Global Structure of the Nightside Proton Precipitation during Substorms using Simulations and Observations

Matthew L. Gilson
University of New Hampshire, Durham

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Abstract
In regions of thin strong current sheets, the first adiabatic invariant of protons can be violated leading to pitch angle diffusion into the loss cone and ultimately auroral precipitation. The central plasma sheet typically provides a stretched enough magnetic field configuration to account for the nightside proton precipitation. During substorms, the outflow from the near earth reconnection line at approximately 20 RE brings magnetic flux from the highly stretched magnetotail into the near earth magnetosphere. Once there, the flux piles up forming an azimuthally localized region where the magnetic field is more dipolar. Current flows into and out of the ionosphere at the edges of this dipolarized region forming the substorm current wedge (SCW). As the substorm continues, the SCW typically grows azimuthally and radially as the result of the continued flux pileup. Using the OpenGGCM global MHD simulation, we show that the proton precipitation can be split azimuthally due to the arrested scattering in the strongly dipolarized region at the center of the SCW. However, at the edges of the SCW where the dipolarization is not as complete (and certainly outside the SCW), the mean gyroradii increase due to the energization of the near earth magnetotail may be sufficient to facilitate continued scattering. The simulation predictions of auroral splitting are compared to a statistical study using data from the IMAGE SI-12 instrument. The IMAGE SI-12 frequently shows localized azimuthal splitting of the proton aurora similar to the simulations. Additionally, the splitting of the proton aurora is much more common for stronger substorms (lower AL and onset latitude) winch is also argued to be consistent with the simulations.

Keywords
Physics, Fluid and Plasma

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Global Structure of the Nightside Proton Precipitation during Substorms using Simulations and Observations

BY

Matthew L. Gilson
B.S., Applied Physics, Grove City College, 2007

DISSERTATION

Submitted to the University of New Hampshire in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in
Physics

December, 2011
This dissertation has been examined and approved.

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I would like to begin by thanking my advisor, Professor Jimmy Raeder. Thank you for sending me to workshops and conferences where I have had the opportunity to see (and contribute to) the cutting edge developments in space physics. Thank you for discussions, advice and support. Also, thank you for giving me the freedom to explore this topic at my own pace and in my own way while being available for discussions and to answer questions when I needed it.

Secondly, I would like to thank the members of my thesis committee (Professor Maurik Holtrop, Professor Mark Lessard, Professor Lynn Kistler, Professor Kai Germaschewski and Dr. Larry Kepko). Thank you each for your comments and input during my thesis proposal, classes and discussions. Specifically, thank you Larry for encouraging me to look into the IMAGE data to do the statistical study that is now chapter 6 of this dissertation. I believe that has helped to make this dissertation much more convincing.

I would like to acknowledge my collaborators, specifically Dr. Yasong Ge and Professor Eric Donovan. Discussions with these two researchers have been particularly illuminating and influential on the direction and interpretation of these results.

Dr. Douglas Larson and Dr. Alex Vapirev also deserve credit and gratitude as much of the code which formed the backbone of this research originated from their repository. The original versions of the fieldline tracer and plasma sheet visualization algorithms were written by them. Their code provided an excellent place to start building the tools eventually used in this dissertation.

Stephen Abbott, thank you for constantly answering all my programming questions about C, python and coding style. I just hope that someday my knowledge of Fortran will be useful to you.

Thank you to my undergraduate professors Dr. D.J. Wagner, Dr. Jeff Wolinski, Dr. Kevin McKay, Dr. Mark Fair, Dr. Shane Brower and Dr. Glen Marsch. Particularly, thank you Mark for getting me interested in computational physics. Thank you Jeff for the undergraduate research opportunities you provided. Thank you Dr. Shane Brower for preparing me for graduate school by teaching the most difficult class I’ve ever taken (and somehow managing to make it a positive experience).

Of course, this work would not have been completed without the financial support from grant NAS5-02099 from the National Aeronautics and Space Administration and grant ATM-0639658 from the National Science Foundation. Also, Dr. Stephen Mende
provided the IMAGE data used through NASA’s CDAweb interface. Without that data, this dissertation would not exist.

Finally, (and most importantly) I would like to thank my family. Mom and Dad, thank you for your love and support through college and graduate school.

Above all else, thank you Kathleen and Zadok for being the best family I could ever ask for. Kathleen, you’re my best friend and I want to make you proud. Graduate school would have been a lonely place without you. Thank you for listening to me while I attempted to sort my thoughts. I think that it was more helpful than you realize. Zadok, I hope you always keep your curiosity. There is a lot of life in you and it is contagious. Thank you for all the energy and excitement you bring to my life.
# Contents

Acknowledgements iii  
List of Acronyms vii  
List of Figures viii  
List of Tables xi  
Abstract xii  

1 Introduction 1  
1.1 Substorms ................................................. 1  
1.1.1 Substorm Current System .................................. 7  
1.1.2 Mapping .................................................. 9  
1.2 Proton Aurora ............................................... 11  
1.2.1 Sources .................................................. 14  
1.2.2 Isotropy Boundary ......................................... 17  
1.2.3 Proton Aurora during Substorms .......................... 20  
1.3 Motivation ................................................... 22  
1.4 Goals of this Dissertation .................................... 24  

2 Global Magnetohydrodynamics using the OpenGGCM simulation 25  
2.1 Introduction .................................................... 25  
2.2 OpenGGCM ..................................................... 26  
2.2.1 Parametrization of resistivity ................................ 28  
2.2.2 Boris Correction ............................................. 30  
2.2.3 Outer Boundary Conditions .................................. 31  
2.2.4 Inner Boundary Conditions ................................... 31  
2.2.5 Numerics ................................................... 34  
2.2.6 Remarks ................................................... 37  

3 The Proton Precipitation Algorithm 39  
3.1 Introduction .................................................... 39  
3.2 Algorithm ..................................................... 40
List of Acronyms

ASI  All-Sky Imager
BBF  Bursty Bulk Flow
CD   Current Disruption
CPS  Central Plasma Sheet
CRCM Comprehensive Ring Current Model
CTIM Coupled Thermosphere-Ionosphere Model
DF   Dipolarization Front
EMIC Electromagnetic Ion Cyclotron (waves)
EUV  Extreme Ultraviolet
FAC  Field-Aligned Current
FAST Fast Auroral SnapShoT Explorer
FLC  fieldline curvature
FUV  Far Ultraviolet Imager
GBO  Ground Based Observatory
GEO  Geocorona Photometers
GOES Geostationary Operational Environmental Satellite
GSE  Geocentric Solar Ecliptic (coordinate system)
HENA High-Engery Neutral Atom (Imager)
IB   Isotropy Boundary
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMAGE</td>
<td>Imager for Magnetopause-to-Aurora Global Exploration</td>
</tr>
<tr>
<td>LENA</td>
<td>Low-Energy Neutral Atom (Imager)</td>
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<tr>
<td>MENA</td>
<td>Medium-Energy Neutral Atom (Imager)</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamic</td>
</tr>
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<td>MSP</td>
<td>Meridian Scanning Photometer</td>
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<tr>
<td>NENL</td>
<td>Near Earth Neutral Line</td>
</tr>
<tr>
<td>OpenGGCM</td>
<td>Open Geospace General Circulation Model</td>
</tr>
<tr>
<td>PBI</td>
<td>Poleward Boundary Intensification</td>
</tr>
<tr>
<td>R_E</td>
<td>Earth Radius (6378km)</td>
</tr>
<tr>
<td>RPI</td>
<td>Radio Plasma Imager</td>
</tr>
<tr>
<td>SCW</td>
<td>Substorm Current Wedge</td>
</tr>
<tr>
<td>SI</td>
<td>Splitting Index</td>
</tr>
<tr>
<td>SI-12</td>
<td>Spectrographic Imager 12 (121.8 nm)</td>
</tr>
<tr>
<td>SI-13</td>
<td>Spectrographic Imager 13 (135.6 nm)</td>
</tr>
<tr>
<td>THEMIS</td>
<td>Time History of Events and Macroscale Interactions During Substorms</td>
</tr>
<tr>
<td>WIC</td>
<td>Wideband Imaging Camera</td>
</tr>
<tr>
<td>WTS</td>
<td>Westward Traveling Surge</td>
</tr>
</tbody>
</table>
# List of Figures

1.1 Reconnection model of a substorm ........................................... 5  
1.2 Current Disruption model of a substorm ................................. 5  
1.3 Illustration of the Substorm Current Wedge .............................. 8  
1.4 Charge exchange diffusion of proton aurora ............................. 13  
1.5 A simple schematic of a particle in a converging magnetic field ...... 14  
1.6 FAST orbit number 2000 overview ........................................... 19  
1.7 White light onset with proton aurora and red-line ...................... 21  

2.1 Gridcell structure used by OpenGGCM ..................................... 35  
2.2 Example grid ........................................................................ 36  

4.1 Position of THEMIS probes on March 23, 2007 ......................... 52  
4.2 Simulation ionospheric parameters at the position of maximum electron precipitation ................................................................. 54  
4.3 Simulated AL index for March 23, 2007 .................................... 55  
4.4 Simulated proton aurora for March 23, 2007 ............................. 56  
4.5 CPS $V_x$ and Temperature for March 23, 2007 simulation ............ 57  
4.6 Mapped proton aurora and CPS $B_z$ for March 23, 2007 simulation . 58  
4.7 CPS average gyroradius and number density for March 23, 2007 simulation ................................................................. 60  
4.8 Ionospheric density and temperature in March 23, 2007 simulation . 61  
4.9 DST, AU, AL and AE indices for April 28, 2001 ...................... 62  
4.10 Solar wind input for the April 28, 2011 simulation .................... 63  
4.11 IMAGE FUV data of the April 28, 2001 substorm .................... 65  
4.12 Comparison of OpenGGCM with Geotail magnetic field data for April 28, 2001 ................................................................. 66  
4.13 IMAGE WIC, SI-12 and simulation precipitation for April 28, 2001 . 67  
4.14 Provisional AL and simulated AL for the April 28, 2001 event ....... 69  
4.15 Mapped proton aurora and $B_z$ in the CPS for the April 28, 2001 simulation ................................................................. 70  
4.16 Plasma temperature and $V_x$ in the CPS during the April 28, 2011 event 72  
4.17 Average proton gyroradius and magnitude of magnetic field in the CPS during the April 28, 2011 event ............................... 73  
4.18 Solar Wind input for the Jan. 31, 2001 simulation .................... 76
List of Tables

5.1 Image Instruments .................................................. 98
ABSTRACT

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by

Matthew L. Gilson
University of New Hampshire, December, 2011

In regions of thin strong current sheets, the first adiabatic invariant of protons can be violated leading to pitch angle diffusion into the loss cone and ultimately auroral precipitation. The central plasma sheet typically provides a stretched enough magnetic field configuration to account for the nightside proton precipitation. During substorms, the outflow from the near earth reconnection line at approximately 20 RE brings magnetic flux from the highly stretched magnetotail into the near earth magnetosphere. Once there, the flux piles up forming an azimuthally localized region where the magnetic field is more dipolar. Current flows into and out of the ionosphere at the edges of this dipolarized region forming the substorm current wedge (SCW). As the substorm continues, the SCW typically grows azimuthally and radially as the result of the continued flux pileup. Using the OpenGGCM global MHD simulation, we show that the proton precipitation can be split azimuthally due to the arrested scattering in the strongly dipolarized region at the center of the SCW. However, at the edges of the SCW where the dipolarization is not as complete (and certainly outside the SCW), the mean gyroradii increase due to the energization of the near earth magnetotail may be sufficient to facilitate continued scattering. The simulation predictions of auroral splitting are compared to a statistical study using data from the
IMAGE SI-12 instrument. The IMAGE SI-12 frequently shows localized azimuthal splitting of the proton aurora similar to the simulations. Additionally, the splitting of the proton aurora is much more common for stronger substorms (lower AL and onset latitude) which is also argued to be consistent with the simulations.
Chapter 1

Introduction

1.1 Substorms

Substorms are a global reconfiguration of the earth’s magnetic field over relatively short timescales. The process begins by transferring solar wind energy and plasma into the magnetosphere on the dayside. That energy is subsequently dissipated on short timescales ($\sim 1 - 2$ hr) and the additional plasma is rapidly ejected. This phenomena was originally described by Akasofu [1964] in terms of auroral features.

It is generally accepted that substorms progress in three distinct phases. The growth phase, originally described by McPherron [1972], is associated with equatorward drifting auroral arcs. Typically the growth phase arc is east-west aligned and stretches from one horizon to the other. The growth phase concludes with the onset of the expansion phase. At the onset of the expansion phase, a few things happen within the first $\sim 2$ minutes. First, an approximately fifteen degree segment of the most equatorward (earthward) arc brightens (auroral activation) and often forms a quasi-periodic rayed or wave-like structure within the first ten seconds [Liang et al. 2008]. A second signature is the initiation of irregular pulsations in the ultra-low frequency range. These pulsations are referred to as Pi (Pulsed, irregular) pulsations [Heacock 1967] and generally start approximately the same time as the onset [Murphy et al. 2009]. After that, the stable growth phase arc breaks up (auroral breakup) into
smaller filaments, and the aurora expands both azimuthally and poleward. Generally the westward edge of the expansion is associated with the most intense aurora and is known as the Westward Traveling Surge (WTS) [Hoffman et al. 1994]. The term “onset” in the literature is ubiquitous and can refer to any of the phenomena listed above associated with the onset of the expansion phase. One final feature of the onset is that there are highly energetic particles “injected” into the geosynchronous region [Arnoldy and Chan 1969]. Dispersionless injections are measured which may indicate that the acceleration is local and a result of the instability which leads to the current disruption (discussed shortly) [Lopez et al. 1990]. Others [Birn et al. 1997] argue that the dispersionless injection appears to be the result of adding a new, high-energy population. At other times, the injections are not dispersionless [Spanswack et al. 2009] and the heating may be a combination of heating in the diffusion region (for low energy particles) and betatron acceleration (for high energy particles). However, the location and mechanism responsible for the injection are still an area of active research. During the rest of the expansion phase, the aurora continues to expand poleward and westward dissipating energy in the ionosphere. Eventually, the substorm moves into recovery where it gradually returns to a quiet configuration.

From a magnetospheric standpoint, substorms can be described as an imbalance in reconnection rates between the dayside magnetopause and the nightside plasma sheet. In other words, during the growth phase, the magnetopause reconnection is faster than that in the magnetotail leading to a buildup of magnetic flux in the lobes. The pressure built up from the additional lobe flux squeezes the magnetotail into a more stretched geometry which strengthens (and decreases the stability of) the cross-tail current sheet. As the tail continues to be squeezed by the lobes, the inner boundary of the Central Plasma Sheet\(^1\) (CPS) creeps earthward. This process can also

---
\(^1\)The CPS is the region of space containing the cross-tail current sheet.
be imagined as an earthward motion of the transition between dipole-like and tail-like magnetic field geometry. The earthward propagation of the CPS is responsible for the equatorward drifting of the low-latitude boundary of the auroral emissions. After onset, the picture changes and the lobe flux is reconnected into the magnetotail faster than at the magnetopause. The magnetic field becomes more dipolar ("dipolarizes") as the reconnected flux piles up in the inner magnetosphere and the flux is eventually convected back to the dayside at low latitudes along the flanks.

As will be discussed shortly, the transition from non-dipolar to more dipolar magnetic field in a region of space is important for the substorm current system. Because of this, understanding the dipolarization process is critical for understanding substorm dynamics. There are two types of dipolarization discussed in the literature. The first is the aforementioned flux pile up dipolarization. The second is a transient dipolarization front (DF) associated with channels of fast moving plasma known as Bursty Bulk Flows (BBFs) [Runov et al. 2009; Ge et al. 2011]. In both cases, it is typical to identify the dipolarization by the z-component of the magnetic field.

Research into the mechanism that leads to the substorm onset is ongoing. Clearly the fast reconnection in the magnetotail supplies the energy and plasma, but the mechanism responsible for the fast reconnection remains in question. At the present time, most substorm explanations fit into one of two conceptual frameworks. The first framework is the Reconnection Model also known as the Near Earth Neutral Line model (NENL) [Russell and McPherron 1973]. In that framework, the onset of fast reconnection is initiated in the near earth magnetotail (~15-25 RE). The outflow from the reconnection site penetrates to the inner magnetosphere where the onset arc maps (Figure 1.1). The brightening could be the result of a plasma instability or field aligned current associated with flow breaking. The second framework is called Current Disruption (CD) [Lui 1988, 1996]. In this framework, the inner magnetosphere
becomes unstable first leading to the diversion of the cross-tail current into the magnetoosphere which leads to auroral onset. In this model, the onset of fast reconnection is attributed to wave propagation from the initial unstable point (Figure 1.2) It is now accepted by both models that the onset arc maps magnetically to a region closer to the earth than the reconnection region. However, there is not agreement about how distant that region actually is.

In order to address this problem, the Time History of Events and Macroscale Interactions During Substorms (THEMIS) satellites were launched in 2007. The THEMIS mission consisted of five identical satellites with orbits designed to be aligned radially in the magnetotail at apogee over Canada. To supplement the satellite observations, a series of Ground Based Observatories (GBO) in Canada were equipped with all-sky imagers ASI to pinpoint the exact timing and location of the auroral activation [Donovan et al. 2006].

Initial results from THEMIS claimed to solve the problem showing signatures of reconnection 92 seconds prior to auroral brightening [Angelopoulos et al. 2008a]. However, a new substorm onset time sequence has been recently popularized by Nishimura et al. [2010b,c]. This sequence begins with a Poleward Boundary Intensification (PBI) that forms a north-south arc. As north-south arcs have previously been associated with earthward plasma flows [Lyons et al. 1999], the interpretation is that new plasma flows into the current disruption region (~ 6 – 10RE). This new plasma is responsible for triggering the instability that diverts the cross-tail current into the magnetosphere. It is important to note that while the plasma for this scenario originates from the polar cap (i.e. downtail), the scenario fits more closely into the CD framework. It is also important to note that many PBIs do not lead to substorm onset. In contrast to this scenario, Kepko et al. [2009] presented a clear event which showed the formation of high latitude aurora approximately six minutes prior to onset. That aurora
Reconnection Model

Figure 1.1: Reconnection (or Near Earth Neutral Line) model of a substorm. In this model, reconnection leads to current disruption and that leads to the onset of auroral brightening.

