are known as Speiser, or transient orbits. The exact value of this turnover point changes for most fields, but is typically around 0.5. Speiser orbits are otherwise similar to the resonant orbits in their trajectories.

Unlike guiding center particles, these non-adiabatic particle orbits do not exhibit gyrotropic motion as their primary form of motion within this \( z_o \) range. In Figure 1.3a) we see an example of a Trapped particle orbit. This particle moves in such a way that it remains in the current sheet for a long time. The figure-eight pattern seen is typical of such an orbit, as it gyrates around the oppositely pointed \( B_x \) components above and below the center of the current sheet. Over the course of the entire orbit, the particle moves only a slight distance in the \( y \) direction. If we examine the orbit in more detail we can see that there are large magnetization currents present. When the particle is near the center of the current sheet, it tends to move in the \(-y\) direction. This contributes negative current. When it is away from the sheet, it moves in the \(+y\) direction, contributing positive current. This effect is important in producing a current sheet model when coupled with the Speiser-like orbits.

Figure 1.3b) shows an example of a Speiser-like, or transient orbit \cite{Speiser, 1965}. This orbit shows the dramatic change from gyrotropic to non-gyrotropic motion within \( z_o \) of the center of the current sheet. Outside of \( z_o \), the particle simply gyrates around the field line but when it reaches \( z_o \), the motion changes dramatically. The particle moves so that it meanders about the weak \( B_z \) field at the center of the current sheet. When the particle is inside the current sheet, it contributes a great deal of positive current directly at the center, and little outside that region.
It is also important to note that in a typical orbit in a representative magnetic field model, the particles will drift Earthward as a result of the cross-tail electric convection field, and as a result of this they will encounter changing $\kappa$ regimes as they move and as they are energized. The result of this change is that any given particle may follow one basic type of orbit in one region, and another type in a different region.

The full current sheet can be thought of a combination of all these types of orbits, with the Speiser orbits contributing most of the current near the center, and the Trapped orbits acting to thicken the current sheet at the edges. Detailed studies [Kaufmann and Lu, 1993, Larson and Kaufmann, 1996] have shown that self-consistent current sheets can be generated by adding together the current contributions from selected groups consisting of combinations of these orbit types. This work is a continuation of these projects.

1.7 Velocity Space Distribution Functions

Much of the basic physics of plasmas is formulated in a statistical way. In order to explain and predict the behavior of such large ensembles of particles under the influence of external and inter-particle electric and magnetic fields, it is necessary to formulate a kinetic theory of plasma. The fundamentals of this approach are described in great detail in Ichimaru [1992]. After first defining the Klimotovich distribution to be the sum of all individual particles in a given system, we then average over all similar systems that have the same macroscopic properties. The result of this averaging is an equation that describes the behavior of a theoretical system of plasma in terms of a probability distribution. In the absence of collision effects, this equation is known as the Vlasov equation, or also sometimes the collisionless Boltzmann equation:
The Vlasov equation is the basic equation which prescribes the kinetic dynamics of collisionless plasmas. It may also be written as\[ \frac{d}{dt} f_\sigma(r, v, t) = 0. \] It is the formulation of the particle conservation law in a seven-dimensional collisionless phase space. It is important to realize that this equation is exact, there are no assumptions made in its derivation. Solving this equation for the correct function \( f_\sigma(r, v, t) \) using realistic magnetic and electric fields (remember that \( E \) and \( B \) include interparticle effects as well as outside fields) will give a complete solution to all the plasma behavior, from wave modes to instabilities. However, in practice it is impossible to analytically solve this in a general way for arbitrary fields, so other methods must be used.

Typically, the most common parameters that are obtained from distribution functions are the velocity moments. They have the general form:

\[ n^{th} \text{ moment} \propto \int f_\sigma(r, v, t)v^n dv \]  

(1.5)

In practice the only moments used are \( n=0, 1, 2 \) and sometimes 3. These moments are defined as number density, bulk velocity, temperature and heat flux respectively. Also note that the temperature and heat flux quantities are calculated in the rest frame of the plasma. Mathematically, this means that they are integrated over \( (v - v_{\text{bulk}})^n \) for \( n=2, 3 \) respectively. These quantities measure internal energy (temperature), and internal energy flow (heat flux), respectively.

Another way of analyzing these distribution functions is by plotting them. For example, even though we can easily integrate \( \int f_\sigma(r, v, t)v dv \) to get the bulk velocity, this does not tell us the shape of the distribution, or what physical effect may have caused that
bulk motion. The bulk motion caused by an adiabatic drift may look different in velocity space than the drift caused by a non-adiabatic effect.

Directly looking at the velocity space distribution functions of data and/or models is not a new idea. Many researchers have attempted to model distribution functions for a wide variety of magnetospheric and auroral configurations. Birn et. al [1981] modeled several two dimensional velocity distributions of PSBL flows. Using two different models they obtained good agreement with the data from the ISEE 2 and IMP 8 satellites for several cases. Both models assumed a Maxwellian energy distribution. The first model deformed the distribution by assuming that the magnetic field increased in the flow direction. The other ‘adiabatic deformation,’ as they called the method, assumed that the Maxwellian was originally non-deformed and subsequently accelerated. Onsager, et. al., [1991] used a similar approach, this time assuming that reconnection was occurring down-tail and modeling PSBL plasmas there. However, this type of approach will only be valid in adiabatic regions, such as the PSBL.

Martin and Speiser [1988] and Speiser and Martin [1992] tried to model distribution functions to examine the effects of a nearby neutral line on velocity distributions. This approach used Speiser-type particles in a one dimensional hyperbolic tangent field with a null point. Injecting test particles in various regions, they found that there were enhancements of particle flux density in regular ridges in the vicinity of the null point. These ridges were understood to be indicators of distance from the null point, and a way of predicting its location. The main problem with this approach is that the modeled distributions are not self-consistent. These ridge like features may not be present in a plasma that
contains orbits over larger regions of phase space and configuration space, smearing any possible features out until they are no longer visible.

Other efforts [Ashour-Abdalla et al., 1996a; Ashour-Abdalla et al., 1997; Ashour-Abdalla et al., 1998; Ashour-Abdalla et al., 2000] used measured distributions coupled with a Large Scale Kinetic particle code to trace these distributions back to their source, as a way of determining source regions. These methods are only as good as the global magnetic field used to trace them, although broad classifications of particle sources can be made with good certainty. They are also not self-consistent. Ashour-Abdalla et al. [1996b] used a fractal approach in a different analysis. In that case they modeled the fractal dimensionality of Geotail and Galileo distributions. The conclusion here was that the granularity of ion distributions is a real property of magnetotail distributions, and is possibly indicative of a highly non-linear and complicated system.

In this work we will be examining not only distribution functions from our model, but also distribution functions measured by the Geotail satellite for comparison purposes. There are several papers detailing the types of distributions commonly measured. Nakamura et al. [1991] used AMPTE/IRM data in a survey of ion distributions near the neutral sheet. Their observations indicated that several classes of distributions exist in the plasma sheet. Highly isotropic distributions are common in quiet times, with an occasional fast flow in periods of low activity as well. Fast flows are common in times of high magnetic activity, showing beam like features. Other distributions seen include ‘pancake’, or ring distributions, which have a depletion of particle flux at low energies, with only a high energy ring left over. An important conclusion is that ion distributions show generally a single population, allowing the fluid parameters to be useful in general. Nakamura et al.
[1992] also did a similar survey of the PSBL. Another plasma sheet survey was conducted by Frank et al. [1994b]. In this survey, non-adiabatic acceleration distributions measured by Galileo were studied. Conclusions are that distributions can be classified in two major types. One class is called 'lima bean' distributions. These are high speed, high temperature flows that are similar to the PSBL distributions. The other type is a colder distribution with smaller bulk speeds. These lima bean distributions are interpreted as evidence of Speiser-type orbits. The colder distributions were interpreted to be a result of particles being ejected from the current sheet after only a few interactions. Frank et al. [1996] did another study, this time using the first set of measurements by Geotail. Ion distributions seemed to show evidence of differential memory [Burkhart and Chen, 1991], which means that the shape of the present distributions appeared to be heavily influenced by past evolution. Now it is our turn to analyze these distributions, with the help of the COT model. First, we need to introduce the Geotail satellite.

1.8 The Geotail Satellite

Geotail was launched on July 24, 1992 [Mukai, et al; 1994]. The initial orbit configuration of Geotail was extremely elliptical. After 4.5 pre-calculated revolutions around the moon, the spacecraft was set into an orbit that carried it out to an apogee of ~220 RE on the nightside. This allowed Geotail to make a survey of the extreme far tail. After this survey, in the Fall of 1994, Geotail was maneuvered into a low inclination orbit with a perigee of 8 RE and an apogee of 50 RE. In February 1995 a further orbit change moved the orbit to a perigee of 9 RE and an apogee of 30 RE. This is the region of interest in this study. The CPI data available for this study ranged from March 2, 1995 to February 26, 1998, or approximately 3 years. Figure 1.4 shows the typical spatial coverage for one year.
Figure 1.4: Geotail orbit example. The above figure shows the orbital coverage of Geotail from Jan 1, 1995 to Jan 31, 1996. The coverage in the X, Y plane is most important. The central torus is the region of the best data sampling, with only a small number of orbits in the -X, -Y sector diverging from this regular torus. The coverage for the year from 1996 to 1997 is the same as the region in the torus. Note also the small range in the Z plane. The satellite mostly stays near the ecliptic plane, so any large scale movement in the Z direction is primarily due to the tail flapping effect.

in more detail. There are some orbits in this plot from the previous period of apogee at 50 Rs, but the central torus is the region of interest.

1.9 Comprehensive Plasma Instrumentation (CPI)

This is the primary source of data for this study, courtesy of L. A. Frank and W. R. Paterson [Frank, et. al; 1994a]. The CPI instrument consists of three parts: (1) the Hot Plasma Analyzer, (2) the Solar Wind Plasma Analyzer and (3) the Ion Composition Analyzer. Distribution function and fluid moment data for this study was derived solely from
the Hot Plasma Analyzer (HPA). The Solar Wind Plasma Analyzer and the Ion composition Analyzer were not used in this study. The Solar Wind Instrument does not measure magnetotail plasma well, and we do not need to know the ion composition of the tail in order to compare distribution plots with a model.

Figure 1.5 shows the schematic for this instrument. The CPI-HPA instrument consists of three spherical-segment plates. The inner and outer plates are grounded, while the middle plate is tunable in steps from 65 mV to 2.4 kV to analyze different energy bands. The E/Q values of the detector range from 1.3 V to 48.2 kV in 64 passbands. There are nine separate sensors, each with a slightly different range of angular coverage. There are 9 sectors in $\theta$, and due to the rotation of the spacecraft about the $z$ axis, we get effectively 16 sectors in $\phi$. This gives an effective measurement of the distribution function $f_\sigma(E, \theta, \phi)$ in spacecraft coordinates, which are similar to Geocentric Solar Ecliptic coordinates (the $x$ axis is Earth-sun direction, $z$ axis is parallel to the ecliptic plane, and $y$ completes the right handed orthogonal system).

Once a distribution function is measured, moments of this distribution can then be taken to give us density, velocity, etc. Both the measured distributions and the derived moments are available to us for all data in the aforementioned time frame, for all times that the spacecraft was in or near the magnetotail. The moment data is for 3 cycles, giving us a measurement nearly every minute.

1.10 Low Energy Particle (LEP)

The LEP instrument is in many ways similar to the CPI instrument. This instrument is also a plasma analyzer, consisting of three units of sensors [Mukai, et al; 1994], (1) LEP-EA, or Energy-per-charge Analyzers, (2) LEP-SW, or Solar Wind ion analyzer,
Figure 1.5: Schematic of the HP/CPI and SW/CPI instrumentation. From Frank, et. al, 1994b, pg. 26 Shown are the top and side views. The sectors labeled P1-9 on the HP instrument are at the 9θ bins. The spinning spacecraft provides the remaining coverage in φ, 16 bins when a complete cycle is done. A complete cycle takes 22 seconds.
and (3) LEP-MS, or Mass Spectrometer. Only the LEP-EA instrument is used in this study. The basics of its construction are similar to that of the CPI-HPA instrument described above (Figure 1.5 again). The main difference lies in the better time resolution of this instrument, 12 seconds for one cycle vs. the 22 second cycle described above. The count rates are also higher for this instrument, due to a much higher geometrical factor. Moment data from this satellite is available on the Internet, at the Geotail LEP data site (http://www.darts.isas.ac.jp/spdb/index.html). It can be useful to compare the data from the two instrument packages against one another, as discrepancies/agreements will decrease/increase our confidence in the measurements. Also, the higher time resolution is invaluable in analyzing individual cases with more precision.

1.11 Magnetic Field Experiment (MFE)

The previous two instruments measure both ion and electron properties, but we also need to know the magnetic fields to get a fuller picture. The MFE experiment [Kokubun, 1994] onboard the Geotail spacecraft measures just that. See Figure 1.6 for a basic schematic. This instrument consists of 2 fluxgate magnetometers and a search coil magnetometer. The fluxgate magnetometers are a standard instrument package. They can measure magnetic field magnitude in seven ranges, from ±16 to ±65536 nT. along three orthogonal axes. Finally, the time resolution of this instrument is even better than that of the LEP-EA instrument, approximately 3 seconds. This allows us to correlate magnetic field activity with ion and electron measurements with a good degree of accuracy.
Figure 1.6: Magnetic Field Experiment. Sensors a) and b) are located at 4 and 6 meters out from the spin axis respectively. They are redundant flux gate magnetometers. Sensor c) is a search coil magnetometer located at 4 meters out on the opposing boom arm. It is designed primarily for measuring magnetic field fluctuations. See text for details.

1.12 Consistent Orbit Tracing

Finally, we come to the theoretical model that this research is primarily based on. In order to accurately represent the plasma in a magnetotail-like configuration, we want to incorporate all the preceding information in this introduction. Recall that the main topics were the magnetotail itself, the different orbit types that are seen therein and the Vlasov equation that describes the distribution functions in any plasma. The COT method was developed to allow us to generate plasma models for any magnetic field configuration prescribed, using the simple Lorentz force to solve the Vlasov equation.

The basics of the COT method are presented here, though a much more rigorous description is detailed in Larson and Kaufmann [1996]. A seminal paper by Bernstein, Green and Kruskal [1957] describes a method of obtaining the plasma required to maintain any preselected electrostatic potential. Using this method Poisson's equation could be
satisfied for arbitrary potentials, by summing the potentials for electron and ion distribution functions and obeying the proper boundary conditions.

In a similar fashion, the COT method prescribes a magnetic field. Using the fact that $\nabla \times B = \mu_0 J$, we can combine groups of ions and electrons that carry different types of current to satisfy Ampere's law, as well as ultimately solve the Vlasov equation. The types of current required and the groups run are largely dependent on the particle orbits themselves. As stated previously, the Speiser type particles exhibit a specific current profile, and so do the Trapped particles. Combinations of groups that are dominated by one or the other, or even a mixture of the two are then used to fit the current. The resulting combination is then self-consistent, in that the current required by Ampere's law purely from the magnetic field calculation is matched by the current carried by the plasma, derived solely from the orbit calculations. We should point out that there are few limitations placed on this fitting process. When the individual currents are being fitted, the only requirement in the fit is that none of the coefficients may be negative. This would reverse the sense of the current contributions, essentially creating unphysical orbit currents that cannot exist with the fields as they are. Otherwise, any value is allowed. Typically, fitting weights are on the order of 1 or less, with none larger than around 10 or so. The individual groups already have contributions to the final answer that are on the order of magnitude of the goal current, requiring only small weights to complete the least squares fit.

There are several steps to be carried out in this process. First, we prescribe the magnetic field. This is done in the following chapters for each field used, and the details of these fields are left until then. Once the magnetic field is chosen, then the current is fixed, and we can now look at the particle orbit contribution. The next step is to determine
which ion groups need to be run to give us a complete set of partial distributions that can be combined to give a good final combined distribution. In this step, ion orbits are initialized at key points with the intention of making each individual group dominated by one type of orbit, either Speiser or Trapped. If this is possible, then the final fitting becomes easier, as the different contributions are complementary, as discussed previously. The ions traced in these groups are allowed to evolve normally as the Lorentz force dictates, and the resulting motion is saved into distribution functions that are updated for each ion. The value of an element of the distribution function at any point in phase space is proportional to the time it remains in that phase space box. Ions are traced continuously until they are out of our region of interest, and will not come back. For instance, a Speiser type particle that leaves the current sheet Earthward will always mirror and come back to the current sheet, unless it hits the Earth. This would stop the trace. The trace of this particle would also stop if the mirrored particle came back to the current sheet Earthward of our innermost boundary by more than 2 Larmor radii. Such an orbit would never come back into our grid, and can then be stopped. We keep track of this motion for every particle, making sure that no orbits are prematurely discontinued.

Once all the ion groups are finished, we start the fitting process. In most cases, electrons are assumed to be adiabatic, so using quasi-neutrality along with the ion densities, we can derive an adiabatic electron current contribution for each ion group, giving a summed current contribution for each. Using these summed groups, we then calculate the fitting weights by a least-squares fit. Once the weights are obtained, then the final combined ion distribution is generated by adding the individual ion distributions together, each multiplied by their respective weight. The fitting procedure is now finished.
Now that we have a description of the method, it is instructive to look at previous efforts with this model. Kaufmann and Lu [1993] did a first analysis of this type of modeling using a 1-D magnetotail model which varied only in the \( z \) (north-south, or normal to the ecliptic plane) direction. Several classes of orbit types characterized by the \( \kappa \) parameter were studied. Contributions from each of these type of orbits was needed to generate a self-consistent current sheet, although it was also concluded that it is impossible to build a self-consistent sheet with such a simple magnetic field.

Effects of \( B_y \) on particle orbits were investigated in Kaufmann, Lu and Larson [1994]. Several interesting effects appeared with this addition. Odd-N resonant orbits disappeared when the value of \( B_{yo} \) exceeded several tenths of a nT. Other effects included a mechanism for producing Birkeland currents if the non-adiabatic orbits were included.

Larson and Kaufmann [1996] derived a more sophisticated COT version using a 2-D tail-like field, varying in \( x \) (Earth-Sun) as well as \( z \), for several different tail models and particle energies. In this version, some of the difficulties associated with the 1-D version disappeared, and good fits were found to several different current sheet models, with particles of three different energies. Fluid parameters were found to match well with observations of quiet time magnetotails.

Kaufmann, Kontodinas, Ball and Larson [1997] investigated nonguiding center orbits. It was shown that an isotropic pressure tensor does not produce the same current as the full pressure tensor calculated from the COT model. Near the center of the current sheet, the pressure tensor becomes unmagnetized, with several off-diagonal elements becoming important. Another conclusion was that changes in the tail field can cause the particles to pass through one or more resonant regions, where the quantity \( \langle v_y \rangle / \langle v_o \rangle \)
reaches a peak, then falls rapidly. If this effect were to apply to a real magnetotail, it could be another mechanism for current disruption at the onset of the expansion phase of a substorm. A companion paper [Kaufmann, Larson, Kontodinas and Ball, 1997] investigates force balance effects. Forces were found to be largely balanced in the $y$ direction between electrons and ions, although the ions dominated in the $x$ and $z$ directions. Substorm processes are addressed as purely pressure imbalances. This viewpoint is corroborated by Vasyliunas [2001], where he concludes that plasma bulk flows cause electric fields, and not the other way around, as long as the electric field in question is not externally driven.

This paper also addresses the important question of uniqueness in the COT approach. It is concluded that the distributions are not unique. However, the orbit types that are needed to generate a self-consistent current sheet are constrained. In general, although we cannot specify with certainty whether a given distribution is the only solution, we can place external constraints on various bulk parameters, e.g. current, bulk flow, temperature to narrow the scope of modeling. One more study to mention is that of Kontodinas [1998]. In this COT study a thin current sheet model was generated. The magnetic field used here is also used in this study, and will be described in detail in the next chapter. This model was used to examine in detail all the terms of the energy equation, as well as the generalized pressure equation.
CHAPTER II

CONFINED CROSS-TAIL ELECTRIC FIELD MODEL

In this chapter the computer models will be discussed. Starting with the relevant background theory I will first show the derivation of the magnetic and electric field models used. The orbit tracing solutions that have been generated will then be explored in detail.

2.1 Magnetic Field Models

Recall from the beginning of the first chapter that this project aims to generate orbit tracing models of fast flow configurations in magnetotail like magnetic fields. In order to proceed with this project, the first step is to define a magnetic field that realistically represents the magnetotail for the configurations desired.