Current Disruption Model

Figure 1.2: Current Disruption model of a substorm. In this model, a plasma instability in the near earth region diverts the current into the ionosphere leading to the auroral brightening. The reconnection is enhanced shortly afterward due to waves from the original unstable region.

Figures taken from: http://www.igpp.ucla.edu/public/THESIS/SCI/Pubs/Nuggets/reconnection/tail_reconnection.HTML
then penetrated to the breakup arc with the onset occurring when the high latitude aurora reached the onset location. For this event, the formation of the high latitude aurora happened equatorward (earthward) of the polar cap boundary so this scenario is fundamentally different than the one proposed by Nishimura et al [2010b]. For the Kepko et al [2009] event, the THEMIS satellites showed fast flows consistent with the formation of the high latitude aurora and consistent with the initiation of near earth fast reconnection prior to auroral onset.

As pointed out by Raeder et al [2010], it is clear that multiple researchers looking at the same data can draw completely different conclusions. An example of this is the discussion in Angelopoulos et al [2008a] and Lui [2009]. Part of the ambiguity is due to the azimuthal uncertainty in the data. While THEMIS provides data at five points almost radially aligned, there are still very few opportunities to sample the plasma at points off that meridian. In effect, azimuthal propagation of the plasma features can appear to be propagating earthward or tailward depending on the event.

Auroral Emissions

The aurora produce a number of different emission lines which can be observed from space and on the ground. This dissertation deals specifically with the hydrogen Ly-α emission (121.8 nm). While other hydrogen emissions are present and observed from the ground (Hα and Hβ for example) their use is limited in this dissertation. Other emission lines (red-line, green-line and blue-line for example) are also important in substorm research. The green-line (557.7 nm) is excited by high energy (> 1 keV) electrons [Sharp et al 1983]. The blue-line (427.8 nm) responds to medium energy electrons [Eather and Mende 1971] and the red-line aurora (630.0 nm) typically responds to low energy electrons [Rees and Roble 1986]. Recently, Kepko et al [2009]
proposed that the red-line aurora may be related to the outflow from the reconnection site.

1.1.1 Substorm Current System

A number of magnetic signatures are associated with substorms in ground based magnetometer data. One of more significant signatures is the enhancement of the auroral electrojet. In the midnight sector, generally a westward current (electrojet) along the auroral oval is enhanced. This westward electrojet causes southward perturbations of the magnetic field that is measured by GBOs in the auroral zone. At any given time, twelve ground stations measure the local magnetic field. The maximum southward deviation from quiet conditions in any of the stations is used to derive the AL index. A corresponding index (AU) is derived from northward perturbations and is used to measure the eastward electrojet. Finally, the AE index is defined by the difference between the AU and AL indices at any point in time and is meant to measure the overall activity in the electrojets. Substorm expansion does not typically enhance the AU index appreciably, but it does enhance the AL index. Both AL and AE are used to identify substorms routinely. For this dissertation, we use the AL index as it is a more fundamental measurement for substorm expansion.

The magnetospheric origin of the westward electrojet is due to the Substorm Current Wedge (SCW). The SCW develops in an azimuthally localized region of the tail where the magnetic field quickly becomes more dipolar early in the expansion phase. Outside the SCW, the field remains highly stretched. In the highly stretched region, there is a large cross-tail current sheet with the current running from east to west as a consequence of Ampere’s Law and the highly stretched field configuration. However, in the more dipolar region, there can be little current. Because of current continuity, the current must go somewhere and therefore, it is diverted along the
Figure 1.3: Illustration of the Substorm Current Wedge (SCW). The strong cross-tail current is diverted along the edges of the dipolarized region into the ionosphere where it adds to the westward electrojet before returning to the tail along the other edge of the dipolarized region.

fieldlines into the ionosphere where it becomes the major contributor to the westward electrojet [Nagai et al. 1987, for example]. The SCW was originally described by McPherron et al. [1973] and is illustrated in Figure 1.3.

As the expansion phase continues, the near earth reconnection at $\sim 20R_E$ is constantly depositing new flux in the near earth region. That flux continues to pile up and increase the size of the dipolar region in the tail effectively increasing the radial and azimuthal extents of the SCW.

A number of authors have studied the azimuthal [Nagai et al. 1987; Nagai 1987; Belehaki et al. 1998; Watson and Jayachandran 2009] and radial expansions [Lopez and Lui 1990; Baumjohann et al. 1999] of the SCW. Typically, these studies have been done using satellites at geostationary orbit or only for a single substorm. As such, little can be said about how the substorm current wedge evolves outside of geostationary orbit other than the dipolarization statistically grows outward from the inner magnetosphere [Baumjohann et al. 1999]. Additionally, most of the studies have used a pair of GOES satellites for the magnetic field instruments with typical satellite footpoint separations on the order of thirty degrees. Thus, the spatial and temporal resolutions of the measurements are limited.

1.1.2 Mapping

Much of the substorm debate revolves around the inability to map ionospheric signatures (e.g. aurora) to magnetospheric features (e.g. pressure gradients, vortical flows, etc.). In order to map ionospheric features to the magnetotail (or vice-versa), authors [Sergeev et al. 2010, for example] often use variants of the semi-empirical Tsyganenko models [e.g. Tsyganenko 1989, 1996, 2002a,b]. However, due to their empirical nature, these models at best represent an average magnetospheric configuration for a set of input parameters. As such, there is no internal mechanism to
estimate the error in using this type of mapping. Angelopoulos et al. [2008b] used the T02 model with a range of input parameters to estimate the uncertainty in the mapping for a specific event. However, even using this approach they found that the empirical mapping did not agree with the expected mapping for any of the input parameters provided. There is also no self-consistent way to include time dependence in the empirical mappings. This can be a severe limitation for studies during high geomagnetic activity (e.g., substorm expansion) as the global magnetic field reconfigures on short timescales. Finally, the late growth phase poses a significant challenge to mapping because the amount of magnetic flux threading the central plasma sheet is very small. Since all of the closed flux leaving a region of the ionosphere must pass through the CPS (where the magnetic field is very small), small ionospheric regions map to very large regions of the magnetosphere.

A recent study by Kubyshkina et al. [2011] highlights the difficulties using empirical models to map the onset of a substorm. Using an extremely fortunate satellite configuration between THEMIS and GOES satellites, they were able to construct a time-dependent mapping model for a substorm on March 29, 2009. Based on their mapping, a satellite footprint can move by nearly four degrees in latitude during the growth and expansion phases. In contrast, the T96 empirical model had nearly static footprints throughout the entire substorm.

Due to the large uncertainty in empirical mapping for specific events, physics-based mapping has been gaining popularity in recent years. The basic idea is to connect a physical process in the ionosphere with its source in the magnetotail. One recent example has been presented by Nishimura et al. [2010a]. They found a very high correlation between chorus waves seen by the THEMIS spacecraft and a specific patch of pulsating aurora seen by an ASI. This remarkable observation allowed them to pinpoint the footprint location of the THEMIS spacecraft to a relatively small
region of the ionosphere (~10km) with a high degree of certainty. For the event they studied, the spacecraft footpoint deviated by 0.83 degrees in latitude and 1.05 degrees in longitude from the footpoint from an empirical model. In general, the pulsating aurora is the most equatorward (earthward) auroral form [Cresswell 1971; Viereck and Stenbaek-Nielsen 1985, and references therein]. Therefore, it is reasonable to expect that the empirical models would do best in this region. Unfortunately, using chorus waves and pulsating aurora also has a number of limitations. Clearly, this mapping technique only works if there is a satellite equipped to measure the chorus wave spectra in a region of the magnetosphere where the chorus waves are generated. This limits the satellite’s orbital inclination as chorus waves are generated only within a few degrees of the magnetic equator. The satellite’s apogee is also limited since chorus waves are only observed in the near-earth magnetosphere. Obviously, more physics based connections need to be made to map other regions of the magnetosphere.

In light of the uncertainty in empirical models and the limitations of physics based mapping, more physics based tools need to be developed to increase the likelihood of being able to map a particular feature during a particular event.

1.2 Proton Aurora

In 1939, Vergard [1939] identified the H-α and H-β hydrogen balmer lines in the aurora. It was noted that these emissions were Doppler shifted to shorter wavelengths [Memel 1951]. The Doppler shifted Ly-α transition is also commonly observed in the aurora. It is now readily accepted that these emissions are due to charge exchange between precipitating protons and atmospheric neutrals. The proton picks up an electron and becomes an excited hydrogen neutral which then emits a photon when
the electron drops to a lower energy state. The reaction is written as:

\[
X + H^+ \rightarrow X^+ + H^*
\]

\[
H^* \rightarrow H + h\nu
\]

where \(X\) is an atmospheric neutral. In general, the fast moving hydrogen is likely to collide and reionize starting the entire process over again, i.e.:

\[
H + X \rightarrow H^+ + X + e
\]

Since the precipitating proton can have considerable velocity along the line of sight of a ground or space based instrument, the emission is Doppler shifted and broadened. The Doppler shift is important for space borne spectrometers to distinguish between the cold geocoronal Ly-\(\alpha\) and the auroral emission.

A second important consequence of this reaction sequence is referred to as the “beam spreading effect”. Since the incident proton spends a significant portion of its time as a neutral hydrogen atom, it is not bound to the local magnetic fieldline and can therefore diffuse across the field (Figure 1.4) [Davidson 1965]. Calculations by Jasperse [1997] predict that an incident beam with a half-width of 120 km at an altitude of 600 km can spread by about thirty-three percent by the time it reaches 280 km. After that, there is very little additional spreading as the mean-free path rapidly decreases in the more dense atmosphere.
Figure 1.4: Charge exchange diffusion of proton aurora. An incident proton picks up an electron from an atmospheric neutral and is unbound from the local fieldline. As the electron drops to the ground state, a photon is emitted. Further collisions can ionize the hydrogen again and the process can start over.

1.2.1 Sources

Loss Cone

Since the force on a particle in a magnetic field is always perpendicular to the particle’s direction of motion and the local magnetic field, a particle in a converging magnetic field will always experience a net force toward the lower magnetic field region. This is shown schematically in figure 1.5. Typically, it is easier to think in terms of adiabatic invariants. If the change in the magnetic field is small for the period of time it takes for the particle to complete a single gyration, it can be shown that:

$$\mu = \frac{mv^2}{2B} \approx \text{constant}$$  \hspace{1cm} (1.1)
where \( v_\perp \) is the velocity perpendicular to the local magnetic field direction and \( \mu \) is the particle’s magnetic moment. In this limit, the particle’s motion is said to be “adiabatic”. It is also customary to define the pitch angle \( (\alpha) \) as

\[
\alpha = \tan \left( \frac{v_\perp}{v_\parallel} \right)
\]  \hspace{1cm} (1.2)

where \( v_\parallel \) is the velocity parallel to the local magnetic field direction. Using equations 1.1, 1.2 and conservation of energy, it can easily be shown that

\[
\frac{\sin^2(\alpha_{eq})}{B_{eq}} = \frac{\sin^2(\alpha_{iono})}{B_{iono}}
\]  \hspace{1cm} (1.3)

where the subscripts “eq” and “iono” refer to the values at the equatorial plane and the ionosphere respectively.

A particle’s mirror point is the point at which its pitch angle is ninety degrees (or equivalently, where \( v_\parallel = 0 \)). The loss cone is the set of pitch angles which allow the particle to reach the ionosphere, collide and precipitate prior to reaching the altitude of its mirror point. From equation 1.3, the size of the loss cone in the equatorial plane is:

\[
\sin(\alpha_{eq}) \approx \alpha_{eq} \leq \sqrt{\frac{B_{eq}}{B_{iono}}}
\]  \hspace{1cm} (1.4)

where a small angle approximation was used since \( B_{iono} \) is generally much greater than \( B_{eq} \).

In order for the proton aurora to persist for longer than it takes for an average proton to bounce between mirror points, some mechanism must exist to continually move particles into the loss cone. Two mechanisms which have been proposed are wave-particle interactions and fieldline curvature (FLC).
Wave-Particle Interactions

Waves can cause a particle to “violate” the first adiabatic invariant by supplying electric fields or by having magnetic field oscillations that resonate with the particle’s gyrofrequency. Since ions are much heavier than electrons, any electric field that could influence their motion is shorted out quickly by the fast moving electrons. However, the electromagnetic ion cyclotron (EMIC) wave has been show to efficiently scatter protons into the loss cone \[\text{[Fuseher et al. 2004; Yahnm and Yahmna 2007; Zhang et al. 2008; Spasojevic and Fuseher 2009].} \]

EMIC waves have frequencies on the order of the ion gyrofrequency and therefore can violate the conservation of the first adiabatic invariant. Observationally, EMIC waves are generally confined to the flanks \[\text{[Mm et al. 2011] and are therefore not typically relevant to the proton precipitation near the substorm onset. Because of this, we will focus the remainder of our discussion on the fieldline curvature mechanism.}\]

Fieldline Curvature

In regions of the magnetotail where the magnetic field becomes highly stretched (small radius of curvature), the small variation constraint on equation 1.1 is no longer satisfied and the first adiabatic invariant is no longer conserved, i.e. the motion of the particle becomes non-adiabatic in that region. Since the particle continues to conserve energy but the perpendicular energy is proportional to the local magnetic field strength, the pitch angle also must change. Using simulations of particles in a contrived magnetic field, \[\text{Sergeev and Tsyganenko [1982] showed that where the ratio of the magnetic field radius of curvature (} R_c \text{) to the gyroradius (} \rho \text{) dropped below eight there was strong pitch angle scattering whereas there was little scattering above this}\]
boundary. This boundary is often seen in the literature as the $\kappa$ boundary, where

$$\kappa = \sqrt{\frac{R_e}{p}} \leq \sqrt{8} \sim 3$$  \hspace{1cm} (1.5)

[Büchner and Zelenyi 1986]. Some sources [Liu et al. 2007; Delcourt and Martin 1994; Delcourt et al. 1996; Büchner and Zelenyi 1989] also place a lower boundary on $\kappa$. For $\kappa$ less than one, the particle can enter “Speiser” or serpentine orbits where the particle becomes confined primarily to the plasma sheet [Speiser 1965]. Delcourt et al. [1994] showed that the scattering can happen over a single gyro-orbit and Delcourt et al. [1996] showed that the scattering maximizes around $\kappa \sim 2$.

In general, Delcourt et al. [1996] showed that whether a scattered ion finds itself in the loss cone is dependent on its initial pitch angle and gyrophase. Particles with small pitch angles (less than a few degrees) tend toward larger pitch angles, however these particles are rare since most of them are probably previously precipitated out. One consequence of this is that particles scattered into the loss cone from waves prior to entering the central plasma sheet are likely to find themselves scattered back out of the loss cone. Particles with large equatorial pitch angles (greater than 30°) are typically not scattered effectively. Particles between these two extremes tend toward larger or smaller pitch angles depending on their gyrophase when they encounter the field reversal. In other words, particles near (but not in) the loss cone are more likely to be scattered into it than particles that are far away.

### 1.2.2 Isotropy Boundary

Polar orbiting satellites such as the Fast Auroral SnapshoT Explorer (FAST) satellite that measure precipitating ion distributions frequently measure single loss cone distributions at altitudes above the proton aurora and double loss cone distributions
The boundary between the full downgoing with empty upgoing loss cones and empty downgoing and upgoing loss cones is referred to as the Isotropy Boundary (IB). As an example, panels 4 and 5 of Figure 1.6 show the clear transition in precipitating energy flux as a function of pitch angle for a randomly selected FAST overflight. The IB is marked with a black vertical line. A second boundary often referenced in the literature is the b2i [Newell et al. 1996], boundary. The b2i is the maximum of the integrated precipitating flux over all energies typically measured by the Defense Meteorological Satellite Program (DMSP) satellites. Newell et al. [1998] has shown that this boundary correlates very well with the IB. Because of this, the two boundaries are often used interchangeably in the literature.

Using the Geostationary Operations Environmental Satellites (GOES) Sergeev et al. [1993] showed that the IB latitude is highly correlated ($r \sim .9$) with the magnetic field inclination angle (degree of stretching) at geosynchronous orbit ($6.6 \, R_E$). Shortly thereafter, Sergeev and Gvozdevsky [1995] defined the MT index based on the IB latitude to characterize the amount of stretching in the magnetotail. Donovan et al. [2003b] demonstrated a procedure for calculating an approximate MT index from meridian scanning photometer (MSP) data. Meurant et al. [2007] used the algorithm developed by Donovan et al. [2003b] to approximate the b2i latitude and applied it to data from the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite. In that study, it was demonstrated that the IB latitude remains correlated with the degree of stretching even during the substorm expansion phase.

Since the IB latitude is so well correlated with the field stretching, it is assumed that the FLC mechanism is the dominant mechanism in generating the nightside proton aurora in this study. Because the FLC mechanism is inherently tied to the field
Figure 1.6  FAST overview plot for ions on overflight number 2000. From left to right, the invariant latitude of the spacecraft is increasing. The IB is the vertical black line. In panels 4 and 5, no precipitation is found with pitch angles near 0 and 180 degrees equatorward of the IB. Poleward of the IB, only the upgoing loss cone (180 degrees) is empty.
geometry, the proton aurora should contain qualitative (and possibly quantitative) information about the mapping.

It is important, however, to mention that not all measurements made at the IB are completely consistent with the FLC interpretation. The IB latitude is, in general, a function of energy. In a naive interpretation, higher energy particles would typically have larger gyroradii and, by equation 1.5, would more readily scatter than their lower energy counterparts. This would imply that the IB latitude for high energy particles should be equatorward of the IB latitude for lower energy particles. This ordering can be seen in panels 4 and 5 of figure 1.6 as the double loss cone for the low energy ions persists to slightly higher latitudes than the double loss cone distribution for the higher energy ions. Donovan et al. [2003a] showed that this is the case for approximately 10% of the FAST auroral oval crossings that they examined. (They examined ~ 1000 crossings). Nearly 10% of the crossings were completely inconsistent with the FLC interpretation (i.e. the lower energy IB was poleward of the high energy IB). The remaining crossings were ambiguous. Typically, the inconsistent crossings were distributed over early morning local times whereas the consistent crossings tended toward evening local times. If that precipitation is caused by FLC, the discrepancy could be due to precipitating He\(^+\) generated by charge exchange between geocoronal hydrogen and CPS ions [Kistler et al. 1998] as the FAST ESA instrument used in that study did not have the mass resolution to discriminate between ion species. An alternate explanation given by Donovan et al. [2003a] is that the proton drift paths may lead to anisotropic distribution functions.

1.2.3 Proton Aurora during Substorms

Figure 1.7 shows a white light onset taken from an ASI. The nearly vertical scans are the proton aurora (blue) and red-line aurora (red-orange). In the figure, it is
clear that the onset arc rests on the poleward edge of the proton aurora (and on the equatorward edge of the red-line auroral emission). This is the typical latitudinal ordering of auroral forms during a substorm onset [Lessard et al. 2007]. Because of this, it is generally accepted that the onset occurs in a region of highly stretched magnetic field in the magnetotail (or at least in the transition from moderately to highly stretched).

Typically, protons supply only a small percentage of the total energy input into the ionosphere [Hubert et al. 2002]. During substorms, this percentage is even smaller than normal. This is probably accounted for because the electron energy input can increase by an order of magnitude, whereas the proton precipitation sometimes only increases by $\sim 50\%$ [Mende et al. 2001].

Figure 1.7: White light onset with proton aurora (blue) and red line (red-orange) scans superimposed. Generally, the onset sits on the poleward edge of the proton aurora and equatorward of the red-line emission. (Figure courtesy of Eric Donovan)
Proton Auroral Fading

Liu et al. [2007] reported that the luminosity of the proton aurora can decrease by as much as twenty percent in the late growth phase. Their interpretation was that the late growth phase corresponds with a large reduction in the equatorial magnetic field (increased stretching). In the regime where \( \kappa \leq 1 \) the adiabatic scattering is quenched and particles tend toward “Speiser” orbits [Speiser 1965]. If the global field stretches to the point where \( \kappa \leq 1 \) almost everywhere, then the loss cone would be closed and the precipitation quenched.

It is also important to mention that proton auroral fading is a somewhat controversial topic. Mende [2003] did not find any fading of the pre-onset proton aurora although he did find that the pre-onset proton aurora tends to decrease in latitudinal extent resulting in a net decrease in global precipitation. The reason for the discrepancy is still an open question. Liu et al. [2007] remarked that the discrepancy could be due to the different spectral lines imaged for the studies. Where Liu et al. [2007] used MSPs imaging the H-\( \beta \) line, Mende [2003] used the spectrometer on the IMAGE spacecraft imaging the Ly-\( \alpha \) spectral line. However, it is unclear why the H-\( \beta \) line would exhibit fading whereas the Doppler shifted Ly-\( \alpha \) would not.

1.3 Motivation

Substorms, by themselves are typically a relatively benign phenomena, and therefore, it is worth asking why they are worth studying. As already mentioned, they are responsible for transferring solar wind energy and mass into the magnetosphere during the growth phase. Since that mass and energy cannot accumulate indefinitely, substorms release it during the expansion phase. While there are other modes of transport in the magnetosphere (steady magnetospheric convection for example),
substorms are observed much more frequently and are therefore critical to understanding the magnetosphere as a whole.

Second, substorms are inherently tied to the sudden onset of fast magnetic reconnection. Gaining a better understanding of reconnection is important across the entire range of plasma physics. One example, not too far removed from magnetospheric physics, is the fast reconnection associated with solar flares [Birn and Hesse 2009, for example]. In substorms as well as solar flares, there is a clear thinning of the plasma sheet, fast reconnection and the ejection of a plasmoid. In the latter case, the ejected plasmoids are often referred to as coronal mass ejections (CMEs). CMEs which hit the earth are often associated with strong geomagnetic storms. Many industries (particularly those that rely on high precision GPS technology) now want more reliable “space weather” forecasts.

Studying substorms has a few distinct advantages compared to studying solar flares. The most notable difference is that substorms can be studied using in-situ data, whereas the plasma conditions inside solar flares are much too volatile to be able to send a spacecraft there. Because of this, much more data is available about the plasma populations initiating fast reconnection in substorms and models are better (although still poorly) constrained.

The term substorm implies that there is a relationship between substorms and storms. When the term was coined, it was believed that storm-time ring current was a direct result of substorm expansion [Akasofu 1964]. This belief is no longer popular, however, that is not to say that substorms have no relationship with storms. Indeed, there are substorms associated with storms. Substorm particle injections probably play some role in the buildup of the storm-time ring current. A lot more work needs to be done to understand how substorms influence storm dynamics. Understanding the sources of substorm particle injections may illuminate some answers.
1.4 Goals of this Dissertation

One of the primary goals of this dissertation is to design and use an algorithm to calculate the proton precipitation using the OpenGGCM global MHD simulation. Specifically, we want to use the simulated proton precipitation to study substorms. To that end, Chapter 2 briefly discusses the OpenGGCM simulation and its ability to simulate substorms. Chapter 3 describes the algorithm we used to calculate the proton aurora using OpenGGCM along with its limitations and assumptions.

Chapter 4 will present a series of three event studies. In each event, the global proton precipitation splits on the eastward edge of the westward traveling surge. To our knowledge, this auroral feature has not been discussed before. When mapped to the magnetotail, the split in the proton precipitation is caused by the strongly dipolar magnetic field inside the substorm current wedge quenching the proton scattering.

In order to validate the simulation, Chapter 6 presents a statistical study using data from the IMAGE spacecraft far-ultraviolet instrument. The study shows that the proton auroral splitting is common and that it has a strong dependence on AL and onset latitude. (Stronger substorms are more likely to have split proton aurora). A brief overview of the IMAGE spacecraft and specifically the far-ultraviolet imager is presented in Chapter 5 since that data is used extensively in Chapter 6.

Finally, we summarize our results and present our plans for future extension of this work in Chapter 7.
Chapter 2

Global Magnetohydrodynamics

using the OpenGGCM simulation

2.1 Introduction

Historically, scientific progress has been made experimentally and theoretically and often there has been significant interplay between the two. Theories are tested by experiments and experiments raise new questions that need to be modeled theoretically in order to be understood. Ideally, experimentalists have full control over their experiments. They can vary the system a little bit at a time to determine how the system works. In some disciplines, however, this simple framework does not work because the system is too large, too small or too complex for the experimentalist to have any control over the experiment. This is the case with the magnetosphere.

In the magnetosphere, the dynamics are influenced externally by the sun and internally by the coupling to the ionosphere. Magnetospheric scientists are necessarily passive observers. Because of this, the traditional experimentalist has been replaced by observationalists in magnetospheric sciences. Typically, we observe the plasma upstream from a solar wind monitor such as the Advanced Composition Explorer (ACE) or WIND satellites. At any given time, we also have a combination of in-situ measurements and remote sensing instruments on satellite payloads within various
regions of the magnetosphere or on the ground. However, due to the cost of creating satellites, at any given time the magnetosphere is grossly under-sampled. Ground based data can be very difficult to interpret because the source regions are often not well understood. Because of this, theoretical models are generally poorly constrained. As such, much of our understanding of the magnetosphere is built up from statistical models and results for specific events are interpreted in light of those statistical models.

With the exponential growth in computational power, simulations have been used to gain control over magnetospheric experiments. Numerical experiments can be performed with contrived boundary conditions that can illuminate the important physical processes. Simulations also place additional constraints on theoretical models and vice-versa. Global magnetospheric simulations allow satellite measurements to be placed in a global context for individual events instead of being forced to rely on statistical models.

Simulations always try to solve a system of equations which approximates the physical system. Typically, many simplifying assumptions must be made to arrive at a tractable system of equations. After that, another level of approximation is introduced by discretizing the equations. As such, it is always important to validate the model against observations. Good model-data agreement lends credence to the simplifying assumptions and also increases our confidence in the simulation’s validity in regions where there is no observational data.

2.2 OpenGGCM

A large portion of this dissertation uses the Open Geospace General Circulation Model (OpenGGCM) numerical simulation of the magnetosphere [Raeder 2003]. The OpenGGCM is a magnetohydrodynamic (MHD) simulation with a dedicated iono-
sphere module. As such, it covers all the regions of interest for this study. OpenGGCM was originally written in the early 1990s at the University of California Las Angeles (UCLA). A version of the model is still run there and is commonly referred to as the UCLA model. The simulation uses a modified cartesian Geocentric Solar Ecliptic (GSE) coordinate system. In GSE coordinates, the X axis points toward the sun, the Z axis points northward, normal to the ecliptic plane and the Y axis completes the right handed coordinate system. A typical simulation domain is from approximately 40RE upstream to as far as 1000RE downstream. The extent in the Y and Z directions are generally between 40RE and 100RE. Since the resolution needs to be so fine to resolve all of the important regions of the magnetosphere, OpenGGCM must run simultaneously on a large number of computers to achieve an adequately resolved result in a reasonable amount of time. The parallelization is done using the message passing interface (MPI) standard.

The MHD equations are a combination of Maxwell’s equations for electricity and magnetism and the equations of fluid flow. They can be cast into a number of different forms for use in different numerical methods. Generally, either the “Full conservative” or the “Gas dynamic conservative” formalisms are used. The full conservative formalism allows the conservation of mass, momentum, total energy and magnetic flux in a finite difference scheme. However, it suffers in regions where the plasma

\[ \beta = \frac{p}{(B^2/2\mu_0)} \]

becomes small. In these regions, the pressure becomes the difference of two large numbers and therefore it is difficult to resolve numerically due to roundoff error. Since the magnetosphere has very large magnetic fields in the inner magnetosphere, this formalism is not typically used to solve the MHD equations for global models (with a few exceptions). OpenGGCM’s approach for modeling the global system is to use the gas dynamic (or semi-conservative) formalism [Raeder et al. 2001a].
In this formalism, the MHD equations are:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) \quad (2.1a) \\
\frac{\partial \rho \mathbf{v}}{\partial t} &= -\nabla \cdot (\rho \mathbf{v} \mathbf{v} + p \mathbf{1}) + \mathbf{j} \times \mathbf{B} \quad (2.1b) \\
\frac{\partial e}{\partial t} &= -\nabla \cdot ((e + p) \mathbf{v}) + \mathbf{j} \cdot \mathbf{E} \quad (2.1c) \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \quad (2.1d) \\
\nabla \cdot \mathbf{B} &= 0 \quad (2.1e) \\
\mathbf{E} &= -\mathbf{v} \times \mathbf{B} + \eta \mathbf{j} \quad (2.1f) \\
\mathbf{j} &= \nabla \times \mathbf{B} \quad (2.1g) \\
e &= \frac{\rho v^2}{2} + \frac{p}{\gamma - 1} \quad (2.1h)
\end{align*}
\]

where the quantities $\rho$, $\mathbf{v}$, $\mathbf{E}$, $\mathbf{j}$, $\mathbf{B}$, $\eta$, $p$ and $e$ have their usual meanings (i.e. mass density, plasma bulk velocity, electric field, current density, magnetic field, resistivity, pressure and plasma energy respectively). The semi-conservative formalism allows the numerical conservation of mass, momentum and plasma energy. Total energy, however, is not strictly conserved.

### 2.2.1 Parametrization of resistivity

There are a large number subtleties that must be dealt with when using a fluid model for a global simulation. It is easily shown that when the resistivity ($\eta$) is zero in Ohm’s law (equation 2.1f) the magnetic field is “frozen” with the plasma flow. With a non-zero resistivity, however, the fieldlines are no longer frozen within a plasma fluid element resulting in magnetic reconnection. Birn et al. [2001] showed that Ohm’s law (equation 2.1f) produces reconnection rates that are far too slow for a constant and
realistic value of \( \eta \). However, a localized ("anomalous") resistivity can reproduce reconnection rates similar to those produced by kinetic models. The specific model used by OpenGGCM is:

\[
\eta = \begin{cases} 
\alpha |j_2|^2 & \text{if } j_2 \geq \delta \\
0 & \text{otherwise}
\end{cases}
\]

(2.2)

where \( \alpha \) and \( \delta \) are constants that can be adjusted to determine the resistivity strength and threshold for turning on, \( \epsilon \) is a small number to prevent division by zero and \( \Delta \) is the grid spacing. Raeder et al. [1996] showed that without this current dependent resistivity, the magnetosphere tended toward steady convection with very well balanced dayside and nightside reconnection. (Reconnection is able to proceed even when the resistivity is zero due to numeric resistivity introduced by discretizing the equations).

Parameterizing the resistivity in this way does not capture the small scale features of the reconnection region (e.g. the quadrupolar magnetic field due to Hall reconnection [Runov et al. 2003]), but it is assumed that by capturing the reconnection rate, the global system should be relatively unaffected by the small scale details. In order to better model the physics on the small scales, the code would need to use a more generalized form of Ohm’s law:

\[
\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta \mathbf{j} + \frac{1}{en} \mathbf{j} \times \mathbf{B} + \frac{1}{en} \nabla \cdot \mathbf{P} + \frac{1}{\epsilon_0 \omega_{pe}^2} \frac{d\mathbf{j}}{dt}
\]

(2.3)

where \( e \) is the fundamental unit of charge and \( n \) is the number density. The parametrization of resistivity in equation 2.2 and equation 2.1f are used instead of equation 2.3 because the additional terms in 2.3 either operate on sub-gridscale length scales or
because they permit the inclusion of waves that would severely limit the timestep the
simulation could use to advance the equations.

2.2.2 Boris Correction

A second modification which must be made to obtain a solution in a reasonable
amount of time is the “Boris Correction”. In some regions of the magnetosphere
(particularly the lobes and near the Earth), the Alfvén speed \( \frac{B}{\mu_0 \rho} \) can get very high
due to very strong magnetic field and/or very low density \( \rho \). In general, the timestep
is limited by the Courant-Friedrichs-Lewy (CFL) condition which states:

\[ \Delta t \leq \frac{\Delta}{V} \]  \hspace{1cm} (2.4)

where \( V \) is typically the speed of the fastest traveling wave in the system, \( \Delta t \) is the
timestep, and \( \Delta \) is the local grid spacing. The CFL condition basically states that
information can only travel from one cell to its neighbor during a single timestep.
This condition needs to be satisfied at every point on the grid in order to avoid an
unphysical exponential growth of the solution, and thus a localized but fast Alfvén
wave can force the global timestep to be prohibitively small. A solution to this
problem was proposed by Boris [1970]. Nature limits the speed of a (relativistic)
Alfvén wave to the speed of light. If one uses an artificially small speed of light,
then the Alfvén speed in the simulation will also be limited. In practice, this is
accomplished by reducing the \( j \times B \) and the perpendicular component of the \( \nabla p \) force
in the offending regions [Raeder 2003].
2.2.3 Outer Boundary Conditions

For event studies, the OpenGGCM typically uses minimum variance analysis [Sonnerrup and Cahill 1967, 1968] to propagate satellite measurements to the sunward boundary of the simulation at the solar wind speed. (Hereafter, this process is referred to as MINVAR). This assumes that the solar wind is nicely oriented into layers oriented at the same angle with respect to the sun-earth line [Raeder et al. 2001b; Weimer et al. 2002, 2003]. Alternatively, the inflow solar wind parameters can be taken directly from the satellite measurements, however in this case the $B_x$ component must be set to a constant in order to insure that the divergence of the magnetic field is zero (equation 2.1e).

All of the other faces of the computation domain use “free flowing” boundary conditions (i.e.):

$$\frac{\partial \Psi}{\partial n} = 0$$

where $\Psi$ is any of the variables in OpenGGCM and $n$ is the normal to the boundary).

2.2.4 Inner Boundary Conditions

The MHD equations are not solved within the inner boundary of the simulation. For a typical simulation, the inner boundary is placed near 3.5 $R_E$. At the inner boundary, the simulation is coupled to the ionosphere module by field-aligned currents (FACs) and synthetic particle precipitation; the feedback is provided through the polar cap potential. The parallel current along with the number density and temperature are mapped to the ionosphere along dipolar fieldlines. At the ionosphere, particle precipitation is calculated using simple empirical relations. For the diffuse electron precipitation, the precipitating energy flux is calculated as the thermal energy.
multiplied by the thermal velocity:

\[ F_E = n_e k T_e (k T_e / 2 \pi m_e)^{\frac{3}{2}} \]  \hspace{1cm} (2.6)

where \( n_e \) is the (magnetospheric) number density, \( k \) is Boltzmann’s constant, \( T_e \) is the (magnetospheric) electron temperature and \( m_e \) is the electron mass. To calculate the discrete precipitation, the Knight relation is used [Knight 1973]:

\[ F_E = \frac{e^2 n_e}{\sqrt{2 \pi m_e k T_e}} \max(0, -j ||) \]  \hspace{1cm} (2.7)

At this point, to proceed further with the evolution of the entire system, the ionospheric potential is needed. The potential is computed assuming the fieldlines are radial:

\[ \nabla \cdot \Sigma \cdot \nabla \Phi = -j || \sin I \]  \hspace{1cm} (2.8)

where \( I \) is the inclination angle and \( \Phi \) is the potential. \( \Sigma \) is the height integrated conductance tensor:

\[ \Sigma_{\theta \theta} = \frac{\Sigma_P}{\sin^2 I} \]
\[ \Sigma_{\theta \lambda} = \frac{\Sigma_H}{\sin I} \]
\[ \Sigma = \begin{pmatrix} \Sigma_{\theta \theta} & \Sigma_{\theta \lambda} \\ -\Sigma_{\theta \lambda} & \Sigma_P \end{pmatrix} \]  \hspace{1cm} (2.9)

where \( \Sigma_P \) and \( \Sigma_H \) are the Pederson and Hall conductances. At this point, the conductances can be computed either using an empirical relation, or via an ionosphere model. For all the simulations in this dissertation, the Coupled Thermosphere-Ionosphere Model (CTIM)[Fuller-Rowell et al. 1996] was used. CTIM takes the precipitation parameters calculated by OpenGGCM and the solar UV and EUV fluxes and returns
(among other things) the ionospheric conductances needed to solve equation 2.8. Further details on the coupling between OpenGGCM and CTIM can be found in Raeder et al. [2001b].

Once the potential is known, the velocity at the inner boundary of the simulation can be calculated from $v = (-\nabla \Phi) \times B/B^2$. The temperature and number density are fixed at the inner boundary and remain constant throughout the simulation, although this deficiency should be removed once the simulation is fully coupled to the Comprehensive Ring Current Model (CRCM) [Fok et al. 2001]. The inner boundary magnetic field is set to the dipole field which historically was at a fixed orientation throughout a run. For short simulations, such as the substorms presented in this dissertation, this is probably not a big issue. However, for longer simulations (like the ones required for geomagnetic storms), the fixed dipole approximation is questionable since the dipole changes orientation by twenty two degrees every twelve hours. Unless otherwise noted, all simulations presented in this dissertation used a fixed dipole orientation.