The field models must be physically realistic. There are decades of measurements of magnetic fields showing typical values for the various components everywhere in the magnetosphere. Using the Geotail magnetic field measurements of this data set, we can examine the ranges of these components easily. The GSE coordinate system is used throughout this dissertation, as the Geotail measurements are in this coordinate system. $B_x$ ranges from zero at the center of the current sheet to perhaps $\pm 20$ to $\pm 40$ nT at the edges of the current sheet, becoming even larger as we enter the lobes. $B_y$ has a similar range, although it tends to have a smaller maximum magnitude, the range from 0 to $\pm 20$
nT is normal. $B_z$ is critically important. The value of $B_z$ controls the finer motions of Speiser-like particles in the current sheet region [Huang and Frank, 1994]. The adiabaticity parameter $\kappa$ is sensitive to the curvature of the field lines in this center region, and since $B_x$ tends to zero here, $B_z$ becomes even more important. Typical values for $B_z$ range from 100 nT or more in the near-Earth dipolar region to 1 to 2 nT or even less in the far tail. In the region of interest, from $r = -30$ to $-10$ RE, $B_z$ can range from 5 nT outside $x = -13$ RE, increasing to between 10 to 15 nT as we move Earthward [Kaufmann, Ball, Paterson and Frank, 2000]. Obviously, any theoretical model must take these average values into account.

In the sections below, the different kinds of magnetic field models and modeling techniques will be briefly introduced. Strengths and limitations will be addressed as they pertain to this orbit tracing study.

1. Data Based Models There is one dominant data based model available. This model has been made by N. A. Tsyganenko and other collaborators [Tsyganenko and Usmanov, 1982; Tsyganenko, 1989; Tsyganenko, 1993; Tsyganenko, Stern and Kaymaz, 1993; Tsyganenko and Peredo, 1994; Tsyganenko and Sibeck, 1994; Tsyganenko, 1995; Tsyganenko and Stern, 1996; Tsyganenko, 1997; Tsyganenko, 1998]. They have used an exhaustive approach to model the entire magnetosphere based on mapping satellite data to several different sets of fitting functions chosen for their ability to model the currents seen in a given spatial region. As is obvious from the references, this has been an ongoing task for decades. There are two main implementations of this approach, known as T89 and T96, according to the year they were released. The latest models have included realistic
modules that add Birkeland currents, magnetopause currents and a method for warping the magnetotail shape as desired.

There are valid reasons for not using these models, as comprehensive as they seem. Each is complex and would require a great deal of computational time in the orbit tracing model. Another problem with these two models is that of limited flexibility. They are based on averages over many different field configurations, binned by a small number of parameters (Kp index for T89, and 4 solar wind parameters for T96). It is difficult to get a particularly extreme field from such a scheme, and the nature of this distribution function analysis requires fairly extreme, non-average type field configurations.

2. Magnetohydrodynamics Another important subset of field modeling is the magnetohydrodynamic (MHD) approach. The MHD approach aims to solve the fluid dynamics equations in a self-consistent way for large regions. Two extensive review papers of large scale simulations are used as guides here [Walker and Ashour-Abdalla, 1995; Birn, Hesse and Schindler, 1996]. There are two general approaches to this type of solution. One attempts to solve the entire magnetosphere at once. This is the global approach. It is a powerful way of discerning how solar wind effects propagate throughout the magnetosphere, and how the global magnetosphere responds to these external stimuli for various initial conditions. In a global MHD simulation the entire magnetosphere, ionosphere and solar wind system is modeled. A set of initial conditions is assumed and then a solar wind is imposed as a time-dependent boundary condition to drive the simulation. The other approach is local. Local models attempt to do more detailed studies of smaller regions.
The first global studies that were successful to any degree were carried out by Spreiter and Alksne [1969]. This was a simple gas-dynamic model designed to solve for the position of the bow shock. The first true MHD model [Leboeuf, et al., 1978] modeled the magnetosphere and the magnetosheath self-consistently. Since then the speed of computer calculations has increased dramatically, allowing for even more powerful models. Several researchers have modeled the response of a magnetosphere to a southward IMF [Walker et al., 1993; Fedder et al., 1995a; Ogino et al., 1994]. Another simulation was able to generate a distant tail out to past 160 RE [Fedder and Lyon, 1995b]. Other simulations predict that if the IMF stays northward for prolonged periods of time that the magnetosphere will be closed to solar wind plasma [Fedder and Lyon, 1995b; Ogino et al., 1994; Raeder et al., 1994]. These are examples of the kinds of problems that are attempted with these global MHD models.

Local models on the other hand do not try to model the entire magnetosphere. They attempt to look at only smaller regions within the larger magnetosphere to take a closer look at a particular aspect of plasma behavior. The magnetotail itself is an active topic of research. There are several problems that are often addressed in these local models. One of these is current sheet formation. There have been many studies of current sheet development using this local MHD approach [Hahm and Kulsrud, 1982; Schindler and Birn, 1993; Wiegelmann and Schindler, 1995 for example]. These models all provided evidence for the formation of high \( \beta \) current sheets, or thin current sheets at active times. The quantity \( \beta \), or plasma beta, is the ratio of plasma energy density to magnetic field energy density. One thing these MHD models do not address are particle effects. This is an important question, and one that requires a different approach. Particle codes
that model current sheets [Pritchett and Coroniti, 1994] and hybrid codes, which utilize MHD equations for electrons and orbit trajectories for ions [Hesse et al, 1996] also show this result. Other kinds of local modeling analyze current disruption and diversion [Birn and Hesse, 1996] and plasmoid and X-line formation [Birn and Hones, 1981; Birn et al, 1989; Birn et al, 2001; Birn and Hesse. 2001; Otto, 2001; Ma and Battacharjee, 2001; Yin et al, 2001ab]. Recently there has been a concerted effort to consolidate the many different kind of MHD, hybrid and particle code simulations of these reconnection events. This collaboration is known as the Geospace Environment Modeling Magnetic Reconnection Challenge [Birn et al, 2001]. Despite all the work that has gone into these models, they are still not useful for this problem. We need something simpler to trace particles in. There are simply too many complexities involved with these models. Also, although the particle codes seem as if they are similar to this orbit racing project, there are major differences.

3. Kinetic Codes. A particle code or hybrid code can also be self-consistent. It is instructive to examine these kinds of methods in some detail, since they incorporate ion orbits explicitly in the modeling in a different way than the COT model does. There are a large number of assumptions that go into one of these simulations. To illustrate this we will look at a typical simulation in some detail, then discuss several similar projects with less detail.

Pritchett and Coroniti [1992] carried out a hybrid simulation to analyze the formation and stability of a one dimensional current sheet. There were several steps to this process. First, a one dimensional current sheet was generated using ion dynamics only. Electrons were assumed to be massless, and only contributed to charge neutrality. Proton
equations of motion were solved for a large number of ions (hundreds of thousands) starting with an initial magnetic field, $B = B_x(z)\hat{x} + B_z\hat{z}$. Current and density are recorded, and the magnetic field is updated using Ampere's law until the field approaches an equilibrium value. This field equilibrium depends heavily upon the initial conditions of both the magnetic field and the boundary ion population. Next they incorporate this 1D solution into a 2D simulation to test its stability. The same general method is used to solve this system. In this case particles are introduced along select sections of the outer boundaries, using the 1D equilibrium field as the starting field. These ions are strictly limited in velocity. This approach continues until a new equilibrium is reached, at which point a third change is made. Now they keep $B_z$ constant and derive a self-consistent value of $B_x(z)$, using an iterative procedure to continually update the vector potential using the particles' canonical momenta. Finally, using this third equilibrium, the particles are iterated into yet another new equilibrium in which $B_z$ is allowed to change.

Clearly, there are a large number of assumptions and somewhat arbitrary parameterizations used in this example. Other hybrid and kinetic codes are similar in the way they critically depend on boundary conditions when arriving at an equilibrium. Pritchett and Coroniti [1995] used a fully 2D simulation with a dipole and tail model to simulate thin current sheet formation. In this case an initial tail field model was assumed using three piecewise constant tail fields. An asymptotic ion population was then chosen using specific values of $T_i$ and ion velocity. After an initial equilibrium was reached, electron effects were added. These electrons were run using a common assumption in these kinds of simulations, namely that the mass ratio of electrons to ions was about 1 to 16. After this
new version came to an equilibrium, a cross-tail electric field was added and yet another equilibrium was solved.

Other researchers have carried out similar simulations. *Burkhart et al.*, [1993] also did a simulation of thin current sheets. In this case a 1D hybrid code was run to test several parameters that are important to current disruption theories. Two different versions are run, one with time independent boundary conditions and another with varying boundary conditions. The constant boundary conditions are fairly simple. At $z=0$, the boundary is assumed to be reflecting, and at the outer $z$ edge, the ion population is assumed to be a Maxwellian. This outer edge is used for injecting new particles into the simulation. The time dependent solutions are obtained by monotonically decreasing the parallel components of the velocities injected at the outer edge. These simulations all gave similar results. One interesting aspect of this paper is that some simple distribution functions are presented for one of the simulations. Picking a specific spatial range in the gridding region, they plot scatter plots of velocity pairs. In these plots, a single dot represents one particle. Increasing the dot density is the same as an increase in the flux density. These simple distributions were found to be similar in shape to those seen by the AMPTE/CCE spacecraft while measuring current disruption events.

A third example of these kinds of particle code was done in a recent paper by *Nishikawa and Ohtani* [2000]. A full 3D two particle simulation was run to test the evolution of a thin current sheet configuration under the influence of a southward IMF field. This particular model was run on a supercomputer, a Cray C90 and T90. While the previous particle codes used typically several hundred thousand to a million particles, this version uses approximately 2 million electron-ion pairs with the same mass ratio mentioned.
before. Initially, the plasma is all assumed to be solar wind plasma. After a short period of time an Earth dipole magnetic field is slowly turned on. This dipole is kept constant after it reaches the normal Earth's magnitude for the rest of the simulation. At a much later time step, after the plasma and magnetic fields have had time to come to an equilibrium, the solar wind IMF field is turned southward. Then the system is allowed to come to a final equilibrium, and the analysis of the resulting fields can begin.

We can see from these hybrid and fully kinetic models that there are advantages to them that our model cannot match. Wave instabilities can be analyzed with such a scheme, as well as the timing responses of large groups of particles to external stimuli. Simple distributions functions have been analyzed, and it appears that more complex ones can be saved, though I am not aware of any of these kind of models that have done so. There are some serious drawbacks that make these model unsuitable to the task at hand though.

First, the current sheets that are generated are highly dependent on the boundary conditions. The resulting equilibria are not necessarily comparable to the real magnetosphere. There are also issues concerning the electrons. The unphysical electron-ion mass ratios are a possible source of errors in these models. For example, in the Pritchett and Coroniti [1995] paper it was found that electrons carry the majority of current in a thin current sheet configuration. Without using a realistic electron mass, it is difficult to discern if this result is real, or purely a numerical approximation. Ions in the magnetotail are often non-adiabatic when the current sheet thickness is on the order of the ion Larmor radius, and the electrons are mostly adiabatic. If we change the electron mass to a value that is on par with the ions, then we can get an imaginary particle that has both a similar
adiabiticity as protons, as well as the relatively larger mobility of electrons. This could cause serious problems in the analysis of the current carriers. This problem cannot be solved with measurements yet, since the fluctuations in electron velocities are typically much larger than the averages. Every electron current contribution to the total current is dominated by these fluctuations, making estimates of their average contribution difficult.

4. Analytic Magnetic Field Models. We have instead focused on an analytical magnetic field model for this project. These models are much simpler than any of the previous discussed analyses, as well as being much simpler to adjust. It just remains to pick the form of this magnetic field model.

There are several classes of analytical models. For a good review article detailing many of the techniques used in field modeling the paper by Stern [1994] provides a thorough introduction. One interesting method of modeling fields uses Euler potentials. Starting with two Euler potentials, $\alpha(x)$ and $\beta(x)$ (not plasma beta, this is a new arbitrary function), the magnetic field can be defined by $B = \nabla \alpha \times \nabla \beta$. The power of such an approach lies in the fact that a field line is now given by the line of intersection of any two surfaces defined by $\alpha(x) = A$, and $\beta(x) = B$, where $A$ and $B$ are general constants. There are several drawbacks to this method that render the point moot however. First and foremost, Euler potentials are not linearly additive, making it extremely difficult to separate a field model by components. Also, the currents generated by deforming known potentials are difficult to control.

Other analytic models include the Toffoletto-Hill [Toffoletto and Hill, 1993] and the Hilmer-Voigt [Hilmer and Voigt, 1995] models. These models were developed for specific purposes, and are not suited for adaptability for this project. The Toffoletto-Hill
models were designed to mimic the tail-solar wind interconnection. They specifically addressed issues related to open magnetospheres, and the convection at the lobes caused by solar wind effects. The Hilmer-Voigt model was intended to be used in studies related to near-Earth substorm effects. No real attempt was made to provide a realistic magneto-tail in this model, making it unsuitable for this kind of tail study.

The analytical model that has had the most use is based on a pressure balance principle, the equilibrium field model.

2.2 Equilibrium Magnetic Field Model

This group of field models is based on the assumption that the magnetotail is static, so that an average pressure balance can be assumed. Following the derivation by Zwingmann [1983] we can arrive at a useful magnetotail model. Since the starting point to this model is the assumption of pressure equilibrium, we must first establish which components of pressure are important to include.

There are six unique elements of the pressure tensor. In Cartesian coordinates
\[ p_{ij} \propto \int f(v)(v_i - v_{ibulk})(v_j - v_{jbulk}) \, dv, \] with \( i, j \in \{x, y, z\} \). Note that two tensor elements with the same indices reversed are the same since the above integration is commutative, so nine combinations reduce to six. The largest components are the diagonal elements, \( p_{xx}, p_{yy} \) and \( p_{zz} \). Often this tensor can be diagonalized to a parallel/perpendicular coordinate system in which the off-diagonal elements are identically zero. In general, if the distribution function is completely isotropic, then all the elements will vanish except the diagonal elements. Furthermore, if we have do have an isotropic distribution function then all the diagonal elements will be the same, and we can simplify the pressure tensor to just a scalar pressure. This means that the parallel and perpendicular pressures are the same, or nearly
so. We will make this assumption, although we should have an estimate of not only the size of these off-diagonal elements, but how much the different diagonal elements may differ.

*Kauffmann et al.,* [2000] used long term data from the Geotail CPI instrument to estimate the magnitudes of pressure anisotropies in the time averaged current sheet. In the periods that had the highest values of plasma $\beta$ the typical $p_\parallel/p_\perp$ ratio is near 1.0. As we look to smaller values of $\beta$ this ratio increases to a value of 1.1 or 1.2 as we near the outer edge of the current sheet. This observation tells us that it is reasonable in this case to assume that the diagonal elements are comparable to each other, making the scalar pressure assumption a decent one. The differences between these parallel and perpendicular pressures are no more than 10-30%. If these two components are nearly the same, then it is also reasonable to assume that the pressure tensor is nearly isotropic, and therefore diagonal.

An even more encouraging sign is that typically when the value of $\beta$ is highest in the central plasma sheet the current sheet is likely to be thinner than normal. When $\beta > 1$ we are in a plasma dominated region. Since the pressure ratios are closest to 1.0 for the highest $\beta$ plasmas, this makes this assumption even more reasonable. We can safely assume that the adoption of isotropic pressure in this case is a reasonable one, and can be done with only small errors on the order of 10%.

Another test of these off-diagonal elements was done in the thin current sheet models used by *Kontodinas* [1998]. He found that the values of the diagonal elements of the Cartesian pressure tensor were within 10% or so of each other. For his thin_011 model, which is the same magnetic field model used here, the first $xbox$ at $z=0$ had all three tensor...
elements around 2.5 nPa. In his model the gridding was done in \(x\), and at the innermost edge, these values had increased to greater than 3 nPa. The \(p_{xx}\) component was larger than the other two, by a factor of about 3.6 nPa to 3.4 nPa. Comparing these values with the off-diagonal elements showed that \(p_{xz}\) was the only one that was comparable to the diagonal elements, ranging from 0.5 nPa at the first \(xbox\) to less than 2 nPa. It was also shown that these elements peaked away from the current sheet proper. At \(z=0\), this tensor element remained small, less than 0.25 nPa on average. The other two off diagonal elements were much smaller than this one, and can be neglected. These results agree well with the measurements mentioned above, allowing us to conclude that the usual use of isotropic pressure in deriving this model is reasonable.

The pressure balance requirement with isotropic pressure \(\nabla \cdot \vec{P} = \nabla p\) is:

\[
j \times \vec{B} - \nabla p = 0
\]  

(2.1)

Using this relation as our starting point we can arrive at an equation describing how a balanced vector potential behaves in a tail-like field. First, we must make several assumptions. The magnetic vector potential is restricted to \(A = A_y(x, z)\hat{y}\), because we are assuming that there is no \(y\) dependence in this tail field. It only depends on \(x\) and \(z\), and the current will only have a \(J_y\) component.

There are several reasons to make this two dimensional choice. First, the equations have not been solved for the more general three dimensional case. The geometry of the current sheet makes the choice of which two dimensions to include simple. Since the current sheet is observed to flow primarily in the \(y\) direction, it is clear that this is the dominant current contribution. Knowing that the curl of \(A_y\) is proportional to \(J_y\), we can see

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that any $y$ dependence in the vector potential will not allow us to adjust the current sheet in any way, as this component does not contribute to the $y$ current.

Choosing Coulomb gauge gives us that $\nabla \cdot \mathbf{A} = 0$. We also assume that the tail field is static so that time derivatives are identically zero. First rewrite the gradient of pressure using the chain rule from basic calculus to get:

$$\nabla p = \frac{\partial p}{\partial A_y} \nabla A_y$$

(2.2)

Limiting our current to $J = J_y \hat{y}$ and then rewriting $\mathbf{B}$ in terms of $A_y$ we can simplify the pressure balance equation to:

$$j_y \nabla A_y = \frac{\partial p}{\partial A_y} \nabla A_y$$

(2.3)

Canceling the common gradient factor and using Ampere's law to eliminate the current we arrive at:

$$\nabla^2 A_y = -\mu_0 \frac{\partial p}{\partial A_y}$$

(2.4)

To this point, the equations are exact. However, we must now choose how the pressure changes with $A_y$. The common choice [Birn et al., 1975; Zwingmann, 1983] is to assume that:

$$p = p_c e^{-2(A_y/A_c)}$$

(2.5)

where $p_c$ and $A_c$ are some arbitrary scale factors. This relation is assumed *ad hoc* in the paper by Birn simply because the actual pressure relation would be rigorously based on complicated entry and loss calculations along a field line. Bypassing this calculation he assumes a monotonic relation, which is given by Equation 2.5. A physical motivation for
this can be gained from observing how the vector potential changes as we move away from the current sheet. The magnetic field is a minimum at the center of the current sheet, increasing in magnitude as we move away from the center. The vector potential can be calculated from the magnetic field as \( A = 1/(4\pi) \int (B \times \hat{r}/r^2)dr' \). At the center of the current sheet a simple symmetry argument can show that we also have a minimum vector potential here. If we are at \( z = 0 \), then for every element of \( B(r) \) that adds from a positive \( z \) area, we also have a corresponding point at negative \( z \). Since \( B_x \) reverses sign at \( z = 0 \), there is no contribution due to this component as every \( \pm z \) location will cancel, leaving only the contribution from \( B_z \) term. As we move away from the current sheet in \( z \), this symmetry goes away, and \( A \) will increase. For pressure balance between magnetic field and particle pressure, the particle pressure must be inversely proportional to the vector potential, so that when \( A \) is largest, \( p \) is smallest. This relation satisfies that requirement in a simple way. By using this relation between pressure and the vector potential, we can arrive at an equation for \( A \):

\[
\nabla^2 A = \frac{e^{-2A}}{L^2} \tag{2.6}
\]

The quantity \( A \) is the normalized magnetic potential, \( L \) is the scale size of the gradient, and is given by \( L = A_c \sqrt{2 \mu_0 p_c} \). A description of a method to solve this equation can be found in *Ames* [1967]. For a magnetotail-like solution the most relevant parameter, \( A_y \) gives us \( B_x \) and \( B_z \) components. The general solution to first order in \( \varepsilon \) is:

\[
A_y = A_{yo} \left[ \ln \left( \frac{\cosh \left( \frac{z f(\varepsilon x)}{L} \right) }{f(\varepsilon x)} \right) \right] \tag{2.7}
\]
The function \( f(\varepsilon x) \) is arbitrary within certain physical parameters, e.g., \( B_x \) remains finite as \( x \to \infty \), for instance. The parameter \( \varepsilon \) is defined to be the ratio of scale sizes in \( x \) and \( z \), such that \( \varepsilon \) is small. There are several well studied versions of this function. Some of these early versions were reviewed in Karimabadi et al., [1990]. One drawback to all of these models is the general thickness of the current sheets that they produce. A new function needed to be derived that could produce a relatively thin current sheet to model more extreme cases. In this case the function chosen is:

\[
f(\varepsilon x) = e^{\frac{\varepsilon x}{a_c - \varepsilon x}}
\]  

(2.8)

This function was originally derived by Wang and Battacharjee [1998], but the version used here is slightly different, as modified in Kontodinas [1998]. The parameter \( \varepsilon \) is a measure of the ratio \( L_z/L_x \), or the scale size ratio in \( z \) and \( x \). It is a small number on the order of 1/10, or 1/100. The other parameter \( a_c \) is a measure of the current sheet thickness. Kontodinas uses the values \( \varepsilon = 0.005 \) and \( a_c = 0.07 \) respectively for the tail model he labeled thin_011, which is also used here.