While the inner boundary is only a small part of the system, it is critically important. Raeder et al. [1996] showed that small scale processes can have large influences on the global system. One result from that study was that uniform conductivity in the ionosphere prevents the development of substorms. This is not surprising as the conductivity determines how tightly the magnetic fieldlines are bound to the ionosphere. However, the coupling between the ionosphere and the magnetosphere can be relatively loose [Raeder et al. 2001b]. Since the ionosphere evolves on timescales much larger than the timescales of the magnetosphere, coupling between the OpenGGCM and CTIM is only done every sixty seconds simulation time. CTIM is run as a separate process and for computational efficiency, CTIM lags OpenGGCM by sixty seconds. In other words, OpenGGCM uses the values of conductance supplied by CTIM for
the previous sixty seconds rather than waiting for CTIM to complete calculating the
conductance with the parameters just supplied.

2.2.5 Numerics

OpenGGCM uses a 4th order hybrid technique to integrate the gas-dynamic parts
of the equations [Harten and Zwas 1972]. In regions of discontinuities, the scheme
degraded to a 1st order Rusanov scheme. This allows for adequate shock resolution in
the code. The magnetic portion of the equations is slightly more difficult due to the
constraint that \( \nabla \cdot \mathbf{B} = 0 \) (equation 2.1e). In fact, equation 2.1e can be thought of
as a transport equation when combined with Faraday’s law (equation 2.1d). Taking
the divergence of equation 2.1d yields:

\[
\nabla \cdot \frac{\partial \mathbf{B}}{\partial t} = -\nabla \cdot \nabla \times \mathbf{E} \\
\frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = 0 
\]  

(2.10)

Therefore, if \( \nabla \cdot \mathbf{B} = 0 \) at some time, it must remain so forever. Unfortunately, a
non-zero \( \nabla \cdot \mathbf{B} \) is not something that can be tolerated as it gives rise to unphysical
parallel acceleration (see Evans and Hawley [1988] and references therein). There are
a few approaches to dealing with this issue numerically. The equations can be recast
to use the magnetic vector potential with the disadvantage that for a second order
scheme very high truncation error can result when calculating the Lorentz force (see
the discussion in Evans and Hawley [1988]). Another common approach is to use a
divergence cleaning method [Dedner et al. 2002, for example]. Typically, methods of
this type have the disadvantage that they need to solve a Poisson equation on the
global grid at each step in order to satisfy 2.1e. Solving the Poisson equation can be
costly and it also introduces non-local effects. In typical finite difference schemes, the
solution at any grid point is only dependent on its close neighbors. However, with a
divergence cleaning method, the solution at any given grid point depends on all other
points on the global grid. This effectively allows information to be transported in the
simulation at speeds greater than the speed of light [Balsara and Kim 2004]. The
“constrained transport” solution to this problem was proposed by Evans and Hawley
[1988] and is used by OpenGGCM. A “Yee grid” is used where the magnetic field is
defined on the cell faces and the electric field is defined on cell edges and the fluid
quantities are defined at the cell centers (Figure 2.1). This allows the discretization
to preserve the condition in equation 2.10 to within roundoff error. When using a Yee

![Gridcell structure used by OpenGGCM. The Magnetic field is offset onto
the cell faces and the Electric field is defined on the cell edges. (Figure from
Raeder [2003])](image)

grid, the fields need to be interpolated to the cell centers to solve some of equations
2.1, however, this is a small price to pay for magnetic flux conservation.
Figure 2.2: Example grid used in this dissertation. (Note that the actual grid had ten times higher resolution than shown). The grid allows higher resolution near earth and in the magnetotail.

A second aspect of OpenGGCM’s numerics is the actual grid structure used by the simulation. Uniform grid structures are not frequently used in global MHD models because the magnetosphere is a big place and to adequately resolve the important regions (e.g. the central plasma sheet), would mean that other regions with a much more smooth solution would be grossly oversampled. As an example, a uniform grid \((dx=0.25 \text{ R}_E, \ dy=0.25 \text{ R}_E, \ dz=0.16 \text{ R}_E)\) would take over 217 million cells in moderately sized domain of \((64\text{ R}_E)^2 \times 530\text{ R}_E\). Using a stretched cartesian grid (Figure 2.2), \textit{Raeder et al.} [2008] constructed a grid with similar resolution in the central plasma sheet using less than 38 million cells.

The constrained transport algorithm easily adapts to a stretched grid configuration. Mainly, if the grid coordinates are constructed such that they can be written as analytic functions of the grid indices \((i, j, k)\) (i.e. \(x=x(i), y=y(j), z=z(k)\)), then
derivatives on the grid can simply be computed as:

\[
\frac{\partial F(x, y, z)}{\partial X} = \frac{\partial F}{\partial \alpha} \frac{\partial \alpha}{\partial X} = \frac{\partial F}{\partial \alpha} \left( \frac{\partial X}{\partial \alpha} \right)^{-1}
\]

where \( X \) is \( x, y \) or \( z \) and \( \alpha \) is the corresponding index. This has the advantage that derivatives are the same as the derivative on a uniform grid multiplied by a geometric factor which can be precomputed [Raeder 2003]. Another advantage of this grid structure is that it is easy to decompose the domain for parallel computing (compared to more complex grid structures like adaptive mesh refinement).

2.2.6 Remarks

There are a few things important for this study about OpenGGCM that still need to be mentioned. First, the single fluid MHD equations do not model ring current physics. Because of this, results in the inner magnetosphere (inside geosynchronous orbit) need to be treated with caution, and the simulation mapping may be somewhat distorted especially for simulations during high geomagnetic activity (magnetic storms). Future work in coupling OpenGGCM to an inner magnetospheric model should help to alleviate this problem. Additionally, in a highly stretched plasma sheet, kinetic effects which are not captured by MHD become more important. Also, as noted earlier, OpenGGCM uses a current dependent switch to essentially turn on the reconnection. Since the actual mechanism which is responsible for the onset of fast reconnection during substorms is still unknown, the consequences of that parametrization are also unknown and therefore care must be taken in interpreting the results.

However, OpenGGCM and its predecessor (the UCLA model) have been shown to produce a large number of substorm features such as auroral brightening, ground mag-
netic perturbations, dipolarization, fast earthward flows associated with reconnection and the westward traveling surge [Raeder et al. 1996, 2001b, 2008, 2010; El-Alaoui et al. 2009; Ge et al. 2011]. In the case of Angelopoulos et al. [2008b], the simulation mapped the THEMIS spacecraft footpoints into the westward traveling surge whereas available empirical models did not. Since the spacecraft all recorded flow enhancements and energized particles, it was assumed that the simulation mapping was in better agreement with the data than the empirical model. Some substorm features such as particle injections cannot be resolved by the MHD. This deficiency should be improved in the future by two-way coupling an inner magnetosphere model to the OpenGGCM.
Chapter 3

The Proton Precipitation Algorithm

3.1 Introduction

The parameterization for the proton precipitation that was proposed by Sergeev et al. [1983] described in Section 1.2.1 is particularly suited for adapting into a global magnetohydrodynamic (MHD) framework. Since this study is mainly concerned with substorms and nightside aurora, we have chosen to only model the proton aurora caused by fieldline curvature (FLC) scattering of protons into the loss cone (see Section 1.2.1). Wave particle interactions are not included because they are not currently well parametrized in terms of MHD variables. If the model can reproduce observed features by only including the contribution from the FLC scattered protons, it will strengthen the argument that FLC is the dominant scattering process in the nightside proton aurora.

The global MHD model used for this study is the OpenGGCM. OpenGGCM is described briefly in Chapter 2 and elsewhere [Raeder et al. 1996, 2001b,a; Raeder 2003]. The global MHD fields (magnetic field, temperature and number density) were used as the input for the proton precipitation code discussed in the following sections.
3.2 Algorithm

To calculate the global proton precipitation from fieldline curvature, fieldlines are traced from every point on the OpenGGCM ionospheric grid. A simple Runge-Kutta algorithm is used to integrate the fieldlines:

\[
\frac{dx}{ds} = \frac{B}{|B|}
\]

where \( s(x) \) is the path of a fieldline. A number of different order algorithms were attempted and it was found that anything over second order gave similar results. For all the results presented, a fourth-fifth order adaptive stepsize algorithm was used, although the tri-linear interpolation used on the fields is only accurate to second order in space and therefore the fieldlines are likely to be accurate to only second order in space. On closed fieldlines (fieldlines which return to earth without intersecting with the simulation domain limits), the \( \kappa \)-parameter is calculated in the CPS. A number of different definitions were tested for finding the CPS along a fieldline (minimum of the magnetic field strength, maximum of plasma \( \beta \), sign change of \( B_x \)), but in the end we choose to use the maximum distance from the earth of any point along the fieldline. All the above definitions gave similar results in our region of interest, however the one chosen was at least as memory efficient as the others and also provided a reasonably smooth solution even in the inner magnetosphere and on the flanks where there is no significant current sheet.

The curvature is calculated by:

\[
\frac{\hat{n}}{R_c} = -(\hat{b} \cdot \nabla)\hat{b}
\]
where $R_c$ is the radius of curvature and $\hat{b}$ a unit vector pointing in the direction of the local magnetic field. To get the average gyroradius ($\rho$), a few assumptions need to be made about the particle distribution. For this study, we assumed a Maxwellian distribution and so the gyroradius can be calculated as:

$$\rho = \frac{mV_{th}^2}{e|B|} = \frac{\sqrt{2mkT}^3}{e|B|}$$

(3.3)

where $V_{th}$ is the average thermal speed of a particle in one direction, $m$ is the particle mass, $k$ is the Boltzmann constant, $T$ is the MHD temperature and $e$ is the particle’s charge. The $\kappa$-parameter is then calculated via equation 1.5. Early versions of the code calculated the $\kappa$-parameter at every point along a fieldline. However, assuming that the minimum value of $\kappa$ is in the CPS seemed to make no difference for the simulation and is slightly more computationally efficient.

The precipitating energy flux is then calculated by:

$$F_E = f(\kappa)n_p kT(kT/2\pi m_p)^{\frac{1}{2}}$$

(3.4)

Equation 3.4 is the same as equation 2.6 with proton parameters substituted instead of electrons and modulated by an additional function of $\kappa$. For this study, $f(\kappa)$ was taken to be:

$$f(\kappa) = \begin{cases} 1 & \text{for } \kappa_{min} \leq \kappa \leq \kappa_{max} \\ 0 & \text{otherwise} \end{cases}$$

(3.5)

i.e., the loss cone is either completely full or completely empty, or equivalently, the scattering isotropizes the distribution. The temperature and number density are taken from model parameters near the inner boundary. Typically, $\kappa_{max}$ was set to $\sqrt{8}$ and $\kappa_{min}$ was set to zero for this study to agree with Sergeev et al. [1983]. Other functions of $\kappa$ have been reported in the literature, for example [Liu et al. 2007, and
references therein] used a form:

\[ f(\kappa) \propto \exp(-0.97\sqrt{\kappa}) \]  \hspace{1cm} (3.6)

over the above range. This form was briefly experimented with, however, attempts
to use it were abandoned for reasons described in Section 3.3. The code has been
written to allow different functions of \( \kappa \) to be easily added if the limitations described
in Section 3.3 are ever removed.

Since the proton precipitation code spends most of its time tracing fieldlines, the
code has been written to make it nearly trivial to calculate other quantities on the
global ionospheric grid that require the fieldline connected to that point (e.g. flux
tube volume, the open-closed boundary, equatorial crossing point, etc.). This design
has already made it useful in the study of Ge et al. [2011] and will hopefully continue
to be useful for science studies in the future.

\section{3.3 Limitations}

The simplified algorithm described above has a number of limitations which need to
be kept in mind when interpreting the results.

\textbf{Transit Time}

The above algorithm does not account for transit time from the equatorial plane to
the ionosphere. In a dipole field, equation 3.1 can be integrated directly in spherical
coordinates yielding:

\[ r = L \sin^2(\theta) \]  \hspace{1cm} (3.7)
where $L$ is the equatorial crossing distance. The arc length can be computed along the fieldline as:

$$S = \int_{s_0}^{s_f} ds(x) = \int_{s_0}^{s_f} \sqrt{dr^2 + r^2 d\theta^2}$$  \hspace{1cm} (3.8)$$

since the azimuthal component of a dipole field is zero. Using equations 3.7 and 3.8 and integrating from the ionosphere to the equatorial plane yields:

$$S = \frac{L}{2\sqrt{3}} \left( \text{asinh} \left( \sqrt{3} \left( 1 - \frac{r_0}{L} \right) \right) + \sqrt{3} \sqrt{1 - \frac{r_0}{L} \sqrt{4 - 3\frac{r_0}{L}}} \right) \hspace{1cm} (3.9)$$

where $r_0$ is the distance from the earth’s center to the assumed emission height. For an emission altitude of 250 km and equatorial crossing distance of 6.6 $R_E$, equation 3.9 yields a distance of approximately 8 $R_E$. A 30 keV field aligned proton travels approximately 0.38 $R_E$ and will therefore take slightly over 20 s to reach the ionosphere. 8 keV protons – the energy the IMAGE SI-12 spectrometer is most sensitive to (see Section 5.3 in Chapter 5) – take on the order of 40 s to reach the ionosphere. In contrast, electrons with $\frac{1}{5}$th the energy of the protons (the typical ratio of proton energy to electron energy in the CPS [Baumjohann and Paschmann 1989]) arrive in about 1.3 seconds and 2.5 seconds respectively. Therefore, while the electrons arrive almost immediately, the protons take significantly longer to reach the ionosphere.

In reality, the path taken is not completely dipolar, but the protons are also often scattered at $L$ values greater than 6.6 $R_E$ and very few of the protons are actually directly field aligned. Therefore, the estimated time lag between the arrival of the protons and electrons should be interpreted as a lower limit. As such, the proton precipitation produced by the above algorithm probably arrives on the order of one minute earlier than it should compared to the simulated electron aurora, however, since the energy flux calculation (equation 3.4) is performed using values closer to
the simulation inner boundary, transit time should be less important and the relative intensities of the proton precipitation to electron precipitation are self-consistent.

**Beam-Spreading Effect**

No attempt has been made to model the beam spreading effect of the proton aurora discussed in section 1.2 of chapter 1. This is partially due to the grid. The OpenGGCM typically uses an ionospheric grid with resolution of two to three degrees in longitude and 0.5 degrees latitude. In the auroral zone, one degree latitude is approximately 100km and one degree longitude is approximately 50km. Thus, the ionospheric resolution (in the auroral region) is about 50km latitude by 150km longitude. The beam spreading would cause precipitation to “leak” into one or two adjacent cells, but probably not much further. In order to actually compute the beam spreading effect self-consistently, a much more complicated ionospheric model would be necessary. The lack of the beam spreading in the code probably only causes boundaries in the proton aurora to appear sharper than they actually are. In effect, we have modeled proton auroral precipitation as can be measured by low altitude polar orbiting satellites, not proton auroral brightness as is measured by optical or far-ultraviolet imagers.

**Model Resolution**

For typical plasma sheet parameters ($T \sim 4.2$keV, $|B| \sim 10\text{nT}$ [Kwelson and Russell 1995; Borovsky 2003]), equation 3.3 yields gyroradii of approximately 1000 km. In order to resolve the $\kappa \sim 3$ boundary, the grid spacing must be on the order of 9000 km which is easily resolved for OpenGGCM. To resolve the $\kappa \sim 1$ boundary, the resolution must be on the order of 1000 km which is resolvable by high resolution runs. However, substorms and storms are not “typical” conditions as they can increase
the plasma temperature by more than a factor of four [Baumjohann 1991] and/or decrease the equatorial magnetic field. Fortunately, these two effects generally happen separately. The temperature increase occurs at the start of the expansion phase which corresponds to dipolarization and an increase in the local magnetic field. The worst case scenario with a temperature $\sim 4.2\text{keV}$ in a highly stretched field ($|B| \sim 7.5\text{nT}$) yields $\rho \sim 0.2R_E$. To resolve the $\kappa = 3$ boundary, we need to resolve a curvature of approximately $R_c \sim 1.8R_E$.

As such, in order to be confident that we have adequately resolved field curvature required for the proton scattering, we generally try to have a resolution on the order of 1000 km ($\sim 0.15R_E$) particularly along the Z axis for substorm runs. With this resolution, we are confident that we can at least resolve the $\kappa = 3$ boundary. Below the $\kappa = 1$ boundary is a difficult regime to resolve. This limitation on our ability to resolve particularly low values of $\kappa$ prohibits equation 3.6 from being useful for this study. This limitation is not only due to the grid resolutions feasible to run on current computers, but is actually a limitation in the MHD equations themselves. In deriving the MHD equations, two very important assumptions must be made. First, $\Omega_r \tau \ll 1$ where $\Omega_r$ is the gyrofrequency and $\tau$ is the typical timescale. The second, more limiting assumption of MHD is that $\rho/L \ll 1$ where $L$ is the typical length scale of the system. Therefore, MHD is not strictly valid in regions with small values of the $\kappa$-parameter because in those regions, the gyroradius is not larger than the length scale for changes in $B_z$. Finally, the current dependent resistivity in our model may not tolerate a magnetic field geometry stretched enough to allow the $\kappa = 1$ boundary to be resolved.
\section*{\kappa Dependence}

As stated in the previous section, MHD assumptions limit the range of valid \( \kappa \) that we can resolve. Additionally, models of the loss cone filling due to FLC scattering depends significantly on the distribution of the particles (in pitch angle and gyrophase) prior to scattering (see section 1.2.1 and Delcourt and Martin [1994]; Delcourt et al. [1996]). There is, however, no self-consistent way to obtain those distributions from a global MHD model. This further illustrates the necessity of using the simplified form of \( f(\kappa) \) in equation 3.5. However, low altitude polar orbiting satellites routinely measure loss cone distributions that are either mostly full or mostly empty which is consistent with our parametrization. This implies that the details of the scattering are mostly insignificant for modeling the resulting precipitation.