One more parameter must be fixed. The specific solution for the magnetic potential using Equations 2.7 and 2.8 can be written as:

\[
A_y = -B_c a_c \ln \left[ e^{\frac{\varepsilon x}{a_c - \varepsilon x}} \cosh \left( \frac{z \varepsilon x}{a_c - \varepsilon x} \right) \right]
\]  

(2.9)

The parameter \( B_c \) is a measure of the magnitude of the tail field, in nT. The value used by Kontodinas as well as here is \( B_c = 80nT \). 

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Field lines to scale

\[ Z, R_E \]

Field lines not to scale, for magnification purposes.

\[ X, R_E \]

Figure 2.1. Field Lines of Thin Current Sheet Model. These are some sample field lines of the thin current sheet model.

### 2.3 Dipole Field

Although the tail model is the most interesting analytically, we also couple this field with a magnetic dipole representing the Earth. The equations representing a dipole magnetic field are well known, and in cartesian coordinates take the following form:

\[
B_D = -\frac{3m_{xz}}{r^5} \hat{x} - \frac{3m_{yz}}{r^5} \hat{y} - \frac{m(3z^2 - r^2)}{r^5} \hat{z}
\]  

(2.10)

The dipole moment \( m \) of the Earth is approximately equal to \( -31000 \text{ nT R}_E^3 \).

The combination of these two fields forms the magnetic field used here (Figure 2.1)
2.4 Electric Field Model

Before we concentrate on the form of the electric field chosen in this section for the orbit tracing, we should briefly examine the average electric fields that are seen in the magnetotail. Kaufmann et al., (1993) did a detailed mapping study in which the Heppner and Maynard (1987) average electric field model was traced from the ionosphere down to the current sheet. In this field line mapping the Tsyganenko T89 field was used. Depending on the Kp used, average electric fields varied from 0.06 mV/m to 0.3 mV/m. In this study, these electric fields are assumed to be quiet time, and the ones used in this section and subsequently in the orbit tracing models will have much larger peak values over smaller regions.

The electric field chosen for this section was of a simple form:

\[ E_y = E_{yo} e^{-(y/y_0)^2} + E_{y\text{constant}} \] (2.11)

This form of the electric field allows us to alter the magnitude and width of the confined field easily. It also tells us that since \( E_y \) is a function of \( y \) only then the relation \( \nabla \times E_y = -\frac{\partial E_y}{\partial z} \hat{x} + \frac{\partial E_y}{\partial x} \hat{z} = 0 \) is identically true, assuring us that our electric field contributes no time-dependence, from \( \nabla \times E = -\frac{\partial B}{\partial t} \). The \( E_{y\text{constant}} \) term was chosen to ensure that the particle orbits retain some kind of net convective drift even outside our peak field region. This ensures that the particle orbits will exit our region of interest in a reasonable time.

Three different thicknesses of the electric field were chosen to model. The characteristic scale size is the Larmor radius of a typical ion meandering about the weak \( B_z \) near the center of the current sheet. A quick calculation tells us if we assume that a typical particle is meandering about \( B_z = 2.5 nT \) (\( = B_z \) at the center of our spatial box) with an
energy of 5 kev, the radius is approximately 0.7 R_E. This value assumes that all the particle’s energy is perpendicular to B_z at the center. Picking a 5 keV Maxwellian temperature distribution means that the average energy of the particles is 1.5 times this temperature, or 7.5 keV. This corresponds to a Larmor radius of 0.8 R_E. Since we will be using a Maxwellian energy distribution, not a single energy, we use 1.0 R_E as a scale size. We have implemented three main electric field models. In Equation 2.11 above, we use the values y_0 = 1.0, y_0 = 3.0 and y_0 = \infty, or a constant electric field for these scale sizes. Models Y01 and Y03 also incorporated a small constant electric field of 0.1 mV/m, to ensure that particles traced outside the regions of largest field still drift out of our spatial grid region in a reasonable time. A fourth model was also run as a test of some features seen in the thinnest, y_0 = 1.0, version.

To derive an estimate for a suitable electric field magnitude, we can start with the simplest version of Ohm’s law for a plasma:

E + V x B = 0

(2.12)

This equation can be derived in many different ways. This particular form is related to the original Ohm’s law, J' = \sigma E'. In general for a plasma the conductivity \sigma is extremely large, approaching infinity, so the only way to avoid infinite currents is to require that \(E' = 0\) in the rest frame of the plasma. To arrive at the specific relation above, we need to transform into the Earth’s reference frame, where all the measurements are taken. The equation for a general Lorentz transformation of an electric field is

\[ E' = \gamma (E + V \times B) - (\gamma^2 / (\gamma + 1)) V (V \cdot E) \]  

Jackson [1975]. Since we are not in a relativistic plasma, \(\gamma = 1\), and since in this particular case \(V \cdot E\) is zero because the two quantities can be chosen to be perpendicular, we reduce to the relation \(E' = E + V \times B\).
Requiring the electric field in the plasma rest frame, $E'$, to be zero yields Equation 2.12, and also satisfies the perpendicular requirement.

Returning to Equation 2.12 first recognize that since we required $E = E(y)$ only, this places limits on the magnetic field and velocity components that can contribute. Solving Ohm’s law for $E_y$ yields $E_y = -\left[-V_x B_z + V_z B_x\right]$. There are no other components that contribute to this electric field. To simplify this further, recall that near the center of the current sheet we have symmetry in $z$. Since this is true, we expect $V_z$ to be close to zero and so we can solve for the bulk flow:

$$V_x = E_y / B_z$$

(2.13)

Now that we have a relationship between bulk flow and the cross-tail electric field, we can select the values to be used in the different models.

For the thinnest model, we originally wanted the magnitude of the electric field to contribute a maximum convection at the center of the current sheet of 1000 km/s. A flow speed of this magnitude is fairly uncommon, but well within the limit of flows that have been seen in the central plasma sheet region [Angelopoulos et al, 1992; Angelopoulos et al 1994; Baumjohann et al, 1990]. A value of 1.5 mV/m originally gave a bulk flow of this magnitude. However, as the orbit tracing models developed some of the gridding in the $x$ direction was changed so this value now corresponds to a maximum bulk flow of approximately 700 km/s, since we have altered the gridding region so it has a stronger average $B_z$.

The nature of the modeling being done here lends itself to being more instructive when analyzing the most extreme configurations since there tend to be more obvious features in distribution functions. Now that we have a peak flow value to work with, we can fix the remainder of the parameters.
In order to ensure that particles that are traced outside the region of high electric field drift Earthward, and out of our grid region in a reasonable amount of time, we also impose a small constant electric field of 0.1 mV/m everywhere, as stated above. This does not affect the peak flow value much, but as Figure 2.2 shows, without this small field the electric field would quickly fall to near zero outside the peak region of our thinnest electric field model.

We must be careful not to make the cross-tail potential unphysically large. The potential difference across the entire tail measured through ionospheric convection studies is about 50 kV at quiet times [Reiff and Luhman, 1986]. This gives us a rough idea of the limits of our potential. Not all of this potential will be contained within the small confined electric field that we are modeling, so we then require the cross-tail potential difference of each different thickness to be approximately the same. The potential difference of these fields over some symmetric distance from \(-\alpha\) to \(\alpha\) is:

\[
\Phi_{\text{total}} = \int_{-\alpha}^{\alpha} E_{yo} e^{-\left(y/y_o\right)^2} dy + E_{yc} \Delta y \tag{2.14}
\]

Figure 2.2 shows the numerical integration of the three models from \(Y = -5\) to \(+5\ R_E\). Although the above integral can be evaluated exactly over all \(y\) values from \(-\infty\) to \(\infty\), a close look at the electric field used in the intermediate width field (Yo3) shows that much of the field lies outside our gridding region (\(-2.5\) to \(2.5\) in \(y\)), thus integrating over all space would not be realistic.

Before we examine the results of these models, we should first identify what basic properties we expect the final models to show. The constant electric field model should ideally show no change in the distribution functions in the 10 different \(y\)boxes. The elec
Figure 2.2 Electric Field Parameters. The label const refers to the constant electric field in the Yoc model. Yo1 and Yo3 are also labeled.
tric field is constant across the tail, and the magnetic field changes are insignificant as well since the tail magnetic field has no $y$ dependence. Any changes that are visible in this model (denoted as $Y_{oc}$) are expected to be common to all models, regardless of electric field width. They will be understood as effects caused by the way in which particles were chosen and the particular gridding used. As we thin the electric field in the different models, it is expected that anomalies will appear, especially in the distribution function plots.

### 2.5 Gridding of the Confined Electric Field Models

Before we explore the models in detail, first we need to understand the choices made in spatial and velocity gridding in the various models. First, we analyze the spatial gridding.

For the gridding in the Sun-Earth direction, or $x$ axis, we pick one $x$-box, with boundaries from $-30$ to $-20$ $R_E$. We need to pick our grid and particle orbits together so that the plasma bulk $V_x$ agrees with the $E_y/B_z$ of the fields. The discussion in Section 2.6 explores this velocity requirement in much greater detail. We also need to understand why looking at the tail in this particular $x$ range is desired, as opposed to the range from $-25$ to $-15$ $R_E$, for instance. There are three main reasons. First, the data set we have for Geotail covers radial values from $-30$ into $-10$ $R_E$. This places a first limit on the region of interest. The second limit is related to the commonly measured parameters of these fast flow events. As we move farther out into the tail like regions, the average and peak bulk speed flows increase [Baumjohann et al, 1990]. These more drastic flow speeds are exactly the sort of events that we need to compare with. Finally, as we move farther out in the tail, the field lines become more stretched, and more importantly, the current sheet gets thinner as we move away from the more dipolar field lines near the Earth. There is no
guarantee that our modeled field will be similar in thickness and field strength to any single fast flow event measured out in the mid tail region, but picking this xgrid in this way maximizes the chances that any given event will be similar to our gridded region.

Examining the gridding in z next we pick 40 zboxes symmetrically folded about z=0 into 20 zboxes. Particle orbits are kept in a symmetric region about the center of the current sheet from z = -0.4 to z = 0.4 RE. They are then folded into 20 zboxes with a new range of z = 0.0 to z = 0.4 RE. This has been done in every COT model, since the magnetic fields that have been used up to now have all been symmetric in z [Larson and Kaufmann, 1996]. The statistics of particles can be essentially doubled by using this technique. The range of z used is dependent on the thickness of the current sheet. In this case the current sheet has a characteristic thickness of about 0.11 RE [Kontodinas, 1998]. This thickness is a measure of the cross-tail current density from peak value to half peak. Setting the edge of z at 0.4 RE assures us that the complete current sheet will be gridded in z, and using 20 zboxes assures us of having enough boxes in that range to represent the rapid change in z that happens from center to edge.

The most important gridding axis for this study is the y axis. The electric field varies only in y, so we need to carefully consider the box sizes needed. We already have defined a spatial scale in y, the average ion gyroradius about $B_z$ which is approximately equal to 1 RE. Since we are interested in how the distribution functions change as we move away from the peak of each electric field model, we need to use a spatial scale in the gridding that is smaller than the electric field width. For this reason, we chose 10 yboxes, gridded from -2.5 to 2.5 RE. This makes every ybox 0.5 RE wide. Keeping the same
ybox gridding for all models also allows us to compare the models together, both as they change in y, and also as they change in $E_y$ magnitude.

For several reasons, trying to grid significantly more than 200 to 300 spatial boxes quickly becomes intractable with the current algorithms. Although computer memory is not a significant issue with the rapid cost decrease of memory chips, the computational time needed to run the extra particle groups needed for large numbers of spatial boxes quickly becomes prohibitive. As an example, in the present study using an SGI R10k Indigo$^2$ a typical run of 1000 particles takes 3 to 4 hours. If we were to keep the number of yboxes and zboxes constant at 200, and triple the number of xboxes, we could very well triple the number of final groups needed. In addition, since the particle orbits themselves are complex, it is not always clear how to initiate particles with even one xbox, let alone three. Thus we would also spend far more time identifying the groups needed than if we had just one xbox.

Before we examine the velocity gridding, we should examine the spatial scales of our boxes in each direction as compared with typical orbit parameters. The question to be answered is what will happen to the modeled distributions if we change the size of the spatial boxes? There are two extreme cases. First, what will happen if we make our boxes much smaller? There is a clear scale size in this case, the ion Larmor radius. If we pick our box sizes too small, then we will get only parts of orbits contributing in any given spatial box. Unless we trace a gigantic number of particles in such a scheme, large magnetization effects will be prevalent in all the boxes. Clearly, this will bias the saved distributions immensely, and should be avoided. Another issue here is the number of randomized parti-
cles that will actually interact with these new small boxes. It will be extremely difficult to balance the parallel and anti-parallel contributions of these particle orbits to make the velocities consistent if we only keep small sections of each orbit in a given spatial box.

The other extreme is making the spatial boxes much larger than we have. This would introduce a different, although less extreme, set of potential errors. In this case, we would have good statistics, as the particles would remain in each spatial box for large sections of orbit. We would lose when we looked at the fields, however. As it is, the magnetic field $B_z$ component changes by a factor of slightly greater than 2 from $x_{\text{min}}$ to $x_{\text{max}}$. If we increase the $x_{\text{box}}$ size by another factor of 2, then we would be mixing disparate sections of magnetotail field with large differences in current requirements into one spatial grid as if they had similar average values. The problem becomes even more pointed if we were to increase the size of the $z_{\text{grids}}$. This field component changes rapidly from 0 nT at the center of the current sheet to more than 40 nT at the box edge in 20 $z_{\text{boxes}}$.

The box sizes used here were chosen to allow for a balance between the gradients of the fields and the scale sizes associated with particle motion. As we can see from this conjecture, the box sizes chosen are reasonable so long as the fields do not change too much (more than a rough factor of 2 or so) in a spatial box and the particle orbits are well contained within the spatial grids.

Velocity gridding is much simpler. We designate 30 boxes in each velocity direction, ranging from $-\alpha$ to $\alpha$. This parameter $\alpha$ is the maximum velocity along an axis that is kept. We need to balance choosing this value between a large number to keep every particle possible, and a small value to have good resolution in the velocity boxes. Since we are using 5 keV Maxwellian distributions to choose each particle's initial energy, this
gives us a starting velocity scale. A 5 keV proton has a velocity of 1000 km/s. Since we are picking energies along a continuum, we expect many energies to be larger than this. Also, since the electric field will energize particles, we need to make sure that for a typical particle interacting with this electric field, it will not gain so much energy that it lies outside this boundary.

Let us look more closely at this energization effect. If a particle doubles its energy, its velocity increases by only a factor of \(\sqrt{2}\). Examining the potential plot in Figure 2.2, shows us that for every model, even the thinnest electric field model, a typical Speiser particle that meanders in the current sheet for 5 RE won’t gain more than 10 keV in energy. For a 5 keV particle initially, this is still only an increase in velocity of a factor of \(\sqrt{3}\).

The final value chosen for the maximum velocity based on these estimates is 2500 km/s. This is 2.5 times the typical velocity of a 5 keV particle, allowing us to keep up to a 30 keV particle with little or no loss of information. Later on when we examine the fourth model with an unphysical electric field value, we need to drastically increase this value of \(\alpha\) to both keep the higher energy particles we see and to increase the statistics of the quickly moving particles therein.

### 2.6 Fluid Parameters of Three Main Electric Field Models

In the COT model, the main goal of the fitting procedure is to match the cross-tail current \(J_y\) of the particles to the \(J_y\) required by the magnetic fields. This places a limit on a combination of two moments of the velocity space distribution function; density and \(V_y\). We place no restrictions on the shape of the distributions in the velocity space, since that is expected to be controlled by the particle orbits, and cannot be determined beforehand.
Conversely, the current is determined beforehand, and so this becomes, in a sense, a boundary condition for the model.

Since we are primarily interested in modeling fast flows, it also is required that $V_x = E_y/B_z$ should be satisfied. Unlike $J_y$, we do not have an active control over this value. Examining each kind of non-adiabatic orbit may show that this velocity requirement is met even in those cases. However, there is an easier way to show that this velocity must be present. We can transform into a frame of reference in which $E_y = 0$, similarly to when we derived Ohm's law. To do this we need to assume that $B_z$ is constant. In our region of the magnetotail, this is true over a wide range in $y$. $B_z$ changes slowly with $x$, but this does not affect the calculation. Recalling the form of the simple Ohm's law $E = V \times B$, or more specifically $E_y = V_x \times B_z$, we can see that a change in either $B_z$ or $V_x$ can make $E_y = 0$. Since we cannot change the magnetic field in a coordinate frame transformation, we must change $V_x$ only. The value of this transformation velocity is simply $V'_x = V_x - E_y / B_z$. This shows that the plasma's rest frame where $E_y = 0$ is moving with respect to the Earth at the velocity given by the Ohm's law convection.

To satisfy this velocity requirement means that we have to balance parallel and anti-parallel flows closely. We also need to allow enough room in our xgrid for all particles to $E \times B$ drift in the fields without cutting off the particles either too soon, or in a biased way.

The main method used in trying to balance these parallel and anti-parallel flows was to start particles using a wide randomization in initial $y$ position. The initiation region for particles is randomized approximately five Larmor radii to either side of the $ybox$ grid edges. The exact $y$ randomization width is $10 R_E$, which corresponds to 20 $yboxes$. This ensures that as long as we use enough randomized particles at all different $y$ values, as
well as randomized energy, pitch and phase angles, we can balance out the parallel and
anti parallel contributions of the Speiser like particles outside \( z_0 \), as well as any other
effects in the bulk flow that may be due to parallel flows. Doing this ensures that each
individual group already closely matches the \( V_x \) requirement before we even try to fit cur-
rent. In these large groups, 5000 particles were used for each initiation point, using a
Maxwellian energy distribution of 5 keV, and random pitch and phase angles. Figure 2.3
shows the individual current and velocity contributions for two groups used in the \( YoI \)
model. One of these groups is dominated by Speiser particles, the other by Trapped orbits.
This kind of selection makes the fitting easier, and is used in all models.

Some explanation is required to understand these fluid parameter plots (such as
Figure 2.3, below) completely. On the bottom of the \( V_x \) plot for the Speiser dominated
group, there are two labels, one labeled \( ybox1 \), the other \( ybox10 \). They point to the first
and last group of \( yboxes \) plotted in this figure respectively. The first 20 points of each plot
is a plot of \( J_y \) versus \( z \) for \( ybox1 \). The immediate next point is the first \( zbox \) of \( ybox2 \).
This trend continues, until the last point of the plot, which is the \( zbox20 \) point of \( ybox10 \).
This method is a concise way of viewing the fluid parameters.

In Figure 2.3, the cross-tail current density \( J_y \) and Earthward bulk velocity \( V_x \) are
shown for the two main groups used in fitting the \( YoI \) model. The first two plots show
these parameters for the group dominated by Trapped particles. Note that in the current
plots, each box has negative current at the center of the current sheet, turning to a positive
current at around 0.1 \( R_E \) (or the third or fourth \( zbox \)). This is consistent with the orbit
element seen in Chapter 1, Figure 1.3. The velocity of this group is plotted below, along
with the expected velocity derived from \( V_x = E_y / B_z \). As we can see, although it does
Figure 2.3 YoI Model Individual Group Plots. See text for details.
not match perfectly, it is close in many of the boxes. If these velocities were not even this close to the expected velocity, then the final fits would have little chance of being even this good.