We have experimented with using \( \kappa_{\text{min}} = 1 \), however the results were nearly identical to the results where \( \kappa_{\text{min}} = 0 \) because it is very difficult for the OpenGGCM to resolve a current sheet that thin. However, the thickness of the current sheet at the end of the growth phase is also not well constrained in the observations. Because of this, it is difficult to determine how well the simulation repro...

If \( \kappa \) could be better resolved in the simulation, perhaps the pre-onset fading discussed by Liu et al. [2007] would be reproduced by our model. As it is, the simplified \( f(\kappa) \) is not able to capture any noticeable pre-onset fading. Otherwise, the form of \( f(\kappa) \) used for this study does a reasonably good job of reproducing the observed proton auroral features qualitatively as will be discussed in Chapter 4.

\section*{Particle Distributions}

The proton precipitation code tests whether precipitation will be generated in a particular region based on the average gyroradius. For a given \( R_c \) and magnetic field magnitude, our model produces a critical temperature where the scattering is ar-
rested completely. In reality, Maxwellian distributions with temperatures just above and just below the critical temperature would likely produce very comparable precipitation because in both cases a significant portion of the particles that make up the distribution would have gyroradii sufficient to cause the scattering. This is a particularly important limitation for substorms because the dispersionless particle injections tend to energize the high energy ions while not significantly energizing the thermal ions [Birn et al. 1997]. Because of this, our code sometimes produces sharper precipitation boundaries than are observed. Also, the MHD cannot reproduce the dispersionless injections associated with substorms, however it does energize the background thermal plasma effectively raising the particle gyroradii. It is assumed that the MHD energization is sufficient to capture the global features of the proton aurora. This is a significant assumption and therefore it is important to validate the results with observational data.

3.4 Remarks

MHD models are not able to resolve the gradient curvature drifting of ions that arises because the magnetic field at the particle location is a function of its gyrophase. As a result, ions drift westward while electrons drift eastward. The drift is proportional to the ion’s perpendicular energy, so the high energy portion of the population drifts much faster than the low energy portion. Since OpenGGCM is not able to resolve this effect, the eastward proton precipitation may be overly energetic and the westward might be under energetic in our model. However, the proton aurora is generated in the region of stretched field and there is, therefore, very little flux penetrating a particles gyro-orbit. It is unlikely that gradient curvature drift will be very important this far out in the magnetosphere. In any event, future versions of OpenGGCM with coupling to an inner magnetosphere model should help to answer this question.
Currently, the proton precipitation code works as a separate process after OpenGGCM has completed. There are a few possible benefits to having it run with OpenGGCM. First, in order to calculate the proton precipitation, the full 3-dimensional fields are needed and therefore, the temporal resolution is limited by the frequency of 3-dimensional output files requested. This is a disadvantage because OpenGGCM produces a lot of data. The data file size scales with the total number of grid points. As such, it is often desirable to only output selected 2-dimensional planes in order to save storage space. However, this is not an option if proton aurora information is desired. The second disadvantage is that most of the output options of OpenGGCM currently require an all-to-one blocking communication call. As such, file input and output (IO) is a major bottleneck for the code’s scalability. A second advantage to moving the proton aurora code into the OpenGGCM code base would be that if the inner boundary solver was ever modified to accept proton precipitation, the code would benefit (especially if the dayside proton precipitation was also able to be parametrized). In most cases, the proton aurora only provides about 10% of the power input into the ionosphere [Hardy et al. 1989], however, in some rare cases, it can be the dominant source of energy flux into the ionosphere [Su et al. 2011; Frey et al. 2001].

There is, however, a significant challenge to moving the proton precipitation code into OpenGGCM. Since it requires tracing a large number of fieldlines, the tracer would have to be parallelized. Parallelizing the tracer would be difficult as it would be hard to balance the load from one process to another. Another option would be to move all the necessary data onto a single node (or cluster of nodes) and have those nodes operate the same as the current proton precipitation code. However, this would also introduce a bottleneck similar to the IO bottleneck currently in the code since it would again require all-to-one communication. Also the node holding the proton
aurora solver would need to have enough memory to store five full MHD fields in memory at a time which could be a problem for very large simulations.
Chapter 4

Simulation Results

4.1 Introduction

In this chapter, we show the results of three substorm simulations using the OpenGGCM global MHD model described in chapter 2. For comparison purposes, data from the IMAGE Far Ultraviolet (FUV) Imager are also used. For a more detailed description of the FUV imager, see chapter 5. For the remainder of this chapter, it is assumed that the FUV wideband imaging camera (WIC) images the discrete electron emissions whereas the FUV spectrographic imager 12 (SI-12) images only the diffuse proton emission.

Plasma Sheet Extraction

For many of the results presented here, we have extracted the plasma sheet for the purposes of plotting the data. In general, the plasma sheet is a 3-dimensional surface, however to simplify the visualization, we project the values from the plasma sheet onto the z=0 plane. For our purposes, the plasma sheet location can be extracted by finding the gridpoint with maximum plasma $\beta$ between GSE $z$ -12 $R_E$ and 12 $R_E$ for each set of gridpoints with the same x and y values. This algorithm works pretty well except in regions outside the magnetopause, on the dayside or in the inner magnetosphere. Basically, it gives sensible results where there is a plasma sheet and
non-sensible results elsewhere. The method used here is similar to the method used by El-Alaoui et al. [2009] and Raeder et al. [2010], except in the former case the maximum pressure is used instead of the maximum β and they use the z=0 plane where the results do not make sense (Raeder et al. [2010] used the plane where Bx = 0). El-Alaoui et al. [2009] also use a slightly more complicated algorithm in the inner magnetosphere. However, since all these regions are outside our range of interest (the CPS), our simplified algorithm is sufficient.

Also for the purposes of data visualization, plots of the magnetosphere are presented in the GSE coordinate system. Plots of the ionosphere are in a polar solar magnetic (SM) coordinate system. The azimuthal angle is labeled by local time and therefore 12 points sunward.

4.2 Events

4.2.1 March 23, 2007 Event

On March 23, 2007, THEMIS observed a substorm with an onset at about 11:10 UT. This was one of the first substorms captured by the THEMIS probes and as such, the event is described in detail in Angelopoulos et al. [2008b]; Kealing et al. [2008]; Runov et al. [2008]; Lessard et al. [2009] and Raeder et al. [2008] and has been named the “THEMIS first light” substorm. In the coast phase of the THEMIS mission, prior to insertion into final orbit, the five THEMIS probes were orbiting in a string-of-pearls configuration (i.e. one satellite following the next along the orbit path) which was useful for studying azimuthal propagation of the magnetospheric plasma. For this event, all five spacecraft were located toward the dusk flanks as shown in Figure 4.1. Mapping the footpoints of the spacecraft using the standard TS01 model [Tsyganenko 2002a,b] placed the spacecraft a full two hours MLT west of the auroral activation.
Figure 4.1: Position of THEMIS probes on March 23, 2007. All five probes are located in the dusk sector in a string-of-pearls configuration. Figure adapted from Angelopoulos et al. [2008b].

However, since all the spacecraft measured flow enhancements, dipolarization, and an increase in energetic particles, the mapping produced by the TS01 model is not likely to be correct. Varying the input indices (DST, AE) did not significantly improve the results [Angelopoulos et al. 2008b]. The discrepancy is probably due to the large solar wind $B_y$ penetrating into the magnetosphere or because the stretched field in the growth phase is not well represented by the empirical model as discussed in chapter 1. OpenGGCM has been used to address the mapping problem for this event. Raeder et al. [2008] describes the grid and other relevant parameters for this simulation. It was shown that the simulation qualitatively produces the large scale features of the substorm (e.g. auroral brightening, fast flows and dipolarization at the THEMIS probe locations, etc.). Additionally, the mapping of the THEMIS footpoints in the simulation placed them in the auroral activation as expected. Therefore, it is assumed
that the simulation mapping is better than the empirical mapping [Angelopoulos et al. 2008b].

Since the event simulation was already completed, verified, and used by Raeder et al. [2008, 2010], and since the event was well studied by others [Angelopoulos et al. 2008b; Keilng et al. 2008; Runov et al. 2008], this event was the first to be post processed by the proton aurora code described in chapter 3. Figure 4.2 shows the maximum values for the proton aurora and the discrete electron precipitation in the top two panels. The brightening of the precipitation is not as explosive as reality, however there is clearly an increase in the precipitating electron energy flux starting at around 10:45UT and a second significant increase just before 11UT. The proton energy flux, however, starts its increase prior to 10:30UT. This brightening of the proton aurora prior to the brightening of the electron precipitation is not typically observed. In fact, proton auroral fading is a common feature in meridian scanning photometer data [Liu et al. 2007]. Raeder et al. [2008] mentions that the simulation does the worst at reproducing the plasma temperature and density for this event because not all of the plasma from the initial conditions had been replaced. This is probably one reason for the observed brightening. Secondly, the simulation produces an over-dipolarized tail (Figures 4 and 5 in Raeder et al. [2008]). Another part of the discrepancy is that the MHD does not well reproduce the explosiveness of substorm onset for this event. In fact, the simulated AL index begins to slowly drop earlier than 10:30 in the simulation (Figure 4.3). So there is a reasonable amount of ambiguity in the simulation about when the onset actually occurs. The remaining panels of Figure 4.2 will be discussed shortly.

Figure 4.5 shows a projection of the CPS on the z=0 plane. The MHD temperature is plotted in panels a-d. In panels e-h, the x-component of the flow velocity is shown. The contours are $B_z$ and are identical for panels with the same time. In the simulation,
Figure 4.2: Simulation ionospheric parameters. The panels show (from top to bottom) maximum precipitating proton flux, maximum precipitating discrete electron flux, and number density and temperature at the location of most intense proton precipitation. The last panel shows the square root of the temperature and number density normalized by their pre-onset values (taken at 10:15 UT).
the reconnection site is located at approximately -15 GSE very close to the midnight meridian as inferred by the bipolar flow signature in $V_x$. A dipolarization front (DF) is generated on the earthward side of the reconnection region and propagates earthward. The DF propagates to the more dipolar region of the tail ($\sim 8-10R_E$) where the magnetic flux is deposited. This flux causes the dipolar region (i.e. the SCW) to grow tailward and to expand azimuthally. This is shown in panels e-h of Figure 4.6. In the first column, the ionospheric proton precipitation has been mapped along magnetic fieldlines to the CPS at the same times. The contours on the plots are the same as the contours in the corresponding panels of Figure 4.5.

From Figure 4.6, it is clear that the modeled proton aurora is not generated inside the SCW. Comparing with 4.4 reveals that the SCW divides the precipitating energy flux into the ionosphere as well. This azimuthal splitting of the ionospheric proton precipitation will hereafter be referred to as “splitting”. This is a consequence of the fieldline curvature (FLC) model. Since the model requires a highly stretched (low
Figure 4.4: Simulated proton aurora for March 23, 2007 (units of $\mu W/m^2$). Contours are of the discrete electron precipitation.
Figure 4.5: Central plasma sheet $V_x$ (km/s) and Temperature (keV) computed by the March 23, 2007 simulation. Times are the same as in Figure 4.4.
Figure 4.6: Mapped proton aurora ($\text{mW/m}^2$) and central plasma sheet $B_z$ (nT) computed by the March 23, 2007 simulation. Times are the same as in Figure 4.4.
radius of curvature) field geometry, the more dipolarized field inside the SCW does not satisfy the scattering criteria in equation 1.5. Alternatively, the reduced scattering could be caused by a reduced average gyroradius (decreased plasma temperature or increased magnetic field magnitude by equation 3.3). Panels a-d of Figure 4.7 show that the average gyroradius inside the SCW is smaller than outside the SCW. While the plasma temperature inside the SCW is larger than outside (Figure 4.6), the total magnetic field inside is also larger resulting in a net decrease of the average gyroradius inside the SCW for this event.

The proton precipitation intensity, however, is highly dependent on the temperature. Figure 4.8 shows the ionospheric number density and temperature profiles. The number density does not change much, however the ionospheric temperature is gradually enhanced. This is consistent with Figure 4.2. In the time between 10:25 UT and 10:40 UT, the ionospheric number density is relatively constant at the location of the most intense proton precipitation whereas the ionospheric temperature is gradually enhanced. Since the precipitating energy flux depends only on the number density and the temperature in our model (see equations 3.4 and 3.5), the enhanced precipitating energy flux for this event is due to the energization of the CPS plasma.

Unfortunately, for this event there is very little proton auroral data available since the onset happened off the west coast of Alaska and no satellite borne global proton auroral imagers were operational in 2007. Thus, an actual comparison with observational proton precipitation is difficult for this event. Because of this, we will present two additional event studies in this chapter.

4.2.2 April 28, 2001 Event

The second and third substorms that we will present are from the IMAGE dataset. More details about the IMAGE spacecraft and its instrumentation can be found in
Figure 4.7: Central plasma sheet average gyroradius (km) and number density (1/cc) computed by the March 23, 2007 simulation. Times are the same as in Figure 4.4.
Figure 4.8: Ionospheric density (top four panels) and temperature (bottom four panels) in March 23, 2007 simulation.
Chapter 5. On April 28, 2001, the IMAGE far ultraviolet (FUV) imager started collecting images of the northern auroral oval at 11:05 UT. The first few images show significant westward propagating precipitation. After 11:54 UT, there is very little auroral precipitation on the oval until a substorm onset shortly after 13:00 UT. Frey et al. [2004] determined the onset to be at 13:07:49 UT.

Figure 4.9: Provisional DST, AU, AL and AE indices for April 28, 2001. The vertical lines are at 11:54 UT (the last significant aurora in the global images) and at 13:07:49 UT (the onset of the substorm simulated here).

The magnetosphere was in a relatively disturbed configuration for a few hours prior to the onset. For the substorm at 13:07 UT, the AL index dropped below 1000 nT (see Figure 4.9), however there is significant activity in the AL index as early as 05:00 UT. This is probably due to a significant compression of the magnetosphere inferred by the largely positive DST (~40 nT) during that time. The AL index shows a minimum shortly before 11:00 UT which indicates that the westward propagating precipitation was probably due to a small substorm with an onset prior to the time when the auroral oval entered the IMAGE FUV field of view. Since there were
approximately two hours between the 13:07 UT onset and the previous onset, the onset at 13:07 UT was isolated.

The compression of the magnetosphere for this event was due to a high speed solar wind \( (V_x \sim -650 \text{ km/s}) \) with average density \( (\sim 5 \frac{\text{particles}}{\text{cc}}) \). At the time of the onset, the number density increased to \( \sim 8.5 \frac{\text{particles}}{\text{cc}} \) which increased the solar wind ram pressure. This event also had a significantly above average \( y \)-component to the interplanetary magnetic field. At the time of the substorm onset, \( B_y \) was approaching 20nT. The solar wind data from ACE, propagated to the simulation inner boundary is shown in Figure 4.10.

![Figure 4.10: Solar wind input for the April 28, 2011 simulation propagated to the inner boundary. The vertical lines are at the times cited in the text.](image)

Figure 4.11 shows snapshots of the precipitation during this event in the early expansion phase. Approximately four minutes after the initial brightening of the aurora, the IMAGE SI-12 instrument shows the beginnings of azimuthal splitting in the proton aurora. After eight minutes, the splitting is complete and by twelve minutes,
there is nearly fifteen degrees separating the two precipitation regions. There is also a clear brightening and poleward expansion of both the proton and electron precipitation. From the images, it is evident that the most intense portion of the westward proton precipitation correlates well with the most intense electron precipitation in the WTS. The split in the proton aurora persists until after 14:30UT for this event.

**Event Simulation**

This event was chosen to simulate early on from a few other candidates due to the relatively simple solar wind and clearly observed azimuthal splitting. A few of the other candidates posed significant challenges when we tried to simulate them. In some cases, the simulation did not reproduce a substorm, in other cases it was very difficult to keep the simulation stable.

For this event, the simulation domain was chosen to be from -500 RE to 24 RE in the x direction and from -64 RE to 64 RE in the y and z directions. The grid had nearly 37 million cells (616x200x300) with a minimum resolution of approximately 0.2 RE in x, 0.25 RE in y and 0.16 RE in z and the highest resolution region spanned the tail to a distance of approximately 40 RE. The grid used for this simulation was shown previously in Figure 2.2.

During this event, the Geotail satellite was located upstream in the magnetosheath and was therefore able to be used to check the input into the simulation. A comparison of Geotail data with the OpenGGCM simulation data is provided in 4.12. It is clear that the simulation does a good job propagating the y and z components of the interplanetary magnetic field. However, the simulation does a poor job with the x component of the magnetic field. Most likely the discrepancy is caused by the MINVAR procedure used to propagate the solar wind to the simulation boundary. This indicates that the solar wind for this event was not well ordered into sheets as
Figure 4.11 IMAGE FUV data of the April 28, 2001 substorm. The left hand panels show the data from the WIC instrument (electron precipitation) while the right hand panels show the data from the SI-12 instrument (proton aurora).
assumed by the MINVAR procedure. Typically, the global magnetospheric dynamics are not strongly influenced by the IMF $B_x$ component unless the $B_x$ component dominates the other components.

![OpenGGCM vs Geotail](image)

Figure 4.12: Comparison of OpenGGCM data with Geotail during the April 28, 2001 substorm. The IMF $B_y$ and $B_z$ components are well represented in the simulation, however the $B_x$ component is not well reproduced by the simulation.

One notable feature of this substorm is the aurora which extends far into the afternoon sector. This aurora is clearly seen in the SI-12 data (figure 4.11), but can also be seen less clearly over the dayglow in the WIC images. Figure 4.13 shows the simulated proton precipitation with contours of the simulated discrete electron precipitation along with the IMAGE WIC data for a similar time period. The simulation reproduces significant auroral precipitation in the afternoon sector which is qualitatively similar to the observations.
Figure 4.13: IMAGE WIC electron precipitation (top row), IMAGE SI-12 proton precipitation (second row) and simulated electron (contours) and proton (color) precipitation during the April 28, 2001 substorm. The simulation reproduces the proton auroral splitting and the significant afternoon sector aurora.
The simulation also reproduces the splitting of the proton aurora, significant proton precipitation in the eastward bulge and an auroral brightening at approximately the correct time. In both the simulation and the data, the split region persists long into the recovery phase and reaches a maximum width of approximately thirty degrees longitude (two hours MLT).

However, despite these similarities, there are a number of notable differences between this simulation and the actual event. The simulation does not reproduce splitting of the proton aurora until after 13:23 UT whereas the data shows the splitting nearly ten minutes earlier in the expansion phase. Also, the simulated onset occurs significantly further west and poleward compared to the real onset.

As previously mentioned, it appears that there was a small auroral activation prior to 11:05 when the first WIC images were taken as evidenced by expanded and westward propagating aurora. The simulation actually reproduces a sequence of earlier substorms with the most significant one occurring just after 12:00UT. Figure 4.14 shows a simulated AL index compared to the provisional AL index for this event.

This delay was probably because much of the plasma from the initial conditions had not convected out of the system when the initial substorm was supposed to occur. It is not unreasonable that the simulation produces a substorm near 12:00 UT as there is a slight enhancement in the AL index (Figure 4.14) and a significant enhancement in AU at that time (Figure 4.9), however the WIC images did not record any significant auroral precipitation. In any event, it is clear that the simulation had not fully recovered from the previous substorms at the time of the onset at 13:07, however, the simulation does a reasonably decent job of reproducing the overall magnitude of the AL index.

The simulated substorm has a much higher latitude onset (≈70 degrees latitude) compared to the observations (64 degrees). This is probably because there was not
Figure 4.14: Provisional AL (red) and simulated AL (black) for the April 28, 2001 event. The simulation produces multiple enhancements in AL and does not fully recover in time for the substorm of interest at 13:07 UT.

as much time to load flux into the lobes from the dayside reconnection due to timing of the previous substorm. The second major difference is that the plasma sheet was already highly energized at the onset time. This highly energized plasma (large gyroradius) prevented the proton aurora from splitting until later in the expansion phase.

In order to better understand why the simulation onset was approximately an hour and a half MLT west of the onset location, it is necessary to look at what is happening in the magnetotail. Figures 4.15, 4.16 and 4.17 show $B_z$, the mapped proton aurora, the average proton temperature, plasma velocity, proton gyroradius and magnitude of the magnetic field on the plasma sheet. The same contours of $B_z$ are included for plots with the same timecode. From the contours of $B_z$, it is evident that the simulation produces a secondary dipolarized region centered around $y \sim -7\,R_E$ GSE. This region contains much less flux than the primary dipolarized region. However, it
Figure 4.15: Mapped proton aurora and $B_z$ in the central plasma sheet for the April 28, 2001 simulation.
likely provided enough magnetic pressure to push the onset further westward. The secondary dipolarized region probably originated due to component reconnection at the magnetopause. It is possible that the simulation overestimated the reconnection rate at the magnetopause and stored more flux into the lobe at early morning local times due to the unusually large $B_y$. That extra flux was then reconnected into the tail via slow reconnection to form the secondary dipolarized region. Alternatively, the extra early morning lobe flux may be a result of the IMF $B_x$. A combination of IMF $B_x$ and dipole tilt could influence which fieldlines reconnect at the magnetopause. Since the simulation did not get the IMF $B_x$ correct, it is possible that some of the flux was loaded into the wrong part of the tail.

The differences between the simulation and the observations make it difficult to use this event to validate the proton precipitation code. However, the proton precipitation produced in this simulation does have some similarities to the observed proton aurora. Because the simulation produces a substorm that has some features in common with the observations, we hypothesize that the simulation results are what would be expected in a non-isolated substorm. As such, it is worthwhile to examine the cause of the splitting in this event as well.

The splitting of the proton precipitation in this event is similar to that of the “first light” substorm, but there are some notable differences. Unlike the first light substorm, no significant splitting is seen in the proton precipitation at the onset although a weak SCW begins to form immediately. As mentioned previously, the lack of initial splitting is attributed to the high temperature plasma in the source region. Shortly after 13:20 UT, a new DF is driven towards the inner magnetosphere at the front of a strong flow channel (compare Figure 4.16 panel e with Figure 4.15 panel e). This DF is associated with lower temperature plasma than is in the inner magnetosphere at the time (panel a in Figure 4.16) and the $\kappa$ scattering criteria is

71
Figure 4.16: Plasma temperature and $V_x$ in the central plasma sheet at four different times during the April 28, 2011 substorm.
Figure 4.17: Average proton gyroradius and magnitude of B in the central plasma sheet at four different times during the April 28, 2011 event.
satisfied (panel a in Figure 4.15). In fact, the signature of this DF can be seen at the poleward boundary of the proton aurora between 20 and 22 MLT in panel a of Figure 4.13. As this DF reaches the SCW, the flux pile-up is finally sufficient to cause splitting of the proton aurora. However, the splitting of the proton precipitation does not nicely follow contours of $B_z$ as it did during the first light substorm (particularly, look at panel c of Figure 4.15). In that plot, there is highly energetic precipitation coming from the region -7.7 RE GSE whereas a nearby region of similar $B_z$ does not satisfy the scattering criteria. The reason for this difference is clearly the plasma temperature in those regions (panel c in Figure 4.16). Where the plasma temperature is high, the resulting gyroradius is sufficient to continue the scattering in the less dipolarized region of the SCW. For this event, the temperature has a strong azimuthal gradient at the very edge of the precipitation. This gradient is reflected in the mean gyroradius (Figure 4.17) which causes the sharp cutoff in the precipitation.

This event implies that the plasma temperature can play a role in facilitating the splitting in regions where the dipolarization is weak but the temperature is significantly enhanced. A more detailed discussion of this is deferred until Section 4.3.

### 4.2.3 January 31, 2001 Event

Since the simulated substorm on April 28 was not isolated whereas the real substorm was, we have simulated a third event on January 31, 2001. This substorm was randomly selected by Gilson et al. [2011] (presented in Chapter 6) to demonstrate the proton auroral splitting. Upon further inspection, the simple solar wind data made it a prime candidate for simulating. According to Frey et al. [2004], the onset occurred at 8:26:08 UT although the onset could probably be placed two minutes earlier. This event had remarkably constant solar wind for approximately eighteen hours leading up to the substorm. Since $B_z$ was marginally southward and the so-
lar wind was constant, the simulation was probably able to more closely mimic the magnetospheric configuration prior to the onset. The propagated solar wind input to the simulation is shown in Figure 4.18. The substorm seems to be triggered by the arrival of an interplanetary shock as evidenced by the sudden increase in the number density, thermal pressure (temperature), and magnitude of $V_x$. The shock IMF was strongly southward with $B_z$ dropping near or below -10nT for over an hour after the shock arrived. Prior to the shock arrival, the IMF was slightly southward ($\sim$-2nT) but mostly in the -x GSE direction with a magnitude of $\sim$ 6nT. The other solar wind parameters were also very quiet ($V_x \sim -370 \text{ km/s}$, $n \sim 5.1 \text{ cc}$).

The grid used for the simulation of this event was similar to the other grids in this study. The grid domain stretched to 750 R$_E$ in the tail with the y and z bounds at $\pm$64R$_E$. Otherwise, the grid settings were the same as used for the March 23, 2007 substorm.

For this event, the Cluster satellites were upstream in the magnetosheath. A comparison of the simulation with satellite data is presented in Figure 4.19. The OpenGGCM simulation does a much better job reproducing magnetosheath $B_x$ component especially near the onset time for this event compared to the previous event.

As a result of the quiet IMF, the auroral oval was very quiet up to the time of the substorm onset. Figure 4.20 shows a comparison of the simulated AU and AL indices compared with the provisional AU and AL indices from the OMNI database. The simulation well reproduces the quiet period leading up to the substorm onset as well as the general shape of the AL index after the onset.

The simulation also well reproduces the auroral onset signatures. An overview of the IMAGE data is presented in Figure 4.21 and an overview of the simulation is presented in Figure 4.22. For comparison, four consecutive frames have been taken out.
Figure 4.18: ACE solar wind data propagated to the sun facing boundary of the simulation. The vertical black line is the substorm onset time in the Frey et al. [2004] list.
Figure 4.19: Cluster (red, 60s averages) comparison with OpenGGCM simulation data (black).
Figure 4.20: Simulated (black) and observed (red) auroral indices on January 31, 2001.
of the sequence and blown up and are plotted along side the OpenGGCM simulation data for comparable times in 4.23.

Figure 4.21: Overview of WIC images during Jan. 31, 2001 substorm. Images start at 07:57:30UT and proceed in approximately two minute steps from left to right and from top to bottom. The onset (determined by Frey et al. [2004]) is the first image in the third row.

In the WIC images, there is a enhancement near 21 MLT at about 70 degrees latitude that brightens and expands slightly poleward prior to 08:26:08 UT. In fact, that same spot had been brightening and dimming as early as 08:17 UT. In the sim-
Figure 4.22: Overview of simulated discrete precipitation during the Jan. 31, 2001 substorm. The times are approximately the same time as in Figure 4.21.
ulation, the discrete precipitation also begins to increase much earlier than the onset, although very gradually. At the time of the onset, the simulation produces slight poleward expansion and the aurora begins to propagate slowly westward. Similar to the observations, the simulation also produces the onset at ~70 degrees latitude. However, in the simulation, the true auroral onset happens at ~08:40 UT. At that time, there is a significant auroral brightening accompanied by a rapid westward propagation.

In the observations, a PBI is evident on the midnight meridian for at least eighteen minutes prior to the onset. A second PBI is evident very near the onset location eight minutes prior to the onset. These PBIs are interesting in light of the recent work by Nishimura et al. [2010c,a]. The simulation reproduces a similar structure which persists until the significant enhancement of the precipitation near 08:40UT in the simulation (Figure 4.24). Whether the PBI is important to the onset of the substorm is beyond the scope of this dissertation, however it will make for an interesting study in the future.

At the onset time, the GOES 10 and 8 satellites were located at (-6.19,0.73,-2.21) and (-4.28,-5.04,0.03) \( R_E \) GSE respectively. A comparison of \( B_z \) at the GOES satellite and virtual satellites in the simulation is provided in Figure 4.25. The data nicely shows the stretching of the magnetotail during the growth phase. The simulation reproduces this, although the flux appears to be loaded into the tail more quickly than in the observations. After the onset, the simulation reproduces the very rapid stretching of the magnetotail consistent with the observations, however, the simulation tail remains stretched whereas GOES 10 observed a strong dipolarization shortly after 08:30 UT. The simulation does produce this dipolarization, however it is reproduced slightly west of the virtual GOES 10 satellite and slightly later (see Figure 4.26). This strong dipolarization coincides with a significant enhancement in the electron
Figure 4.23: (top) IMAGE WIC auroral onset and expansion. (bottom) Simulation onset. In the simulation, the poleward expansion happens approximately ten minutes earlier, but the brightening and westward traveling are delayed until 08:40UT.
Figure 4.24: Poleward boundary intensification at the midnight meridian. This figure also shows the early poleward expansion in the simulation although for timing analysis the onset is placed at 08:40UT to be consistent with other onset signatures as discussed in the text. The slightly expanded auroral form probably corresponds with the PBI observed at the onset location in the observations.
precipitation and appears to be triggered by the shock that arrived at approximately 08:36UT in the simulation.

As noted earlier, most of the signatures of the substorm in the simulation tend to lag behind the observed signatures by about fifteen minutes (compare Figures 4.20, 4.21, 4.22 and 4.25). This seems reasonable since the shock is not propagated to the boundary of the simulation until after the substorm was supposed to have started. Additionally, onset times in the simulation have been known to vary compared to the observed onset times [Raeder et al. 2008].

Since the simulation reproduces the main features of the January 31, 2001 substorm, we now proceed to compare the simulated proton precipitation with the observed proton precipitation. The observed proton aurora expands significantly poleward for this event. Approximately ten minutes after the onset the observed proton aurora splits azimuthally on the 22 MLT meridian (Figure 4.27). The splitting is not as significant as in the data for the April 28, 2001 event or in the simulation of the March 23, 2007 event. However, there is a clear poleward motion of the proton isotropy boundary and the separation into two distinct precipitation maxima. As the substorm continues, the splitting becomes only slightly more pronounced before quickly disappearing.

The simulation reproduces similar splitting in the early expansion phase after about fourteen minutes. Figure 4.27 shows the simulated proton precipitation beside the SI-12 data. The images start approximately twelve minutes after onset for the simulation and six minutes post onset for the SI-12 data. The simulated proton precipitation also splits very near the 22 MLT meridian. Compared to the auroral images, the splitting in the simulated precipitation is along more well defined boundaries. Also the simulated precipitation does not expand as far poleward as the aurora in the images. However, it is important to remember that the auroral images show the
Figure 4.25: GOES 10 $B_z$ (top) and GOES 8 $B_z$ (bottom) data (red) compared with OpenGGCM virtual satellites (black).
Figure 4.26: Strong dipolarization during the Jan. 31, 2001 simulation on the central plasma sheet. The green contours are the contours $B_z = 0$ and the purple contours are of $V_x = 0$. The green dot is the position of the GOES 10 spacecraft and the cyan dot is the position of the GOES 8 spacecraft.

auroral precipitation after the beam spreading effect has taken place (see section 1.2) whereas the simulated proton flux shows the precipitation before the beam spreading. Also the simulation does not include a realistic particle injection. The high energy particles from the injection would more readily scatter than the thermal population.

The simulation also produces significantly more proton precipitation at the early morning local times compared to the SI-12 images. One possible reason for this is that the simulation does not include any gradient curvature physics. As such, the simulation does not cause any of the high energy protons to drift westward. However, it is also likely that the simulation inner boundary conditions (constant temperature
Figure 4.27: Comparison of simulated proton precipitation (left column) with IMAGE SI-12 data (right column) during the Jan. 31, 2001 substorm. Images are separated by approximately two minutes. The simulation times are delayed by ~ 15 minutes because the substorm occurs later in the simulation than observations.
and density) tend to prevent azimuthal gradients from forming, especially in the inner magnetosphere. In either case, coupling the global code to the CRCM should help to alleviate the problem because the CRCM will provide new inner boundary conditions to the simulation and also include the gradient curvature physics that the MHD lacks (see section 2.2.4).

The simulated proton auroral splitting is caused by the dipolarization (and increased magnitude of the magnetic field) due to flux pile-up in the substorm current wedge (SCW) similar to the previous two events. Figures 4.28, 4.29 and 4.30 show the mapped proton aurora, $B_z$, temperature, $V_x$, mean gyroradius and magnitude of the magnetic field. Similar to the April 28, 2001 simulation, only the most dipolarized region near the center of the SCW is able to prevent $\kappa$ from falling below the scattering threshold. Less dipolar regions of the SCW with lower total magnetic field are still able to satisfy the $\kappa$-scattering criteria. Also similar to the previous events, the simulated isotropy boundary maps to $\sim 7 - 8R_E$.

In further development of this event, the dipolarized region on the far eastern (duskward) flank continues to dipolarize, but the two dipolarized regions remain separated. The splitting persists in the simulation much longer than in the SI-12 images. It is unclear in the observations whether the split region disappears because the field begins to stretch again, or because the average gyroradius is further increased due to continued particle energization. Alternatively, it is possible that at that point in the substorm, waves were able to scatter protons into the loss cone even though the $\kappa$-scattering criteria was not satisfied. More simulations with better satellite conjunctions will be necessary to determine importance of wave-particle interactions for the global structure of the nightside proton aurora.
Figure 4.28: Mapped proton aurora and $B_z$ on the central plasma sheet for the Jan 31, 2001 simulation.
Figure 4.29 Plasma temperature and $V_x$ on the central plasma sheet for the Jan 31, 2001 simulation
Figure 4.30  Mean gyroradius and magnitude of the magnetic field on the central plasma sheet for the Jan 31, 2001 simulation
4.3 Remarks

The proton precipitation code seems to well reproduce the general features of the observed proton aurora. Mende [2003] showed that the proton aurora is statistically located equatorward of the discrete electron aurora for local times westward of the onset whereas eastward of the onset, the discrete electron precipitation is generally at lower latitudes. The OpenGGCM simulation does not typically produce a large amount of discrete electron precipitation eastward of the onset, however the precipitation produced is typically equatorward of the simulated proton aurora. This is the case in each of the three simulations described above and also in a simulation of the event on February 27, 2009 published by Ge et al. [2011]. The proton auroral signatures in the latter simulation will be the subject of another paper.

In this chapter, we have also presented simulations of the azimuthal splitting of the proton aurora due to fieldline curvature (FLC). This is expected in our model. From equations 3.2, 3.3 and 1.5, it is clear that:

\[ \kappa^2 \propto \frac{R_c|B|}{\sqrt{T}} \]  

During substorms, the plasma temperature can increase by a factor of \(~4\) [Baumjohann 1991]. If we use the nominal CPS temperature and a slightly lower \(|B|\) (\(T = 4.2\text{keV}, |B| = 7.5\text{nT}\)) then the expected gyroradius in the CPS during the growth phase is roughly \(0.2\ R_E\). In order to satisfy the \(\kappa\)-scattering criterion, the growth phase radius of curvature must drop below \(1.75\ R_E\ (R_{\alpha_0})\). Typically, this condition is easily satisfied as the current sheet thickness is often \(~2000\text{km}\) or less [Baumjohann et al. 2007; Zhou et al. 2009]. If the field inside the SCW dipolarizes completely, it
can be shown (from equation 3.3) that:

\[ R_c = \frac{R}{2} \] (4.2)

in the equatorial plane where \( R \) is the radial distance to Earth’s center. Additionally, the magnitude of the magnetic field increases significantly. Thus, if the magnetic field dipolarizes completely, an amplification factor can be defined as:

\[ A_T = \frac{T_f}{T_0} \]

\[ A = \frac{k_f}{k_0} = \left( \frac{R_c|B_f|}{\sqrt{T_f}} \right)^{\frac{1}{2}} \left( \frac{R_c|B_0|}{\sqrt{T_0}} \right)^{\frac{1}{2}} = \left( \frac{M}{2R^2 R_c B_0 \sqrt{A_T}} \right)^{\frac{1}{2}} \] (4.3)

where \( M \) is Earth’s magnetic dipole moment \((30.4 \mu T R_E^3)\) and the subscripts 0 and \( f \) denote pre-dipolarization and post-dipolarization values respectively. The amplification factor \( (A) \) can be thought of as how much bigger \( \kappa \) is than the scattering threshold \((\kappa = 3)\).