The second set of plots in Figure 2.3 show a group dominated by Speiser particles. Although the currents that this group carry are significantly different from the current carried by the previous group, we can see that the bulk velocity is similar. This means that no matter what coefficients we have to use to weight these two groups, the final velocity of the combined group will not be critically dependent on either group. Using these two kinds of large groups as a foundation for the final combined group allows us to add in other small groups to make the final current fit better. These small groups were randomized over a much smaller y range, and tend to be weighted much less in the fit than these two large groups. Since the velocities in the small groups are not consistent, adding them may make the final combined velocity not as consistent as we would like. However they will drastically improve the current fits, and in this case may even improve the velocities. In the Yo1 case, they are weighted similarly to the 20 ybox groups, because the symmetry in y of these larger groups is largely gone when the particle orbits encounter the electric field region. In the other cases the 20 ybox groups are weighted much more than the others.

Now we can turn to the completed fluid parameters of the three main models. Figure 2.4 shows the current density fits for each model in order. Figure 2.4a) shows the current profiles for the thinnest electric field model Yo1, 2.4b) for the intermediate thickness model Yo3 and 2.4c) shows the constant electric field model Yoc.
Figure 2.4 Current Density Fits for Three Main Models. $Y_{oc}$ is the constant version, $Y_{o3}$ is the broad changing field and $Y_{o1}$ is the narrowest field.
Examining this plot shows that, as a whole, the current profiles seem to fit well. There are two main features to look for in a fit of this type, the current magnitude and the current width. The peak currents match well overall. Each peak is about 40 nA/m² for the goal current. The fit tends to vary in the Yo1 case more than the other two. In the first two boxes, the fit is bad. This is true in general for all three cases, so it is careful to remember that any distribution functions analyzed in these boxes may not be accurate. In the remaining boxes there is also some fluctuation but the general shape of the current profiles looks reasonable. Looking at the peak values for the other two cases, Yo3 and Yoc, shows that the same difficulty in ybox1 and ybox2 occurs in both cases. However, in these two cases the peaks are fit well everywhere else.

The width is also well fit in all cases, except for the aforementioned first two boxes. Even in some of the yboxes in Yo1 that did not fit the peak value well show a good matching thickness trend in all other yboxes, with only one or two boxes that are not ideal.

The only possible reason for this problem with the first few boxes may lie with a peculiarity with the gridding. Although we are only examining the regions from $y = -2.5$ to $y = 2.5$, the complete gridding range included up to $y = 5.0$. We originally thought that there would be some large asymmetry in $y$ in the $V_x$ flow that would show up only if these other boxes were kept. This did not turn out to be true. However these extra boxes may be skewing the fits, causing the first couple of boxes to be more poorly fit in favor of these extra boxes. The reason we did not run these models without the extra boxes was due to time constraints. Because of the way the code is arranged, we need to make a new program version every time we want to run a new grid. This did not seem necessary, though if we were to start this project again, only the boxes actually used
Figure 2.5 $V_x$ Plots for the Three Main Models
would be saved. This would not affect the boxes that are well fit, but may fix the few that are not. Concluding the look at the current fit, we can say that the currents are well matched by our particle distributions even with these first few bad boxes.

Figure 2.5 shows the $V_x$ bulk flow for the three main models. A cursory examination of these plots shows reasonably good agreement with the expected values. There are several features that need to be understood fully before we can proceed further. The first two $y$-boxes in each plot tend to fit poorly. This is no real surprise, and it is reasonable to expect that if the currents are not fit well in a given box that the bulk flow in that same box may also be bad.

Note also that the velocities tend to match much better for small $z$ values than for larger ones. This can be interpreted easily, since as we move away from the current sheet in $z$, the field lines become more closely parallel to $x$. This means that we have more parallel streaming orbit effects here, and we have not been able to eliminate all of the possible imbalances. However, this is not a real problem, since the higher $z$-boxes are not as important in the distribution function analysis. Remember that trapped orbits gyrate out to 1.8 $z_0$ on average. The non-adiabatic effects will not be present outside of $2z_0$, and for this model $2z_0$ occurs at around $z_{box6}$ or $z_{box7}$. Any orbits outside of this range will be completely guiding center.

2.7 Distribution Function Plots

Figure 2.6 shows a diagram of a distribution function. Several circles are drawn in this sphere, labeled $a$, $b$ and $c$. Each circle represents a slice across the $v_z$ axis. Slice $a$ is at some positive value of $v_z$ slice $b$ is at $v_z = 0$, and slice $c$ is at the exact negative value of the slice at $a$. In the plots to come, we have the ability to plot slices at any value of the
velocity on any axis, but the values at $v_z = 0$ were chosen to plot for all cases. There are two main reasons for this. First, there are simply too many slices to plot for the 4 models, each with 10x20 spatial boxes to choose from. We also will be showing plots of the Geotail data. Plotting complete sets of slices along all the axes would quickly become impossible to make any sense of. We need to limit the number of slices. The second reason to choose that particular slice is that it is the most likely one to show these non-adiabatic effects. Since the modeling is mostly concerned with effects in the $v_y$ (current) and $v_x$ (bulk flow) directions, we can see that these directions need to be included. Therefore we only need to specify a value of $v_z$ to fix. The best choice is $v_z = 0$, because the magnetic field used is symmetric about $z$, so there is no reason to expect any excess of particles either northward or southward, especially with the folding of the distributions discussed previously. One other note on notation. From here on it is assumed that $V_x$ refers to the bulk flow, and $v_x$ refers to the velocity axis. This is true for all other directions.

There are some other features on these plots that must be explained. First, the magnetic field arrows are plotted on every slice as an arrow centered on the $v_x$, $v_y$ origin. Its length is scaled so that the largest magnitude field seen in a given figure sets the maximum length. Only the $B_x$ and $B_y$ components are shown although the vectors are scaled with all three components of $B$.

Another feature that should be mentioned is the contour plotting that we overlay on each distribution plot. These contours are not plotted at any specific values of flux, rather the plotter simply draws three levels of contour on each plot. They are only meant to serve as a guide to the eye, to highlight high and low areas of flux in each plot. The flux levels span typically from $10^{-17}$ to $10^{-12}$ s$^3$/m$^6$. The distributions that are plotted can vary widely
Figure 2.6 Distribution Plotting Diagram. This figure illustrates the plotting technique used in examining the velocity space distributions functions.

over different boxes and models, so we decided to use the color table as the absolute identifier of flux level, and let the contours serve as only a secondary guide. I want to emphasize this point, because it becomes important in the analysis of a later model. The contour plots are spaced individually for each separate distribution slice. One slice’s contours have no correlation with any other, they are solely based on the minimum and maximum contour levels present in that plot and that plot alone.
The label at the upper left, just over the first distribution plot is the value of the maximum velocity. It is the magnitude of velocity at the outer positive edge of a velocity axis. In the first three cases, the magnitude used is 2500 km/s. This means that the axes in $v_x$ and $v_y$ range from $-2500$ to $2500$ km/s in each direction.

2.8 Yoc Model Distribution Function Plots

Figure 2.7 shows the distribution function slices for the Yoc version. The top row of 5 plots show the $v_z = 0$ slices for the first 5 yboxes, ranging from $y = -2.25$ RE to $y = -0.25$ RE. The bottom row shows the other 5 yboxes, from $y = 0.25$ to $y = 2.25$ RE (for the rest of this chapter, all positions are implicitly assumed to be in RE). Since the magnetic field changes little in this $y$ range we expect the distribution functions to be identical. Clearly, Figure 2.7 shows that there are differences.

The first feature that we see is the general trend in $y$ towards increased temperature, or more specifically towards a more granular, diffuse kind of distribution. As we move from $y = -2.25$ to $y = -0.25$, we can clearly see that the distributions become sparser and more patchy. This becomes even more apparent as we continue to move across from $y = 0.25$ to $y = 2.25$. Note that in the first couple of distributions at $y = -2.25$, $-1.75$, and $-1.25$ we do not see the distribution function edges hitting the edge of our plotting velocity boundary except in one or two isolated spots. However, in the last few plots, at $y = 1.25$, $1.75$ and $2.25$, the distribution plots meet this edge everywhere, and there are clearly particles that have been lost at the edge of our plot. Since the electric field points in the $y$ direction, any net motion in $y$ by the plasma will result in energization and heating. Since the particles that were chosen had no initial $y$ dependence in
Figure 2.7 Yo6 Distribution Function Plots

Ev=0.4 nV/m Constant Version
Z=0 Vz=0 km/s Slices
2500 km/s

|Bmagmax| = 4.1 nT, gsm coordinates, f(v), s²/m²

Y = 0.25
Y = 0.75
Y = 1.25
Y = 1.75
Y = 2.25
Y = 2.75
Y = 3.25
Y = 3.75
Y = 4.25

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energy, the resulting combined groups will end up with a \( y \) dependence due to the presence of this field.

Another feature that shows clearly is the tendency for an enhancement of particle flux in both positive \( v_x \) and positive \( v_y \) for each distribution slice. This is to be expected, for two reasons. First, since we are modeling a thin current sheet, we expect to see a significant excess of ions carrying positive current in the \( \hat{y} \) direction. There need to be more Speiser particle orbits carrying the excess \( +J_y \) current needed at the center of such a current sheet. In the \( \hat{x} \) direction, we also will see an excess, simply because there is a convective flow in this region. Although this flow is not large, on the order of 160 km/s, it is consistent and will be present in all these plots. This feature can be interpreted as purely due to the fields chosen, and the self-consistent nature of this modeling technique.

One final curious feature that seems to be present in all these plots are the holes in the center of these distributions. There are ten plots present in this figure, and seven of them seem to show an interesting lack of flux at or near the center of each plot. It is difficult to determine if this anomaly is a feature of the distributions, or a problem in the way we select particles. A later part of this chapter will address this issue in more detail.

### 2.9 \( Yo_3 \) Distribution Function Plots

We first point out that in Figure 2.8 there is a small difference from Figure 2.7. Each plot in Figure 2.8 is labeled not only by position in \( y \), but also the value of \( E_y \) for each distribution slice is labeled. Since this model has a characteristic electric field thickness of \( 3 R_E \), we do not expect the electric field to change drastically from one \( y box \) to the next, but over the entire thickness of the spatial gridding in \( y \), we do expect to see enough of a gradient in the electric field that there may be features that emerge due to this change.
The effects that were seen in the Yoc model are evident here. The phase space graininess, or heating effect, is clear as we compare the boxes at positive \( y \) to those at negative \( y \) values. There is a distinct trend towards both increased patchiness in the distributions and increasing size. Another effect that was observed is the general trend towards excess flux in positive \( v_y \) which is important for the current. From the fluid parameters we can see that the fits are good here, although there are some features in this plot that are interesting.

There are essentially three regions of interest in Figure 2.8. The slices from \( y = -2.25 \) to \( y = -1.25 \) are similar. The electric field does not change much in this distance, from only 0.44 mV/m to 0.6 mV/m. The distributions all look similar to the same slices seen in the constant electric field version seen previously.

From \( y = -0.75 \) to \( y = 0.75 \) there are some differences that appear. Starting in \( y = -0.75 \) there is a subtle trend towards a more unbalanced distribution towards the \( +v_x \) direction. The electric field increases to its maximum in this region, with values of 0.66 to 0.69 mV/m in these boxes. This unbalancing effect becomes much more apparent in the next box at \( y = -0.25 \). In this box the distribution is obviously skewed in the \( +v_x \) direction. There is little of the high-intensity distribution in the \( -v_x \) region. Note also that the distribution is starting to go into and past the edge of the gridding region in the \( +v_x \) direction. This is due to both the increased flow and the heating effect. These trends are also visible in the \( y = 0.25 \) and \( y = 0.75 \) boxes. The box at \( y = 0.25 \) shows similar features to \( y = 0.75 \), although the heating effect is causing the high intensity flux region to be much less concentrated in one region. The box at \( y = 0.75 \) is also similar in its gross features to the conjugate box at \( y = -0.75 \), although the heating effect has made a drastic
Figure 2.8 $Y_03$ Distribution Function Plots
change, causing the high intensity flux that contributed the majority of the $+v_x$ component to be spread out and patchy. This was expected from the previous model, and the larger electric field in this model will only serve to heighten this effect.

Finally, in the last three boxes from $y = 1.25$ to $y = 2.25$ we see the distribution return to the same kind of features seen in the negative $y$ boxes from $y = -2.25$ to $y = -1.25$. There are no drastic changes other than the increased patchiness caused by the heating effect. In fact, the distributions look similar to those seen in the same boxes in the previous model.

Now we can examine the next model. This new model has the largest electric field magnitude coupled with the thinnest distribution of the electric field. We then expect the general trend seen in this $Yo3$ model to continue, with large anisotropies in the center region of the electric field.

2.10 $Yo1$ Model Distribution Function Plots

Figure 2.9 shows the $Yo1$ distribution plots. The two features that we saw in the $YoC$ version do indeed reoccur here. There is a definite trend towards phase space graininess or heating, and this is visible in the same ways as before. Also we see the same enhancements in the $+v_y$ direction as in the previous $YoC$ and $Yo3$ versions, although there are some slight differences here. Now let us examine these differences.

The first three boxes from $y = -2.25$ to $y = -1.25$ are fairly featureless. The densities of these boxes are significantly higher than the others, as can be seen from the large amount of high intensity flux. There is little to say about these boxes. The electric field changes from 0.11 to 0.41 mV/m. This alone should produce some kind of feature,
though aside from a subtle enhancement in the $+v_x$ side of the box at $y = -1.25$, there is not much to see here.

We start to see some interesting effects when we move into the four center boxes. In the box at $y = -0.75$, we start to see a strong anisotropy. There is a distinctive lack of flux in the region where we have $-v_x$ and $-v_y$ flows. This feature becomes even stronger when we enter the regions of the highest electric fields, in the boxes at $y = -0.25$ and $y = 0.25$.

These two boxes show a strong asymmetry in the $v_x$ and $v_y$ directions. There is almost a complete lack of distribution flux of intensity greater than $10^{-14}$ s$^3$/m$^6$ or so in any direction except those that contribute positive $v_x$ and $v_y$ velocities. This implies that the particle orbits in this region are predominantly moving across the tail and Earthward. The other velocities are not as populated in this distribution in this high electric field region. This could result if the Speiser particles were being preferentially accelerated across the tail, and the Trapped particles were being accelerated Earthward quickly. These issues will be dealt with in more detail in a later section of this chapter.

Now we turn to the remaining boxes, ranging from $y = 0.75$ to $y = 2.25$. The box at $y = 0.75$ shows similar features to the box at $y = -0.75$. The heating effect again makes these distributions more patchy and sparse on the positive $y$ side of the electric field. Similarly the boxes ranging from $y = 1.25$ to $y = 2.25$ show little anisotropy, although the box at $y = 1.25$ shows a subtle effect similar to that seen in $y = -1.25$. Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 2.9 Yo⊥ Distribution Function Plots

Yo=1 Eymax=1.6 mV/m
Z=0 Vz=0 km/s slices
2500 km/s

|Bmagmax| = 4.1 nT, gsm coordinates

f(v), s^-1/m^3

Y=-2.25 Ey=0.11 Y=-1.75 Ey=0.17 Y=-1.25 Ey=0.41 Y=-0.75 Ey=0.95 Y=-0.25 Ey=1.50

Y = 0.25 Ey=1.50 Y = 0.75 Ey=0.95 Y= 1.25 Ey=0.41 Y= 1.75 Ey=0.17 Y = 2.25  Ey=0.11
From the previous three models, it is obvious that there is an effect seen in the orbit plots that depends upon the width of the electric field. However, it remains to be seen whether the enhanced magnitude used in the YoI model is more responsible for the effects noted above, or whether the width of the field is primarily responsible for the 'lima bean' shaped distribution seen in the center boxes of the YoI model.

2.11 YocBigE Model Fluid Parameters

To test this conjecture, we have generated a fourth model. This new model uses an electric field that is constant across all the $y$ boxes, but has a magnitude equal to the peak magnitude used in YoI, 1.6 mV/m. This large electric field has required us to make one change in the model. Where before we could use 2500 km/s as the maximum magnitude for the edge of our velocity binning, this large electric field requires us to change that value. The value selected is 4000 km/s. This allows us to keep particles up to almost 100 keV with no losses. This large electric field will cause particles to be accelerated Earthward quickly as well. This effect will reduce the time that particles spend in our gridding region. Making this maximum velocity larger will also improve statistics in each velocity box, helping to offset this effectively reduced particle density.

Figure 2.10 shows the same fluid parameters for this model as seen in Figures 2.4 and 2.5 for the previous three models. We can see that these fluid parameters closely match what we saw with the Yoc version. The cross-tail current is matched well except for the first two $y$ boxes. We also see that the convection drift in the $x$ direction matches fairly well with the expected value, although the first 3 boxes do not show good agreement. These disagreements closely match the problems in the Yoc model, so are not an impediment to continuing.
2.12 *YeeBigE* Model Distribution Function Plots

Figure 2.11 shows the distribution function plots in the same format as the previous three models. The new maximum velocity is now put in place of the old one in the proper place on these plots.

At first glance, these distributions do not look interesting. There do not appear to be any drastic features. There is no obvious 'lima bean' kind of shape in any of these boxes. There are some subtle features that appear in several of these boxes that at first glance may appear to indicate this feature, but upon careful examination we can conclude otherwise.

The first thing to notice is that the heating effect seen in the other models is present and much more pronounced. It does not appear at first to be as drastic as in the other models, but since the magnitude of the maximum velocity is so much higher than in the previous models, a larger change will appear less significant. In this case we can clearly see that the overall size of the distributions is increasing as we move across the tail. In general, the shape of these distributions appears to be nothing more interesting than a shifted Maxwellian. The outer boundary of all the plots is fairly circular, with only some higher energy particles in the final few *y* boxes contributing any flux outside this rough shape. The asymmetries in *+v*$_x$ and *+v*$_y$ are always present, and there is no systematic deformation in the shape of these plots.
Figure 2.10 Fluid Parameters for YocBigE model.

We need to examine the appearance of the higher flux areas within the overall distributions. These show some interesting features. In the $y = -0.25$ and $y = 0.25$ boxes, there appear to be similar features to those that appear in the same boxes in the Yol model. This is somewhat disquieting. If these features can occur here, then are they solely due to the magnitude of the electric field? Alternately are they a feature of the way in which we chose particles? If they are solely a feature of the electric field magnitude, then they should also occur in all $y$-boxes that are fitted well. If we examine the other boxes that fit
this description (e.g. every ybox other than the first three) we see that this is not the case. In the $y = 1.25$ box there is not any of this higher flux for instance. The final two boxes show a slightly different shape of this higher level flux than before. These observations point towards electric field magnitude as not being the cause. There is also a question as to whether these higher flux levels are drifting in the field, or are stationary. As we shall see, this is not as important a question as it first appears.

What about the way in which particles were chosen then? If this was true, then all the models would show a similar kind of feature in the middle. Since we are dealing with a constant field, we should look back at the first model examined, $Yoc$, and compare it with this one. In $Yoc$, we determined that the main effects were only due to the heating effect seen as we moved across the tail. Looking back at Figure 2.7 we can see that there are no features of this type that occur in these middle boxes. What else could be the explanation? One culprit could be the flux levels.

Looking again at Figure 2.7 for the $Yol$ model the middle boxes show that there is a drastic deformation in the higher flux levels associated with the peak electric field. If we compare with the surrounding flux levels in these middle yboxes, we can see that this higher flux level is greater than the surrounding background levels by approximately a ratio of $5\times10^{-13}$ to $10^{-14}$. This is a factor of fifteen in the flux levels. In the $YocBigE$ version, we have a ratio of about $5\times10^{-14}$ to about $1-3\times10^{-14}$. This is factor of only two to five times. A factor of 15 in the flux levels is more meaningful than a small factor of 2-5.

Another point to remember is that the contours that are drawn are only meant to be an assistant to the color table. In this case they are misleading. The minimum and maximum flux levels present in the $YocBigE$ case are much closer together than in the other
Ey = 1.6 mV/m Constant Version
Z = 0 \ Vz = 0 \text{ km/s} \ Slices
4000 \text{ km/s}

\[ |B_{\text{magmax}}| = 4.1 \text{nT, gsm coordinates} \]

10\(^{-17}\) \ 10\(^{-16}\) \ 10\(^{-15}\) \ 10\(^{-14}\) \ 10\(^{-13}\) \ 10\(^{-12}\)

\( f(v), \text{s}^3/\text{m}^4 \)

Figure 2.11 *YocBigE* Distribution Function Plots
models. This means that the three contours that are drawn in this case are not at comparable values to those seen in the other models.

The regions of higher flux that do not seem to be drifting are not significant in that as we have just shown they are not significant features. They are not much more than statistical fluctuations of flux density. In some of the boxes they appear to be drifting, in others they do not. There is no obvious common characteristic that these weak enhancements share.

We can conclude that the drastic deformation seen in the distribution function plots of the Yol model are a function of the width and magnitude of the electric field. The other models show either no obvious deformations of this type (Yoc and YocBigE) or only weak deformations (Yo3). The next logical step is to look in some real spacecraft data to see if these modeled distributions are similar at all to those seen in fast flow events.

There are several other issues we need to address before we do that. First, there is the issue of holes in the distributions. Are they a real effect, are they statistical or are they related to how we picked particles? Second, we need to have a firm grasp of how the particle orbits are contributing to the features seen in Yol. We would also like to explore the granularity of these distributions. First we address the issue of holes.

2.13 Distribution Function Holes

Figure 2.12 shows two different groups of particles, each ranging from $y = -2.25$ to $y = -0.25$. Only the first five $y$-boxes were chosen to plot for this purpose, since the boxes on the other side of $y$ exhibit the same behavior. Each group was traced in the Yoc model, using the same input parameters. Each of these two groups is dominated by
Figure 2.12 Two Versions of the Yoc Trapped Group

Yoc Trapped Groups
Z=0 Vz=0 km/s Slices
2500 km/s

$|B_{magmax}| = 4.1 \text{nT}, \text{gsm coordinates}$

$10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12}$

$f(v), \text{s}^3/\text{m}^6$

$V_Y \quad V_X$

$Y=-2.25 \text{ V1}$
$Y=-1.75 \text{ V1}$
$Y=-1.25 \text{ V1}$
$Y=-0.75 \text{ V1}$
$Y=-0.25 \text{ V1}$

$Y=-2.25 \text{ V2}$
$Y=-1.75 \text{ V2}$
$Y=-1.25 \text{ V2}$
$Y=-0.75 \text{ V2}$
$Y=-0.25 \text{ V2}$
Trapped particles. If the holes are not statistical in nature, then we should see the same features reproduced in two groups run the same way with a different randomized group of particles. As we can see, there are small differences.

The first five plots, labeled V1, are slices taken from the group that contributed trapped particles across the entire $ygrid$ region for the $Yoc$ model. As we can see, several of them have characteristic holes at the center of the distribution. The boxes at $y = -1.25$, $y = -0.75$ and $y = -0.25$ all show this effect. The other two boxes do not show this effect as clearly.

The second group of five plots show slices of a group that was run using the same parameters as V1. This second group consisted of ions that were picked from the same initial distribution in velocity as V1, including all randomization and spatial grid settings. It is labeled V2. Other than the particular particles selected by the randomization routine, these groups are identical in every way. It is clear from this group that these holes do not appear to be consistent. The plots at $y = -1.25$ and $y = -0.25$ do not show holes. Rather they show a peak. On the other hand the box at $y = -0.75$ shows the same kind of hole that was visible in V1. This suggests that these holes are not a feature of the electric field, but are more an effect of the statistical nature of our particle choices.

Figure 2.13 shows a similar group of plots for the $Yoc$ group that contributed primarily Speiser orbits. These groups do not show any statistical fluctuations in this hole region, unlike the previous Trapped groups. Every distribution in this figure regardless of the version shows a depletion region in the same general area where the holes occur.
Figure 2.13 Two Versions of the Yoc Speiser Group
Another feature that is apparent is the complementary natures of these two kinds of particle orbits. Looking at the places where the Trapped particles in Figure 2.12 contribute flux, we can see that if we were to overlap those distributions with these new Speiser distributions in Figure 2.13 the result could be a balanced distribution. An equal ratio of these two kinds of orbits would give an isotropic distribution. The peaks of the Trapped distributions lie in a sharp region along the negative $v_y$ axis. The Speiser particles contribute most of their flux in a sort of umbrella shape that always has holes in the spots that the Trapped particles fill. It is also clear that the Trapped group has some Speiser type particles, since there is particle flux in the regions that the Speiser group fills in.

From these observations it is clear that the Trapped particles will contribute to this hole region, and the Speiser groups do not. There must be some reason for this, as we are picking particle energies from the same distribution in both initiation regions. As it turns out, there is a reasonable way to understand this, based on the electric field drifts that individual particles are subject to.

The Speiser group is initiated at the edge of the current sheet. Particles are started here with random energy, pitch and phase angles so that they will generally follow a field line tailward and interact with the current sheet, usually in a Speiser orbit fashion. There are effects caused by the electric field drift, $v_E = E \times B / B^2$, that prevent low energy particles started at our initiation point from reaching the center of the current sheet in our $x$grid. We have chosen this initiation region at $x = -22.0$, $y$=randomized and $z=0.4$. Although there is some randomization used in $x$ also, it is not important here, and the randomization in $y$ does not affect this argument. In this region the magnetic field is predominantly $B_x$. The magnitude of $B_x$ becomes large rapidly as we move away from the
current sheet, ranging from 0.0 nT at the exact center to ~30 nT at \( z=0.1 \) \( R_E \), increasing to over 40 nT as we reach \( z=0.4 \) \( R_E \). Contrast this with the \( B_z \) values that range from 3.45 to 3.29 nT in this same range. For the \( Y_{oc} \) model, the magnitudes of the electric field drift in \( z \) ranges from \( (E_y/B_x)/(1 + B^2_z/B^2_x) \) values of \(-13\) km/s at \( z=0.1 \) to \(-10\) km/s at \( z=0.4 \). The negative sign means that a particle being traced forward in time is being forced towards the current sheet by this drift.

Particles will be affected differently by this kind of drift depending on their velocity. A 5keV particle has an average total velocity of 1000 km/s. Assuming isotropy means that the particle is moving at about 600 km/s in each direction. The parallel component of 600 km/s for this particle will dominate any electric field drift effects. If this particle is moving tailward, then the electric field drift will force it towards the current sheet at around 10 km/s, a small effect. There is also the bulk convection of 160 km/s forcing this particle Earthward. These drifts will have an effect on this particle, but it will make it to the current sheet inside our grid, albeit slightly Earthward of the point it normally would reach with no electric field drifts acting.

Contrast this with the low energy particle that inhabits the region where the holes appear. We can assume that a typical particle here is in the lowest velocity bin of our velocity grid. Assuming isotropy, and that the particle has the midrange of velocity in each bin gives us a magnitude of 80 km/s for each component. We can see that the electric drifts will dominate this particle. There are two cases, each of which guarantees that this particle will not make it to the current sheet.

First, if this particle is moving tailward towards the current sheet, it will have a parallel velocity of about 80 km/s in the \(-x\) direction. There is a drift of \(-10\) km/s in \( z \) acting
to force this particle towards the equator faster than normal. Now add in the 160 km/s Earthward drift from the electric field, and we can see why this kind of low energy particle will hardly ever make it to the current sheet in our box (also remember that the Earthward edge of our $x_{grid}$ is at $x = -20 \, R_E$). Instead of moving tailward towards the center of our gridding region, the particle is moving Earthward, out of our box. It will never reach the current sheet in our gridding region.

The other case is a little more subtle. If this particle is heading Earthward, 80 km/s in the positive $x$ direction, then in order for it to have reached this point in space, it had to drift southward from a higher $z$ region. The parallel flow here is primarily in the $x$ direction, so there will be little net motion towards the current sheet. The only motion in the $z$ direction in this region comes from the electric field drift associated with the $B_x$ component. Since this drift acts to force the particle southward, the particle had to drift in from a point far away from our grid, and it will never contribute in the center of the current sheet. Also note that this particle will have a net Earthward drift of 240 km/s, since its parallel $x$ velocity and the bulk convection velocities will add here.

These effects have been seen in several dozen orbit plots, and are reproducible over a wide range of low velocity pitch and phase angles. There seems to be little extra insight that can be gained from plotting one of these myriad orbit plots, so the above explanation should suffice.

The way to force the Speiser groups to contribute these particles in the center of our grid would be to change the location of the initiation point, moving it tailward and closer to the sheet. This will have some effects on how the higher energy particles interact.
with the sheet, but it will fix the low energy problem, and should largely remove these holes in the distributions.

2.14 Ion Orbital Contributions to Distribution Plot Features

Finally, we want to understand the nature of the features seen in the $YoI$ model. Since we have just examined two sets of groups from the $Yoc$ model, we can compare how these two kinds of groups contribute to the combined distributions in the $YoI$ model.

In Figures 2.12 and 2.13, we could see that there was little $y$ dependence in each groups distribution functions. This was represented in the combined version that we examined (Figure 2.5). We now want to analyze the contributions that each orbit type make to the combined $YoI$ group.

Figure 2.14 shows the group that contributes Trapped particles. The fluid parameters for this group were analyzed in section 2.6, Figure 2.3. This figure is organized identically to Figure 2.7 in which the combined distribution for $YoI$ was plotted. We can see that the Trapped orbit characteristic is apparent in all the boxes. There is a strong feature that shows as we near the peak electric field regions. Although the shape of the distribution does not change, the flux levels drop dramatically as we enter the peak field region in $y = -0.25$ and $y = 0.25$. The distributions here are sparse, with little high flux. Contrast this with the distributions at $y = -2.25$ and $y = 2.25$. In these boxes the flux levels are high. This explains the lack of distribution flux seen in the combined $YoI$ (Figure 2.7 again) model at these same boxes for the negative $v_y$ component. The Trapped particles that contribute in the negative $v_y$ region are moving Earthward quickly, thus we have a low density of Trapped particles here. This movement can also be seen in the shifting towards positive $v_x$ that appears in the boxes near $y = -0.25$ and $y = 0.25$. 

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This density drop is also reflected in the fluid parameters in Figure 2.3. The current drops considerably as we near the center of the electric field, until at the peak electric field region, this group contributes negligible current compared with the y edges.

Figure 2.15 shows the Speiser dominated group for the Yo1 model. It is also organized the same way as the original combined group in Figure 2.7. We see that there are several interesting features that appear here. First, there is a similar tendency towards a diminishing particle flux density as we near the peak electric field regions. This matches what was seen with the Trapped particles. However, the shapes of these distributions are altered as well, and it is more than just the general shifting towards positive $v_x$ that we saw in Figure 2.14.

There is a distinct anisotropy seen as we near the electric field region. In the boxes at $y = -1.75$ and $y = -1.25$ there are distinct enhancements of higher intensity flux towards the positive $v_x$ direction. In the boxes between $y = -0.75$ and $y = 0.75$ we can see that the Speiser particle ‘umbrella’ shape is clearly centered around a strong positive $v_x$ value.

In the box at $y = 1.25$ a surprise appears. The high level flux is centered in the negative $v_x$ direction. This is visible to a smaller degree in the box at $y = 0.75$ as well. This strange effect is likely due to the electric field causing particles that would balance this feature being accelerated in such a way that they do not return to our grid region to balance this effect. Recall from the fluid parameter plots (Figure 2.3) of this group that as we moved across the tail that the bulk velocities in $x$ became negative for the most positive $y$boxes. This effect was mostly removed in the Yo1 combined model when we added in some of the other groups that were randomized over smaller $y$ regions. These other groups

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Figure 2.14 Trapped Particle Distribution from Yo1 Model
Figure 2.15  Speiser Particle Distribution from Yo1 Model
acted to balance the flows, as well as the currents. Thus the distribution plots on the more positive $ybox$ values will tend to be skewed for these individual groups.

Finally, there is an easy way to understand why the Trapped particles show little anisotropy compared with the Speiser particles when the electric field width approaches an ion Larmor radius. The ion Larmor radius that we are referring to is the radius of a Speiser particle, not a Trapped particle. Recall Figure 1.3 from Chapter 1. In this figure we saw simple examples of both a Speiser and a Trapped orbit. The Speiser orbit meandered about the weak $B_z$ about the center of the current sheet, giving us an ion Larmor radius of $r_{LS} = (mv_\perp)/(qB_z)$. However, when we analyze the Trapped particles, we can see that the way the orbit gyrates in this case implies that the proper field component to be used here is $B_x$. Furthermore, the value of $B_x$ that is relevant is at the point where the orbit starts to turn over, or where the velocity perpendicular to the field is entirely in the $z$ direction. This would place the field at around $z = z_0$, giving us a Larmor radius in this case of $r_{LT} = (mv_\perp)/(qB_x(z_0))$. If we have two particles with identical perpendicular velocities, then the Larmor radii will have the ratio:

$$\frac{r_{LS}}{r_{LT}} = \frac{B_x(z_0)}{B_z(0)}$$  \hspace{1cm} (2.15)

Using some typical numbers here of $B_z(0) = 2.5$ nT and $B_x(z_0) = 25.0$ nT we can see that these particles will have a factor of ten between their gyration radii. In other words, the scale sizes of these two particle types are an order of magnitude different. The Speiser particles will see a large gradient in the electric field as they cross the current sheet with typical scale sizes of 1 $R_E$. The Trapped particles will only see a small electric field change in an orbit that is typically 0.1 $R_E$ in scale.
For a numerical comparison, we compare the Yoll model peak electric field of 1.6 mV/m at \( y = 0 \), with the value at \( y = r_L \). We can see the striking difference in the potential gradients that these two orbit types see by doing this. Using 1 \( R_E \) for the Speiser particles gives an electric field value of 0.65 mV/m. This is a difference of 0.95 mV/m, a large potential change. For the Trapped particle having a 0.1 \( R_E \) Larmor radius, we get an off-peak electric field value of 1.58 mV/m. This is almost no difference. From these examples we can see that the Trapped particles will behave as if they were under the influence of a strong constant local electric field, while the Speiser particles will see a very strong gradient.

2.15 Statistical Effects

Figure 2.16 shows the first 5 \( y \)boxes of two different distribution functions. Both are examples of a group dominated by Trapped particles, randomized over 20 \( y \)boxes in the Yoll model. The top row shows a group run with 1250 particles, the bottom row shows a group run with 20 thousand particles. This can be compared with the top row of Figure 2.13, which shows a similar group run with 5 thousand particles. This shows us the statistical effects of increasing the number of particles in a group by successive factors of 4 (1250 x 4 = 5000; 5000 x 4 = 20000).

We can see that the three groups all have similar features. They all show a strong Trapped particle signature, with a characteristic decrease in particle flux as we enter boxes with larger electric fields. The statistics in the 1250 particle case are clearly poor, although the features identified in the 5000 particle case are visible. The 20 thousand particle case shows a very smooth distribution, with much of the granularity seen in the 5000 particle case disappearing. The features seen in the 5000 particle case are still visible, and
Yo1 Model, Statistics Tests
Z=0 Vz=0 km/s Slices
2500 km/s

$|B_{mag max}| = 4.1 \text{nT, gsm coordinates}$

Figure 2.16 Statistics Tests in the Yo1 Model Field
there is little difference in the low electric field regions. Only in the peak electric field region does there appear to be a difference in the distributions, and it appears to be a minor effect. The distributions show the same general shape and the peak fluxes occur in the same places. The main differences occur in the low flux background regions, which are much smoother in the 20 thousand particle case than the 5 thousand particle case.

The fluid parameters are not plotted here. The reason for this is that they are virtually identical to those seen in Figure 2.3. Each of these groups with differing numbers of particles show nearly identical velocity plots. The only difference in these plots is that the group containing twenty thousand particles is much smoother than the others. Also, the currents that each group contributes is identical in shape to each other. The only differences are of overall magnitude, and since these groups will ultimately be used in a fit, the fitting weights will adjust accordingly.

To conclude this section, we have shown that there are interesting features that appear in velocity distributions when subject to an electric field that is of the same general scale size as an ion Larmor radius. Speiser orbits and Trapped orbits are affected differently in this region. The Speiser orbits exhibit a pronounced asymmetry in the +\(v_x\) and +\(v_y\) directions that the Trapped particles do not. This seems to be the origin of the distribution function features. Next, in Chapter 3 we look through several case studies of Geotail data to see if these kinds of features are recognizable in a real fast flow event.
In this chapter four case studies will be shown. These case studies are intended to be compared with the results from Chapter 2 concerning the distribution function features in models of confined electric fields. Appendix A describes the search engine and the parameters of this search from the Geotail CPI database. This chapter concentrates on the four events chosen from that search.

The events will be explored in detail. Fluid parameters for each event will be analyzed, and the times most likely to show distinctive distribution features will be identified. These times will be plotted using a similar configuration used in the previous chapter. Conclusions about each event will be reached separately. They will then be compared with each other to draw more general conclusions about events in real data.

3.1 Data Introduction

In Appendix A a more detailed discussion is given concerning the relevant parameters to examine when picking cases. The entire data set was searched using a well defined set of parameters to limit the cases to those that have a good chance of being similar to our models. More than twenty cases were found. These cases were examined to see which
ones had either the highest flows, the longest durations or both. Four of them were chosen solely based on these macroscopic parameters for distribution function analysis.

All of the cases chosen have a high peak $V_x$ velocity. The smallest one has a peak of 700 km/s, the largest reaches a peak of 1000 km/s. Another important characteristic that was focused on in these events was duration. The shortest of these events has an enhanced bulk flow for approximately 7 minutes, the longest lasts for over half an hour. In many of these cases, this period of enhanced $V_x$ lasts longer than the period of large $E_H$ electric field that was the original search parameter. This parameter $E_H$ is derived from the magnetic fields and bulk velocity components, and stands for high electric field. These groups are not perfect for comparison though. Two of them have significant $-V_y$ components throughout the convection event. There are also varying degrees of fluctuation in these events. However, these events are likely to be as close to the parameters of the model as any that can be found.

One minor difficulty should be noted. Since the database that we have of Geotail data is given in 3 cycle sums, we are also plotting 3 cycle summed distributions. However, in all but one of these cases the two sum cycles are slightly off by 1 or 2 cycles. This makes essentially no difference in the analysis, but the $E_H$ values on the plots may be different than those mentioned in the text. These values will be close to one another, and since this is as much of a qualitative analysis as a quantitative, these small differences are not important.

3.2 Case 1: November 1, 1995

Figure 3.1 shows the fluid parameters for this event. The satellite was located at approximately $(-22.7, -6.2, -1.5) R_E$ at this time. All satellite positions in this chapter
will be in the form \((x,y,z)\), where the coordinate system is in satellite coordinates, which are essentially the same as Geocentric Solar Ecliptic (GSE) coordinates. The GSE coordinate system has the \(x\) axis in the Sun-Earth direction, with Earth as the origin. The \(z\) axis is perpendicular to the ecliptic plane, and the \(y\) axis completes the right handed orthogonal system.

Geotail CPI measures quiet time plasma until about 02:00 Universal Time (UT). Before this time the bulk velocities are low. \(V_x\) is small, with the magnitude staying between \(\pm 200\) km/s. The spacecraft makes a slow crossing of the center of the plasma sheet at approximately 01:50, where the sign of \(B_x\) slowly changes from negative to positive. The ion temperature is steady in this region, with an average value of approximately 1-3 keV.

There is a short burst of high \(V_x\) flow from 01:48 to 01:55 UT concurrent with a current sheet crossing where \(B_x\) changes sign. In this short period, the \(V_x\) magnitude ranges from 140 to 300 km/s, with an average \(V_x\) of 230 km/s. At 01:54 there is a clear dipolarization signature, as \(B_z\) jumps from 1.6 to 4.5 nT. \(B_z\) remains near this magnitude for the rest of the event.

At 02:04 UT, the main flow event begins. From 02:04 to 02:27 UT the \(V_x\) flow remains high, ranging from a low of 100 km/s to a high of 960 km/s, with the average \(V_x\) approximately 460 km/s in this period. The \(E_H\) parameter does not track exactly with these \(V_x\) flow magnitudes. Since \(V_y\) is important in the derivation of this parameter the periods of highest \(E_H\) correlate with high magnitudes of both components of velocity. During the period of high \(V_x\) flow from 02:04 to 02:27 UT, \(E_H\) fluctuates from a mini
Figure 3.1 November 1 1995 Data Event Ion Fluid Parameters

minimum of 0.8 mV/m to a maximum of 4.4 mV/m, with an average $E_H$ of 2.5 mV/m.

In this high $E_H$ time period, we need to pick several distribution functions to study. In keeping with the previous chapter, we will pick the $V_z = 0$ slice of several
times. There were ten distribution plots per page in the previous chapter, so we will pick the ten most likely times to show features in each of these data events. This is done primarily to limit the number of plots made. There are many plots that can be made of this data, but there is not enough time or space to show them all. We need to limit the data in some consistent way. We do this by keeping the number of distribution slices for each event fixed at ten plots on one page for each of the four events in this chapter.