Equation 4.3 is plotted in Figure 4.31 for a few different temperature enhancements and the average value for \( \kappa \) in a dipole field is plotted in Figure 4.32. If the field dipolarizes completely, \( \kappa \) is increased by a factor of approximately 3 at 7-8 \( R_E \). Deeper in the CPS \((\sim 12 \ R_E)\), the amplification factor drops to near 2 \((\kappa \sim 6)\). Of course, if the magnetic field does not completely dipolarize, \( \kappa \) could drop below \( \sim 3 \) (at least for the highest energy portion of the distribution) resulting in scattering. Thus, a complete azimuthal splitting of the proton precipitation is not necessarily expected for all substorms, but it is very reasonable to expect it for strong substorms where the dipolarization is most complete.

93
Figure 4.31: Amplification of $\kappa$ after complete dipolarization for different temperature enhancements (equation 4.3). For this plot, $|B_0| = 7.5\text{nT}$, $R_{co} = 1.75R_E$ (see text)

Even though the simulation seems to reproduce the global structure of the proton aurora, it will always be difficult to completely validate the proton auroral splitting due to the development of the SCW using only the simulation. Part of the difficulty is that our results rely critically on the temperature and magnetic field geometry in the CPS. However, the CPS is a region of the magnetosphere where the assumptions of MHD are likely to be violated. Thus, it is difficult to comment on the accuracy of the OpenGGCM’s density, temperature and field curvature in that region. It is also currently not possible to find regions where the EMIC waves may grow as that physics is not included in the MHD approximation. Additionally, determining the onset time in the simulation is difficult because the onset signatures are not as explosive as they
are in observations which leads to some ambiguity in the interpretation of the results. Because of this, the remainder of this study will examine proton auroral data from the SI-12 instrument on the IMAGE satellite to see if the data is consistent with the model of proton auroral splitting presented in this chapter.
Chapter 5

The IMAGE satellite and instrumentation

5.1 Introduction

The second half of this study was performed using global auroral images. Global auroral imaging has a long history starting with the Dynamics-Explorer missions [Frank et al. 1981]. Since then, multiple satellites have carried auroral imagers. Notable examples include Viking [Anger et al. 1987] and Polar [Torr et al. 1995] and most recently IMAGE [Mende et al. 2000a,b,c].

Satellite imagers have advantages and disadvantages when compared to ground based all-sky imagers (ASIs). Satellite imagers operate when it is cloudy, do not suffer from light contamination from the moon or nearby sources like roads, and have much less distortion of the field of view. Also, they give a truly global view of the aurora. However, they do not typically have the temporal or spatial resolution of ASIs. As such, it would be optimal if the two measurements could be operated at the same time. ASIs would provide the small scale details while the satellite imagers would be able to provide the global context.

IMAGE was the most recent satellite to provide global images of the proton and electron precipitation. Because of this, the IMAGE dataset was used extensively in...
this study. The purpose of this chapter is to present an overview of the IMAGE spacecraft and with a specific focus on the far ultraviolet (FUV) imagers. Section 5.2 contains a broad overview of the orbit and instruments of the IMAGE spacecraft. Then section 5.3 contains a more detailed description of the FUV imagers.

5.2 IMAGE spacecraft and instrumentation

The Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) [Burch 2000; Gibson et al. 2000] was NASA’s first MIDEX (Mid-size Explorer) mission. The satellite was launched at the peak of the last solar maximum on March 25, 2000. The orbit was highly elliptical with an apogee over the northern hemisphere of 7.2RE, a perigee of 1000km and the orbital period was 14.2 hours. The satellite was spin stabilized with a rotation period of approximately two minutes. During the 2-year main phase of the mission, the apogee precessed from forty degrees north latitude to ninety degrees north latitude and back. The satellite remained operational after the main phase until the telemetry readings were no longer received after December 18, 2005.

The IMAGE mission is unique in that it was the only satellite mission to collect no \textit{in-situ} data. IMAGE used a number of different techniques to image various aspects of the magnetosphere. The High, Medium and Low Energy Neutral Atom (HENA, MENA and LENA) imagers were designed to image the ring current, inner plasma sheet, substorm injection boundary and polar outflow ions. The Extreme Ultraviolet (EUV) imager primarily imaged the plasmasphere. The Radio Plasma Imager (RPI) was designed to locate regions of different plasma densities by reflecting radio waves at the plasma frequency off the boundaries. Finally, the Far Ultraviolet (FUV) imager was used to image the aurora and geocorona at various wavelengths. Table 5.1 provides a listing of all the instruments onboard the IMAGE spacecraft for
The FUV imager was the only instrument used in this study, and therefore warrants further discussion.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Instrument</th>
<th>Team Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>HENA</td>
<td>High Energy Neutral Atom Imager</td>
<td>Dr. Donald Mitchell</td>
</tr>
<tr>
<td>MENA</td>
<td>Medium Energy Neutral Atom Imager</td>
<td>Dr. Craig Pollock</td>
</tr>
<tr>
<td>LENA</td>
<td>Low Energy Neutral Atom Imager</td>
<td>Dr. Tom Moore</td>
</tr>
<tr>
<td>EUV</td>
<td>Extreme Ultraviolet Imager</td>
<td>Dr. Bill Sandel</td>
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<tr>
<td>RPI</td>
<td>Radio Plasma Imager</td>
<td>Dr. Bodo Reinisch</td>
</tr>
<tr>
<td>FUV</td>
<td>Far Ultraviolet Imager</td>
<td>Dr. Stephen Mende</td>
</tr>
</tbody>
</table>

Table 5.1: Instruments onboard the IMAGE spacecraft.

5.3 IMAGE FUV Overview

The FUV suite [Mende et al. 2000b] on the IMAGE spacecraft consisted of three components that imaged in the spectral band from 120-190 nm. The Wideband Imaging Camera (WIC) [Mende et al. 2000a] imaged the aurora in the entire spectral region from 140-190nm. The Spectrographic Imager (SI) [Mende et al. 2000c] imaged only the Doppler shifted Lyman-α (121.8nm) and the OI 135.6 emission. Finally, the Geocorona Photometers (GEO) were designed to measure the geocoronal Lyman-α (121.6nm). GEO data was not used in this dissertation. One of the design goals for the FUV suite of instruments was to have spatial resolution better than one degree at all times. For all instruments, the entire auroral oval was visible from altitudes upwards of 4 R_E. It is also important to note that the FUV instrument was rigidly fixed to the rotating spacecraft facing outward. As such, only one image could be obtained per revolution which limited the temporal resolution to about two minutes and the time integration for the imagers to approximately ten seconds.
**Wideband Imaging Camera**

A schematic of the Wideband Imaging Camera (WIC) is shown in figure 5.1. The WIC was designed to be sensitive to all the auroral emission lines in the far ultraviolet wavelength band with the exception of the emission lines covered by the SI instrument and the OI 130.4 nm emission due to its high rate of scattering. To that end, the WIC passband was chosen to be 140 nm to 190 nm.

![Schematic of the Wideband Imaging Camera](image)

Figure 5.1: Schematic of the Wideband Imaging Camera on the IMAGE spacecraft. Figure from Mende et al. [2000a] (Figure 1)

Compared to the SI instrument, the WIC was a relatively simple design with some of the parts actually coming from the Viking satellite spares. Details of the Viking FUV imager can be found in Murphree et al. [1994]. The IMAGE WIC had a 30° field of view, however, only a 17° × 17° portion was used for each image. The camera would read data for approximately ten seconds each satellite rotation. Snapshots were taken approximately every 33 μs and then the raw counts were summed taking into account the motion of the field of view of the camera due to spacecraft rotation. Thus, to
produce one image, approximately three hundred frames were superimposed. The downside of this method was that background counts from the CCD could quickly become large. In order to minimize that error, the WIC intensifier had to have a much higher gain than previous imagers.

The WIC was equipped with a 512 × 256 pixel CCD, however, the resultant image (after summing) yielded a 256 × 256 pixel grid due to the spacecraft rotation. From apogee, a single pixel corresponded to an area of 42km × 42km which was significantly better than required by the mission objectives.

**Spectrographic Imager**

A schematic of the Spectrographic Imager (SI) onboard the IMAGE spacecraft is shown in figure 5.2. As noted above, the design goals were to image the Doppler shifted Ly-α proton auroral emission and the OI 135.6 nm emission. The OI 135.6 nm emission is produced by precipitating electrons and it is easily imaged even when present in dayglow. A second, brighter OI emission is at 130.4 nm, however, this emission is scattered in the atmosphere and therefore difficult to image. As such, the SI needed to be able to reject the OI 130.4 nm emission, but image the 135.6 nm emission. the SI-13 instrument was sensitive to wavelengths of 135.5 ± 2.5nm. This passband also meant that the data also included a few nearby LBH bands [Hubert et al. 2002].

The Ly-α emission is more difficult to image from a spacecraft. In order to distinguish the doppler shifted Ly-α from the geocoronal Ly-α, a high resolution spectrometer was clearly needed. The spectrometer also needed to efficiently reject the nitrogen emissions clustered around 120nm.

Constraints on the size and weight of the instrument limited the spectral resolution to approximately 0.2 nm even though higher spectral resolution would have
been preferable since at that resolution a majority of the doppler shifted Ly-\(\alpha\) is not resolvable against the geocoronal background. As such, it is important to note that the instrument was not able to effectively image proton aurora generated by proton precipitating with energies below \(\sim 8\) keV.

In order to satisfy the spatial resolution requirements, the SI aperture was designed to yield a \(15^\circ \times 15^\circ\) field of view. Both of the spectral channels (120.8 nm and 135.6 nm) were equipped with a \(128 \times 128\) pixel CCD. At apogee, this corresponded to a spatial resolution of approximately \(90\) km \(\times \) 90 km.

Pre-flight calibrations showed that the SI instrument met all the requirements for the mission. Specifically, the upper limit on cold geocorona Ly-\(\alpha\) contamination was 2%.
5.3.1 Meteor Impacts

A few times during the satellite’s mission, pieces of the wire booms were lost [Mende 2011] (presumably from meteor impacts). The resulting change in the spacecraft’s center of mass caused some variations in the spin axis of the spacecraft. Fortunately, the FUV flight hardware was designed to handle arbitrary spin, and the images were able to be brought back into focus with minimal data loss. However, the spacecraft had errors in the pointing information after that [Frey et al. 2004] and so the mapped pixels at times may have an error of a few degrees at apogee (much smaller as the spacecraft approached perigee). Even with these errors, the relative positions of auroral features should be minimally affected.
Chapter 6

Statistics of Proton Auroral Splitting from the IMAGE Spacecraft

6.1 Introduction

In chapter 4, we showed that the field line curvature (FLC) model for proton precipitation predicted the azimuthal splitting of the proton aurora when used in the OpenGGCM global MHD model. The splitting corresponded to the substorm current wedge (SCW). Because of the limitations of global MHD models, it is important to validate the MHD predictions with satellite data. Additionally, the proton precipitation code does not include any wave particle interactions. It is entirely possible that wave particle interactions within the SCW could wash out the split region. One final possibility is that the plasma temperature enhancement during substorms could cause the average proton gyroradius to increase to the point where it could scatter even in the less stretched field in the SCW. In this chapter, we use the imagers described in Chapter 5 in an attempt to validate the simulation results.
6.2 Event Selection

The substorms for this study were taken from the original list published by Frey et al. [2004]. The list contains ~ 2400 substorm onsets viewed from IMAGE spacecraft during the first 2.5 years of operation (from May 2000 to December 2002). The criteria for determining a substorm onset used by Frey et al. [2004] was:

1: There had to be a clear local brightening of the aurora.

2: The aurora had to expand to the poleward boundary of the auroral oval and spread azimuthally in local time for at least twenty minutes.

3: The onset had to be separated by at least thirty minutes from a previously identified onset.

Most of the auroral onsets were determined from the WIC images, but occasionally some onsets were identified better in the SI-13 images (both of these instruments are sensitive to the electron aurora). For each substorm, the onset location was determined by the brightest pixel in the auroral bulge. Our substorm list is a subset of the Frey et al. [2004] list.\(^1\) Our acceptance criteria were as follows:

1: **Isolated:** No substorm onsets within 90 minutes

2: **Good Coverage:** The auroral oval had to be in the field of view of the camera for the entire period, and no more than two consecutive missing frames were acceptable.

3: **Clearly Distinguishable:** The substorm onset brightening also had to be clearly distinguishable from the background in the SI-13 (proton aurora).

\(^1\)Data provided by S.B. Mende through NASA’s CDAweb. Software to extract and do coordinate transformations on the data can also be found at CDAweb.
4: No Limb Distortion: The pixel size near the enhanced auroral precipitation could not be severely distorted due to a poor viewing angle.

These criteria are very similar to the event criteria used by Meurant et al. [2007]. From the original list, only 356 events remained after applying the above selection criteria. A large number of the events exhibited longitudinal splitting of the proton aurora similar to the simulations in chapter 4.

While the isotropy boundary latitude (hereafter IBA) is in general dependent on the energy of the precipitating particles (in other words, there is an IBA for 3keV protons and one for 30 keV protons), the IMAGE SI-12 spectrometer was most responsive to protons around 8 keV. Thus, for the remainder of this chapter, IBA corresponds to the isotropy boundary latitude for precipitating protons with energies around 8 keV.

6.3 Longitudinal Splitting

The splitting manifested itself in a number of different ways for different events. During some of the events, the IBA would have a sudden latitude increase in an azimuthally localized region. This often corresponded to a significant reduction in precipitating flux in that region, but not always (assuming that the SI-12 photon counts are proportional to the precipitating energy flux for that event). An example of this splitting is in Figure 6.1. Figure 6.1 shows nine consecutive images from the SI-12 spectrometer arranged from left to right and top to bottom. The first two frames show the onset. By the third frame, the aurora is well expanded. In the fourth frame, the splitting begins to become visible on the onset meridian. The fifth through ninth frames show the continued development of the split region.

One important feature of this event that should be stressed is that a visual inspection of panels two and six in the figure reveals that the splitting occurs very close
Figure 6.1: Example of proton auroral splitting seen by the IMAGE SI-12 spectrometer on March 13, 2001. The images are at taken at a cadence of approximately two minutes.
to the meridian of the most expanded precipitation. In general, this precipitation is co-located in longitude with the westward traveling surge [Mende 2003; Gérard et al. 2004; Hubert et al. 2002]. This is a common feature among the events surveyed in this study.

6.3.1 Quantification of the Splitting

An algorithm was developed to quantify which events were split and which were not split (hereafter referred to as split events and non-split events). Each event was composed of ~90 images (one image every two minutes). Each image was inspected visually to determine whether it looked like a split event or a non-split event. If it appeared to be split, the time between initial splitting and the onset (from the Frey et al. [2004] list) was recorded. We also recorded the maximum width and average expansion speed. These final two values were not actually used except to compare with the mostly automated algorithm described next.

Then, meridian scans were extracted from the data using a natural neighbor interpolation algorithm using from the freely available scientific python distribution (www.scipy.org). The scans were extracted every degree in longitude on the night side of the auroral oval. Each scan was then fit to an equation of the form

\[ \text{Counts}(\phi) = A(\phi)e^{\frac{(\lambda - \lambda_{\text{max}}(\phi))^2}{2\sigma(\phi)^2}} + B(\phi) \]  

(6.1)

where \( \phi \) is the longitudinal coordinate of the scan. This fitting is similar to what was done by Donovan et al. [2003b] and Meurant et al. [2007]. From the form of equation 6.1, it is clear that \( \lambda_{\text{max}}(\phi) \) was the latitude of the maximum precipitation along the scan at \( \phi \). Since not all of the fits did a good job matching the data, fits with \( \sigma(\phi) \) greater than twenty degrees were discarded as having unrealistically expanded
aurora. For the remaining scans, the integral of the photon counts was computed and normalized to the scan length (hereafter \( I(\phi_i) \)). For each image, the average of the \( B(\phi_i) \) was taken to be an estimate for the background counts. After that, the \( I(\phi_i) \) were passed through a simple boxcar averaging filter to smooth the data so that local maxima and minima could be more easily detected. The filtered data will be referred to as \( I_f(\phi_i) \). The size of the boxcar was ten degrees. An interactive computer program was then used to find the local maximum of the \( I_f(\phi_i) \) nearest a mouse click on the auroral image. (Hereafter, the subscript \( f \) and functional dependence on \( \phi \) have been dropped for simplicity). Two local precipitation maxima \( (I_{\text{west}} \text{ and } I_{\text{east}}) \) were selected for each image and the computer program found the deepest local minimum \( (I_{\text{min}}) \) between the two maxima. The splitting index was defined as:

\[
\Delta I_{\text{west,east}} = I_{\text{west,east}} - I_{\text{min}} \\
SI = \frac{\min(\Delta I_{\text{west,east}})}{\text{counts}_{\text{background}}} 
\]

(6.2)

The mean of the \( B(\phi_i) \) for a given image was taken to be \( \text{counts}_{\text{background}} \). The computer program then computed the meridian where \( I_{\text{min}} \) had risen by half the corresponding \( \Delta I \). The difference between these two meridians was recorded as the split width. Figure 6.2 shows a simple schematic for how the algorithm works.

A few other algorithms were experimented with. One promising algorithm used the maximum of the photon counts (instead of the integrated counts along a meridian). However, that did not work well for events where there was a significant increase in the IB\(\lambda\) but not necessarily a large reduction in precipitation. (A good example of this is the fourth row in Figure 4.27). A second algorithm briefly experimented with was using the IB\(\lambda\) algorithm defined by Donovan et al. [2003b] and used by Meurant et al. [2007] with IMAGE SI-12 data. In this algorithm, the IB\(\lambda\) is assumed to be 1.4 \( \sigma \) lower than \( \lambda_{\text{max}} \) for each \( \phi_i \). Using that, we tried to look for poleward jumps
Figure 6.2: Schematic of how the Splitting Index algorithm works. The integrated counts along each meridian (red dots) are passed through a simple boxcar averaging filter (black line). The depth and width of the split region were then defined as shown above and the splitting index was computed according to equation 6.2.
in the IB\textsubscript{4}, however that algorithm failed in regions where the maximum intensity became comparable to the background (i.e. the center of the split region). The above algorithm seemed to perform reasonably well in both of these cases.