Whenever possible the points picked should be consecutive times. If too much time is skipped between measurements, the magnetotail configuration may have changed too much to allow us to compare two plots even from the same data event with any confidence.

In this event, the ten measurements from 02:04 to 02:14 are chosen. In this time period, only two of these measurements are significantly below 2 mV/m. These two points can be a basis of comparing different electric field strengths directly. Another advantage to this time period is that only one $V_y$ measurement in this time period is negative.

Figure 3.2 shows the distributions for the ten spacecraft measurements chosen. The format for these plots is identical to the plots used for the orbit tracing models, with a few minor differences. In this case each slice is labeled by time in UT, and the $E_H$ value in mV/m. Also note that in this case the value plotted for the maximum magnetic field magnitude (Bmagmax) has real meaning in this case. The magnetic fields will be different for each time, and this maximum magnetic field magnitude gives us a way of scaling the fields so that they can be compared in a meaningful way.
November 1, 1995
Vz=0 Slices
3000 km/s

|Bmagmax| = 15.0 nT, gsm coordinates

f(v), s²/m³

0204:20 Eh=2.4 0205:26 Eh=3.3 0206:31 Eh=1.9 0207:37 Eh=3.3 0208:42 Eh=0.3

0209:48 Eh=1.9 0210:56 Eh=2.7 0212:02 Eh=2.0 0213:10 Eh=3.4 0214:16 Eh=1.3

Figure 3.2 Distribution Function Plots for November 1, 1995 Event
Table 3.1: Case 1 Parameters

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<th>$V_y$, km/s</th>
<th>$B_z$, nT</th>
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<td>291</td>
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<td>-213</td>
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<td>8.3</td>
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These slices look similar to the middle boxes in the YoI model from Chapter 2 (Figure 2.7). The times from 0204:20 to 0213:10, excluding 0208:42, exhibit extreme isotropy. The flux is highly concentrated in the $+v_x/+v_y$ region in the same way that the YoI model showed in the peak electric field boxes at $ybox5$ and $ybox6$. These times are associated with high values of $E_H$, ranging from 1.9 to 3.4 mV/m. The only two times that do not show this signature are the ones associated with low $E_H$, 0208:42 and 0214:16, with $E_H$ values of 0.3 and 1.3 mV/m respectively.

Table 3.1 shows some relevant fluid parameters and magnetic field measurements for these plots. All of the plots in this group show significant anisotropy except the ones at 0208:42. There are two possible reasons for this. At this time, the magnitude of $B_z$ becomes small, 0.4 nT. Also, the flow velocity becomes small here, with $V_x$ only around $-30$ km/s. The times that flank this period have flow speeds much larger than this value.
From this one case we cannot be sure if it is the small magnetic field or the small flow that makes this distribution isotropic.

If we assume that these distribution features are associated with an electric field of the same general width as the ion Larmor radius, we can estimate the thickness of this electric field using simple estimates. Using a similar argument to the one in which we picked the electric field scale, we can estimate the thickness of the electric field here. We make the assumption that a typical value of $v_\perp$ can be derived assuming the average $E_\perp$ is approximately equal to the average ion temperature. The average ion temperature for these ten measurements is approximately 7 keV, with small fluctuations on the order of no more than 2 keV. Couple this number with the average $B_z$ of 5.5 nT, and we can make a rough estimate for the average Larmor radius for these ions. The value of $B_z$ is also fairly steady, with only one value significantly different than the average. We get a result of approximately 0.4 $R_E$. This is just a rough estimate, but it seems to be reasonable. The average energy of these measurements is close to the energy of our models. The magnetic field is a little larger than double the value that we used. These facts indicate that because we see similar looking distributions we can calculate the electric field width to be about half that of our models, since Larmor radius is inversely proportional to $B_z$.

Concluding this discussion of Case 1, we can see that there is clear evidence for distribution function features similar to those seen in the $YoI$ model. There is some question as to the reason why the time at 0208:42 shows such small anisotropies. Both the flow velocity and the magnetic field are small there, so it could be either.
3.3 Case 2: May 15, 1996

The fluid parameters for Case 2 are plotted in Figure 3.3. This event occurred on May 15, 1996. Geotail was located at (-11.7, 0.7, 1.5) RE. In many ways this event is similar to Case 1. We see a quiet period before the main event occurs. During this quiet time from 00:45 to 01:15 UT, the plasma flows are steady and not large. There is a gradual current sheet crossing at 00:54 UT, then a fast flow event begins at 01:15.

At this time, there are several obvious signs that we are in an excited magnetotail state. From 01:15 to 01:22, the flow velocity $V_x$ ranges from 150 km/s to a high of 680 km/s. The average $V_x$ in this period is approximately 390 km/s. We also see a dipolarization signature in $B_z$ at 01:16. At this time $B_z$ suddenly jumps from 2.9 to 6.5 nT. This larger $B_z$ remains for the rest of the event.

The $E_H$ parameter is large in a small band in this event. From 01:16 to 01:22 $E_H$ ranges from a minimum of 1.4 mV/m to a maximum of 6.3 mV/m. The average $E_H$ in this time period is 3.5 mV/m. The distribution functions chosen to plot overlap this period of high convection electric field, from 01:15 to 01:25 UT.

Figure 3.4 shows the distribution plots for this event. One thing that is immediately apparent is that the temperature and densities of this case are much higher than those of the previous case. This is mainly due to the fact that this event occurs much closer to the Earth than the previous case. The plasma density and temperatures are all higher here. The magnetic fields are also changed, with higher average $B_z$ values as the dipole becomes stronger.
There are five times that have high $E_H$ in this event during the period from 0117:21 to 0121:41 UT. The values of electric field in this time period range from 1.9 to 5.5 mV/m. The previous two times have small electric fields, with an average value for the
first three plots of 0.6 mV/m. The last three also have small fields, with an average electric field of 0.8 mV/m. The three distinct periods seen here show different kinds of distributions.

The first two times plotted, 0115:12 and 0116:17, show little anisotropy. They appear to be Maxwellian distributions, with an enhancement in the positive $v_x$ velocities showing that there is some bulk flow here. There are no obvious deformations here otherwise. Table 3.2 shows some velocity and magnetic field components for these times. The values of $B_z$ are small, both around 2 nT. Also, the flow speeds are relatively small. They do not approach the peak velocities seen in some of the later times.

Likewise the final three times from 0122:45 to 0124:54 are not deformed much. In fact these events show a distinct negative $V_x$ flow, although the magnitude is small, only approximately -40 km/s. $B_z$ is fairly large for these three times, larger than 9 nT for all three. However, the trend here is for decreasing $B_z$, as opposed to the periods of highest anisotropy which showed a distinctive increase in this parameter. These beginning and end times are not what we are interested in though.

The main event shows different signatures. From 0117:21 to 0121:41 the distributions show strong deformations. The shape of these deformations is again similar to the features seen in the YoI model. Because of the higher densities overall, this event is not as clear as the previous one, but it still shows features that support the model in the other four large $E_H$ times. The value of $B_z$ consistently increases over the entire event. The peak anisotropies seem to occur just before the peak magnetic field value though.
Figure 3.4 Distribution Function Plots for May 15, 1996 Event
Table 3.2: Case 2 Parameters

<table>
<thead>
<tr>
<th>Time, UT</th>
<th>$V_x$, km/s</th>
<th>$V_y$, km/s</th>
<th>$B_z$, nT</th>
<th>T, keV</th>
</tr>
</thead>
<tbody>
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<td>159</td>
<td>-38</td>
<td>2.1</td>
<td>9.6</td>
</tr>
<tr>
<td>0116:17</td>
<td>362</td>
<td>2</td>
<td>2.6</td>
<td>10.9</td>
</tr>
<tr>
<td>0117:21</td>
<td>593</td>
<td>162</td>
<td>3.0</td>
<td>8.5</td>
</tr>
<tr>
<td>0118:28</td>
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<td>349</td>
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<td>9.6</td>
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<td>0121:41</td>
<td>388</td>
<td>184</td>
<td>12.9</td>
<td>10.9</td>
</tr>
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<td>-30</td>
<td>-31</td>
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<td>0123:50</td>
<td>-39</td>
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<td>7.7</td>
</tr>
<tr>
<td>0124:54</td>
<td>-45</td>
<td>66</td>
<td>9.0</td>
<td>9.3</td>
</tr>
</tbody>
</table>

At 0117:21 and 0118:28 we see the largest anisotropies. These times correspond to the highest $V_x$ flow speeds, not the highest magnetic field or $E_H$ value. The value of $B_z$ peaks at 0121:41, 3 minutes after the highest flow speeds.

Again, we can estimate an electric field width from these five distorted distributions. There are more changes in this case than in the previous one, particularly in $B_z$ but we may still make an estimate of electric field thickness using the average values for the fast flow times. Using an average ion temperature of 10.6 keV and an average $B_z$ of 6.8 nT, we get a value of approximately 0.4 $R_E$ for the Larmor radius.

To conclude the examination of Case 2, we have seen similar anisotropies for a case that occurred much closer to the Earth than Case 1. The densities and temperatures were both higher than in the previous case, as were the average values of $B_z$. Similar looking distributions were seen, although the increased densities and temperatures made...
any features less obvious than in the previous case. Also, it is seen that the values of $B_z$ and $E_H$ had less to do with the presence of anisotropy than the magnitude of the Earthward flow velocity does.

3.4 Case 3: November 24, 1996

Figure 3.5 shows Case 3, which occurred on November 24, 1996. Geotail was located at $(-22.2, -0.4, -2.6) \text{ R}_E$. This event is similar to Case 2, in that it does not last a long time, although it has a large peak flow velocity.

Like the previous two cases, before the fast flow event occurs, the magnetotail is quiet. The plasma flows are small, and there are no large fluctuations in the magnetic field parameters. At 10:20 UT, the event begins.

In this event, we have a fast flow that begins at 10:20 and lasts until 10:35 UT. $V_x$ ranges from a minimum of 110 km/s to a maximum of 850 km/s, with an average flow speed of 470 km/s. Unlike the two previous cases, there is no obvious dipolarization in $B_z$. The magnetic fields appear to be steady throughout this event, with only gradual changes occurring.

$E_H$ peaks from 10:20 to 10:31 UT, with a minimum of 1.4 mV/m and a maximum of 6.0 mV/m. The average $E_H$ in this period is 3.3 mV/m. The first point is the lowest electric field, so we choose the final ten points in this group to plot, from 10:21 to 10:31 UT.

Figure 3.6 shows the distribution plots for this case. These plots are similar to those seen in Case 1, which is not surprising since Geotail is in a similar location during this event. $E_H$ remains large for almost all of this event, with only the plot at 1022:38 being less than 1.1 mV/m.
All of these plots show the same features seen in Cases 1 and 2, although there seems to be more fluctuation in this case than in the previous two. Another strange observation is that the lowest $E_H$ time shows some of the strongest anisotropy at 10:22:28 UT.
November 24, 1996
Vz=0 Slices
3000 km/s

| Bmagmax | = 15.1 nT, gsm coordinates

f(v), s/m^3

10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12}

1021:33 Eh=3.0
1022:38 Eh=0.3
1023:42 Eh=2.7
1024:46 Eh=3.2
1025:50 Eh=1.1

1026:55 Eh=3.5
1027:59 Eh=1.2
1029:03 Eh=1.4
1030:07 Eh=3.9
1031:12 Eh=3.5

Figure 3.6 Distribution Function Plots for November 24, 1996 Event
Table 3.3 Case 3 Parameters

<table>
<thead>
<tr>
<th>Time, UT</th>
<th>$V_x$, km/s</th>
<th>$V_y$, km/s</th>
<th>$B_z$, nT</th>
<th>T, keV</th>
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<td>407</td>
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<td>5.5</td>
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<td>1023:42</td>
<td>383</td>
<td>362</td>
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<td>7.5</td>
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<td>1024:46</td>
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<td>1030:07</td>
<td>268</td>
<td>44</td>
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<td>489</td>
<td>133</td>
<td>6.9</td>
<td>6.4</td>
</tr>
</tbody>
</table>

The high flux enhancements that have been seen are present here in the $+v_x/+v_y$ region for almost all these plots.

Table 3.3 shows the same parameters for these plots as the previous tables showed for their respective events. There is more $B_z$ fluctuation in this event than in the other two events so far, although there are only three individual times that have values that are significantly different than the average.

From 1021:33 to 1025:50 we have similar velocity components. $V_x$ is large and positive in all these cases, as is $V_y$. The typical value of $B_z$ here is around 3 to 5 nT. The temperature is fairly steady around 6 to 8 keV. The time at 1022:38 has a value of $B_z$ much smaller than the others, with $B_z = 0.4$ nT here. Although this parameter is significantly different than the other times in this subset, the distribution shows little difference. There is less flux at low velocities than in the other plots, but the rest of the distribution...
looks similar to the others. This supports the conclusion that from Case 2 that the velocity of the flows is more important in determining the anisotropies in these cases.

The next three times from 1026:55 to 1029:03 have negative components of $V_y$. Although the distributions are not oriented in the positive $V_y$ direction, there are still anisotropies present. The correlation with $V_x$ still shows here, as the time 1027:59 has the smallest $B_z$ value of these three, 1.8 nT, but the time with the smallest $V_x$ bulk flow, 1029:03 shows the least anisotropy.

The last two plots show little anisotropy, as the flow velocities are small. In 1030:07 $B_z$ jumps to 14.3 nT, but since $V_x$ is only around 270 km/s, there is little anisotropy when compared with the previous times with large flows. This time also shows a large value of $E_H$ which does not correspond to a large flow.

The temperature and $B_z$ values of approximately 7 keV and 5 nT respectively are nearly identical to Case 1. This gives us a Larmor radius estimate of 0.4 RE again.

Case 3 shows similar conclusions to the first two cases. Periods of the largest anisotropy occur during the highest flow periods, not during the high $E_H$ periods. The anisotropies that are here are again similar to those seen in the Yol model.

3.5 Case 4: January 18, 1998

The final event examined in this chapter is Case 4, which occurred on January 18, 1998. Geotail was located at (-26.5, 7.1, -2.7) RE. Figure 3.7 shows the fluid parameters of this event. This event is different than the other three, in that the fast flow lasts for a long time. The period of high $E_H$ is not as long, but on the whole this is a much longer lived event than the other events in this chapter.
Like the previous cases, the magnetotail is quiet before the fast flow event occurs. From 13:01 to 13:09 UT there is a small flow burst. This small burst ranges from a minimum of 100 km/s to a maximum of 300 km/s, with an average flow speed of 210 km/s. At 13:20 UT the main event begins.

The main flow event lasts from 13:20 to 13:57 UT. $V_x$ ranges from 150 km/s to a maximum of 830 km/s, with an average flow speed of 430 km/s. During this event $B_z$ shows some fluctuations, but there is no obvious single dipolarization as in some of the previous cases.

Although the period of enhanced $V_x$ lasts for a long time, the magnitude of $E_H$ does not. The reason for this is that the magnitude of $B_z$ remains fairly large throughout this event (approximately 5 nT). The only times in this event that fit the search parameters also have large $V_y$ components. In this case, many of these $V_y$ components are negative, making this event less than ideal to compare with our model. However, it can be useful to see what kinds of effects this can have, so we will proceed with this case.

The maximum values of $E_H$ occur between 13:27 and 13:35 UT. In this time $E_H$ ranges from 1.1 mV/m to a maximum of 4.9 mV/m. The average value is 3.4 mV/m. There are only 9 points in this period, so we pick the point immediately preceding the first one to round out our ten distributions plots. We will be plotting the ten distributions from 13:26 to 13:35 UT.

Figure 3.8 shows the distribution plots for this event. This event is not as clear as the previous three. There are several times here that show consistent $-V_y$ flow. This may be related to the location of this event. We are located at $y=7.1 R_E$ here. The plasma that flows Earthward in this region must also have a large flow in the $-y$ direction, since the
magnetic field in this region has to connect back to the Earth. Contrast this with Case 1 which was located at \( y = -6.2 \) \( R_E \). This first case showed significant positive flow at all times. The magnetic field in these regions has a large average \( y \) component that will act to
January 18, 1998
Vz=0 Slices
3000 km/s

$|B_{\text{magmax}}| = 13.8\, nT$, gsm coordinates

1326:56 $E_h=1.3$
1328:03 $E_h=4.2$
1329:07 $E_h=2.7$
1330:11 $E_h=4.1$
1331:15 $E_h=2.4$
1332:19 $E_h=4.0$
1333:23 $E_h=4.1$
1334:27 $E_h=3.8$
1335:31 $E_h=1.7$
1336:35 $E_h=0.6$

Figure 3.8 Distribution Function Plots of January 18, 1998 Event
Table 3.4: Case 4 Parameters

<table>
<thead>
<tr>
<th>Time, UT</th>
<th>$V_x$, km/s</th>
<th>$V_y$, km/s</th>
<th>$B_z$, nT</th>
<th>T, keV</th>
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</tr>
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</table>

channel any plasma towards the Earth. This is contrary to the model, in which we con­
centrated on the midnight plane which has little to no $B_y$ component. It is instructive to see
what kinds of effects this has on the distributions though.

Similar features to the previous cases can be seen in 1328:03 through 1331:15 UT.
The high flux portions of these distributions are oriented primarily in the $+v_x$ direction,
with small $v_y$ components. From 1332:19 to 1335:31 the distributions are clearly aligned
towards the $-v_y$ direction. Other than this flow direction change, the shape of the distribu­
tions are still similar to those seen in the previous three data events and the $YoI$ model.

The first two plots at 1326:56 and 1328:03 show small $V_y$ flows. There is signifi­
cant anisotropy in the second time here, as the flow velocity increases from 320 km/s at
1326:56 to 450 km/s at 1328:03. There is also a large increase in the value of $B_z$, from 4.0
to 9.5 nT. These two times are similar to the other cases.
The remaining times here all have significant $-V_y$ flows. The $V_x$ flows still dominate the overall convection, but the distributions show this negative $y$ flow without question. Aside from the orientation of the anisotropies, the shape that these distributions display is similar to the other events. There does not appear to be a strong correlation with instantaneous magnetic field orientation, since the magnetic field $y$ component fluctuates considerably, yet the flow remains in the same direction.

Calculating the electric field width for this case in the same way as the previous models yields a value of 0.4 $R_E$, for an average ion temperature of 6.5 keV and average $B_z = 5.5$ nT. Again, this agrees well with the other three events.

3.6 Case Study Conclusions

We have examined four fast flow events here. The events were chosen for their large peak flow velocities and duration. The four events all showed similarities in the velocity space distributions despite their differences in location. Distribution features similar to those seen in the $YoI$ model were observed in all cases to some degree. The two events that most closely matched the magnetic field model, Case 1 and Case 3, occurred in a region of the magnetotail that most closely matched the conditions of the model, although Case 1 occurred on the flank of the magnetotail that will cause more $V_y$ flow in general. The event that took place near Earth, Case 2 also showed some of these features to a lesser degree. The last event was measured in the opposite magnetotail flank from Case 1, and showed effects due to the predominantly negative $V_y$ flow there.

It is interesting to contrast these two flank $V_y$ flows with long term convection studies carried out by many different groups [Angelopoulos et al., 1993, Paterson et al., 1998; Hori et al., 200]. These studies, using different data sets, have shown that the pre-
dominant plasma flow in the flanks is directed away from the Earth. The flow approaches the Earth and bends to flow around it, not towards it as these two flank events have shown. It is unclear whether these two events are atypical for fast flows, or if there is a more interesting effect occurring. More flank fast flow events are needed for study to answer this question.

These cases all show features similar to those observed in the YoI model. Electric field widths were calculated for all of these events assuming that the distributions seen were occurring in electric fields similar to the YoI model. In all cases, a width of 0.3 to 0.4 RE was derived. This width will be approximately half the width of the electric field region if the comparison to the YoI model is correct (remember that $y_o=1.0$ RE is half the width of the electric field region in the models). This corresponds to a thickness of the electric field region to approximately 0.8 RE in all the cases. The periods of greatest anisotropies were determined to occur for the highest values of $V_x$, not the highest values of $E_H$. 

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CHAPTER IV

SUMMARY AND DISCUSSION

The goal of this work was to identify a plasma configuration in the magnetosphere that has a good chance of exhibiting distinctive non-adiabatic features in velocity space distributions. Once a suitable kind of event was established, then orbit tracing models were to be run to determine the extent of these features. Finally, once the models were understood, spacecraft data was to be analyzed to see if the kinds of features seen in these modeled distributions could be seen in real data. All of these goals have been accomplished.

The magnetotail configuration chosen was a fast flow event. There were several reasons to choose such a configuration. One reason was that these fast flows are commonly seen during or just after the Growth phase of substorms. In this period the current sheets are much thinner than usual, and there is a much better chance to see distinctive features in these distributions. Also, the fast flows events are simple to find in spacecraft data and are unmistakable in their signatures.

Three main models were used to generate the main orbit tracing models. Using the COT technique we generated self consistent models of the ion distribution functions that were bounded by well-defined Cartesian and velocity space bins. These models showed
some interesting features in the distribution functions as we allowed the electric field width to become as thin as the ion Larmor radius about the weak $B_z$ at the center of the current sheet. A fourth model was also generated as a test of the electric field magnitude used in the thinnest electric field width. This model showed only weak features and it was concluded that the width of the electric field was the main contributor to the features that were seen in the $YoI$ model.

We also explained the appearance of the holes that were seen in the distribution functions as due to a peculiarity of the way we picked particles. The low energy particles that would fill in this region were found to not be able to make it into the spatial gridding region for one of the main groups used.

We also analyzed some of the individual groups that were used in the final fit of the $YoI$ group to see if we could understand the nature of the features seen in the $YoI$ combined model. From these groups we concluded that the Trapped kind of particles keep the same shape, with only two effects occurring as the electric field width decreased and the magnitude increased. One, the density gradient became pronounced in the peak electric field region. This is easily explained, since the particles are drifting Earthward much faster in the higher electric field regions thus they will spend correspondingly less time in those boxes. The other effect was a pronounced shifting of the distribution in the direction of the flow, in effect moving the origin of the distributions from $V_x = 0$ to $V_x = E_y/B_z$.

The Speiser particles showed similar kinds of effects, although the shape of these distributions became somewhat distorted as we approached the peak field regions. There was also a change in the density gradient, although it did not appear to be as drastic as the
Trapped particles exhibited. There was also a general shift in the origin that was similar to the Trapped particles.

The features that were seen in the combined group were a combination of the way these two groups behaved slightly differently under the influence of these fields. The Trapped particles were essentially just moving Earthward faster when they are within the higher electric field regions. The Speiser particles showed some evidence towards preferential acceleration cross-tail, as the individual distribution function that was examined showed some highly skewed distributions on the positive y side of the gridding. The Trapped particles on the other hand did not show this kind of effect.

The next step was to look for these features in spacecraft data. Appendix A details the search methods used to find the case studies that were examined in Chapter 3. These cases clearly showed similar distributions as the Yol model. The same kinds of anisotropies were seen. Each case that was examined was also located in a different region, yet the features were visible to some degree in all of them. Another interesting feature of these cases was seen when a simple estimate of the electric field width was done. Every one of the four cases had an ion gyroradius on the order of 0.4 RE. The electric field width is interpreted here to be several ion gyroradii in thickness.

An observation from these cases was the fact that the two cases that occurred on the flanks seemed to show a bulk flow in the y direction that was completely contrary to the observed convection pattern for long time averages. We will examine the data set (covered in more detail in Appendix A) to see if there are any more flank cases here that show these flow patterns.
To finish this summary, we can say with confidence that there are non-adiabatic features present in these magnetotail fast flow events that can be successfully reproduced with an orbit tracing approach.

4.1 Electric Field Width

The electric field widths that were estimated from the Geotail data are not a first estimate. Baker et al., [1996] summarizes much of the work that has been done previously in this regard. It has been known since the days of the IMP satellites [Sarris et al., 1976; Krimigis and Sarris, 1979] that these acceleration regions were likely to be localized in azimuth direction. Since then there have been many different attempts to determine the size of these regions. Lin et al., [1991] used two satellite measurements to make an estimate of a few RE. Later efforts have given similar values. Angelopoulos et al., [1996] used conservation arguments to infer a scale size of BBF's on the order of 1 to 2 RE. Ohtani et al., [1992] made a detailed case study of a single event and concluded that the width in this case was certainly less than 6 RE. Sergeev et al., [1995] used ISEE 1 and 2 measurements to get an estimate of 1 to 2 RE.

It seems that the estimate from Chapter 3 agrees well with these observations. If we assume that the electric field width is on the order of 2 gyroradii (which is the electric field width of Yo1), then we have an electric field region that is likely wider than 1.0 RE. To get an upper bound, we can compare these data distributions with the Yo3 model. We see much more deformed distributions in the data than that model shows. An upper limit of 6 gyroradii (electric field region width of Yo3) can then be estimated, giving us an upper bound of approximately 3 RE. We can conclude from purely in situ observations that sev-
eral different cases located in different regions spatially all have electric field thicknesses
between rough limits of 1 to 3 $R_E$, or several ion gyroradii.

This kind of result is exactly the sort of *in situ* calculation that this distribution
function analysis is best at. Instead of having to make estimates using several satellites or
long term averages the nature of the magnetotail configuration at one point can give infor-
mation about larger regions. By understanding the way that particle orbits contribute to
the distribution functions here, we can make simple calculations that not only agree with
each other, but with several other kinds of analyses that have been done to determine the
same parameters.

### 4.2 Flank Flow Directions

In Chapter 3 there was a strange observation made. In the two cases that were
located on the flanks of the magnetotail at opposite sides, the main flows in the $y$ direction
seemed to be preferentially pointed towards midnight. However, several studies based on
long time averages of convection have shown that the average flows in these regions tend
to flow not so much towards midnight as away from midnight. These long term flows act
in such a way as to divert so that they flow around the Earth, much like water would flow
around an obstacle. In this section we take a look at the other events that were examined
in Appendix A to see if there are any other cases that occurred near the flanks of the mag-
netotail that show this result.

Six cases were found other than those two, in which $|y| > 6.5 \ R_E$. Table 4.1 shows
the relevant parameters:
Table 4.1 Flank Flows

<table>
<thead>
<tr>
<th>Date</th>
<th>Position (X,Y,Z), R_E</th>
<th>$V_y$ avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 12, 1995</td>
<td>-10.8, 8.2, 4.4</td>
<td>+60</td>
</tr>
<tr>
<td>Nov 11, 1995</td>
<td>-13.3, 8.8, -2.8</td>
<td>+100</td>
</tr>
<tr>
<td>Apr 12, 1996A</td>
<td>-16.0, 11.8, 1.8</td>
<td>+60</td>
</tr>
<tr>
<td>Apr 12, 1996BC</td>
<td>-16.1, 10.3, 1.9</td>
<td>-80</td>
</tr>
<tr>
<td>Feb 26, 1997</td>
<td>-18.5, -6.7, -2.7</td>
<td>+250</td>
</tr>
<tr>
<td>Jan 7, 1998</td>
<td>-13.1, 12.8, -1.5</td>
<td>-50</td>
</tr>
</tbody>
</table>

There are five cases here that occur on the +y side of the magnetotail. Three of them have predominantly positive y flow, two have negative y flow. There does not appear to be any consistent pattern here. The one case that occurs on the -y side has a large average flow in the positive y direction. This is inconclusive. All we can say is that the flow in the y direction for these events does not seem to be strongly related to the location in y instantaneously, though it likely is correlated in the way seen in the convection studies on average.

4.3 Pressure Tensor Analysis.

In a project of this type, we have put the emphasis on qualitative comparisons between orbit tracing models and spacecraft data. Although this can be informative, it does little to provide any hard factual support for the arguments put forth concerning the
presence and cause of the anisotropies present. It was important to see if there was some obvious parameter that provided a clear measure of this anisotropy. It would also be helpful if this parameter could distinguish between adiabatic and non-adiabatic types of anisotropy.

We made an attempt to look at the pressure tensor elements. These pressure tensor elements, especially the off-diagonal elements can show us whether there are correlations between different velocity components, or enhancements along one axis or another. As an example, consider $p_{xy}$. This pressure tensor element is a measure of the correlation between motion in $x$ and motion in $y$. If this element of a particular velocity space distribution is significantly positive, for example, then if a particle chosen from that distribution is moving in the positive (negative) $y$ direction, there is a greater than average change that it is also moving in the positive (negative) $x$ direction as well. Since we found that there was a distinct enhancement in the positive $v_x$ and $v_y$ regions of the distribution function for the YoI model, it was considered a strong possibility that this parameter could be a diagnostic for this kind of feature.

Unfortunately, the results proved inconclusive. There were no clear trends in the models, and the spacecraft data shows too much fluctuation to be sure if any enhancements in one or another pressure tensor element is real or not. Continuing in this line of reasoning, we tried to also analyze the momentum tensor elements.

The momentum tensor is formed in nearly the same way as the pressure tensor, except that the bulk flow is not incorporated into the integrations. The results here were also inconclusive. There were no obvious features visible in any of the off-diagonal ele-
ments. There was one interesting feature in the diagonal elements, though it is obvious upon reflection.

During the periods of largest flow, the $v_{xx}$ momentum tensor element is significantly larger than the other two elements. This makes sense, since the majority of the flow vectors are in the $x$ direction. There tends to be an enhancement of up to 50% in this elements compared with the other two diagonal elements.

We can conclude from this section that there is no easy way to analyze the anisotropies present in these distribution features other than qualitatively analyzing them. The orbit tracing analysis has proven to be the only way to try to understand the physics of these distributions, although further work in this area could very well provide a diagnostic technique that is usable.

4.4 Further Work

We have shown that this orbit tracing model can do a good job of reproducing distribution function features that are seen in real data. Ideally, we would like to identify other configurations that are likely to show distinctive features and do the same analysis to see what we can learn.

Appendix B presents an analytical model of a magnetotail with a null point, or X-line that is located in the mid tail region. This kind of configuration is likely to show interesting features in distribution functions, and this would be a logical next step in a further study. In this dissertation we have been able to see changes in the distribution functions as we move across the tail in the $y$ direction. For this X-line model the most important direction for change is the $x$ direction. As we near the region where the magnetic field goes to zero, it is expected that the current sheet will change its thickness, until we reach the
actual null point which will correspond to the thinnest sheet. A self-consistent analysis of such a configuration may be able to show enough changes in the distributions to allow us to determine satellite distance away from a null-point. This would be a useful technique to find and analyze these near-Earth neutral lines, giving us a better grasp on the acceleration and current disruption region in turn.
APPENDIX A

DATA SEARCHING METHODS

In this appendix we will detail the search method used to find suitable data events for comparison with the orbit tracing models detailed in Chapter 2. First we will quickly summarize the programs written to do various searches on these large data sets. Then we will present the particular search used to find enhanced convection events. These events will be examined in detail to show how we arrived at the four events chosen for study in Chapter 3.

A.1 Datasearcher.c

To search through several years of Geotail data quickly and with versatility was a goal of this work. To that end a software package was developed that does this. It is capable of multiple searches of virtually any parameter, either fundamental or derived with only a few simple commands. Several different options were incorporated to facilitate different requirements in reporting the results. Any size file may be searched, up to the limits of available memory, without modification. The code was designed to be able to do practically any search of any parameter with minimal modifications. The main reason to write code that could be modified so easily was that we were never sure at any step in the data analysis whether the search routine being used was a useful one. It proved necessary to
change the parameters of the search many times, looking for different kinds of features in the fluid parameters and magnetic field values before a suitable set of parameters was decided upon.

The basic unit of the search engine was the linked list. All the programming was done in C. See Figure A.1 for a visual guide to the following description. The first step was ordering all the data sequentially. A simple bubble sorter was written to do this, since the data was originally available to us in several unordered files.

The resultant large file (approximately 86 megabytes) was then read into the main search program, called datasearcher.c. Each measurement time was read into a separate structure. Any data parameter that is desired can be generated from the raw data and stored in this structure with its own unique identifier. The power of this method is that whenever a new parameter is desired in a search there are few additions that need to be made, since so much of the code structure is defined in only one place. This makes additions or modifications quick and easy.

These structures were then linked together in a large chain from the first data measurement to the last. To ensure that there was no memory problems, each new measurement block was created and linked as it was read, until the end was reached. When the searches are done, the results can then be stored in each measurement structure, as many as required. The simplicity of this architecture allows us to sort through the results of the searches and report only those measurements that have the correct combinations of search result true/falses. This format also allows us to do more sophisticated searches that require time as a parameter, if for instance we wanted to search for periods when $B_z$ jumped more
Data List

This list contains all the spacecraft data for one measurement, both basic and derived parameters.

The results of each search are stored separately for each list, and can be used in different ways as desired.

Search List

Each of these lists contains all the parameters used in one search.

All searches are contained within a list of this type.

Each of these boxes represents one element of a linked list. Each linked list element is a structure that can contain any parameters needed in a search. The advantage to using this type of architecture in a search routine is speed. Any new search desired can be implemented quickly and with a minimum of code changes, since much of the data is defined in one place, instead of several.

Figure A.1 Datasearcher.c data structure diagram.

than 10 nT in one cycle time. All the parameters for each time are available at once, without needing to resort to common blocks or multiple variable passing to subroutines.

Recall here that a 3 cycle measurement is approximately 66 seconds. This is the duration between successive points in our data set in general, with regular large data gaps.
when the spacecraft exits the magnetotail region. Summarized here are the specifics of the search, the initial results and the final events chosen.

**A.2 Enhanced Convection Events**

This search was performed on the Geotail data set in order to find the enhanced convection events that were discussed in Chapter 3. Here we will define the search parameters used and show the initial results. Since there were many more cases found than needed, we had to pare down the list of cases to a more manageable number to make several case study comparisons with the fast flow model. The criteria used to do this selection will also be discussed here.

There have been several studies about the statistical aspects of fast flows in the magnetotail [Angelopoulos, 1992; Angelopoulos et al., 1994; Baumjohann et al., 1990]. However these studies concentrated on the distribution of fast velocities in the tail. Although these fast velocities are the main signature of these enhanced convection events, they do not provide us with the full picture.

A recent study by Schödel et al. [2001] has used electric field as the primary parameter. The electric field is defined in terms of the velocity and magnetic field components. This assumes the $E \times B$ drift is the mechanism driving these drifts. The search parameters used in both the paper and this search are as follows:

1. $E_H = \sqrt{(V_x B_z)^2 + (V_y B_z)^2} > 2$ mV/m. This definition allows for both the main components of velocity in the current sheet to be measures of the electric field. The magnitude of the field is made to emphasize high levels of convection, and is otherwise somewhat arbitrary.
2. $\beta > 0.5$. We require that the plasma measurement be in the current sheet proper. Choosing this value of $\beta$ helps to guarantee this, although as we shall see it does not work as well as we would hope.

3. $v_\perp > v_\parallel$. We want the perpendicular velocities to dominate the parallel flows. This is important to consider, as one of the main properties of convection drifts are that they are perpendicular to the ambient magnetic fields. From the above definition of $E_H$, this criterion is not guaranteed automatically, so we must impose it externally.

There was also a limitation placed on spacecraft locations. Although we did not use this restriction, in hindsight it was necessary. The region of space that was allowed in this search were $X_{AGSM}$ between $-10$ and $-50$ RE. $AGSM$ stands for Aberrated Geocentric Solar Magnetospheric. This coordinate system removes the average aberration in the magnetotail caused by the motion of the Earth. The coordinates were also limited to $|Y_{AGSM}| \leq 10$. This was meant to remove any Low Latitude Boundary Layer (LLBL) flows as well as restrict the search to a region where large convective flows are more predominant. As we shall see, this requirement was needed. In our case, we would have had to use GSE coordinates had we required this criterion, since the data set was not aberrated, and was not in GSM coordinates.

In this study, we imposed a further limitation on the data. Since the model that we are analyzing is time-independent, it is important to find data events that are as static as possible to compare with. Borovsky et al., [1996] have studied the turbulent aspects of particle and magnetic fields in the magnetotail system. From long term averages, they conclude that the fluctuations in the velocities are strong, with $\frac{\Delta v}{v} \approx 1$, $\frac{\Delta v_x}{v_x} \gg 1$ and $\frac{\Delta v_y}{v_y} \gg 1$. The fluctuations in the magnetic field values are much smaller, but are still

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important, with $\frac{|\Delta B|}{|B|} \approx 0.5$. The densities and temperatures are much more stable in comparison. The characteristic time scales for these fluctuations are on the order of 2 minutes for the flow velocities. This is the value of the autocorrelation time for velocities, which is the period between velocity measurements when they are no longer strongly correlated.

To minimize these turbulence effects, we require the above three parameters to be true for at least 5 consecutive measurements. A consecutive measurement is defined as two true results no longer than 130 seconds apart. In practical terms this means that no more than one false measurement may come between two trues before we discard the event as not within the requirements. Events that last for a longer period of time (5 minutes or longer in this case) are hoped to be long enough that some of the effects of this strong turbulence can be minimized to ensure that we can compare this data with the models in a meaningful way.

Several of the times found are clearly PSBL or perhaps even Solar Wind flow. Figure A.2 shows one representative event of this type. This case was measured on August 23, 1995, and was located at $x = -8.4, y = -16.4, z = 6.2$ RE. Commencing at 06:45 the value of $E_H$ rises to a large stable value slightly below the search threshold. At 0706:11 the search parameters are met. The plasma density is also high, and since there is little $B_x$, the parallel versus perpendicular flow requirement is also met. Although this data event is marked by the parameters above as true, there are several reasons to delete it and others similar to it from consideration.

Several features are immediate warning signs that data events like this one are not what we are interested in. First, the velocities are large and primarily tailward for tens of minutes, even hours at a time. If tailward flows are associated with near-Earth reconnec
Figure A.2 August 23, 1995 Solar Wind Example

tion events in the magnetotail then from the descriptions of substorms given in Chapter 1 we know that tailward flows in these cases are bursty, turbulent and most important, short lived. On the other hand if these tailward flows are associated with the far tail reconnection zone, then Geotail would never see it, since we are Earthward of 30 R_E everywhere in
Scatter Plots of Eh Search Result Locations

Peak Velocity vs. X location

Note: Earthward flows only kept in this case

Figure A.3 Data Event Location and Peak Velocities.

this data set, and the far tail reconnection zone is likely to be well over 100 to 200 \( R_E \)
downtown [Fedder and Lyon, 1995 for example]. Second, the particle densities are huge, in
cases greater than 20/cm³ for the entire time period of the flow. This is much larger than
the typical densities seen in the tail. Finally, the ion temperatures are small, less than 1
keV. All these parameters point towards this event, and other events like it, being solar
wind flow. All events of this type are discarded from further consideration. From this
event it is clear that the original requirement of limiting position was necessary, as this
event would never have been marked if the position parameters requirements were in
place.

There are also differences in the spatial distribution of the remaining events. In
general, as Figure A.3 shows, there is a good selection of data coverage for the tail region
we are looking at. There are several points to note in this figure. First, there are more
events in the near-Earth region than farther out. Second, the events that occur at more tail­
ward regions tend to have both higher peak flow values and higher average flows as well.
The cases that are of most interest to us are the ones that have both high maximum flow
speeds and the ones that last for the longest time.

In the table below, the times found in the search that were not solar wind or PSBL
events are detailed. The velocities are rounded off to the nearest ten km/s and the mag­
etic field parameters are rounded off to the nearest tenth of a nanotesla.