![Figure 6.3: Maximum Splitting Index vs. AL index. The red circles indicate events which were tagged as split in a visual inspection. The blue squares indicate events which were tagged as not-split in the visual inspection. The horizontal blue (red) line indicates the upper (lower) quartile of the not-split (split) events.](image)

To compare the above algorithm with the results from our visual inspection, the SI values were averaged with the SI values of temporally adjacent frames (i.e. a temporal boxcar average) to reduce the effect of a single bad image. We then plotted each event’s maximum (averaged) SI value against the minimum (provisional) AL for the entire event interval. The results are plotted in Figure 6.3. The blue squares represent events which were tagged as not-split during the visual inspection, and the red circles were marked as split during the inspection. The horizontal blue line marks the upper quartile of the not-split events and the horizontal red line marks
the lower quartile of the split events. From this, we place the boundary between split and not-split events at an SI value of 1.2. For the remainder of our analysis, we removed the quartiles in disagreement and the ambiguous events in between the quartile boundaries (i.e. the events between the blue and red lines in Figure 6.3) leaving 264 events.

### 6.4 Results

Of the 264 events, 128 (48%) showed clear auroral splitting from the SI index and our visual inspection. One striking feature of Figure 6.3 is that there is a reasonably strong dependence ($r=-0.53$) of the SI on the AL index. The average AL of the split events was -614nT while the average AL of the not-split events was -293nT. The 63 events with AL lower than -600nT split 94% of the time, whereas the 51 events with AL higher than -200nT split only 6% of the time. This can be seen more clearly from the histogram in Figure 6.4. The events are binned in 100nT AL bins, with blue bars representing the not-split events and red bars representing the split events.

Another observation, readily available from the Frey et al. [2004] list is the latitude of the onsets. In general, the latitude of the onsets in our list correlate very well with the AL ($r=.61$) as shown in Figure 6.5. The linear regressions are also shown for the split and not-split events independently.

The split events and not-split events had average onset latitudes of 63.2° and 65.9° and were distributed as shown in Figure 6.6. This histogram is of similar form to Figure 2 in Frey et al. [2004] (with a small decrease in events around 64.5° due to the ambiguous events we removed for this study). Thus, it is assumed that the events used in this study are representative of all the events in the Frey et al. [2004] list.

The fact that the onset latitude is well correlated with the provisional AL index is not surprising. Lower latitude onsets should correspond to a larger auroral oval which
FIGURE 6.4: Histogram of the number of events with SI $\geq$ 1 (red) and SI $< 1$ (blue) binned by 1000 bins.

The number of events decreases as the SI value increases.
Figure 6.5: AL dependence of onset latitudes for our list of events. Red circles (Blue squares) are split (not-split) events. The red and blue lines are the linear regressions for the split and not-split events respectively. The black line is the regression for all the datapoints.
Figure 6.6: Latitude Distribution of split (red) and not-split (blue) events

is indicative of more magnetic flux stored in the lobes. Since these events have more flux to reconnect, it is sensible that they would typically drive larger field aligned currents (FAC) due to larger pressure gradients and magnetic shear [Birn et al. 2004; Ge et al. 2011; Lui 1996] from enhanced earthward convection and/or flow vortices [Keiling et al. 2009]. As those FAC systems close in the ionosphere, they induce equatorward perturbations of the magnetic field which is measured by the AL index.

In this study, we measured the split region as a function of time. The maximum width of the split region is also moderately anti-correlated with the AL index (r=-0.4) and similarly, the width was also anti-correlated (r=-0.38) with the onset latitude (Figure 6.7).

Since the average time from the initial splitting until the maximum width was realized was seventeen and a half minutes (~8 frames), we were able to produce an
Figure 6.7: Dependence of the maximum width of the split region on AL (Top Panel) and onset latitude (Bottom Panel) In both cases, the trend is toward larger split regions as the AL or onset latitude decrease. The horizontal lines are the averages of all the values in the corresponding bins.
estimate for the azimuthal expansion speed of the split region (Figure 6.8). The expansion speed was mostly uncorrelated with the AL index and the onset latitude. However, from Figure 6.8, it is easy to see that the expansion speed is generally limited to four degrees per minute with an average around 2.2 degrees per minute. If these expansion rates are mapped radially to the SCW at geosynchronous orbit, then the SCW expands at an average rate of \(27 \frac{\text{km}}{s}\). Rarely would the SCW be able to exceed expansion rates of \(50 \frac{\text{km}}{s}\). Also note that the above algorithm allows for the spatial extent of the split region to be measured within the accuracy of the SI-12 resolution every two minutes. If the split truly maps to the SCW, the SI algorithm provides expansion rates at a much higher cadence and spatial resolution than can be provided by GOES satellites.

The final measurement we made for this study was the time from onset (as listed in Frey et al. [2004]) until the first splitting was realized (hereafter \(\Delta t\)). This was the measurement where there was the most significant deviation between the visual inspection of the proton auroral images and the SI algorithm. The discrepancy is clearly illustrated in Figure 6.9. The median \(\Delta t\) was twelve to fourteen minutes for the SI algorithm whereas it was only four to six minutes in a visual inspection of the data. Also, events with a lower AL tended to split sooner than events with a higher AL (Figure 6.10).

### 6.5 Discussion

#### 6.5.1 Differences between visual inspection and SI algorithm

The results from the SI algorithm agreed well qualitatively with the results of the visual inspection. However, there was some quantitative disagreement. As already mentioned, the time from onset to initial splitting (\(\Delta t\)) was much slower using the
Figure 6.8: Average expansion speed of split region dependence on AL (Top Panel) and onset latitude (Bottom Panel). The average expansion speed is 2.2 degrees per minute and is largely uncorrelated with AL and onset latitude.
Figure 6.9: Time from onset (as listed by Frey et al. [2004]) until initial proton auroral splitting in a visual inspection (Top Panel) and from the SI algorithm described in section 6.3.1 (Bottom Panel). Clearly, the SI algorithm is very slow (conservative) in picking out the splitting.
Figure 6.10: Time from onset until first splitting as determined by the SI algorithm. Horizontal lines are average values in each bin.
SI algorithm as compared to the visual inspection. The sluggishness of the SI was probably due to the longitudinal averaging of the data necessary to smooth out the variation from one scan to the next in order to be able to find the local maxima of the noisy data. Each point was the average of ten degrees of data, and as such, local maxima and local minima of the raw data tended to become less extreme, especially in regions of sharp gradients. In any event, it is clear that the SI algorithm does not do a particularly good job when the split region is small.

A second difference is that the width is significantly larger when computed by the SI algorithm. This is most likely due to the automated method used to determine the width (see Figure 6.2). The method was designed assuming that there would be a sharp boundary between the region of proton precipitation and the split region. However, that was not always the case. The width was probably most affected during times when there was a steady increase in proton aurora from the local minima inside the split region to the maxima on either side. The algorithm may be improved if the maximum of the gradients in the integrated counts \( I_f(\phi_i) \) were computed on either side of the local minima and the corresponding \( \phi_i \)'s used to calculate the width.

Remarkably, the visual inspection and the SI algorithm yielded nearly identical distributions for the expansion speed. This may imply that the expansion speed is roughly constant over the course of an event since the SI algorithm systematically omits the early stages of the splitting.

### 6.5.2 Relationship to the Substorm Current Wedge

The expansion rates of the proton auroral split region calculated in this study are very consistent with events studied by others [Belehaki et al. 1998; Watson and Jayachandran 2009, and references therein]. Additionally, stronger substorms (lower AL) typically have more open/lobe flux to reconnect as indicated by their lower on-
set latitudes. That flux gets reconnected and piles up to form the substorm current wedge (SCW). It is reasonable that the events with more flux to reconnect would have larger SCWs. This general relation can be seen in Figure 6.7. Of course, this simple explanation neglects the radial expansion of the SCW and also complicated magnetosphere-ionosphere coupling which can have significant influence on the magnetospheric convection.

In general, we can only expect the proton aurora to correspond to the SCW in regions where the magnetic field curvature dominates all the other parameters which influence the scattering. In other words, wave-particle interactions must not play a significant role and the particle gyroradii must stay below a critical threshold which is a function of the radius of curvature. Since energetic particle injections are routinely observed by geosynchronous spacecraft near substorm onset, it is entirely possible that the particle energization is responsible for the large spread of split widths seen in Figure 6.7. In those strong substorms, it is likely that only the inner portion of the SCW is dipolar enough to prevent scattering whereas the outer portion is still stretched enough to scatter the highly energized particles. This is probably also the case during weak substorms. For these events it is likely that they do not dipolarize as completely as their stronger counterparts and therefore the $k$-scattering can continue. This probably explains why the proton aurora during weaker substorms splits less frequently as shown in Figures 6.4 and 6.6. Alternatively, it is possible that the simple picture of the SCW is not valid for all substorms.

It is difficult to make any definitive statements about the timing of the proton auroral splitting relative to the development of the SCW. There are a few reasons for this. First, as mentioned in the previous paragraph, if the SCW is only marginally dipolarized but the particles are energized, the scattering is still able to proceed efficiently. Second, sharp precipitation boundaries in the magnetosphere do not cor-
respond to sharp auroral boundaries for the proton aurora since the emitting particles spend some of their time as energetic neutral hydrogen atoms (see Section 1.2 and Figure 1.4). This can cause auroral precipitation boundaries to be smeared out over a few degrees in longitude. Finally, relative to electrons, protons are very slow. It can take an 8keV (field aligned) proton on the order of forty seconds to reach the ionosphere from geosynchronous orbit (see section 3.3). As such, there is a lag between magnetospheric processes and their ionospheric projections if the information is being carried by protons. Keeping the last two points in mind, a time delay of a couple minutes between the onset and the first observable splitting of the proton aurora is not unreasonable. For the events which take longer than that, some other explanation (particle energization or wave particle interactions) must be invoked to explain the delay in splitting.

6.5.3 Additional Remarks

The SI algorithm presented above only required a significant decrease in the amount of precipitation between to sufficiently separated meridians to classify an event as split. In the observed split regions, the precipitation was frequently (but not always) reduced to near the background counts. This is probably because even in the most dipolar part of the SCW, the substorm particle injection accelerates a small portion of the distribution to the point where it can satisfy the $\kappa$-scattering criteria.
Chapter 7

Results and Conclusions

7.1 Summary of Important Results

The significant results presented in this dissertation are as follows:

7.1.1 Global proton precipitation simulation

We have created a simulation of the global nightside proton precipitation. The simulation is based solely on the $\kappa = \frac{2e}{\rho}$ scattering mechanism proposed by Sergeev et al. [1983]. Since wave-particle interactions are not included in the code, dayside and flank precipitation is generally not included. In substorm simulations, the code reproduces the major features expected (brightening, poleward expansion, equatorward drifting during the growth phase, etc.). Also, in general, the simulated proton precipitation is displaced equatorward of the simulated discrete electron precipitation at local times westward of the onset. Eastward of the onset, the simulated proton precipitation is displaced poleward of the discrete electron precipitation. In other words, the ordering of the auroral precipitation is the same as the ordering of the region 1 and 2 field aligned currents (with proton precipitation corresponding to downward current). This agrees with the statistical study of Mende [2003]. In the substorms simulated
for this study, the isotropy boundary of the proton precipitation maps to about 7 or 8 \( R_E \).

### 7.1.2 Azimuthal splitting of the proton precipitation

We then presented the proton precipitation from three substorms simulated by the OpenGGCM. In the first simulation (March 23, 2007), the global proton precipitation split near the 01:30 MLT meridian. To our knowledge, this feature of the proton aurora has not been reported in the literature previously. The split resulted in proton precipitation traveling with the westward traveling surge (WTS), but also in a second region of significant proton precipitation forming an analogous eastward traveling surge. We then showed that the simulated proton precipitation maps to a stretched region in the tail adjacent to the substorm current wedge (SCW). There is, however, a reasonable amount of ambiguity in choosing a substorm onset time since the explosive auroral expansion and brightening are delayed compared to the drop in simulated AL (and other onset signatures). Since the proton aurora typically brightens simultaneously with the electron aurora at onset, the simulation timing of the proton precipitation is questionable for this event. Unfortunately, there was no good proton auroral data for this event, therefore more simulations were performed to see if the same result would hold.

The simulation for April 28, 2001 showed similar results. The splitting was caused by the increase in flux and \( R_c \) in the highly dipolarized SCW. The simulation reproduced the observed splitting getting the approximate width correct. However, the comparison of the simulated substorm to the auroral images was not ideal. The location of the onset was inconsistent with observations. Also, the timing of the proton precipitation splitting compared to the timing of the onset was not entirely consistent. Part of this discrepancy was attributed to a prior substorm in the model that was
not present in the observations. However, assuming the proton precipitation code is correct, the simulation shows that the splitting of the proton aurora can be delayed due to highly energized plasma left over from a previous substorm.

Finally, a simulation for the January 31, 2001 substorm had good comparison with data in the magnetosheath (Cluster), at geosynchronous (GOES) and between the simulated proton precipitation and IMAGE SI-12 data. The OpenGGCM was shown to also well reproduce the observed auroral indices. The auroral onset signatures were also similar in the model compared to the IMAGE data (with a time shift of approximately fifteen minutes). Similar to the April 28, 2001 substorm, the simulation reproduced the observed splitting reasonably well (especially in the early expansion phase for this event). Once again, the splitting was arrested in the highly dipolarized region of the SCW.

It is important to point out that somewhat dipolarized regions of the inner magnetosphere were still able to satisfy the $\kappa$-scattering criteria due to increased temperature for the January 31 simulation and the April 28 simulation. Thus, the simulation predicts that the proton precipitation splitting corresponds to the most dipolarized portion of the SCW.

To further validate the predictions of the MHD model with observed data, we examined 356 isolated and high quality substorms that were observed by the IMAGE FUV imagers. The splitting did not happen for every substorm, and the splitting was not always complete. For some substorms (as was the case for the January 31, 2001 substorm), there would be an increase in the latitude of the proton isotropy boundary for an azimuthally localized region. In order to quantify the splitting, we developed a splitting index (SI) based on the integrated proton aurora along 180 meridians on the night side of the auroral oval. A comparison of the SI with a visual inspection of the data showed that the boundary between split and not-split events was at SI=1.2.
Using 264 of the above events, we showed that the proton aurora during stronger substorms (lower onset latitude and AL) was much more likely to split. For the split events, we also measured the width of the split region and the average expansion speed of the split region. The average expansion speed was 2.2 degrees per minute and the expansion speed was uncorrelated with AL or onset latitude. Almost all of the events had expansion speeds below 4 degrees per minute, but a couple had expansion speeds much higher. The expansion speeds presented here agree well with expansion speeds for the SCW presented by Belehaki et al. [1998] and with statistical results from Watson and Jayachandran [2009]. Also, the splitting (based on the visual inspection of the data) occurred about six minutes after onset on average. This timing and other features of the split region are consistent with a model where the split is an ionospheric projection of the most dipolarized region of the SCW when the proton transit time and beam spreading effects are taken into account.

7.2 Conclusion

We have shown that the azimuthal splitting of the proton aurora occurs for nearly 50% of substorms (with a much larger percentage splitting during periods when the westward electrojet is more significantly enhanced). Using a combination of simulation and observations, we assert that the split region maps to the most dipolar region of the SCW. The fundamental assumption is that wave particle interactions are unimportant to the scattering of nightside protons. Indeed, in our simulations, wave particle interactions were unnecessary to reproduce most of the observed features of the nightside proton aurora. The statistical study of proton auroral splitting is also consistent with the assertion that wave particle interactions are unimportant to the global nightside proton auroral morphology.
7.3 Future Work

There are a number of studies which can be done to build upon this work. As mentioned in Chapter 4, the January 31, 2001 substorm has significant activity at the poleward boundary at the midnight meridian prior to the actual auroral onset. The simulation of that event also has similar activity near the midnight meridian. In light of the recent studies by Nishimura et al. [2010c,a], it would be very interesting to see if the PBI and the substorm onset are related in any way. It would also be interesting to find the origin of the PBI in the simulation as the origin of the PBI is still an open question in the model proposed by Nishimura et al. [2010b].

With the Radiation Belt Storm Probes (RBSP) mission scheduled to be launched in 2012, much of the focus in the space science community is moving toward studying the inner magnetosphere. As such, the two-way coupling between the OpenGGCM and CRCM models is a high priority. Once the coupled model has been stabilized and verified, the proton precipitation code will immediately benefit since the OpenGGCM inner boundary conditions will be computed more self-consistently. Currently the inner boundary temperature and density are constants, however in the coupled model, the CRCM will provide the inner boundary density and temperature to the OpenGGCM. This is particularly important for the energy flux calculation in the proton precipitation model. Since the parameters (density and temperature) are taken near the inner boundary, it is expected that the inner boundary conditions would have significant influence. Also, the CRCM will be able to model the substorm particle injections. The pressure feedback will improve the plasma temperature used by the proton precipitation code. Additionally, the CRCM includes the gradient curvature drifting which may or may not influence the distribution function near the
isotropy boundary. Finally, the inclusion of the ring current should influence the simulation mapping.

A series of important questions about substorm particle injections will be able to be studied with the coupled global magnetosphere simulation and the proton precipitation code. During substorms, there is a sudden injection of high energy protons observed by LANL and other satellites. The origin of these particles is not well understood. They may (or may not) be related to the dipolarization of the near earth magnetic field and the energization may (or may not) be adiabatic. Auroral signatures of particle injections have recently become an active area of research [Spanswick et al. 2009; Sergeev et al. 2010]. The proton auroral code with the coupled OpenGGCM-CRCM will provide a platform to attempt to connect auroral proton signatures with the particle injections.

Finally, the isotropy boundary (IB) of the simulated proton precipitation during the substorms presented in this dissertation were consistently near 7 or 8 RE. The radial distance of the IB in the tail is still an open question which is important to put other (poleward) observations in context. However, since the simulated inner magnetosphere does not include any ring current physics, the mapping and degree of magnetic field stretching in the inner magnetosphere may not be correct. The two-way coupled model used in conjunction with the proton precipitation code should provide a more realistic solution.

The proton precipitation code does not need to wait for the two-way coupling between OpenGGCM and CRCM to continue to be useful for other science projects. One project currently under way is showing that the proton precipitation may be enhanced in an azimuthally localized region due to the compressional heating (from an MHD perspective) of the plasma ahead of a strong dipolarization front.
Additionally, up to this point, the proton precipitation code has only been used to study substorms. It would be interesting to see if there is any interesting structure in the global proton precipitation during other types of geomagnetic activity (steady magnetospheric convection for example).
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130


134


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135


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