<table>
<thead>
<tr>
<th>Date</th>
<th>Times start - finish duration</th>
<th>Avg. Position (X,Y,Z) Rₑ</th>
<th>( \langle E_H \rangle ) min to max mV/m</th>
<th>( \langle V_x \rangle ) min to max km/s</th>
<th>( \langle V_y \rangle ) min to max km/s</th>
<th>( \langle V_z \rangle ) min to max km/s</th>
<th>( \langle B_x \rangle ) min to max nT</th>
<th>( \langle B_y \rangle ) min to max nT</th>
<th>( \langle B_z \rangle ) min to max nT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 26, 1995</td>
<td>08:54 - 09:05 11 mins</td>
<td>-12.5, 3.0, 1.3</td>
<td>3.0, 6.3</td>
<td>-50, -190 to 220</td>
<td>-50, -190 to 120</td>
<td>-1, -60 to 80</td>
<td>2.3, 0.7 to 4.2</td>
<td>0.4, -0.8 to 1.8</td>
<td>18.8, 16.0 to 24.2</td>
</tr>
</tbody>
</table>
Table A.1: Fast Flow Search Initial Results

<table>
<thead>
<tr>
<th>Date</th>
<th>Avg Position (X,Y,Z)</th>
<th>(\langle E_H \rangle) min to max (\text{mV/m})</th>
<th>(\langle V_x \rangle) min to max (\text{km/s})</th>
<th>(\langle V_y \rangle) min to max (\text{km/s})</th>
<th>(\langle V_z \rangle) min to max (\text{km/s})</th>
<th>(\langle B_x \rangle) min to max (\text{nT})</th>
<th>(\langle B_y \rangle) min to max (\text{nT})</th>
<th>(\langle B_z \rangle) min to max (\text{nT})</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 12, 1995</td>
<td>-10.8, 8.2, 4.4</td>
<td>2.3, 0.8 to -140 to 140</td>
<td>60, -130 to 270</td>
<td>4, -80 to 70</td>
<td>4.6, 3.9 to 5.3</td>
<td>-2.7, -2.1 to -3.3</td>
<td>15.1, 14.6 to 15.5</td>
<td></td>
</tr>
<tr>
<td>May 18, 1995</td>
<td>-9.6, -3.4, 0.1</td>
<td>3.4, 2.2 to -30 to 140</td>
<td>10, -130 to 270</td>
<td>-50, -210 to 70</td>
<td>-26.0, -20.0 to -30.0</td>
<td>-22.0, -18.0 to -25.0</td>
<td>16.0, 12.6 to 18.0</td>
<td></td>
</tr>
<tr>
<td>Jun 19, 1995</td>
<td>-9.8, 1.5, 1.3</td>
<td>4.0, 1.0 to -150 to 150</td>
<td>90, 10 to -70</td>
<td>20, 60 to 40</td>
<td>37.0, 19.0 to 140</td>
<td>-1.1, -1.5 to -5.0</td>
<td>12.0, 9.5 to 14.8</td>
<td></td>
</tr>
<tr>
<td>Jul 5, 1995A</td>
<td>-10.3, 0.1, 1.2</td>
<td>2.5, 1.0 to -200 to 200</td>
<td>30, -110 to 70</td>
<td>0, -50 to 10</td>
<td>-32.0, -10.5 to 7.2</td>
<td>-8.9, -5.9 to -3.9</td>
<td>22.0, 18.5 to 24.9</td>
<td></td>
</tr>
<tr>
<td>Jul 21, 1995</td>
<td>-10.3, 0.1, 1.2</td>
<td>2.5, 1.0 to -200 to 200</td>
<td>30, -110 to 70</td>
<td>0, -50 to 10</td>
<td>-32.0, -10.5 to 7.2</td>
<td>-8.9, -5.9 to -3.9</td>
<td>22.0, 18.5 to 24.9</td>
<td></td>
</tr>
<tr>
<td>Nov 1, 1995</td>
<td>-22.7, -6.2, -1.5</td>
<td>2.6, 0.8 to -270 to 960</td>
<td>-80, -310 to 150</td>
<td>60, -160 to 360</td>
<td>4.3, -3.6 to 1.9</td>
<td>1.9, -1.3 to 5.7</td>
<td>5.7, 1.6 to 9.1</td>
<td></td>
</tr>
<tr>
<td>Nov 11, 1995</td>
<td>-13.3, 8.8, -2.8</td>
<td>2.6, 0.6 to -70 to 490</td>
<td>100, -40 to 310</td>
<td>20, -61 to 100</td>
<td>-11.0, -5.4 to 10.4</td>
<td>8.5, 5.4 to 10.4</td>
<td>9.7, 7.4 to 11.6</td>
<td></td>
</tr>
<tr>
<td>Mar 17, 1996</td>
<td>-14.0, 5.1, -1.3</td>
<td>3.6, 0.6 to -370 to 220</td>
<td>180, -120 to 0</td>
<td>50, -4.1 to 12</td>
<td>-1.5, -2.7 to 0.4</td>
<td>-0.9, -2.7 to 0.4</td>
<td>14.8, 10.2 to 17.2</td>
<td></td>
</tr>
<tr>
<td>Apr 12, 1996A</td>
<td>-16.0, 11.8, 1.8</td>
<td>3.8, 0.9 to -110 to 540</td>
<td>60, -180 to 340</td>
<td>140, 670 to 340</td>
<td>12.5, 6.3 to 15.4</td>
<td>1.4, -1.0 to 3.2</td>
<td>8.6, 4.0 to 11.7</td>
<td></td>
</tr>
<tr>
<td>Apr 12, 1996BC</td>
<td>-16.1, 10.3, 1.9</td>
<td>3.2, 0.9 to -170 to 580</td>
<td>-80, -440 to 160</td>
<td>-30, -35 to 5</td>
<td>4.0, 3.5 to 4.0</td>
<td>0.9, 4.0 to 7.3</td>
<td>13.5, 11.3 to 16.1</td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Times start - finish duration</td>
<td>Avg. Position (X, Y, Z)</td>
<td>Avg. ( E_H ) \text{ min to max} \text{ mV/m}</td>
<td>Avg. ( V_x ) \text{ min to max} \text{ km/s}</td>
<td>Avg. ( V_y ) \text{ min to max} \text{ km/s}</td>
<td>Avg. ( V_z ) \text{ min to max} \text{ km/s}</td>
<td>Avg. ( B_x ) \text{ min to max} \text{ nT}</td>
<td>Avg. ( B_y ) \text{ min to max} \text{ nT}</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------</td>
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<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>May 15, 1996</td>
<td>01:17 - 01:22 5 mins</td>
<td>-11.7, 0.7, 1.5</td>
<td>4.0, 2.0 to 6.3</td>
<td>210 to 680</td>
<td>160, 40 to 320</td>
<td>-20, -100 to 60</td>
<td>2.1, -15.4 to 9.9</td>
<td>0, -1.5 to 1.8</td>
</tr>
<tr>
<td>Oct 22, 1996</td>
<td>18:34 - 18:42 8 mins and 18:49 - 18:59 10 mins 18 mins total</td>
<td>-12.3, 5.2, -1.8</td>
<td>2.8, 0.4 to 5.4</td>
<td>10, -140 to 250</td>
<td>50, -180 to 180</td>
<td>-50, -200 to 140</td>
<td>-22.0, -29.0 to -15.8</td>
<td>5.3, -2.7 to 17.1</td>
</tr>
<tr>
<td>Nov 24, 1996</td>
<td>10:21 - 10:30 10 mins</td>
<td>-22.2, -0.4, -2.6</td>
<td>3.5, 2.0 to 6.0</td>
<td>580, 210 to 850</td>
<td>160, -70 to 440</td>
<td>-50, -200 to 170</td>
<td>0.8, -6.7 to 9.0</td>
<td>-2.5, -5.4 to 2.6</td>
</tr>
<tr>
<td>Nov 29, 1996</td>
<td>21:18 - 21:23 6 mins</td>
<td>-23.6, 0.0, -2.8</td>
<td>2.8, 1.7 to 3.8</td>
<td>380, 270 to 500</td>
<td>-100, -270 to 40</td>
<td>-80, -160 to 10</td>
<td>5.9, 0.5 to 13.2</td>
<td>-2.8, -6.8 to 0.8</td>
</tr>
<tr>
<td>Jan 12, 1997</td>
<td>18:57 - 19:08 12 mins</td>
<td>-30.4, 0.8, -3.0</td>
<td>3.2, 0.9 to 9.1</td>
<td>410, -290 to 970</td>
<td>190, -290 to 970</td>
<td>-140, -410 to 60</td>
<td>-4.9, -10.3 to -3.9</td>
<td>0.7, 2.7 to 5.5</td>
</tr>
<tr>
<td>Feb 26, 1997</td>
<td>05:39 - 05:45 7 mins</td>
<td>-18.5, -6.7, -2.7</td>
<td>3.4, 2.2 to 5.2</td>
<td>300, 120 to 390</td>
<td>250, 130 to 310</td>
<td>-80, -130 to 10</td>
<td>-6.3, -10.4 to -1.5</td>
<td>-6.3, -13.4 to -1.5</td>
</tr>
<tr>
<td>Jun 3, 1997</td>
<td>10:33 - 10:40 8 mins</td>
<td>-10.6, -1.0, 1.2</td>
<td>2.6, 1.1 to 6.8</td>
<td>30, -90 to 180</td>
<td>20, -140 to 150</td>
<td>-40, -190 to 60</td>
<td>-22.8, -24.2 to -20.1</td>
<td>-5.6, -13.4 to -5.3</td>
</tr>
<tr>
<td>Aug 8, 1997</td>
<td>13:44 - 13:53 10 mins</td>
<td>-8.3, -5.8, 2.9</td>
<td>4.1, 1.5 to 10.3</td>
<td>120, -170 to 440</td>
<td>20, -140 to 400</td>
<td>20, -90 to 190</td>
<td>26.1, 15.7 to 35.8</td>
<td>10.2, -2.5 to 15.5</td>
</tr>
<tr>
<td>Jan 7, 1998</td>
<td>06:24 - 06:31 7 mins</td>
<td>-13.1, -12.8, -1.5</td>
<td>3.1, 1.2 to 6.5</td>
<td>130, 40 to 280</td>
<td>-50, -110 to 20</td>
<td>-80, -200 to 0</td>
<td>-11.8, -18.9 to 0</td>
<td>4.7, 5.8 to 8.7</td>
</tr>
<tr>
<td>Jan 18, 1998</td>
<td>13:28 - 13:34 7 mins</td>
<td>-26.5, -7.1, -2.7</td>
<td>3.9, 2.5 to 4.9</td>
<td>660, 480 to 830</td>
<td>-170, -290 to 50</td>
<td>-109, -230 to 40</td>
<td>-6.2, -10.2 to 0.3</td>
<td>-0.7, -6.2 to 3.9</td>
</tr>
</tbody>
</table>

The four times in Table A.1 that are highlighted in boldface are the four times selected in Chapter 3. They all show characteristics that set them apart from the rest of the groups. Several events have two sections separated by an ‘and’. These events were
flagged separately by the search routine, but since these events are typically only 10 minutes or so apart they are treated as one event in the table.

The normal parameters for a typical group are as follows. The duration of the usual event is typically 5 to 10 minutes. The magnitudes of $E_H$ have a wide range, from small values to greater than 10 mV/m. The flow velocities are where these events distinguish themselves. Some of these events have $V_x$ flows that are predominantly negative. Others are small, less than 100 km/s on average with small peak values that are not much larger than this. The four events chosen each stand out in their own way.

The Case 1 event on November 1, 1995 has a long duration. The search found an event that lasts for more than 18 minutes. The next longest event found in this data set only lasted for 12 consecutive minutes (one other event lasted as long, but there was a 7 minute delay between two separate events). The average magnitude of $V_x$ was large, about 400 km/s with a large peak flow of over 950 km/s. This event is also located within a reasonable place in the magnetotail at $x = -22.7$, $y = -6.2$, $z = -1.5$ RE. Although it is slightly farther out in the flank than is ideal, it is in an ideal spot in $x$.

The Case 2 event chosen was on May 15, 1996. This event, although short lived at only 5 minutes also had large flow speeds. The average $V_x$ flow here was 420 km/s, with a peak flow of 680 km/s. The location was also interesting, as this event occurred much closer to the Earth than the previous event, at $x = -11.7$, $y = 0.7$, $z = 1.5$. The field lines are much more dipolar in this region. Because of this less tail-like field, we can expect to see some differences in the ways that non-adiabatic particles will contribute to the distribution functions. The field line curvature is much weaker here, and the particle Larmor radii are less as well due to the stronger average $B_z$ components here.
The Case 3 event occurred on November 24, 1996 and lasted for 10 minutes. This event was similar to the first event. The flow speeds were similar, with an average $V_x$ of 580 km/s and a peak speed of 850 km/s. The location was even more favorable than Case 1, since we are not as near to the flank at $x = -22.2$, $y = -0.4$, $z = -2.6$.

Finally, the Case 4 event happened on January 18, 1998 with a duration of 7 minutes. The peak flow speeds were also large in this event, with the average $V_x$ of 660 km/s and a peak velocity of 830 km/s. The location was similar to Case 1, since we are far out into the flanks at $x = -26.5$, $y = 7.1$, $z = -2.7$. However in this case we are on the other side of the flank, and can expect to see differences in the way that the bulk plasma flows. For instance, unlike the other three cases, $V_y$ is predominantly negative here. This was discussed further in Chapter 3.

As we can see, the criteria for long durations and high flow speeds are well met by these four groups. We also have a good set of locations for these four groups, with two of them on opposite flanks at similar radial distances, and the other two near midnight at near-Earth and mid-tail regions. Chapter 3 discussed these four events in much more detail.
APPENDIX B

X-LINE MAGNETIC FIELD MODEL

The original outline for this thesis called for two kinds of models. First, the confined electric field models that were the main topic of this thesis, detailed in Chapter 2, were to be generated. These models were then to be compared with spacecraft data. This was done in Chapter 3. The conclusions of these models were summarized in Chapter 4.

The second goal of this thesis was then to have run an X-line model that tried to model fast flows in a different way. By instead of making $E_y$ large, we make $B_z$ small so that the combination of $E_y/B_z$ for some finite $E_y$ was large. This project proved to be unsuitable for inclusion, due to considerations of time and thesis length, so I will simply present the magnetic field equations here, along with the parameters used in the field that was being tested.

Similarly to the previously described model, the X-line magnetic field model used here is a version of the equilibrium field model. The special function used here with Equation 2.7 is:

$$f(x) = a_1 - a_2 \text{sech}(\epsilon x)$$  \hspace{1cm} (B.1)

There is one small correction that needs to be done to the form of this equation when implementing it in practice. The parameter $\epsilon$ is equal to the ratio of scale sizes in $x$. 

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and \( z \), or \( \varepsilon = \frac{L_z}{L_x} \). Making the change of variables from \((\varepsilon x, z)\) to \((x/L_x, z/L_z)\) has the effect of scaling each coordinate correctly, as well as ensuring the correct dimensionality of the hyperbolic function variables. Using this corrected function, we can get our magnetic field:

\[
\frac{B_x}{B_o} = \tanh \left( \frac{x}{L_x} \left[ a_1 - a_2 \text{sech} \left( \frac{x}{L_x} \right) \right] \right) \left[ a_1 - a_2 \text{sech} \left( \frac{x}{L_x} \right) \right] \frac{1}{L_z} \tag{B.2}
\]

\[
\frac{B_z}{B_o} = \frac{a_1 \text{sech} \left( \frac{x}{L_x} \right) \tanh \left( \frac{x}{L_x} \right) \left[ 1 - \frac{z}{L_z} \left[ a_1 - a_2 \text{sech} \left( \frac{x}{L_x} \right) \right] \tanh \left( \frac{z}{L_z} \left[ a_1 - a_2 \text{sech} \left( \frac{x}{L_x} \right) \right] \right) \right]}{a_1 - a_2 \text{sech} \left( \frac{x}{L_x} \right) \cdot L_x} \tag{B.3}
\]

In order to understand where the X-line is in this model, we simply need to examine the \( B_z \) component. Where \( B_z = 0 \), we have a neutral point. Note that when we introduce the dipole field with this tail model there will be additional points where \( B_z = 0 \). These other points are just the regions of the dipole field itself that have zeros, slightly moved in space due to the influence of the relatively weak tail field there. It is the zeros that are solely a part of this tail model that we need to be concerned with.

There are two ways in which \( B_z = 0 \) in this tail field. The first is somewhat obvious:

\[
\text{sech} \left( \frac{x}{L_x} \right) \tanh \left( \frac{x}{L_x} \right) = 0 \tag{B.4}
\]

This happens for any value of \( z \) at \( x = 0 \), since \( \tanh(0) = 0 \) identically. This means we can offset \( x \) by any parameter in order to place the neutral point wherever desired. The second way \( B_z = 0 \) is a little less obvious, but it can have a dramatic effect on the shape of the field lines:
When this condition is met, the $B_z$ component will go to zero, then change signs. Because we are coupling this tail field with a dipole field, this will not drastically change the topology of the field lines, but it will have an effect on the X-line region. The region of negative $B_z$ will be bounded in the $z$ direction since it clearly has a $z$ dependence from the condition imposed by Equation B.5. Similarly there will be boundary for the positive values of $B_z$ past which they too will change sign. To analyze the characteristics of this region, we can make the choice of looking at the extrema of $x$. Recall that sech($0$) = $1$. Applying this yields for $x = 0$:

$$1 - \frac{z}{L_z}[a_1 - a_2 \text{sech}(\frac{x}{L_x})] \tanh\left(\frac{z}{L_z}(a_1 - a_2 \text{sech}(\frac{x}{L_x}))\right) = 0 \quad (B.6)$$

$$\frac{z}{L_z} = \frac{1}{[a_1 - a_2] \tanh\left(\frac{z}{L_z}(a_1 - a_2)\right)} \quad (B.7)$$

We also need to make sure that $B_z$ behaves reasonably as $x$ asymptotes to infinity.

The form of $B_z$ as this occurs is simpler than above, since sech($\infty$) $\to 0$:

$$\frac{z}{L_z} = \frac{1}{a_1 \tanh\left(\frac{z}{L_z} a_1\right)} \quad (B.8)$$

Solving these transcendental equations is not necessary. We only need to try a few representative values of $a_1$ and $a_2$ to see what kinds of $z' = \frac{z}{L_z}$ solutions we get. Below is a table of several values, along with the $z'$ solutions obtained for each choice at the two extrema.
Table B.1 $a_1$ and $a_2$ Parameters

<table>
<thead>
<tr>
<th></th>
<th>$x = 0$</th>
<th>$x = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1 = 20$</td>
<td>$z' = 0.1$</td>
<td>$z' = 0.05$</td>
</tr>
<tr>
<td>$a_2 = 10$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 = 2$</td>
<td>$z' = 1.0$</td>
<td>$z' = 0.5$</td>
</tr>
<tr>
<td>$a_2 = 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 = 0.2$</td>
<td>$z' = 10.0$</td>
<td>$z' = 5.0$</td>
</tr>
<tr>
<td>$a_2 = 0.1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As we can see from this table, there are dramatic differences in the $z$ solutions obtained when we change $a_1$ and $a_2$ by factors of ten. This table shows what happens not only for representative values of $a_1$, in the $x = \infty$ section but also what happens for values of $a_1 - a_2$, in the $x = 0$ section. We picked for this field $a_1 = 2.0$ and $a_2 = 1.0$. Making this choice places the second set of $B_z$ null points at a $z'$ position that is at a reasonable distance away from the center of the current sheet. The exact $z$ location depends on the value that we pick for $L_z$. There are also several other parameters that still need to be fixed.

The scale sizes in $x$ and $z$ are still to be determined, as well as the overall magnitude of the tail field and the offset position of the null point. These parameters need to be picked in conjunction with the Earth dipole field. At this point parameter choice becomes largely trial and error. We still require that the scale length in $x$ must be about an order of magnitude larger than $z$ at least. Another requirement to consider is the thickness of the
current sheets formed by this field. Also the current density required from Ampere's law should be similar in magnitude to typical magnetotail measurements. Finally, the field lines themselves ought to look reasonable, there should be no unexplained features.

Several sets of parameters were tried with the same Earth dipole field used in Chapter 2, Section 2.3. The following parameters were chosen as an example of the kind of field that may be generated from this model. The scale sizes were set so that \( L_x = 10.0 \ \text{R}_E \), and \( L_z = 1.0 \ \text{R}_E \). This choice of scale length in \( z \) sets the location of the second \( B_z \) null point at \( z = 1.0 \ \text{R}_E \). The magnitude of the field was set to be \( B_0 = 25.0 \ \text{nT} \). The xoffset was set at \( x = -25.0 \ \text{R}_E \).

These parameters yielded the field lines seen in Figure B.1. Note that the \( x-z \) axes are not to scale by a factor of four for clarity. We can see the effect of the neutral line as there are field lines reversing direction somewhere between \( x = -30 \) and \( -32 \ \text{R}_E \). These new field lines are no longer connected to the Earth. They connect either to a point downtail at the equator, or they may asymptote to \( x = \infty \).
We can also briefly examine the magnitudes of the currents required to support this field. The current density needed to support this particular field near the vicinity of the null point is about 4.5 nA/m². The width of the current sheet at this point is about 0.75 Rₑ. This is the distance at which the current falls off to about half its peak value. These may not be the best values to model a particular X-line field, but the parameters can be adjusted as desired to fit any kind of current density and current sheet thicknesses desired.

Summing this appendix up, we have derived a new kind of equilibrium field. This new magnetotail like field has a null point in it where the magnetic field strength goes to zero. This null point can be adjusted to appear wherever desired in a magnetotail model. With suitable parameterization this X-line field can be incorporated with an Earth dipole to give a realistic magnetic field that can be used in a variety of simulations and projects.
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